ARE MAGNETIC WIND-DRIVING DISKS INHERENTLY UNSTABLE?

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ABSTRACT

There have been claims in the literature that accretion disks in which a centrifugally driven wind is the dominant mode of angular momentum transport are inherently unstable. This issue is considered here by applying an equilibrium-curve analysis to the wind-driving, ambipolar diffusion-dominated, magnetic disk model of Wardle & Königl (1993). The equilibrium solution curves for this class of models typically exhibit two distinct branches. It is argued that only one of these branches represents unstable equilibria and that a real disk/wind system likely corresponds to a stable solution.

Subject headings: accretion, accretion disks – galaxies: jets – ISM: jets and outflows – methods: analytical – MHD

1. INTRODUCTION

The ubiquity of energetic and highly collimated jets in compact astronomical objects (ranging from young stellar objects to active galactic nuclei) is often interpreted in terms of a universal mechanism: hydromagnetic outflows from accretion disks (e.g., Livid 2000). A pioneering paper that presented semi-analytic self-similar solutions for centrifugally driven outflows, Blandford & Payne (1982) demonstrated that such jets could efficiently transport angular momentum from the underlying disks and suggested this as an alternative mechanism to the radial viscous angular-momentum transport that has traditionally been invoked in accretion-disk models. Königl et al. (1988) and Wardle & Königl (1993, hereafter WK93) subsequently incorporated the disk into the self-similar wind model and suggested that the apparent connection between disks and jets may at least in part be a reflection of the fact that the vertical magnetic angular-momentum transport is a necessary ingredient in the accretion process. Additional semi-analytic models have since been constructed by several authors (e.g., Ferreira & Pelletier 1993, 1994, 1995; Ferreira 1994, 1995; Livid & Payne 1992; Li 1995, 1996; Livid 1998, 2001; Casse & Ferreira 2000ab; Casse & Ferreira 2004) and have served to refine our understanding of the equilibrium configurations. However, the stability of the derived disk/wind solutions is still being debated.

WK93 and Königl & Wardle (1996) argued that wind-driving disks should be immune to the most powerful cataloged disk instabilities. In particular, they pointed out that disks in which a centrifugally driven outflow transports all the liberated angular momentum naturally into a stability “window” in which the magnetic field is strong enough not to be affected by the magnetorotational instability (e.g., Balbus & Hawley 1998) but is not so strong as to be subject to a radial interchange instability (e.g., Spruit et al. 1995). However, Lubow et al. (1994, hereafter LPP94) suggested that magnetic wind-driving disks may nevertheless be inherently unstable. Based on a simplified model, they derived two relations between the mass outflow rate per unit area and the inflow speed at a given disk radius: one of these relations yielded an S-shaped curve and the other a monotonically increasing curve. LPP94 argued that disks that lose angular momentum smoothly at all radii through a wind that removes only a small fraction of the inflowing mass correspond to the two curves intersecting in the middle portion of the S curve and are therefore unstable. This derivation was questioned by Königl & Wardle (1996), who argued that the equilibrium model adopted by LPP94 was overly simplified. In particular, they applied the LPP94 prescription to the more comprehensive model considered by WK93 and showed that both of the resulting equations for the mass outflow rate were independent of the inflow speed and therefore did not yield the equilibrium curves invoked in the LPP94 argument.

This issue was recently revisited by Cao & Spruit (2002, hereafter CS02), who carried out a linear stability analysis on an approximate equilibrium disk model. CS02 derived a WKB dispersion relation and used it to infer that magnetic wind-driving disks are unstable if the wind torque is strong or (when the torque is weak) if the rotation is close to Keplerian, but that magnetic diffusion stabilizes the disk if this torque is small. As interpreted by LPP94 and CS02, the instability reflects the sensitivity of the outflowing mass flux to changes in the inclination of the magnetic field at the disk surface: a perturbation increasing the inflow speed causes the poloidal field to be bent closer to the disk surface, giving rise to a higher mass loss and thereby a higher angular momentum loss; this, in turn, allows more mass to flow in, leading to a further increase in the inflow speed.

