TWO TIMESCALE DISPERSAL OF MAGNETIZED PROTOPLANETARY DISKS

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ABSTRACT

Protoplanetary disks are likely to be threaded by a weak net flux of vertical magnetic field that is a remnant of the much larger fluxes present in molecular cloud cores. If this flux is approximately conserved its dynamical importance will increase as mass is accreted, initially by stimulating magnetorotational disk turbulence and subsequently by enabling wind angular momentum loss. We use fits to numerical simulations of ambipolar dominated disk turbulence to construct simplified one-dimensional evolution models for weakly magnetized protoplanetary disks. We show that the late onset of significant angular momentum loss in a wind can give rise to “two timescale” disk evolution in which a long phase of viscous evolution precedes rapid dispersal as the wind becomes dominant. The wide dispersion in disk lifetimes could therefore be due to varying initial levels of net flux. Magnetohydrodynamic (MHD) wind triggered dispersal differs from photoevaporative dispersal in predicting mass loss from small (<1 AU) scales, where thermal winds are suppressed. Our specific models are based on a limited set of simulations that remain uncertain, but qualitatively similar evolution appears likely if mass is lost from disks more quickly than flux, and if MHD winds become important as the plasma β decreases.

Key words: accretion, accretion disks – magnetohydrodynamics (MHD) – protoplanetary disks

1. INTRODUCTION

Protoplanetary disks have typical lifetimes of a few to 10 Myr (Haisch et al. 2001; Hernández et al. 2007; Bell et al. 2013), but are dispersed on an order of magnitude shorter timescale (Simon & Prato 1995; Wolk & Walter 1996). This two timescale behavior is one of the basic observed properties of protoplanetary disks (Luhman et al. 2010), and is inconsistent with the predicted power-law decline in the surface density of a simple viscous accretion disk (Lynden-Bell & Pringle 1974). It implies that there is a physically distinct dispersal process that rapidly removes the gas and dust at the end of the disk phase.

Photoevaporation leads to mass loss from disks exposed to ultraviolet and X-ray radiation (Alexander 2008; Clarke 2011). Since the work of Clarke et al. (2001), who showed that photoevaporation leads to two timescale disk evolution, it has been the leading candidate dispersal mechanism. Here, we propose another. We assume that angular momentum transport is a consequence of magnetohydrodynamic (MHD) turbulence, and that disks are threaded by a conserved vertical magnetic flux whose strength is a byproduct of the star formation process. As the disk accretes, the relative importance of the magnetic field (characterized by the ratio of magnetic to gas pressure at the disk mid-plane) increases, stimulating stronger MHD turbulence (Hawley et al. 1995) and eventually angular momentum loss in a magnetized disk wind (Fromang et al. 2013; Bai & Stone 2013a). The presence of MHD disk winds has been shown to result in significant changes to the predicted structure of protoplanetary disks on AU scales (Bai 2013). We show that they may also lead to two timescale disk evolution resembling that produced by photoevaporation, but driven by the transport and loss of angular momentum rather than by mass loss. For the purposes of demonstrating the essential elements of our model we ignore the effects of mass loss from MHD disk winds (as well as from photoevaporation), along with potential couplings between MHD and thermal outflows (akin to the radiation/MHD winds discussed by Proga 2003). Mass loss, of course, would occur in a complete MHD wind model, and could in itself drive dispersal (Suzuki & Inutsuka 2009). Depending upon the radial distribution of mass loss, its effects could be almost indistinguishable from photoevaporation.

We describe our one-dimensional disk model in Section 2. The key inputs are the transport and loss of angular momentum in the outer disk, where the bulk of the mass resides and where ambipolar diffusion is important (Armitage 2011). We use results from simulations by Simon et al. (2013a, 2013b) to evaluate these quantities, while acknowledging that there are large uncertainties due to the local nature of these calculations. We show results for the long-term disk evolution in Section 3, and discuss the implications of MHD-driven disk dispersal in Section 4.

