THE ROLE OF TURBULENT MAGNETIC RECONNECTION IN THE FORMATION OF ROTATIONALLY SUPPORTED PROTOSTELLAR DISKS

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ABSTRACT

The formation of protostellar disks out of molecular cloud cores is still not fully understood. Under ideal MHD conditions, the removal of angular momentum from the disk progenitor by the typically embedded magnetic field may prevent the formation of a rotationally supported disk during the main protostellar accretion phase of low-mass stars. This has been known as the magnetic braking problem and the most investigated mechanism to alleviate this problem and help remove the excess of magnetic flux during the star formation process, the so-called ambipolar diffusion (AD), has been shown to be not sufficient to weaken the magnetic braking at least at this stage of the disk formation. In this work, motivated by recent progress in the understanding of magnetic reconnection in turbulent environments, we appeal to the diffusion of magnetic field mediated by magnetic reconnection as an alternative mechanism for removing magnetic flux. We investigate numerically this mechanism during the later phases of the protostellar disk formation and show its high efficiency. By means of fully three-dimensional MHD simulations, we show that the diffusivity arising from turbulent magnetic reconnection is able to transport magnetic flux to the outskirts of the disk progenitor at timescales compatible with the collapse, allowing the formation of a rotationally supported disk around the protostar of dimensions \( \sim 100 \) AU, with a nearly Keplerian profile in the early accretion phase. Since MHD turbulence is expected to be present in protostellar disks, this is a natural mechanism for removing magnetic flux excess and allowing the formation of these disks. This mechanism dismisses the necessity of postulating a hypothetical increase of the ohmic resistivity as discussed in the literature. Together with our earlier work which showed that magnetic flux removal from molecular cloud cores is very efficient, this work calls for reconsidering the relative role of AD in the processes of star and planet formation.

Key words: accretion, accretion disks – diffusion – ISM: magnetic fields – magnetohydrodynamics (MHD) – stars: formation – turbulence

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1. INTRODUCTION

Circumstellar disks (with typical masses \( \sim 0.1 M_\odot \) and diameters \( \sim 100 \) AU) are known to play a fundamental role in the late stages of star formation and also in planet formation. However, the mechanism that allows their formation and the decoupling from the surrounding molecular cloud core progenitor is still not fully understood (see, e.g., Krasnopol’sky et al. 2011 for a recent comprehensive review). Former studies have shown that the observed embedded magnetic fields in molecular cloud cores, which imply magnetic mass-to-flux ratios relative to the critical value a few times larger than unity (Crutcher 2005; Troland & Crutcher 2008), are high enough to inhibit the formation of rotationally supported disks during the main protostellar accretion phase of low-mass stars, provided that ideal MHD applies. This has been known as the magnetic braking problem (see, e.g., Sun & Stone 1993; Li et al. 2008; Fatuzzo & Adams 2002; Zweibel 2002). In principle, AD allows magnetic flux to be redistributed during the collapse in low ionization regions as the result of the differential motion between the ionized and the neutral gas. However, for realistic levels of core magnetization and ionization, recent work has shown that AD does not seem to be sufficient to weaken the magnetic braking in order to allow rotationally supported disks to form. In some cases, the magnetic braking has been found to be even enhanced by AD (Mellon & Li 2009; Krasnopolsky & Königl 2002; Basu & Mouschovias 1995; Hosking & Whitworth 2004; Dunf & Pudritz 2009; Li et al. 2011).3 These findings motivated Krasnopolsky et al. (2010; see also Li et al. 2011) to examine whether ohmic dissipation could be effective in weakening the magnetic braking. They claimed that in order to enable the formation of persistent, rotationally supported disks during the protostellar mass accretion phase a highly enhanced resistivity, or “hyper-resistivity” \( \eta \gtrsim 10^{19} \) cm\(^2\) s\(^{-1}\), of unspecified origin would be required. Although this value is somewhat dependent on the degree of core magnetization, it implies that the required resistivity is a few orders of magnitude larger than the classic microscopic ohmic resistivity values (Krasnopolsky et al. 2010).

