MAGNETIC FLUX EXPULSION IN STAR FORMATION

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ABSTRACT

Stars form in dense cores of magnetized molecular clouds. If the magnetic flux threading the cores is dragged into the stars, the stellar field would be orders of magnitude stronger than observed. This well-known “magnetic flux problem” demands that most of the core magnetic flux be decoupled from the matter that enters the star. We carry out the first exploration of what happens to the decoupled magnetic flux in three dimensions, using a magnetohydrodynamic (MHD) version of the ENZO adaptive mesh refinement code. The field–matter decoupling is achieved through a sink particle treatment, which is needed to follow the protostellar accretion phase of star formation. We find that the accumulation of the decoupled flux near the accreting protostar leads to a magnetic pressure buildup. The high pressure is released anisotropically along the path of least resistance. It drives a low-density expanding region in which the decoupled magnetic flux is expelled. This decoupling-enabled magnetic structure has never been seen before in three-dimensional MHD simulations of star formation. It generates a strong asymmetry in the protostellar accretion flow, potentially giving a kick to the star. In the presence of an initial core rotation, the structure presents an obstacle to the formation of a rotationally supported disk, in addition to magnetic braking, by acting as a rigid magnetic wall that prevents the rotating gas from completing a full orbit around the central object. We conclude that the decoupled magnetic flux from the stellar matter can strongly affect the protostellar collapse dynamics.

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

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1. INTRODUCTION

A longstanding problem in star formation is the so-called magnetic flux problem (e.g., Nakano 1984, see his Section 4). If the magnetic flux observed to thread a typical star-forming dense core (Troland & Crutcher 2008) were to be dragged into a young stellar object, the stellar field strength would be tens of millions of Gauss, more than three orders of magnitude higher than the observed values (which are typically in the kilo-Gauss range, e.g., Johns-Krull 2009). The vast majority of the original magnetic flux of the dense core must be decoupled from the matter that enters the star. When and how the decoupling occurs is a fundamental problem of star formation that has yet to be completely resolved.

The magnetic flux problem lies at the heart of another fundamental problem in star formation: disk formation. If the magnetic flux of a dense core is dragged by the collapsing material into a forming star, as it would be in the ideal magnetohydrodynamic (MHD) limit, it would form a central split magnetic monopole that prevents the formation of a rotationally supported disk through catastrophic magnetic braking (Allen et al. 2003; Galli et al. 2006; Mellon & Li 2008; Hennebelle & Fromang 2008; Seifried et al. 2011). The magnetic flux problem must be resolved in order for rotationally supported disks to form.

The most widely discussed resolution of the magnetic flux problem is through non-ideal MHD effects, including ambipolar diffusion, Ohmic dissipation, and potentially the Hall effect (e.g., Nakano 1984; Li & McKee 1996; Ciolek & Königl 1998; Tassis & Mouschovias 2007; Kunz & Mouschovias 2010; Krasnopolsky et al. 2011). For example, Li & McKee (1996) showed that ambipolar diffusion can enable the protostellar envelope to collapse into the central stellar object without dragging along the magnetic flux. The magnetic flux left behind builds up in a small circumstellar region, confined by the ram pressure of the protostellar collapse. It tends to dominate the gas dynamics close to the protostar, particularly in the region of disk formation. Indeed, the magnetic field accumulated at small radii can be strong enough to suppress disk formation completely through efficient magnetic braking (Krasnopolsky & Königl 2002; Mellon & Li 2009; Li et al. 2011). In this case, the resolution of the magnetic flux problem for the central star does not lead to a resolution of the magnetic braking problem for disk formation.

There is, however, a significant limitation in the (non-ideal MHD) studies of the magnetic flux problem and its consequences to date: the assumption of axisymmetry. Although the axisymmetry greatly reduces the computational demand of the calculations, it limits how fast the magnetic flux released from the central object can expand to large distances. In particular, it suppresses a likely mode for the flux expulsion: dynamic expansion along the direction(s) of least resistance. In this paper, we carry out the first detailed three-dimensional (3D) study of what happens to the released flux using the ENZO MHD code. We find that a magnetically dominated region is inflated by the released flux. The region expands asymmetrically away from the central object, changing the dynamics of the protostellar accretion and disk formation.

