

# Magnetic Spirals in Accretion Flows Originated from Misaligned Magnetic Fields

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#### Abstract

Misalignment between rotation and magnetic fields has been suggested to be one type of physical mechanism that can ease the effects of magnetic braking during the collapse of cloud cores leading to the formation of protostellar disks. However, its essential factors are poorly understood. Therefore, we perform a more detailed analysis of the physics involved. We analyze existing simulation data to measure the system torques, mass accretion rates, and Toomre Q parameters. We also examine the presence of shocks in the system. While advective torques are generally the strongest, we find that magnetic and gravitational torques can play substantial roles in how angular momentum is transferred during the disk formation process. Magnetic torques can shape the accretion flows, creating two-armed magnetized inflow spirals aligned with the magnetic field. We find evidence of an accretion shock that is aligned according to the spiral structure of the system. Inclusion of ambipolar diffusion as explored in this work has shown a slight influence in the small-scale structures but not in the main morphology. We discuss potential candidate systems where some of these phenomena could be present.

*Unified Astronomy Thesaurus concepts:* Magnetohydrodynamics (1964); Star formation (1569); Magnetic fields (994); Gravitational instability (668); Circumstellar disks (235)

#### 1. Introduction

Since the Atacama Large Millimeter/submillimeter Array (ALMA) began its observations, we have entered into a new era of understanding circumstellar disks. Following the publication of the first ALMA continuum observations of HL Tau (ALMA Partnership et al. 2015), there has been fast accumulation of observations of circumstellar disks at various stages of their evolution, including the protostellar stage. The DSHARP (Andrews et al. 2018) survey is complete, and there have been several individual observations from nearby regions, such as Upper Scorpius OB1 (Carpenter et al. 2014), Lupus (Ansdell et al. 2016, 2018; Tazzari et al. 2021), Orion (Ansdell et al. 2017; Dutta et al. 2020; Hsu et al. 2020; Tobin et al. 2019, 2020; Sahu et al. 2021; Sheehan et al. 2020), Chamaeleon I (Long et al. 2017, 2018a), IC 348 (Ruíz-Rodríguez et al. 2018), Taurus (Long et al. 2018b, 2019; Podio et al. 2020), Corona Australis (Cazzoletti et al. 2019), Ophiuchus (Sadavoy et al. 2019; Cieza et al. 2021), Lynds 1641 (Grant et al. 2021), Perseus (Yang et al. 2021).

However, we still have very limited knowledge about the early protostellar stages of circumstellar disks. Observations of these very early stages of disk formation are challenging because such objects are surrounded by the envelope of the collapsing core. The envelope can make it very difficult to differentiate various chemical and physical properties as distinct localized features (see, e.g., Harsono et al. 2021, and the references therein).

Theoretical problems are likely not easier either. Disk formation can be affected by the magnetic field, the dynamical properties of a prestellar core, and chemical and other microphysical effects. Ideal magnetohydrodynamics (MHD) assumptions also lead to a magnetic braking catastrophe preventing disk formation (Allen et al. 2003). As explained in Galli et al. (2006), newly formed stars from a perfectly ideal MHD scenario would have an excessively strong initial magnetic field compared to what is observed around T Tauri stars (see, e.g., Mestel & Spitzer 1956; Johns-Krull et al. 2004). We have to find a way to deal with the magnetic braking problem, but it is impossible to model everything at once; therefore, we choose to focus on the inclined magnetic field and, in a supplementary manner, the influence of one of the nonideal MHD effects.

One possible way of making a rotationally supported disk (RSD) in an ideal MHD system is by misalignment between the mean magnetic field and rotation axis. This was demonstrated by Hennebelle & Ciardi (2009) and Joos et al. (2012) and further elaborated by Li et al. (2013). Li et al. (2013) found, in agreement with previous work, that with a sufficiently large mass-to-flux ratio, disk formation became a possibility. Väisälä et al. (2019) further analyzed the data of Li et al. (2013) with a simple radiative transfer approach, and, in addition to highlighting the physical effects that were missed in the original study, they noted the importance of spiral patterns, especially with the spiraling inflows, as a potential observational signature of misalignment based on disk formation. Väisälä et al. (2019) also noted that the disk can be prone to noncircular motions leading to spiral perturbations and that with sufficient magnetic field, rings could form. However, they did not do a full analysis of torques.