Although the equilibrium configuration examined by CS02 contains more of the relevant physics than the model adopted by LPP94, it is still unclear to what extent the approximations made in that work have impacted the final result. For example, the field line shape used in determining the location of the sonic point and thence the mass outflow rate was not calculated self-consistently. This is reflected in the fact that its adopted form does not have an inflection point near the disk surface — as it should based on the WK93 results. Furthermore, the normalized magnetic torque at the disk surface (\( T_m / \eta V_r / 2V_K \)) is equal to \( V_r / 2V_K \) (where \( V_r \) is the mean radial inflow speed and \( V_K \) is the Keplerian rotation speed), which is typically \( \ll 1 \) even in disks where the magnetic torque dominates the angular momentum removal (e.g., WK93). On the other hand, the normalized diffusivity parameter \((\eta)\) in the notation of CS02) is typically \( O(1) \) in steady-state disks where the diffusivity balances the inward advection of the field by the accreting matter.\(^1\) Since, accord-
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ing to the CS02 analysis, low-$\tilde{T}_{\mathrm{m0}}$ and high-$\eta$ disks are stabilized by magnetic diffusivity, it is unclear whether one could conclude that real disk/wind systems are unstable even if one were to accept the CS02 results.

Numerical simulations offer a potentially effective means of resolving the stability question. However, global numerical studies of a magnetic wind-driving disk incorporating a magnetic diffusion mechanism that enables the system to reach a steady state have only recently become feasible (e.g., Casse & Keppens 2003, 2004). The results reported to date are indicative of stability in that they show that the disk/wind system evolves to a near-stationary state, but they clearly do not yet settle the issue. In an attempt to shed more light on the problem, this paper adopts the equilibrium-curve approach first used by LPP94 but applies it to a more comprehensive physical model. In particular, using the disk/wind solutions of WK93 (§ 2) see also Li 1995, 1996, it is demonstrated (§ 3) that not all equilibrium disk/wind structures are unstable. It is then argued (§ 4) that real disks likely correspond to stable configurations.

2. EQUILIBRIUM DISK/WIND MODEL

Although the WK93 model involves a number of simplifications, it incorporates the full set of structure equations for the disk and the wind and thus may be expected to capture the basic features of an accretion flow in which the angular momentum is removed through a centrifugally driven wind. The model assumes a steady-state, axisymmetric and geometrically thin disk that is in near-Keplerian rotation around a central mass. The disk is threaded by a large-scale, open magnetic field $\mathbf{B}$ that is symmetric about the midplane (where $B_r = B_z = 0$, using cylindrical coordinates $r$, $\phi$, $z$). In anticipation of an application to protostellar systems, the disk is taken to be weakly ionized. In the solutions presented in this paper it is assumed that the field is “frozen” into the ion/electron component and influences the dominant neutral component through ion–neutral collisions (resulting in a relative drift — referred to as ambipolar diffusion — between the ions and the neutrals). In these solutions it is also assumed that the relative drift between ions and electrons (associated with the Hall term in Ohm’s law) and the radial motion of the field lines both vanish.\footnote{WK93 demonstrated that solutions with a nonzero midplane radial ion speed $V_{i,0}$ do not differ qualitatively from those in which the field lines do not move radially. The actual situation depends on the global structure of the star/disk system and may evolve with time. Note, however, that in the disk formation model presented in Krasnopolsky & Königl 2002 the rotationally supported, diffusive disk solution satisfies $V_{i,0} = 0$.}

The disk structure is obtained by solving the mass conservation relation as well as the radial, vertical, and azimuthal components of the momentum equation for the neutrals, assuming isothermality. The ion number density is determined from ionization balance considerations. To further simplify the problem, WK93 considered the molecular-gas regime where the ion density is constant ($n_i \approx 0.5$ cm$^{-3}$); this should typically be applicable on protostellar disk scales $\sim 10^4$ AU, where the disk column density is sufficiently low that cosmic rays can be assumed to penetrate and ionize the entire vertical column. In view of the postulated low ionization the ion momentum equation is approximated by equating the ion–neutral collisional drag to the Lorentz force. The model also incorporates the azimuthal and poloidal components of the induction equation as well as the condition $\nabla \cdot \mathbf{B} = 0$. WK93 restricted attention to a narrow radial band centered on a given radius $r$ and matched the disk solution to a radially self-similar wind model, but very similar results are obtained when a global self-similar model for both the disk and the wind is considered (Li 1996).