2. DISK MODEL

We model disk evolution using a one-dimensional vertically integrated model that includes internal redistribution of angular momentum (“viscosity”) and wind angular momentum loss. The model is similar in spirit to one for black hole disk variability proposed by King et al. (2004). We assume a fixed mid-plane temperature profile $T \propto r^{-1/2}$ appropriate for disk evolution at late times and large radii, when viscous heating is negligible and the thermal balance is dominated by stellar irradiation (Kenyon & Hartmann 1987). For a mid-plane sound speed $c_s$, the disk scale height $h = c_s/\Omega$, where $\Omega$ is the Keplerian angular velocity. We take

$$\frac{h}{r} = 0.05 \left(\frac{r}{10 \text{ AU}}\right)^{1/4}.$$  \hspace{1cm} (1)

Adopting a Shakura & Sunyaev (1973) form for the viscosity, $\nu = \alpha h^2 \Omega$, with a constant $\alpha$ (which we do not assume later), the thermal structure of the disk implies $\nu \propto r$. For the initial surface density we take a steady state radial profile truncated with an exponential cutoff. In the constant $\alpha$ case this is just the
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usual similarity solution (Lynden-Bell & Pringle 1974),

\[
\Sigma(t = 0) \propto r^{-1} \exp(-r/r_0).
\]  

(2)

For the calculations presented in Section 3, we take \( r_0 = 10 \) AU and set the surface density normalization such that the initial disk mass is 0.03 \( M_\odot \). Up to this point, the assumptions closely match those made in evolutionary models for dispersal via photoevaporation, which are consistent with observations when evolved with \( \alpha \sim 10^{-3} - 10^{-2} \) and wind mass-loss rates \( M_{\text{w}} \sim 10^{-10} M_\odot \) yr\(^{-1}\) or higher.

We evolve the surface density of the disk under the action of internal angular momentum redistribution via MHD turbulence (approximately modeled as a local, viscous process; Balbus & Papaloizou 1999; Simon et al. 2012) and external angular momentum loss in a wind. The ambipolar disk simulations show that the internal stress develops a substantial laminar component when the net field is strong, but we treat all internal stresses as if they were a local viscosity. Neglecting any sources of mass loss other than accretion, we have

\[
\frac{\partial \Sigma}{\partial t} = 3 \frac{\partial}{\partial r} \left[ \frac{r^{1/2}}{\partial r} (\alpha \Sigma^{1/2}) \right] - \frac{1}{\partial r} (\alpha \Sigma v_r),
\]

(3)

where \( v_r \) is the radial velocity induced by the wind. Numerical simulations show that both \( \nu \) (or, more usefully, \( \alpha \)) and \( v_r \) are functions of the vertical magnetic field \( B_z \) that locally threads the disk. We parameterize this field via the ratio of the mid-plane thermal and magnetic pressures:

\[
\beta_z = 8\pi \frac{\rho c^2}{B_z^2}
\]

(4)

where the mid-plane density \( \rho = (1/\sqrt{2\pi})(\Sigma/h) \). How the disk evolves depends on the functional forms of \( \alpha(\beta_z) \) and \( v_r(\beta_z) \), and on how \( B_z(r, t) \) varies as gas is accreted.

A vertical magnetic field influences the dynamics of the disk in two ways. First, stronger fields increase the strength of turbulent transport (Hawley et al. 1995). Second, sufficiently strong fields lead to the formation of an MHD disk wind which can carry away both mass and angular momentum (Blandford & Payne 1982). These effects appear to be generic for disks that are unstable to the magnetorotational instability (MRI; Balbus & Hawley 1998), though the details of how the turbulence and wind vary with the field strength depend on the included disk physics (Suzuki & Inutsuka 2009; Fromang et al. 2013; Bai & Stone 2013a). We are interested in the long-term evolution of the disk, so what matters most is the MRI disk physics on the large scales where most of the mass resides and where the viscous timescale is the longest. Here, ambipolar diffusion is an important non-ideal MHD effect (Kunz & Balbus 2004; Bai 2011; Perez-Becker & Chiang 2011). Information as to the strength of turbulence and winds in this regime is available from the vertically stratified ambipolar disk simulations of Simon et al. (2013a), who model MRI turbulence at 30 AU in a disk ionized by stellar far-UV (FUV) photons. We characterize the wind stress via a dimensionless parameter \( |\overline{W_{\varphi}}| \) calculated directly from the numerical simulations (we use the stress derived from an estimate of where the base of the wind lies). \( |\overline{W_{\varphi}}| \) is related to the induced radial velocity via

\[
v_r = -\frac{4}{\sqrt{2\pi}} \frac{\overline{W_{\varphi}}}{c_s},
\]

(5)

with \( A = -1.9, B = 0.57, C = 4.2 \), and \( D = 0.5 \). Obviously, the numerical data to which this fit is anchored is sparse, and the values themselves are uncertain. We have implicitly assumed a specific ionization model, and neglected the radial dependence of the stress across the ambipolar-dominated zone. The inner (Ohmic-dominated) disk physics would be significantly different, but should not affect the accretion rate evolution provided that a steady state is established close to the star. The generic conclusions we draw from the simulations are two-fold: (1) internal disk transport is stimulated by a vertical field, and (2) for strong enough fields angular momentum loss in a wind controls disk evolution. The first of these is robust but of limited importance (our model would work equally well with a constant \( \alpha \)), the second is the critical ingredient.