The rest of the paper is organized as follows. In Section 2, we describe the problem setup, including the equations to be solved, numerical method, and initial and boundary conditions. The numerical results are presented and interpreted in Section 3. The last section, Section 4, includes a discussion of the main results and a short summary.
2. PROBLEM SETUP

2.1. Basic Equations and Numerical Method

We study the formation of stars from the collapse of magnetized dense cores of molecular clouds using an MHD code that includes a sink particle treatment. The usual MHD equations are the magnetic induction equation,

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \tag{1} \]

and the equations for mass continuity, momentum, and self-gravity,

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{2} \]

\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla P - \frac{1}{4\pi} \mathbf{B} \times (\nabla \times \mathbf{B}) - \rho \nabla \phi, \tag{3} \]

\[ \nabla^2 \phi = 4\pi G \rho, \tag{4} \]

where \( \phi \) is the gravitational potential and other symbols have their usual meanings.

The above equations are solved in three dimensions using an MHD version (Wang & Abel 2009) of the ENZO adaptive mesh refinement (AMR) code (Bryan & Norman 1997; O’Shea et al. 2004). It incorporates a sink particle treatment (Wang et al. 2010). The magnetic field is evolved with a conservative MHD solver that includes the hyperbolic divergence cleaning of Dedner et al. (2002). The MHD version of the code is publicly available from the ENZO Web site at http://code.google.com/p/enzo/. It has been used to follow successfully the formation and evolution of magnetized galaxies (Wang & Abel 2009) and star clusters (Wang et al. 2010).

Our goal is to follow both the prestellar core evolution as well as the protostellar mass accretion phase of star formation (after a central stellar object has formed). For the latter, it is crucial to use a sink particle to approximate the stellar object, because including the object in the computation without any special treatment would reduce the time step to such a small value that the simulation would grind to a halt (e.g., Krumholz et al. 2004). In our simulations, we resolve the so-called Jeans length, defined as \( L_J = c_s (\pi \rho_{\text{crit}})^{1/2} \) (where \( c_s \) is the isothermal sound speed), everywhere by at least eight cells, so that the Truelove’s criterion (Truelove et al. 1997) is satisfied. When the density in a cell at the highest refinement level exceeds a threshold density \( \rho_{\text{th}} \) (to be defined below), a sink particle is created at the cell center (see Federrath et al. 2010 for a more elaborate treatment of sink particles). The particle is evolved using an algorithm that is described in detail in Wang et al. (2010).

Briefly, the mass accretion rate onto a sink particle is done in two steps. First, the particle accretes from its host cell using a formula inspired by that of Bondi–Hoyle accretion (Ruffert 1994). The momentum of the accreted material is added to that of the sink particle. The second step involves the merging of small sink particles. This step is controlled by two parameters: the merging mass \( M_{\text{merge}} \) and merging distance \( l_{\text{merge}} \). They are chosen to eliminate artificial particles and to maximize computational efficiency. The simulations presented in this paper use \( M_{\text{merge}} = 0.01 M_\odot \) and \( l_{\text{merge}} = 10^{15} \) cm \( \approx 8 \) AU \( \approx 70 \) AU. Our main results are insensitive to these parameters as long as they are reasonably small.

When a mass is extracted from a cell, due to either sink particle formation or accretion onto an existing sink, the magnetic field in that cell is not altered. That is, the field strength remains the same. This is a crude way to represent the decoupling of the magnetic field from matter at high densities that is expected physically (Nakano et al. 2002) and demanded by the relatively weak magnetic fields observed on young stars (see discussion in Section 1). Determining what happens to the decoupled magnetic flux in three dimensions is the main goal of our investigation.