For specified values of $V_K$, isothermal sound speed $C$, and midplane mass density $\rho_0$, the disk solution at radius $r$ is determined by the values of the neutral–ion coupling parameter $\eta$, defined as the ratio of the (Keplerian) dynamical time to the neutral–ion momentum-exchange time $\tau_{\mathrm{m}} \propto 1/n_i$, the magnetic field strength parameter $a \equiv V_{i,0}/C = B_0/(4\pi \rho_0)^{1/2}C$ (where $B_0$ is the field amplitude at $z = 0$), which gives the ratio of the midplane Alfvén speed $V_{\mathrm{A},0}$ to $C$, and the inflow-speed parameter $\epsilon \equiv -V_{i,0}/C$. The solutions derived by WK93 correspond to the “strong coupling” regime: $\eta > 1$ at all heights. In this case the thermal pressure is not much larger than the magnetic pressure at the midplane (i.e., $a$ is not $< 1$), $B_0$ starts to increase near $z = 0$ and by the time the disk surface (subscript $s$) is reached it generally exceeds $|B_{0,1}|$ (leading to a strong magnetic squeezing of the disk), and the midplane inflow speed is typically of the order of $C$ (i.e., $\epsilon \sim 1$). Li (1994; see also Wardle 1997) showed that “weakly coupled” disk configurations, in which $\eta < 1$ over the bulk of the vertical column, are also possible. In this case $a$ can be $< 1$, $B_0$ only starts to grow well above the midplane (after $\eta$ comes to exceed 1), with $B_{0,1}/|B_{0,1}|$ usually remaining $< 1$ and magnetic squeezing being relatively unimportant, and the mass-averaged inflow speed is typically $\ll C$. Krasnopolsky & Königl (2002) argued that the latter type of disk is likely to arise in the gravitational collapse of a rotating, magnetic, molecular cloud core; however, in this paper attention remains focused on the strong-coupling solutions constructed by WK93.

In the WK93 derivation, the disk solution is matched to the “cold” radially self-similar centrifugal wind solution of Blandford & Payne (1982) by imposing continuity of the mass flux and of $B_r$ and $B_\phi$ at the nominal disk surface (the height where the disk radial electric field component is equal to $-V_r B_r/c$, which is required to lie above a density scale height in the disk). The details of the transition between the diffusive disk interior and the highly conducting wind gas are not considered in this model, and neither is the possibility of heat injection in a disk corona.\footnote{The implications of gas heating above the disk surface have been discussed by Casse & Ferreira 2000, and Ferreira & Cassé 2004; see also Ogilvie & Livio 1998, 2001.} Although these issues are relevant to the determination of the precise range of parameter values that give rise to viable solutions (see § 4), they do not affect the basic properties of the equilibrium curves obtained in the WK93 model. This is verified, inter alia, by the fact that the extension of the WK93 disk solution above the nominal disk surface has similar characteristics to those of the base of the Blandford & Payne (1982) wind solution. Any model refinements that focus on the transition region between the disk and the wind should therefore have no significant effect on the stability analysis carried out in § 3.

The wind model incorporates the Bernoulli and transfield (Grad-Shafrotnov) equations and its solution yields the flow and magnetic field structures above the disk. The wind model parameters are $k$ — the normalized mass-to-magnetic flux ratio, $\lambda$ — the normalized total (particle and magnetic) specific angular momentum, and $B_{1,d}/\tilde{B}$; however, the condition that $B_{1,d}/\tilde{B}$
the wind pass through the Alfvén critical point reduces the number of independent parameters to two. Since $\kappa$ and $\lambda$ can be expressed in terms of the disk solution variables, the Alfvén constraint serves to reduce the number of parameters in the underlying disk model as well. The disk outflow is also required to pass through a “sonic” critical point — this yields the ratio of the “sonic”-point density to the midplane density, which enters into the relationship between the wind and disk parameters.