On the other hand, Machida et al. (2010; see also Inutsuka et al. 2010; Machida et al. 2011) performed core-collapse

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3 See however a recent work that investigates the effects of AD in the triggering of magnetorotational instability in more evolved cold, protoplanetary disks where the fraction of neutral gas is much larger (Bai & Stone 2011).
three-dimensional (3D) simulations and found that, even with just the classical ohmic resistivity, a tiny rotationally supported disk can form at the beginning of the protostellar accretion phase (see also Dapp & Basu 2010) and grow to larger, 100 AU scales at later times. They claim that the later growth of the circumstellar disk is caused by the depletion of the infalling envelope. As long as this envelope remains more massive than the circumstellar disk, the magnetic braking is effective, but when the circumstellar disk becomes more massive, then the envelope cannot brake the disk anymore. In their simulations, they assume an initially much denser core than in Krasnopolsky et al.’s work, which helps the early formation of a tiny rotating disk facilitated by the ohmic diffusion in the central regions. But they have to wait for over $10^5$ yr in order to allow a large-scale rotationally supported, massive disk to form (see discussion in Section 5). While this question on the effectiveness of the ohmic diffusion in the early accretion phases of disk formation deserves further careful testing, we here discuss an alternative more efficient mechanism to diffuse the magnetic flux based on turbulent reconnection.

Before addressing this new mechanism, it is crucial to note first that the concept of “hyper-resistivity” previously mentioned (see also Strauss 1986; Bhattacharjee & Hameiri 1986; Diamond & Malkov 2003) is not physically justified and therefore one cannot rely on it (see criticism in Kowal et al. 2009; Eyink et al. 2011). Therefore, the dramatic increase of resistivity is not justified.

However, one may notice that the problem we face with the magnetic field is not of dissipation of magnetic flux, where, indeed, ordinary resistivity is necessary, but of magnetic diffusion. Frequently in the literature, magnetic diffusion is disregarded for highly conductive astrophysical flows. This is based on the concept of magnetic field being frozen-in into conductive fluids and thus moving together with the fluid. However, the frozen-in condition is true in the absence of magnetic reconnection. When the latter is present, changes in the magnetic field topology are allowed.

On the basis of the Lazarian & Vishniac (1999, henceforth LV99) model of reconnection, Lazarian (2005, henceforth L05) suggested a way of removing magnetic flux in the process of star formation, presenting the concept of “reconnection diffusion” of magnetic field in turbulent media (see also Lazarian & Vishniac 2009). This concept was applied successfully to star formation in Santos-Lima et al. (2010) (see also discussion in Lazarian et al. 2010; de Gouveia Dal Pino et al. 2011, and new numerical calculations in M. R. M. Leão et al. 2012, in preparation). There, Santos-Lima et al. (2010, henceforth SX10) performed 3D MHD simulations of turbulent flows and found a decoupling between the gas and the magnetic field due to reconnection under one-fluid approximation, i.e., without having ambipolar diffusion. In addition, in the presence of gravity, they found a decrease of the magnetic flux-to-mass ratio with increasing gas density in the center of the gravitational potential well, both for systems starting with equilibrium distributions of gas and magnetic field and for dynamically unstable, collapsing systems. This provides evidence that the process of magnetic flux removal by turbulent reconnection diffusion is important to quasi-static subcritical clouds and also to collapsing supercritical cores. Thus it is natural to explore the consequences of the process in other systems.

In this work, we investigate this effect on the removal of magnetic flux from collapsing, rotating protostellar cores. Lazarian & Vishniac (2009) argued that the removal of magnetic fields from circumstellar disks reported in the work of Shu et al. (2006) is due to processes of turbulent reconnection, but have not provided any quantitative study of the effect. A preliminary discussion of the quantitative results can be found in de Gouveia Dal Pino et al. (2011). Here, we show by means of 3D MHD numerical simulations that turbulent magnetic reconnection diffusivity enables the transport of magnetic flux to the outskirts of the core at timescales compatible with the collapse timescale, thus allowing the formation of a rotationally supported protostellar disk with nearly Keplerian profile.

In Section 2 we discuss the theoretical foundations of our work, in Section 3 we describe the numerical setup and initial conditions, in Section 4 we show the results of our 3D MHD turbulent numerical simulations of disk formation, and in Section 5 we discuss our results within a bigger picture of reconnection diffusion processes. Our summary is presented in Section 6.

2. THEORETICAL CONSIDERATIONS

The magnetic diffusion mechanism that we address is the process deeply rooted in microscopic physics of how magnetic fields behave in highly conductive flows. The textbook way to characterize these flows is to use the Lundquist number $S = L_s V_A / \eta$, where $\eta$ is ohmic diffusivity and $L_s$ and $V_A$ are the scale of the system at hand and the Alfvén velocity, respectively. For astrophysical systems $L_s$ is very large and therefore $S \gg 1$. The brute force numerical study of such systems is not feasible as the corresponding Lundquist numbers of the numerical simulations are much smaller. However, if the Lundquist number of the flow does not control magnetic reconnection this opens prospects of modeling magnetic diffusion in astrophysical systems.