2.2. Initial and Boundary Conditions

We model star formation in a magnetized dense core embedded in a more diffuse ambient medium. We choose a spherical core of radius \( R = 5 \times 10^{16} \) cm and an initially uniform density \( \rho_0 = 5 \times 10^{-18} \) g cm\(^{-3}\). These parameters yield a core mass \( M = 1.32 M_\odot \) and a free-fall time \( t_{\text{ff}} = 9.4 \times 10^{11} \) s \( = 29.8 \) kyr. We embed the core in an ambient medium that is 100 times less dense than the core and that fills the entire computational box, which is much larger than the core, with \( L = 5 \times 10^{17} \) cm on each side. We set the temperature for both the core and the ambient gas to be \( T \approx 10^4 \) K initially. The large box size is chosen to minimize the effects of the periodic boundary conditions on the core dynamics; the conditions are adopted to facilitate the computation of self-gravity (through fast Fourier transform on the base grid). Our initial conditions are similar to those adopted by Price & Bate (2007), Hennebelle & Fromang (2008), and Bürzle et al. (2011).

As usual, we adopt a barotropic equation of state (EOS) that mimics the isothermal EOS at low densities and the adiabatic EOS at high densities:

\[ P = \rho c_s^2 \left[ 1 + \left( \frac{\rho}{\rho_{\text{crit}}} \right)^{2/3} \right], \tag{5} \]

with a critical density \( \rho_{\text{crit}} = 10^{-13} \) g cm\(^{-3}\) for the transition between the two regimes. An isothermal sound speed \( c_s = 0.2 \) km s\(^{-1}\) is chosen, corresponding to a temperature \( T \approx 10^4 \) K.

The sound speed yields a ratio of thermal to gravitational energy \( \alpha = 2.5 R c_s^2 / (GM) = 0.29 \) for the core (Truelove et al. 1998). For simplicity, we impose an initially uniform magnetic field everywhere along the \( z \)-axis, with a strength \( B_0 = 2.7 \times 10^{-4} \) G. It corresponds to a dimensionless mass-to-flux ratio \( \lambda_{\text{core}} = 2 \) for the core as a whole, in units of the critical value \( (2\pi G^{1/2})^{-1} \); such a value is consistent with those predicted in dense cores formed in strongly magnetized clouds through ambipolar diffusion (e.g., Lizano & Shu 1989; Basu & Mouschovias 1994; Nakamura & Li 2005), and with the median value inferred by Troland & Crutcher (2008) for a sample of dark cloud cores (after correcting statistically for projection effects). We have also carried simulations for both weaker and stronger field cases, with \( \lambda_{\text{core}} = 4 \) and 1, respectively, and found qualitatively similar results. We should note that the local mass-to-flux ratio on the central magnetic flux tube is somewhat larger than the value for the core as a whole, by a factor of 1.5.

Besides the magnetic field, we impose, in some cases, a rigid body rotation on the core. We adopt an angular velocity of \( \Omega = 4.0 \times 10^{-13} \) s\(^{-1}\), corresponding to a ratio of rotational and gravitational energy \( \beta = 0.036 \). This value is within the range inferred by Goodman et al. (1993) from NH_3 observations of dense cores.

We choose a relatively coarse base grid of 64^3, although the grid is automatically refined, at the beginning of the simulation,
by one level in the central part of the computational domain that includes the dense core. We set the maximum refinement level to 6 for our reference runs, which yields a smallest cell size of $\Delta x \sim 8$ AU. When the Truelove criterion (with a Jeans number $\Delta x / L_J = 1/8$; Truelove et al. 1997) is violated on the finest grid at a threshold density of $\rho_{th} = \frac{\pi c^2}{64G\Delta x^3} = 2.0 \times 10^{-14} \text{ g cm}^{-3}$, a sink particle is created. Effectively, $\rho_{th}$ sets the density above which the gas and magnetic field are decoupled. It corresponds to a hydrogen number density of about $10^{10} \text{ cm}^{-3}$ for the reference runs, which is somewhat below the decoupling density (of a few times $10^{11} \text{ cm}^{-3}$) advocated by Nakano et al. (2002). We have experimented with maximum refinement levels up to 8 (which has a threshold number density of about $2 \times 10^{11} \text{ cm}^{-3}$), and obtained qualitatively similar results (see below).