Figure 1 (which reproduces Fig. 11 in WK93) shows the mapping between the disk and wind solutions obtained in the WK93 model. For given values of $\eta$ and $C$, the disk solutions lie along a double-branched curve in the $\kappa - \lambda$ wind parameter space. The solutions along each curve are parameterized by $a$, which increases from a value $\ll 1$ at the lower-right end of the upper branch to a value $\sim 1$ at the lower-right end of the lower branch. The lower branches of the solution curves end on the long dashed curve, below which the outflows remain sub-Alfvénic, whereas the upper branches end on the short-dashed curve, to the right of which the surface layers of the disk are super-Keplerian. As noted in WK93, $|B_{\phi,x}|/B_z$, and hence the magnitude of the angular momentum that the outflow must carry away, increases with decreasing $a$. Initially, as $a$ decreases from $\sim 1$, $B_{\phi,r}/B_z$ (which scales approximately as $1/a$) increases rapidly, and the corresponding increase in the cylindrical radius of the Alfvén point (the effective lever arm for the back torque exerted by the outflow on the disk, which scales as $\lambda^{1/2}$) increases the value of $\lambda$ and leads to a reduction in the ratio of the mass outflow to the mass inflow rates (estimated as $M_{\text{out}}/M_{\text{in}} \approx 1/[4(\lambda-1)]$). However, as $a$ continues to decrease, the rate of increase of $B_{\phi,x}/B_z$ declines while that of $|B_{\phi,x}|/B_z$ increases, and eventually the mass outflow rate must start to increase (with $\lambda$ going down) to keep up with the angular momentum removal requirements. The transition between these two modes of enhanced angular momentum transport: predominantly by the lengthening of the lever arm (on the lower branch) vs. mainly by a higher mass-loss rate (on the upper branch) occurs at the turning point of the solution curve.

### 3. STABILITY CONSIDERATIONS

A turning point in the equilibrium curve typically signals a change in the stability properties of the corresponding solution. The usefulness of this approach to the disk/wind solutions shown in Figure 1 is perhaps best demonstrated by replotting the curves in the $\lambda - a$ parameter space (Fig. 2, based on Fig. 12 in WK93). In analogy with thermal stability analyses, one may think of the parameter $a$ as representing temperature, the equilibrium value of which is determined by the balance between heating and cooling. Within the framework of the WK93 formulation, in which the midplane density is time independent but the field lines can potentially undergo a secular radial drift, the variation of $a \propto B_0/\sqrt{\rho_0}$ is determined by that of $B_z$ and is governed by the competition between inward advection and outward diffusion (the analogs of cooling and heating, respectively). Specifically,

$$\frac{\partial B_z}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (r V_r B_z) ,$$  

where $V_r = V_z + V_{\phi,r}$. For the solutions shown in Figures 1 and 2, the advection term $V_r$ exactly balances the ion–neutral diffusion handled using the generic Ohmic form and a turbulent-diffusivity parameterization.

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5 WK93 approximated the outflow at this point as still being largely diffusive, in which case the relevant “sonic” speed is the thermal speed of sound. If, however, the ions and neutrals are sufficiently well coupled to effectively form a single fluid at this location, then the critical point corresponds instead to the slow-magnetosonic point (if the shape of the field lines at the “sonic” point is assumed to be given; e.g., [Ogilvie 1997]) or the modified slow-magnetosonic point (if the transfield equation is also included in the calculation — e.g., [LW 1995, Vlahakis et al. 2000]).

6 See Fig. 3 in [L 1995] for the analogous result when the global self-similarity solution is extended to also encompass the disk, with the field diffusion handled using the generic Ohmic form and a turbulent-diffusivity parameterization.