The classical magnetic reconnection that follows the textbook Sweet–Parker scenario (see Figure 1, upper panel), depends on the Lundquist number and it is slow for astrophysical systems. Indeed, in the model all the matter moving with the speed $V_{\text{rec}}$. 

![Figure 1](https://example.com/image1.png)
over the scale $L_\Delta$ should be ejected with the Alfvén velocity through a thin slot $\Delta$. The disparity of typical astrophysical scales $L_\Delta$ and the scale $\Delta$ determined by microphysics, i.e., resistivity, makes the Sweet–Parker reconnection rate negligibly small for most astrophysical applications, including the case of accretion disks. However, this scenario is not valid in the presence of ubiquitous astrophysical turbulence (see Figure 1, lower panels). For the turbulence case, LV99 showed that the reconnection becomes independent of the resistivity, i.e., becomes fast, as the outflow region $\Delta$ gets determined by magnetic field wandering. This challenges the well-rooted concept of magnetic field frozenness for the case of turbulent fluids (see more in Eyink et al. 2011, henceforth ELV11) and provides an interesting way of removing magnetic flux out of, e.g., accretion disks. The LV99 model was successfully tested numerically in Kowal et al. (2009).

The justification of the reconnection diffusion concept in L05 is based on the LV99 model (see also Lazarian et al. 2004 for the case of magnetic reconnection in partially ionized gas). Numerical effects are always a concern when dealing with reconnection and magnetic field diffusion. Indeed, unlike the numerical tests in Kowal et al. (2009), in our simulations the reconnection events are happening on small scales where numerical effects are important. Precisely because of that, the numerical experiments with anomalous resistivity in Kowal et al. (2009) are of key importance. There, using a numerical setup with high resolution in a magnetic reconnection layer, Kowal et al. (2009) showed that in the presence of turbulence the local nonlinear enhancements of resistivity were not important. This confirmed the corresponding analytical prediction in LV99 (see more discussion in ELV11). Appealing to that finding, we claim that the reconnection diffusion that we observe in our simulations is a real effect and not a numerical artifact. Analytical studies summarized in ELV11 also support the notion that magnetic fields are generically not frozen-in when conductive fluids are turbulent. In view of them, the concept of reconnection diffusion in L05 looks very natural.

As emphasized before, the concept above of magnetic flux transport in turbulent flows by reconnection diffusion has been already successfully tested numerically by Santos-Lima et al. (2010) for idealized models of star forming clouds. In the present paper, we study whether the same concept can entail substantial changes for the magnetic field removal in the formation of protostellar disks. An extension to accretion disks in general can be also foreseen (see below).

### 3. NUMERICAL SETUP AND INITIAL DISK CONDITIONS

To investigate the formation of a rotationally supported disk due to turbulent reconnection magnetic flux transport, we have integrated numerically the following system of MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$  \hspace{1cm} (1)

$$\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = -\frac{\epsilon}{\Omega_p} \mathbf{V}_\rho + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} - \rho \nabla \Psi + \mathbf{f}$$  \hspace{1cm} (2)

$$\frac{\partial \mathbf{A}}{\partial t} = \mathbf{u} \times \nabla \times \mathbf{A} - \eta_{\text{Ohm}} \nabla \times \nabla \times \mathbf{A},$$  \hspace{1cm} (3)

where $\rho$ is the density, $\mathbf{u}$ is the velocity, $\Psi$ is the gravitational potential generated by the protostar, $\mathbf{B}$ is the magnetic field, and $\mathbf{A}$ is the vector potential with $\mathbf{B} = \nabla \times \mathbf{A} + \mathbf{B}_{\text{ini}}$ (where $\mathbf{B}_{\text{ini}}$ is the initial uniform magnetic field). $\mathbf{f}$ is a random force term responsible for the injection of turbulence. An isothermal equation of state is assumed with uniform sound speed $c_s$.

The injection of turbulence is accomplished by adding a random velocity field increment at each time step. This velocity field is built in the spectral Fourier space by adding randomly oriented (divergence-free) components having a Gaussian distribution in their norm, centered around a given wavelength. The power of injection is controlled, as well as the correlation in time. A detailed formulation of the method can be found in Alvelius (1999; see also Kowal et al. 2007, 2009, 2011).

We solved the MHD equations above in a 3D domain using a second-order shock-capturing Godunov scheme and second-order Runge–Kutta time integration. We employed a modified version of the code originally developed by Kowal et al. (2007), using the HLL Riemann solver to obtain the numerical fluxes in each time step.

In order to compare our results with those of Krasnopolsky et al. (2010), we have considered the same initial conditions as in their setup.