3. RESULTS

We carry out two sets of simulations: collapse with or without rotation. The former is to illustrate how the magnetic flux decoupled from the stellar material escapes to large distances and the latter the effects of the escaping flux on disk formation.

3.1. Non-rotating Collapse

3.1.1. Sink Particle Evolution

At the heart of our star formation calculation lies the sink particle treatment. As mentioned in Section 2.1, the treatment is needed to allow the simulation to go beyond the initial prestellar core evolution phase of star formation, into the protostellar mass accretion phase. Just as importantly, it provides a simple way to decouple the magnetic flux from the material that enters the protostellar object, as demanded by observations (see discussion in Section 1).

In the left panel of Figure 1, we plot the mass of the star, as represented by the sink particle, as a function of time. The object first appears around $t \approx 36 \text{ kyr}$ (or $\sim 1.2 \text{ tff}$). It grows quickly with a relatively large initial mass accretion rate of $10^{-4} M_{\odot} \text{ yr}^{-1}$. The high initial accretion rate is expected for the uniform density distribution that we adopted for the dense core. It could plausibly be identified with the Class 0 phase of low-mass star formation (Andre et al. 1993). The accretion rate decreases below $10^{-5} M_{\odot} \text{ yr}^{-1}$ after $t = 48 \text{ kyr}$ (or $\sim 1.6 \text{ tff}$), when $\sim 0.75 M_{\odot}$ (or 57% of the initial core mass) has landed on the central star.

To make sure that the sink particle treatment has indeed decoupled the magnetic flux from the material that enters the stellar object, we plot in the right panel of Figure 1 the dimensionless ratio $\lambda$ of all mass (including sink) and all magnetic flux within a small radius (200 AU) around the sink particle. The flux is computed on the $x$–$y$ plane that passes through the star (i.e., the constant $z = z_*$ plane where $z_*$ is the stellar position in the $z$-direction); this plane will be referred to as the equatorial plane of the star or equatorial plane for short hereafter. There is a general trend for $\lambda$ to increase with time, reaching values as high as 50, which is much higher than the dimensionless mass-to-flux ratio for the core as a whole ($\lambda_{core} = 2$). Clearly, the magnetic flux near the protostar did not increase as fast as the stellar mass, and the vast majority of the flux originally associated with the stellar mass must reside outside the small region. It is natural to ask: where did this flux go?

3.1.2. Decoupling-enabled Magnetic Structure

It turns out that the decoupled flux is trapped in a strongly magnetized, low-density structure that expands with time. The left panel of Figure 2 shows the structure in a map of column density (along the $z$-direction) at a representative time $t = 43 \text{ kyr}$ (or $\sim 1.45 \text{ tff}$). At this time, the evacuated region has a size of $\sim 1.2 \times 10^{16} \text{ cm}$ (or about 800 AU). It grows in time, as indicated by the velocity vectors inside the region. The right panel of Figure 2 plots the $z$-component of the magnetic field, $B_z$, on the equatorial plane of the star. It shows that the hollow region coincides with a region of intense magnetic field, leaving little doubt that the structure has a magnetic origin.

One may be tempted to call the low-density structure a “magnetic bubble.” However, as shown in Figure 3, “bubble” does not provide an adequate description of the structure in three dimensions; the dense feature surrounding the evacuated region in the column density map (Figure 2) turns out to be a ring rather than a shell. The reason is that, in the absence of the decoupled magnetic flux, the collapsing core material would settle preferentially along field lines into a dense, flattened structure—a “pseudodisk” (Galli & Shu 1993). The magnetic
Figure 2. Left panel: column density (along the z-direction) and velocity field (on the equatorial plane) of the inner region of the collapsing core at a representative time $t = 43$ kyr (or $\sim 1.45 t_{\text{ff}}$), showing an expanding, evacuated region to the lower left of the star (marked by an asterisk on the map). Superposed on the map are contours of constant $B_z$ (the $z$-component of the magnetic field) on the equatorial plane. Right panel: color map of $B_z$ on the equatorial plane, showing that the evacuated region coincides with a region of intense magnetic field. The tick marks above each panel are in units of $5 \times 10^{17}$ cm (size of the simulation box).