The disk evolution also depends on how the magnetic flux evolves as gas accretes. Many complexities lurk here. Magnetic flux can be dragged inward by the mean flow, diffuse as a byproduct of turbulence (Lubow et al. 1994a; Guilet & Ogilvie 2013), and be lost from the disk at its radial boundaries. Unfortunately the ratio of the turbulent diffusion to the turbulent viscosity remains uncertain in ideal MHD and is unknown in the ambipolar-dominated limit. The simplest model assumes that the magnetic flux,

\[
\Phi = \int_{r=r_m}^{r} 2\pi r B_z dr,
\]

(7)
is conserved within the disk, whose outer edge we define at $\Sigma_{\text{small}} = 10^{-7}$ g cm$^{-2}$. We further assume for most of our models that diffusion acts to keep $\beta_z$ spatially constant as the disk evolves. Together with the fixed thermal structure, these assumptions specify the time evolution of $\beta_z$ given an initial magnetic flux and the evolution of $\Sigma(r)$.

There is an observational argument that flux is not all lost from the disk inner edge. Ordered T Tauri magnetic fields (Yang & Johns-Krull 2011) are strong in absolute terms ($B \approx kG$) but weaker than would be if any significant disk flux was accreted (e.g., $\beta_z = 10^5$ at 10 AU in our initial models implies $B_z \approx 5$ mG, which would lead to a stellar field of $\approx 20$ kG if accreted). Flux probably is, however, lost from the outer disk.

We solve Equation (3) with an explicit finite difference scheme on a logarithmic grid, with 300 zones between $r_m = 0.067$ AU and 6.7 $\times$ 10$^3$ AU. Zero torque boundary conditions are applied at both boundaries.

### 3. RESULTS

Figure 2 shows the time evolution of the inner accretion rate $M$ for varying initial $\beta_z$ and exponentially truncated steady-state disk surface density profiles. The uppermost curve shows the predicted evolution for an initial $\beta_z = 10^5$, which is high enough that the disk remains in almost the zero net field limit for more than 10$^7$ yr. The resulting $\alpha$ is almost constant, there is no wind, and the evolution closely approximates the similarity solution. No two timescale behavior is seen. Stronger initial fields yield a clear transition from an initial viscous phase of slow evolution into a wind-driven phase and rapid dispersal. For a wide range of initial fields, $10^4 \leq \beta_z \leq 3 \times 10^5$, the transition to dispersal occurs for steady accretion rates that lie between $10^{-9} M_\odot$ yr$^{-1}$ and $10^{-8} M_\odot$ yr$^{-1}$. This transition $M$ lies in between those predicted by different internal photoevaporation models, which range between $\sim 10^{-10} M_\odot$ yr$^{-1}$ (for diffuse extreme-UV irradiation; Font et al. 2004) and in excess of $\sim 10^{-8} M_\odot$ yr$^{-1}$ (for X-ray or FUV driven flows; Gorti & Hollenbach 2009; Owen et al. 2010). The disk lifetimes range from less than 0.1 Myr for an initial $\beta_z = 10^4$ to more than 10 Myr for weak-field disks. How the predicted evolution of individual disks translates into the predicted evolution of the disk population depends on the assumed distribution of $\beta_z$, but if the typical value is such as to produce a few Myr disk lifetime then the population statistics would also provide evidence for two timescale evolution.

The two timescale evolution is a consequence of the way that the viscous and wind stresses extracted from the simulations vary with vertical field strength. For a starting $\beta_z \sim 10^5$, the initial evolution of the disk is dominated by viscous spreading and accretion, with the wind playing a minor role. As mass is unloaded from the vertical field due to accretion, flux conservation implies that $\beta_z$ decreases. (This is true despite the increasing disk area for the models considered here.) Initially the main effect of the relatively stronger field is to increase the internal stresses, yielding an $M(r)$ curve that rolls over faster than it would if $\alpha$ were fixed. As $\beta_z$ continues to decrease, the loss of angular momentum in the wind starts to contribute and eventually dominates the disk evolution. The steep dependence of $|W_z\Phi|$ on $\beta_z$, together with the monotonic inflow occasioned by the advective nature of the wind term, leads to a runaway effect. The disk is dispersed rapidly entirely by accretion onto the star. We do not model the feedback effect that the disk inflow exerts on the wind structure, which may lead to instability when the wind becomes dominant (Lubow et al. 1994b). If this effect is present for protoplanetary disks, it would presumably speed dispersal further.