Our code works with Cartesian coordinates and vector field components. We started the system with a collapsing cloud progenitor with initial constant rotation (see below) and uniform magnetic field in the $z$ direction.

Given the cylindrical symmetry of the problem, we adopted circular boundary conditions. Eight rows of ghost cells were put outside an inscribed circle in the $xy$ plane. For the four outer rows of ghost cells, we adopted fixed boundary conditions in the radial direction in every time step, while for the four inner ghost cells, linear interpolation between the initial conditions and the values in the interior bound of the domain were applied for the density, velocity, and vector potential. With this implementation the vector potential $\mathbf{A}$ has kept its initial null value at the outer boundaries. Although this produces some spurious noisy components of $\mathbf{B}$ in the azimuthal and vertical directions in the boundaries, these are too far from the central regions of the domain to affect the disk evolution. In the $z$ direction, we have applied the usual open boundary conditions (i.e., zero derivatives for all conservative quantities: density, momentum and potential vector). We found this implementation far more stable than using open boundary conditions in the $x$ and $y$ directions, or even in the radial direction. Besides, adopting circular rather than square boundaries prevented the formation of artificial spiral arms and corners in the disk.

For modeling the accretion in the central zone, the technique of sink particles was implemented in the code in the same way as described in Federrath et al. (2010). A central sink with accretion radius encompassing four cells was introduced in the domain. The gravitational force inside this zone has a smoothing spline function identical to that presented in Federrath et al. (2010). We do not allow the creation of sink particles elsewhere, since we are not calculating the self-gravity of the gas. We note that this accreting zone essentially provides a pseudo inner boundary for the system and for this reason the dynamical equations are not directly solved there where accretion occurs, although we assure momentum and mass conservation.

The physical length scales of the computational domain are 6000 AU in the $x$ and $y$ directions and 4000 AU in the $z$ direction. A sink particle of mass $0.5 \ M_\odot$ is put in the center of the domain. At $t = 0$, the gas has a uniform density $\rho_0 = 1.4 \times 10^{-10} \ g \ cm^{-3}$. 

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\* As was discussed in LV99 and shown even more explicitly in ELV11, the plasma effects that can enhance the local reconnection speed are not important in the presence of turbulence which induces magnetic field wandering.
and a sound speed of \( c_s = 2.0 \times 10^4 \text{ cm s}^{-1} \) (which implies a temperature \( T \approx 4.8 \times 10^7 \text{ K} \), where \( \bar{m} \) is mean molecular weight in atomic units). The initial rotation profile is \( \omega_0 = c_s \tanh(R/R_c) \) (as in Krasnopolsky et al. 2010), where \( R \) is the radial distance to the central \( z \)-axis, and the characteristic distance \( R_c = 200 \text{ AU} \).

We employed a uniform resolution of 384 \( \times \) 384 \( \times \) 256 which for the chosen set of parameters implies that each cell has a physical size of 15.6 AU in each direction. The sink zone has an accretion radius of 62.5 AU.

Although we are interested in the disk that forms inside a radius of approximately 400 AU around the central axis, we have carried out the simulations in a much larger region of 6000 AU in order to keep the dynamically important central regions of the domain free from any outer boundary effects.

4. RESULTS

We performed simulations for four models which are listed in Table 1. Model hydro is a purely hydrodynamical rotating system. All the other models have the same initial (vertical) magnetic field with intensity \( B_z = 35 \mu \text{G} \). In order to have a benchmark, in the model named resistive we included an anomalous high resistivity, with a magnitude about three orders of magnitude larger than the ohmic resistivity estimated for the system, i.e., \( \eta = 1.2 \times 10^{20} \text{ cm}^2 \text{s}^{-1} \). According to the results of Krasnopolsky et al. (2010), this is nearly the ideal value that the magnetic resistivity should have in order to remove the magnetic flux excess of a typical collapsing protostar disk progenitor and allow the formation of a rotationally sustained disk. We have thus included this anomalous resistive model in order to compare with more realistic MHD models that do not appeal to this resistivity excess.

We have also considered an MHD model with turbulence injection (labeled turbulent model in Table 1). In this case, we introduced in the cloud progenitor a solenoidal turbulent velocity field with a characteristic scale of 1600 AU and a sound speed of

| Model          | \( B_0 \) (\( \mu \text{G} \)) | \( \eta_{\text{Ohm}} \) (\( \text{cm}^2 \text{s}^{-1} \)) | \( \eta_{\text{turb}} \) (\( \text{cm}^2 \text{s}^{-1} \)) |
|----------------|--------------------------|--------------------------|--------------------------|
| Hydro          | 0                        | 0                        | 0                        |
| Resistive      | 35                       | 1.2 \( \times \) \( 10^{20} \) | 0                        |
| Turbulent      | 35                       | 0                        | \( \sim 10^{20} \)       |
| Ideal MHD      | 35                       | 0                        | 0                        |

The induced turbulent velocity field has been intentionally smoothed beyond a radius of 800 AU, by a factor \( \exp[-(R/\text{AU}) - 800^2/400^2] \), in order to prevent disruption of the cloud at large radii. The injection of turbulence was stopped at \( t = 4.5 \times 10^{11} \text{ s} \approx 0.015 \text{ Myr} \). From this time on, it naturally decayed with time, as one should expect to happen in a real system when the physical agent that injects turbulence in the cloud ceases to occur.