Figure 3. 3D view of the inner part of the collapsing core, showing the DEMS, where a bundle of twisted magnetic field lines is surrounded at the “waist” by a dense ring. The star is shown as a red dot located near the inner edge of the ring. The flux left behind evacuates part of the pseudodisk, creating the structure shown in Figure 3, where a bundle of magnetic field lines is pinched near the equator by a dense ring. We will refer to the structure as the “decoupling-enabled magnetic structure” (DEMS for short hereafter).

The strongest evidence for the DEMS being really driven by the magnetic flux decoupled from the material accreted onto the stellar object comes from Figure 4, where we plot the ratio of the stellar mass $M_\star$ to the magnetic flux in the DEMS $\Phi_d$ as a function of time. Not surprisingly, the cells are.

Figure 4. Dimensionless ratio $\lambda_{\star,d}$ of the stellar mass $M_\star$ to the magnetic flux in the DEMS $\Phi_d$ as a function of time. The closeness of $\lambda_{\star,d}$ to the value $\lambda_{\text{core}} = 2$ for the core as a whole indicates that the flux in the DEMS is released by the stellar material.
mostly located inside the dense ring. We are able to determine the ratio over only a limited range in time, because the DEMS becomes apparent only after $t \sim 40$ kyr, and it starts to merge into the background (making an accurate identification of the DEMS difficult) after $t \sim 60$ kyr. As the stellar mass nearly doubles during the early part of this period (see Figure 1), the mass-to-flux ratio remains relatively constant, indicating that $\Phi_d$ increases together with $M_*$. Furthermore, the dimensionless mass-to-flux ratio $\lambda_{sd} = 2\pi G^{1/2} M_* / \Phi_d$ is close to the global value for the initial core, as one would expect if the initial core matter releases its flux on the way to the center. The small deviation from the global value $\lambda_{core} = 2.0$ can come from the fact that local $\lambda$ in the initial core is not exactly 2, and that the DEMS is identified by eye and is not very precise. Nevertheless, the different pieces of evidence presented in this subsection leave little doubt that the DEMS is formed by the magnetic flux decoupled from the accreted stellar mass.

We have checked that the creation and evolution of the DEMS is insensitive to the details of the sink particle treatment. For example, we have allowed more levels of refinement (7 and 8 instead of 6) before the sink particle creation, with higher values for the effective matter–field decoupling density $\rho_{th}$. The results are qualitatively similar, although the shape and orientation of the DEMS are somewhat different. We have also varied the critical density $\rho_{crit}$ in the EOS and obtained a broadly similar result. These tests support the conclusion that the DEMS is robust. Its existence also makes physical sense because, as the decoupled flux accumulates near the protostar, the magnetic pressure builds up, which can only be released through expansion. In hindsight, it is hard to imagine any other outcome.

### 3.1.3. DEMS and Collapse Dynamics

The DEMS modifies the dynamics of core collapse and star formation in several ways. The most obvious is the change to the density distribution and velocity field in the equatorial region where most of the mass accretion occurs. The DEMS produces an evacuated region that expands against the dense, collapsing pseudodisk, as shown in the left panel of Figure 2. There are initially several small, irregular, low-density regions. Only one develops into a full-blown DEMS through runaway expansion. It starts to grow quickly after enough magnetic flux has accumulated in the region that a high magnetic pressure is built up to overwhelm the ram pressure of the collapsing flow. The expansion occurs presumably along the path of least resistance, which happens to lie in the direction toward the lower-left corner in Figure 2; this direction is probably related to the cubic simulation box and Cartesian grid, which break the symmetry in the collapsing flow. As mentioned earlier, by the time $t = 60$ kyr (or about 2 $t_{ff}$), the structure grows to a size comparable to the initial core radius and starts to merge into the background.