The measurements of wind stresses from local simulations (Figure 1) are uncertain, because these simulations do not represent the global geometry that is a key aspect of winds (e.g., Blandford & Payne 1982). One might therefore ask whether the increase in $\alpha$ as the field becomes stronger might suffice to yield two timescale disk evolution, without involving the viscous-to-wind transition at all. It does not. Although the increase in internal stresses as the disk evolves substantially reduces the viscous timescale at fixed radius, the ongoing expansion of the disk means that there is no distinct dispersal phase and the late-time evolution of $M$ follows a power law.

Figure 3 shows the predicted evolution of the surface density with time for weakly and moderately magnetized disks. The onset of wind angular momentum loss in the moderately magnetized case prevents some of the viscous expansion that would otherwise occur, but in broad terms the surface density during wind-driven dispersal declines smoothly across all radii (observationally, “homologously depleting disks”; Wood et al. 2002). This behavior of our models, however, results from assuming that $\beta_z$ has no spatial dependence. It is not a general consequence of wind-driven dispersal. To illustrate this, we show in Figure 4 how the evolution differs if we vary elements of the model. First, we assume that instead of $\beta_z$ remaining constant with radius as the disk evolves, it is instead the differential flux $\delta B/\delta r$ that remains fixed. This change weights the (fixed) flux toward the outer regions of the disk, which are therefore wind-dominated at all times. Dispersal in this case is extremely swift but outside-in. The reduction of the disk area with time means that the gas is finally swept into the star in an accretion burst.
Second, we consider a model with the fiducial flux evolution, but switch off the action of the wind outside of an arbitrary radius which we take to be 30 AU. In this case there is no two timescale evolution, as the purely viscous outer disk is not able to be dispersed by MHD processes. Rather, a cavity develops in the inner disk once the wind becomes important on small scales, with the cavity being fed by the viscous reservoir further out. For the specific case shown in the figure (with initial $\beta_z = 10^5$), the hole only forms when the disk has a low mass, but this is again model-dependent. Clearly, MHD-driven dispersal admits a range of phenomenology, only some of which is consistent with observations.

4. DISCUSSION

Large-scale magnetic fields could play a role in disk dispersal, even if they are too weak to prevent disk formation or to affect the early dynamics. This conclusion rests on several assumptions (1) that disks are threaded by weak vertical fields, (2) that there is a transition to a wind-dominated angular momentum loss regime as magnetic field pressure increases, and (3) critically, that flux is lost from the outer disk more slowly than mass is accreted. The first assumption seems plausible given that one does not expect the strong fields present during star formation to be driven exactly to zero. The second is supported by numerical simulations (Suzuki & Inutsuka 2009; Fromang et al. 2013; Bai & Stone 2013a; Simon et al. 2013a), though these results are preliminary rather than definitive. Using a one-dimensional disk model motivated by simulation results, we found that two timescale disk evolution can occur, though it would be premature to assert that it is inevitable given our current knowledge of magnetic field evolution within disks. In a magnetic dispersal model, the disk lifetime is tied to the strength of the initial magnetic field. Different field strengths can lead to prompt dispersal ($\ll 1$ Myr) or to disks that are almost inviscid and surprisingly massive at late times (Bergin et al. 2013).

We cannot say whether MHD dispersal is consistent with other observed properties of disk dispersal, such as the morphology of transition disks or the evidence that dispersal commonly occurs from the inside out (Koeper et al. 2013). Whether such behavior occurs in MHD dispersal models depends upon how the radial evolution of the net field couples to the disk evolution. If $\beta_z$ first runs away into the dispersal phase in the inner disk, the outcome is a cavity, whereas an outside-in runaway occurs if the flux distribution favors a strong MHD wind from the outer disk. Additional simulations will be required to decide whether non-homologous dispersal is a consequence of non-ideal MRI disk physics, and to determine how rapidly flux can escape from evolving disks entirely.

Although the mass-loss rates from local MHD winds are poorly determined, the radial extent of the wind is expected to be broad and to include the inner disk (Bai & Stone 2013b). The key contrast to photoevaporative outflows—which fall off rapidly in strength inside a critical radius $r_c \approx 0.2GM_s/c_s^2 \approx 2$ AU (where $c_s$ is the sound speed in the heated gas)—is thus that MHD winds would be expected to include a higher velocity component launched from closer to the star.

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