The last of the models (which is labeled ideal MHD) has no explicit resistivity or turbulence injected so that in this case the disk evolves under an ideal MHD condition.

Figure 2 shows face-on and edge-on density maps of the central slice of the disk for the four models at \( \approx 0.03 \text{ Myr} \). The arrows in the top panels represent the direction of the velocity field, while those in the bottom panels represent the direction of the magnetic field.

The pure hydrodynamical model in the left panels of Figure 2 clearly shows the formation of a high-density torus structure within a radius \( \approx 300 \text{ AU} \) which is typical of a Keplerian-supported disk (see also Figure 3, top-right panel).

In the case of the ideal-MHD model (second column panels in Figure 2), the disk core is much smaller and a thin, low-density outer part extends to the outskirts of the computational domain. The radial velocity component is much larger than in the pure hydrodynamical model. The bending of the disk in the core region is due to the action of the magnetic torques. As the poloidal field lines are dragged to this region by the collapsing fluid, large magnetic forces develop and act on the rotating flow. The resulting torque removes angular momentum from the inner disk and destroys its rotational support (see also Figure 3, upper panels).

The third column (from left) of panels in Figure 2 shows the resistive MHD model. As in Model 1, a torus (of radius \( \approx 250 \text{ AU} \)) with a rotationally dominant velocity field is formed and is surrounded by a flat, low-density disk up to a radius of \( \sim 500 \text{ AU} \). Compared to the ideal MHD model (the second column), the structure of the magnetic field is much simpler and exhibits the familiar hourglass geometry.

The last column (on the right of Figure 2) shows the ideal MHD model with injected turbulence (labeled turbulent). A high-density disk arises in the central region within a radius of 150 AU surrounded by turbulent debris. From the simple visual inspection of the velocity field inside the disk one cannot say if it is rotationally supported. On the other hand, the distorted structure of the magnetic field in this region, which is rather distinct from the helical structure of the ideal MHD model, is an indication that magnetic flux is being removed by the turbulence in this case. The examination of the velocity and magnetic field intensity profiles in Figure 3 is more elucidative, as described below.

Figure 3 shows radial profiles of (1) the radial velocity \( v_R \) (top left), (2) the rotational velocity \( \omega_0 \) (top right), (3) the inner disk mass (bottom left), and (4) the vertical magnetic field \( B_z \) (bottom right) for the models of Figure 2. \( v_R \) and \( \omega_0 \) were averaged inside cylindrical shells centered in the protostar with height \( h = 400 \text{ AU} \) and thickness \( dr = 20 \text{ AU} \). Only cells with a density larger than 100 times the initial density of the cloud \( \rho_0 = 1.4 \times 10^{-10} \text{ g cm}^{-3} \) were taken into account in the average evaluation. The internal disk mass was calculated in a similar way, but instead of averaging, we simply summed the masses of the cells in the inner region. The magnetic field profiles were also obtained from average values inside equatorial rings centered in the protostar with radial thickness \( dr = 20 \text{ AU} \).

For an ideal rotationally supported disk, the centrifugal barrier prevents the gas falling into the center. In this ideal scenario, the radial velocity should be null (at distances beyond the accretion sink zone). The top left panel of Figure 3 depicts the curves of the radial velocities for the four models. Above the central sink accretion zone \( (R > 62.5 \text{ AU}) \), the hydrodynamical model (hydro) is the prototype of a rotationally supported disk, the radial velocity being smaller than the sound speed \( c_s = 2.0 \times 10^4 \text{ cm s}^{-1} \) inside the formed disk. In the ideal MHD model, the effect of the magnetic flux braking partially destroys the centrifugal barrier and the radial (infall) velocity becomes very large, about three times the sound speed. The MHD model with anomalous resistivity instead shows a very...
similar behavior to the hydrodynamical model due to the efficient removal of magnetic flux from the central regions. In the case of the turbulent model, although it shows a persisting non-null radial (infall) speed even above $R > 62.5$ AU, this is much smaller than in the ideal MHD model, of the order of the sound speed where the disk forms (between $R \approx 70$ AU and $\approx 150$ AU).