To examine the expansion dynamics more quantitatively, we plot in Figure 5 the distributions of the magnetic pressure, the thermal pressure $P_{th} = \rho c_s^2$, and the ram pressure associated with the radial component of the velocity $P_{ram} = \rho v_i^2$, in the equatorial plane, along the dotted line shown in the left panel of Figure 2. Note the sharp increase (by a factor of $\sim 10^3$) in the magnetic pressure around $r \sim 10^{16}$ cm, which marks the boundary of the DEMS. Inside the boundary, the magnetic pressure is more or less uniform. It is much higher than the thermal pressure, by a factor of $\sim 10^2$, corresponding to a low plasma $\beta \sim 0.01$. The high magnetic pressure is what drives the region to expand. The expansion is slowed down by the ram pressure of the collapsing material outside the strongly magnetized region, which is somewhat smaller than, but comparable to, the magnetic pressure. The spike just outside $r = 10^{16}$ cm on the curve of ram pressure is due to the dense, expanding ring that is prominent in Figure 2. The ring is the collapsing pseudodisk material that has been swept up by the expanding, magnetically dominated region. It has a peak density nearly two orders of magnitude higher than the surrounding medium. The ring is not yet massive enough in our current simulation to become self-gravitating, but we speculate that this might happen under other circumstances; in such cases, the ring may fragment into secondary objects. We will postpone an exploration of this possibility to a future investigation.

A direct consequence of the one-sided expansion of the magnetically dominated region is that accretion onto the central object must proceed in a highly asymmetric fashion. The asymmetric accretion is shown vividly in the left panel of Figure 2, where velocity vectors are plotted in the equatorial plane of the star. While the collapsing flow in the upper-right half of the plane can fall into the star directly, that on the lower-left half is mostly obstructed by the DEMS. Based on the highly asymmetric accretion pattern, one may expect the stellar object to pick up some velocity. We find that the star particle in our simulation does move, but only at a small speed of order $0.1$ km s$^{-1}$, too small to be of any dynamical significance. The reason for the slow stellar motion is probably the following: in the absence of any external force, the total linear momentum of the system, which is initially zero, must be conserved. In particular, the collapsing flow on the lower-left side of the star is diverted by the DEMS to flow toward the star along the dense ring. Its momentum may cancel out that of the unobstructed collapsing flow from the other side to a large extent, at least in this particular simulation. Whether the slow stellar motion is true in general remains to be determined.

The diversion of the magnetized collapsing flow around the DEMS creates an interesting feature: the twisting of magnetic field lines, which is clearly visible in Figure 3. The twisting

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4 We have experimented with runs where subsonic turbulent velocity fields are imposed on the dense core at the beginning of the simulation. The symmetry-breaking turbulence does not change the DEMS qualitatively.
is normally not expected in a non-rotating collapse. However, when the direct path to the star is blocked by the DEMS, a parcel of collapsing flow moves around the structure, twisting the field lines tied to the parcel in the process. Indeed, the magnetic tension associated with the twisted field lines produces a bipolar outflow moving away from the equatorial plane (most visible from the velocity field in the $x$–$z$ or $y$–$z$ plane, not shown), similar to the cases where an initial core rotation is present (e.g., Tomisaka 1998). Such an outflow has not been seen in previous non-rotating collapse calculations.

### 3.2. Rotating Collapse

We have shown that the DEMS strongly affects the dynamics of non-rotating collapse. Here, we wish to examine its influence on the dynamics of rotating collapse in general and disk formation in particular. For this purpose, we impose on the core an initial solid-body rotation with $\Omega = 4.0 \times 10^{-13}$ s$^{-1}$, keeping other parameters the same as in the non-rotating collapse discussed in Section 3.1.