7 It is instructive in this regard to compare the present discussion of the stability properties of the WK93 magnetic disk model with Bell & Lin’s 1993 analysis of the thermal ionization instability in viscous protostellar accretion disks using the disks’ equilibrium vertical structure curves.
drift velocity $V_{D,r}$ at $z = 0$, so the midplane radial ion velocity vanishes along the equilibrium curves.\textsuperscript{8}

In the case of a self-similar disk that matches onto the wind solution, $r V_{r}, B_{z}$ scales as $r^{-3/4}$ (e.g., Krasnopolsky & Königl 1996) and hence the right-hand side of equation (1) when evaluated at $z = 0$, has the same polarity (positive or negative) as $V_{r,\phi}$. This implies that the value of $a$ will decrease with time if advection dominates diffusion, which is consistent with the physical picture of inward gas motion bending the field lines and giving rise to a higher value of $B_{r,\phi}/B_{z} \propto 1/a$. The polarity of $V_{r,\phi}$ in turn depends on the relative magnitudes of the advection ($<0$) and diffusion ($>0$) terms. One can estimate the values of $V_{r}$ and $V_{D,r}$ from the angular momentum and radial ion momentum equations, respectively, which can be taken to have a steady-state form if the timescale of interest is longer than the dynamical (rotation) time and if the field is well coupled to the matter ($\eta > 1$). For a thin Keplerian disk with a symmetric field configuration one obtains, to a good approximation,

$$V_{r,\phi} \approx \left( \frac{2 \pi}{h \kappa} \right) \left( \frac{B_{0,\phi}^{2}}{4 \pi \rho_{0}} \right) \left( \frac{B_{0,\phi} s}{B_{z}} \right)$$

and

$$V_{D,r,\phi} \approx \left( \frac{3 n}{h} \right) \left( \frac{B_{0,\phi}^{2}}{4 \pi \rho_{0}} \right) \left( \frac{B_{0,\phi} s}{B_{z}} \right),$$

where $h$ is the disk scale height. As shown by WK93, $B_{z}$ generally exceeds $|B_{0,\phi}|$, so that the condition of near-hydrostatic vertical equilibrium gives $B_{r,\phi}/B_{z} \approx \sqrt{2}/a$. Furthermore, $|B_{r,\phi}/B_{z}| = \kappa (\lambda - 1)$ from the definition of the self-similar wind parameters. Hence equations (2) and (3) imply

$$\frac{|V_{0}|}{V_{D,r,\phi}} \approx \eta a \kappa (\lambda - 1).$$

Equation (4) indicates that, if one moves to the right of any given equilibrium curve in Figure 2 by increasing $\lambda$ (while keeping the other parameter values fixed), then the value of $|V_{0}|/V_{D,r,\phi}$ will go up. In this way we infer that advection dominates diffusion to the right of the equilibrium curve (with the converse holding to the left of the curve). It follows that, if $a$ is perturbed from its equilibrium value, then, by equation (1), the perturbation will continue to grow if it starts on the lower branch of the curve but will be counteracted if it originates on the upper branch. From this we deduce that the lower branch of an $\eta = \text{const}$ equilibrium curve in Figure 2 (or the upper branch of the corresponding curve in Fig. 1) represents unstable solutions, whereas the upper branch in Figure 2 (or the lower branch in Fig. 1) is stable.

In the heuristic instability argument given by LPP94 and CS02, a decrease in the field inclination to the disk surface necessarily leads to an increase in the mass outflow rate from the disk. However, as noted in §2, the equilibrium solutions of WK93 have revealed that a decrease in the field inclination could also lead to a larger Alfvén radius and that these two modes of angular momentum transport act in competition with each other. As it turns out, the solution branch identified here as being unstable is in fact the one along which an increase in the angular momentum transport is accomplished through a higher mass outflow rate rather than through a lengthening of the effective lever arm. Nevertheless, the inferred existence of a stable branch indicates that a perturbation that reduces the field inclination to the disk does not necessarily trigger an instability. This may be understood from the fact that an increase in $B_{r,\phi}/B_{z}$ also results in greater field-line tension, which tends to oppose the inward poloidal field bending. Whether a given solution branch is stable or not is determined by the extent to which this (as well as any other relevant) stabilizing effect can overcome the destabilizing influence of increased angular momentum removal brought about by the field-line bending.