The top right panel of Figure 3 compares the rotational velocities $v_\Phi$ of the four models with the Keplerian profile $v_K = \sqrt{GM/\rho}$. All models show similar trends to the Keplerian curve (beyond the accreting zone), except the ideal MHD model. In this case, the strong suppression of the rotational velocity due to removal of angular momentum by the magnetic field to outside of the inner disk region is clearly seen, revealing a complete failure to form a rotationally supported disk. The turbulent MHD model, on the other hand, shows good agreement with the Keplerian curve at least inside the radius of $\approx 120$ AU where the disk forms. Its rotation velocity profile is also very similar to that of the MHD model with constant anomalous resistivity. Both models are able to reduce the magnetic braking effects by removing magnetic flux from the inner region and the resulting rotation curves of the formed disks are nearly Keplerian. In the resistive model, this is provided by the hyper-resistivity, while in the turbulent model is the turbulent reconnection that provides this diffusion.

The bottom right panel of Figure 3 compares the profiles of the vertical component of the magnetic field, $B_z$, in the equator of the four models of Figure 2. While in the ideal MHD model, the intensity and gradient of the magnetic field in the central regions are very large due to the inward advection of magnetic flux by the collapsing material, in the anomalous resistive MHD model, the magnetic flux excess is completely removed from the central region resulting in a smooth radial distribution of the field. In the turbulent model, the smaller intensity of the magnetic field in the inner region and smoother distribution along the radial direction compared to the ideal MHD case are clear evidence of the transport of magnetic flux to the outskirts of the disk due to turbulent reconnection (Santos-Lima et al. 2010). We note however that, due to the complex structure which is still evolving, the standard deviation from the average value is very large in the turbulent model, with a typical value of $100 \mu G$ (and even larger for radii smaller than 100 AU) which accounts for the turbulent component of the field.

Finally, the bottom left panel of Figure 3 shows the mass of the formed disks in the four models, as a function of the radius. In the hydrodynamical and the MHD resistive models (hydro and resistive), the mass increases until $R \approx 350$ AU and $\approx 250$ AU, respectively, and both have similar masses. The masses in the ideal MHD and the turbulent MHD models (ideal MHD and turbulent) increase up to $R \approx 250$ AU and $\approx 150$ AU, respectively, and are smaller than those of the other models. Nonetheless the turbulent MHD disk has a total mass three times larger than that of the ideal MHD model.
Figure 3. Radial profiles of the (1) radial velocity $v_R$ (top left), (2) rotational velocity $v_\Phi$ (top right), (3) inner disk mass (bottom left), and (4) vertical magnetic field $B_z$, for the four models of Figure 2 at a time $t \approx 0.03$ Myr. The velocities were averaged inside cylindrical shells centered in the protostar with height $h = 400$ AU and thickness $dr = 20$ AU. The magnetic field values were also averaged inside equatorial rings centered in the protostar. The standard deviations for the curves are not shown in order to make the visualization clearer, but they have typical values of $2-4 \times 10^4$ cm s$^{-1}$ (for the radial velocity), $5-10 \times 10^4$ cm s$^{-1}$ (for the rotational velocity), and $100 \mu$G (for the magnetic field). The vertical lines indicate the radius of the sink accretion zone.

We note that the turbulence injected is non-helical and, therefore, should not modify the angular momentum of the system. However, it could cause some transport due to mixing of the fluid elements. In order to inspect the potential influence of the turbulence on the distribution of angular momentum, we also performed a simulation considering a pure HD model (as in Figure 2, left panel) but injecting turbulence in the system (in the same way as in our MHD turbulent model). As expected, we did not find any substantial change in the Keplerian rotation or in the radial velocity profile when compared to the pure HD model. The only significant change is that the resulting mass of the Keplerian disk is smaller (by a factor of approximately two, in the outer regions) due to the spreading of part of the gas to the disk outskirts by the turbulence.

5. DISCUSSION

5.1. Our Approach and Alternative Ideas

Shu et al. (2006; and references therein) mentioned the possibility that the ambipolar diffusion can be substantially enhanced in circumstellar disks, but did not consider this as a viable solution. The subsequent paper of Shu et al. (2007) refers to the anomalous resistivity and sketches the picture of magnetic loops being formed on the way to eventual removal of magnetic flux. The latter process requires fast reconnection and we claim that in the presence of fast reconnection a more natural process associated with turbulence, i.e., magnetic reconnection diffusion, can solve the problem.