Figure 6 (left panel) shows a snapshot of the rotating collapse at a representative time $t = 47.5$ kyr (or $\sim 1.6$ $t_0$), when the stellar object has accreted $\sim 0.67$ $M_\odot$. The overall morphology is broadly similar to that of the non-rotating case shown in Figure 2, with an evacuated DEMS expanding against a collapsing flow. An obvious difference is, of course, rotation. The rotation is not fast enough, however, to stop the collapse centrifugally, even along directions not directly affected by the DEMS. The lack of complete centrifugal support is illustrated in the right panel of Figure 6, where we plot the infall and rotation speeds along a DEMS-free direction (marked in the right panel as a dotted line). The rotation speed remains well below the Keplerian value except in the region inside a radius of $\sim 8 \times 10^{14}$ cm, where the two become comparable. In this small region, the collapse is slowed down, but not stopped. Its infall speed is $\sim 1.5–2$ km s$^{-1}$, much higher than the sound speed (0.2 km s$^{-1}$). The supersonic infall leaves little doubt that a large-scale rotationally supported structure is not formed in this direction, presumably because of strong magnetic braking, which has been shown to be capable of suppressing disk formation in previous ideal MHD simulations (Allen et al. 2003; Mellon & Li 2008; Hennebelle & Fromang 2008; Seifried et al. 2011).

The DEMS makes disk formation even more difficult. The reason is that the DEMS is a rather rigid structure that prevents the rotating material from completing a full orbit around the central star. To be more quantitative, we compare the magnetic pressure to the ram pressure due to rotation, $P_{\phi, \text{ram}} = \rho v_\phi^2$, along a circle of 400 AU in radius in the equatorial plane in Figure 7. Clearly, the magnetic pressure inside the DEMS ($\sim 0^\circ–100^\circ$ and $\sim 290^\circ–360^\circ$) is higher than the rotational ram pressure outside the DEMS (the two peaks of ram pressure correspond to locations on the dense ring). The DEMS is effectively a magnetic wall that stops the rotating motion of the material that runs into it. This is a new form of magnetic braking that has never been discussed before in core collapse and disk formation.

The rotation has an effect on the shape of the dense ring. Whereas the ring is more or less (mirror) symmetric with respect to a plane in the non-rotating collapse (see the dotted line in Figure 2), it is much less so in the rotating collapse. The reason is that one side of the DEMS expands against the rotating flow, and its expansion is slowed down by rotation (see the lower side of the DEMS in the left panel of Figure 6). The other side expands...
The DEMS formation is a natural consequence of simulating magnetized dense cores: an expanding low-density region driven by the magnetic flux decoupled from the material that has accreted onto the star. This DEMS has implications for both high-resolution star formation simulations and for collapse dynamics including disk (and possibly binary) formation.

The DEMS formation is a natural consequence of simulating magnetized star formation using the sink particle formalism. Sink particles are needed to represent the stellar objects formed because such objects are much smaller and much denser than their parental dense cores (e.g., Krumholz et al. 2004). When the matter from a cell is added to a sink particle, the magnetic flux from the cell cannot be added to the sink as well, on both physical and numerical grounds. Physically, the addition of the magnetic flux to the sink particle would make the stellar field strength much higher than observed (which is, of course, the well-known “magnetic flux problem”). Numerically, the sink particle cannot hold a large magnetic flux, which would produce a large, unbalanced magnetic force in the host cell of the sink particle. The decoupling of the magnetic field from matter required during sink particle mass accretion makes the creation of the DEMS unavoidable in an ideal MHD simulation of the protostellar phase of star formation.

The DEMS that we found is conceptually related to the highly magnetized inner region of protostellar collapse in the presence of non-ideal MHD effects, found previously either semi-analytically (in one dimension) or through two-dimensional (2D, axisymmetric) simulations. It has been shown that, in the presence of ambipolar diffusion, most of the magnetic flux left behind by the stellar mass is trapped in a strongly magnetized region inside a C-shock (Li & McKee 1996; Ciolek & Königl 1998). The situation is similar in the presence of Ohmic dissipation (Li et al. 2011). In both cases, because of the axisymmetry assumed, the collapsing flow has to cross the strongly magnetized inner region where the left-over magnetic flux is parked in order to reach the center. As a result, the highly magnetized region is loaded with high-density material (at least near the equatorial plane: see, e.g., Figure 4 of Li et al. 2011). Strictly speaking, the region is not a (low-density) DEMS, although it does share the same origin as the DEMS: both are driven by the decoupled magnetic flux. Indeed, one may view the case considered in this paper as the high-ionization limit of the general non-ideal case in which the ideal MHD approximation breaks down only at the highest densities (and the breakdown is mimicked here by the sub-grid physics associated with sink particle treatment). In this limiting case, a very small region of intense magnetic field is expected to form close to the protostar and be trapped by the ram pressure of the infalling material in two dimensions. In three dimensions, we find a completely different behavior: an asymmetrically expanding DEMS. The reason is that, in three dimensions, the collapsing core material does not have to go through the strongly magnetized region to reach the central object; it can simply go around the region. The DEMS in three dimensions is able to choose a path of least resistance (which may be influenced by grid geometry), breaking the restrictions imposed in strictly axisymmetric simulations.