4. CONCLUSION

The stability properties of centrifugal wind-driving accretion disks are inferred in this paper from a consideration of the underlying equilibrium model. Specifically, the ambipolar diffusion-dominated disk model of WK93 is shown to possess equilibrium curves with two distinct branches, and it is argued that the turning point between them marks a transition between stable and unstable disk/wind configurations. Although this remains to be verified, a growing perturbation on the unstable branch may well correspond to the unstable mode identified by CS02 and originally given a physical description by LPP94. However, the existence of a generic stable branch implies that such disks are not inherently unstable.

The nonlinear evolution of the instability considered by LPP94 and CS02 has not yet been studied,\textsuperscript{9} so it is still unclear whether it results in a disruption of the disk. If this were the case, then observed systems would naturally correspond to the stable branch of the equilibrium solutions. In fact, in some cases it may even be possible for a perturbed system on the unstable solution branch to undergo a continuous parameter evolution into a stable configuration (see Figs. 1 and 2). One can, however, argue quite independently of the nonlinear outcome of the instability that real wind-driving disks are likely represented by stable solutions. One argument is based on the results of Ferreira (1997) and Casse & Ferreira (2000a), who refined the models used by WK93 and LPP94 (1996) and concluded that the range of viable solutions is reduced; in particular, they inferred that all the allowed “cold” solutions lie on the equivalents of the lower (i.e., stable) branches of the curves in Figure 1 (see Fig. 3 in Ferreira 1997 and Fig. 5 in Casse & Ferreira 2000a). Another argument is based on the likely formation mechanism of effectively steady disks in which the ordered magnetic field originates on large spatial scales. In this picture, which naturally applies to the formation of protostellar disks from the collapse of rotating, magnetic, molecular cloud cores (e.g., Krasnopolsky & Königl 2002), the field is advected inward by the accreted matter but decouples from the inflowing gas as the ratio of the magnetic diffusion time to the inflow time decreases in the vicinity of the central mass. Under these circumstances the field lines are not strongly bent and $B_{r,\phi}/B_{z}$ is of the order of 1.\textsuperscript{10} Hence the parameter $a$ remains $\lesssim 1$ within the strongly coupled region of the accretion flow ($B_{r,\phi}/B_{z}$ would have been $> 1$ had $a$ been $< 1$) and the corresponding equilibrium configurations lie on the upper (i.e., stable) solution branches in Figure 2.

The equilibrium-curve inferences presented in this paper need to be corroborated by an explicit linear stability analysis of the WK93 model as well as of more elaborate equi-

\textsuperscript{8} The incorporation of a possible imbalance between field advection and diffusion into the WK93 model is analogous to the allowance for a departure from vertical thermal balance in the viscous disk solutions.

\textsuperscript{9} It is, however, conceivable that this instability is related to the implosive soliton-like accretion/outflow events discussed by Lovelace et al. (1994).

\textsuperscript{10} $B_{r,\phi}/B_{z} \approx 4/3$ in the asymptotic ($r \to 0$) ambipolar diffusion-dominated disk solution of Krasnopolsky & Königl (2002).
librium configurations. The arguments in support of stable real disks are consistent with the tendency of simulated disk/wind systems to approach a near-stationary state (see § 1), although it is worth noting that the equilibrium models and disk/wind simulations presented to date have been limited to axisymmetric structures. Since the disk and wind are potentially susceptible also to various nonaxisymmetric modes (e.g., Kim & Ostriker 2000), fully 3D simulations are required to conclusively establish their stability properties. It is also worth keeping in mind that the foregoing conclusions are based on a consideration of strongly coupled disks, whereas (as noted in § 2) the structure of protostellar disks may at least in some cases correspond to the weakly coupled regime discussed by Li (1996) and Wardle (1997). Since in the latter type of disk the bulk of the angular momentum is extracted from weakly coupled gas that occupies most of the volume whereas the bending of field lines only affects strongly coupled gas that resides in thin surface layers, it may be expected that such configurations are less susceptible to the field-bending instability considered here than their strongly coupled counterparts. However, a comprehensive study of the stability of weakly coupled disks remains to be performed.

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