Krasnopolsky et al. (2010) and Li et al. (2011) showed by means of two-dimensional (2D) simulations that an effective magnetic resistivity $\eta \gtrsim 10^{19}$ cm$^2$ s$^{-1}$ is needed for neutralizing the magnetic braking and enabling the formation of a stable, rotationally supported, 100 AU-scale disk around a protostar. The origin of this enhanced resistivity is completely unclear and the value above is at least two to three orders of magnitude larger than the estimated ohmic diffusivity for these cores (e.g., Krasnopolsky et al. 2010). On the other hand, these same authors found that ambipolar diffusion, the mechanism often invoked to remove magnetic flux in star forming regions, is unable to provide such required levels of diffusivity (see also Li et al. 2011).

In this work, we have explored a different mechanism to remove the magnetic flux excess from the central regions of a rotating magnetized collapsing core which is based on magnetic reconnection diffusion in a turbulent flow. Unlike the ohmic resistivity enhancement, reconnection diffusion does not appeal to any hypothetical processes, but to the turbulence existing in the system and fast magnetic reconnection of turbulent magnetic
fields. One of the consequences of fast reconnection is that, unlike resistivity, it conserves magnetic field helicity. This may be important for constructing self-consistent models of disks.

In order to compare our turbulent MHD model with other rotating disk formation models, we also performed 3D simulations of a pure hydrodynamical, an ideal MHD and a resistive MHD model with a hyper-resistivity coefficient $\eta \sim 10^{20}$ cm$^2$ s$^{-1}$ (Figure 2). The essential features produced in these three models are in agreement with the 2D models of Krasnopolsky et al. (2010), i.e., the ideal MHD model is unable to produce a rotationally supported disk due to the magnetic flux excess that accumulates in the central regions, while the MHD model with artificially enhanced resistivity produces a nearly-Keplerian disk with dimension, mass, and radial and rotational velocities similar to the pure hydrodynamical model.

The rotating disk formed out of our turbulent MHD model exhibits rotation velocity and vertical magnetic field distributions along the radial direction which are similar to the resistive MHD model (Figure 3). These similarities indicate that the turbulent magnetic reconnection is in fact acting to remove the magnetic flux excess from the central regions, at a rate similar to that provided by the ordinary enhanced resistivity in the resistive model. We note, however, that the disk formed out of the turbulent model is slightly smaller and less massive than the one produced in the hyper-resistive model. In our tests the latter has a diameter $\sim 250$ AU, while the disk formed in the turbulent model has a diameter $\sim 120$ AU which is compatible with the observations.

The effective resistivity associated to the MHD turbulence in the turbulent model is approximately given by $\eta_{\text{turb}} \sim V_{\text{turb}} L_{\text{inj}}$, where $V_{\text{turb}}$ is the turbulent rms velocity, and $L_{\text{inj}}$ is the scale of injection of the turbulence. We have adjusted the values of $L_{\text{inj}}$ and $V_{\text{turb}}$ in the turbulent model employing turbulent dynamical times ($L_{\text{inj}}/V_{\text{turb}}$) large enough to ensure that the cloud would not be destroyed by the turbulence before forming the disk. We tested several values of $\eta_{\text{turb}}$ and the one employed in the model presented in Figure 2 is of the same order as the magnetic diffusivity of the model with enhanced resistivity, i.e., $\eta_{\text{turb}} \sim V_{\text{turb}} L_{\text{inj}} \approx 10^{20}$ cm$^2$ s$^{-1}$. Smaller values were insufficient to produce rotationally supported disks. Nonetheless, further systematic parametric study should be performed in the future.

As mentioned in Section 1, Machida et al. (2010, 2011) have also performed 3D MHD simulations of disk formation and obtained a rotationally supported disk solution when including only ohmic resistivity (with a dependence on density and temperature obtained from the fitting of the resistivities computed in Nakano et al. 2002). However, they had to evolve the system much longer, about four times longer than in our turbulent simulation, in order to obtain a rotationally supported disk of 100 AU scale. In their simulations, a tiny rotationally supported disk forms in the beginning because the large ohmic resistivity that is present in the very high density inner regions is able to dissipate the magnetic fields there. Later, this disk grows to larger scales due to the depletion of the infalling envelope. Their initial conditions with a more massive gas core (which has a central density nearly ten times larger than in our models) probably helped the formation of the rotating massive disk (which is almost two orders of magnitude more massive than in our turbulent model). The comparison of our results with theirs indicates that even though at late stages ohmic, or more possibly ambipolar diffusion, can become dominant in the high-density cold gas, the turbulent diffusion in the early stages of accretion is able to form a light and large rotationally supported disk very quickly, in only a few $10^4$ yr.