The DEMS is a new feature never reported before in 3D numerical simulations of star formation (see, however, Seifried et al. 2011, who recently found a similar feature independently). Hennebelle & Fromang (2008) followed the collapse of magnetized cores using an AMR MHD code, but did not mention any structure similar to our DEMS. The reason for the absence of DEMS in their simulations is probably that they did not use any sink particle in their simulations and thus did not address the issue of magnetic decoupling that is needed to resolve the magnetic flux problem. Machida et al. (2011) did use sink particles in their nested grid MHD simulations. They did not find any DEMS-like structure either, because they removed the magnetic flux associated with the mass accreted onto the sink particle by hand, on the assumption that the magnetic flux is destroyed by Ohmic dissipation (see Shu et al. 2006 for the reason why the flux cannot be destroyed). The flux removal is probably also the reason why the DEMS was not present in smoothed-particle hydrodynamics (SPH) MHD simulations (e.g., Price & Bate 2007; Bürzle et al. 2011). Padoan & Nordlund (2011) carried out global simulations of star formation in turbulent, magnetized clouds using sink particles. They did not find any structure similar to our DEMS. The reason for the absence of DEMS around individual stars either, probably because the ordered magnetic field in their simulations is much weaker than in ours. If a dense core has a larger initial mass-to-flux ratio than adopted here, there would be less magnetic flux to decouple from a given stellar mass, and the smaller decoupled flux would drive a less prominent DEMS.

Although we believe that the DEMS is robust in the limit considered in this paper where the matter and magnetic field are well coupled except at the highest densities, it remains unclear how it will be affected by non-ideal MHD effects, including ambipolar diffusion, Ohmic dissipation and the Hall effect, all of which can play a role in the magnetic field evolution during core collapse and disk formation, at least in two dimensions. The logical next step is to carry out 3D AMR MHD simulations that include both sink particles and non-ideal MHD effects. It would be interesting to determine the extent to which the

4. DISCUSSION AND SUMMARY

We find a new feature in the protostellar collapse of magnetized dense cores: an expanding low-density region driven by the magnetic flux decoupled from the material that has accreted onto the star. This DEMS has implications for both high-resolution star formation simulations and for collapse dynamics including disk (and possibly binary) formation.

Figure 7. Comparison of the magnetic pressure (solid line) and the ram pressure due to rotation in the equatorial plane, on a circle of ~400 AU in radius (shown in the left panel of Figure 6). The azimuthal angle is measured counterclockwise from the x-axis. The magnetic pressure inside the DEMS (the strongly
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collapsing flow reaches the star either by crossing field lines in a strongly magnetized region through non-ideal MHD effects (as in the current 2D simulations, such as Li et al. 2011) or by going around the strongly magnetized region, as we find in this paper. Another effect is the turbulence-enhanced reconnections (e.g., Kowal et al. 2009), which may reduce the amount of the magnetic flux dragged close to the central object and weaken the DEMS.

To summarize, we have carried out simulations of magnetized core collapse and star formation using an MHD version of the ENZO AMR code. A sink particle treatment is used to decouple the magnetic flux from the material that enters the star, which must happen to resolve the well-known “magnetic flux problem” in star formation. We find that the decoupled flux creates a low-density high magnetic pressure region that expands anisotropically away from the protostar. This DEMS has profound effects on the dynamics of core collapse, making the protostellar accretion flow highly asymmetric and the formation of a rotationally supported disk more difficult. It is a generic feature of star formation in strongly magnetized cloud cores that should be included in future simulations, especially those using sink particle treatment.

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