Finally, we should remark that other mechanisms to remove or reduce the effects of the magnetic braking in the inner regions of protostellar cores have also been investigated in the literature recently. Hennebelle & Ciardi (2009) verified that the magnetic braking efficiency may decrease significantly when the rotation axis of the core is misaligned with the direction of the regular magnetic field. They claim that even for small angles of the order of $10^{-20}$ there are significant differences with respect to the aligned case. Also, in a concomitant work to the present one, Krasnopolsky et al. (2011) have examined the Hall effect on disk formation. They found that a Hall-induced magnetic torque can diffuse magnetic flux outward and generate a rotationally supported disk in the collapsing flow, even when the core is initially non-rotating, however the spun-up material remains too sub-Keplerian (Li et al. 2011).

Of course, in the near future, these mechanisms must be tested along with the just proposed turbulent magnetic reconnection and even with ambipolar diffusion, in order to assess the relative importance of each effect on disk formation and evolution. Nonetheless, since MHD turbulence is expected to be present in these magnetic cores (e.g., Ballesteros-Paredes & Mac Low 2002; Melioli et al. 2006; Leão et al. 2009; Santos-Lima et al. 2010, and references therein), turbulent reconnection arises as a natural mechanism for removing magnetic flux excess and allowing the formation of these disks.

5.2. Present Work and SX10

In a recent numerical study in SX10, we showed that magnetic reconnection in a turbulent cloud can efficiently transport magnetic flux from the inner denser regions to the periphery of the cloud, thus enabling the cloud to collapse to form a star.

Here, also by means of fully 3D MHD simulations, we have investigated the same mechanism acting in a rotating collapsing cloud core and shown that the magnetic flux excess of the inner regions of the system can be effectively removed, allowing the formation of a rotationally sustained protostellar disk.

Another empirical finding in SX10 is that the efficiency of the magnetic field expulsion via reconnection diffusivity increases with the source gravitational field. This is a natural consequence of diffusion in the presence of the gravitational field which pulls one component (gas) and does not act on the other weightless component (magnetic field). In terms of the problem in hand, this implies that more massive protostars can induce magnetic field segregation even for a weaker level of turbulence. We plan to explore numerically this issue in a forthcoming work.

5.3. Present Result and Bigger Picture

In this paper we showed that the concept of reconnection diffusion (L05) successfully works in the formation of protostellar disks. Together with our earlier testing of magnetic field removal through reconnection diffusion from collapsing clouds this paper supports a considerable change of the paradigm of star formation. Indeed, in the presence of reconnection diffusion, there is no necessity to appeal to ambipolar diffusion. The latter may still be important in low ionization, low turbulence environments, but, in any case, the domain of its applicability is seriously challenged.

The application of the reconnection diffusion concept to protostellar disk formation and, in a more general framework,
to accretion disks in general, is natural as the disks are expected to be turbulent, enabling our appeal to the LV99 model of fast reconnection. An important accepted source of turbulence in accretion disks is the well-known magnetorotational instability (MRI; Chandrasekhar 1960; Balbus & Hawley 1991), but at earlier stages turbulence can be induced by the hydrodynamical motions associated with the disk formation. Turbulence is ubiquitous in astrophysical environments as it follows from theoretical considerations based on the high Reynolds numbers of astrophysical flows and is strongly supported by studies of spectra of the interstellar electron density fluctuations (see Armstrong et al. 1995; Chepurnov & Lazarian 2010) as well as of H I (Lazarian 2009 for a review and references therein; Chepurnov et al. 2010) and CO lines (see Padoan et al. 2009). The application of the reconnection diffusion mechanism to already formed accretion disks will be investigated in detail elsewhere. It should be noted however that former studies of the injection of turbulence in accretion disks have shown that at this stage turbulence may have little effect on magnetic flux diffusion outward (Rothstein & Lovelace 2008).

6. SUMMARY

Appealing to the LV99 model of fast magnetic reconnection and inspired by the successful demonstration of removal of magnetic field through reconnection diffusion from numerical models of molecular clouds in SX10 we have performed numerical simulations and demonstrated the following.

1. The concept of reconnection diffusion is applicable to the formation of protostellar disks with radius ~100 AU. The extension of this concept to accretion disks is foreseen.
2. In the gravitational field, reconnection diffusion mitigates magnetic braking, allowing the formation of protostellar disks.
3. The removal of magnetic field through reconnection diffusion is fast enough to explain observations without the necessity of appealing to enhanced fluid resistivity.

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6 We note, however, that in the present study, we were in a highly magnetized disk regime, where the magnetorotational instability is ineffective.