Spirals during star formation can emerge due to gravitational disturbances and gravitational instability (see, e.g., Kratter & Lodato 2016, and references therein). Therefore, it is imperative to examine how magnetic and gravitational forces

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Table	1
imulation	Setup

Simulation Setup					
Initial	Boundary	Grid Setup	Equation of State		
Uniform density $\rho_0 = 4.77 \times 10^{-19} \text{ g cm}^{-3}$	r: outflow	Mesh: $96 \times 64 \times 60$	Isothermal (with a sound		
Uniform field $B_0(\lambda)$	$\theta$ : reflective	$r: 10^{14} - 10^{17} \text{ cm}$	speed $a = 0.2 \text{ km s}^{-1}$ ) for		
Solid-body rotation speed $\Omega_0 = 10^{-13} \text{ s}^{-1}$	$\phi$ : periodic	$\theta$ : 0 $-\pi$	$\rho < \rho_c (\equiv 10^{-13} \text{ g cm}^{-3}),$		
		$\phi$ : $0-2\pi$	polytropic ( $p \propto \rho^{5/3}$ ) for $\rho > \rho_c$		

Note. From Li et al. (2013). The initial spherical core with uniform density has 1  $M_{\odot}$  in mass and about 6685 au (10<sup>17</sup> cm) in radius, corresponding to a freefall time of about 95.1 kyr (3  $\times$  10<sup>12</sup> s).

Table 2   Selected Models and Results						
Model	λ	$\theta_0$	RSD	Visual Type	Dominant Torque in the Central Region at Late Stage	
G	9.72	90	Yes/robust	Clear spiral	Gravitational torque	
Н	4.86	90	Yes/porous	Leaking spiral	Magnetic torque	
Ι	2.92	90	No	Looped axis	Magnetic torque	
А	9.72	0	No	Looped plane	Magnetic torque	
D	9.72	45	Yes/porous	Looped plane/leaking spiral	Magnetic torque	
Galpha	9.72	90	Yes/robust	Clear spiral	Gravitational torque	

Note. The second to fifth columns of parameters of the first four rows of models are from Li et al. (2013), with the classified visual types from Väisälä et al. (2019). The last row, of model Galpha, is a new case with ambipolar diffusion (see details in Section 3.7). The last column lists the results of dominant torques.

are acting during misaligned collapse, to determine both how misaligned collapse can work and which factors are decisive. This paper focuses on the magnetized spirals that originate from the misaligned magnetic field; previous works in this line of study had a different focus (Li et al. 2013 focused on the presence of RSD structures; Väisälä et al. 2019 focused on finding potential observable features).

Understanding the mechanisms of magnetic spirals can have significant implications. With recently observed streamers into the class 0 object Per-emb-2 (Pineda et al. 2020), the arc seen by Grant et al. (2021) in [MGM 2012] 512, and the field configuration in HH 211 (Lee et al. 2019), there are observational possibilities to examine spiraling inflows. Sanhueza et al. (2021) were also able to demonstrate streamers in the massive star formation environment of IRAS 18089–1732. Spiral behavior can also happen in a disk plane, like in HH 111 VLA 1, as observed by Lee et al. (2020). As further elaborated in this study, magnetic fields can cause formation of warped protostellar rings, which can provide one possible explanation of some observed warped disks like L1527 IRS around IRAS 04368+2557 (Sakai et al. 2019; Nakatani et al. 2020).

The paper is organized as follows. In Section 2, we present the central analysis methods that we utilize. In Section 3, we display the results of our analysis. In Section 4, we discuss the implication of our results, especially with respect to observations, and in Section 5, we summarize the paper.

## 2. Methods

In this paper, we perform further analysis and postprocessing on data first published in Li et al. (2013). Using the nonideal MHD code Zeus-TW (Krasnopolsky et al. 2010) and incorporating self-gravity, the authors performed MHD simulations of an initially rotating, uniform, dense core with a misaligned magnetic field in a spherical coordinate system. The initial magnetic field was tilted uniformly away from the

rotation axis by different angles. The grid is nonuniform in the radial and meridional directions, with constant ratios ( $\sim 1.08$ for both r and  $\theta$ ) between the nonuniform widths of adjacent active zones. The grid is uniform in the azimuthal direction. The implemented parameters, initial conditions, and boundary conditions are shown in Table 1. The tilt angle  $\theta_0$  and the dimensionless mass-to-flux ratio  $\lambda$  are major free parameters in their series of models. To prevent numerical "hot zones." meaning the locations in the numerical domain where the Alfvén velocity becomes extremely large leading to an infinitesimal timescale, from halting the simulations, a small, spatially uniform resistivity  $\eta = 10^{17} \text{ cm}^2 \text{ s}^{-1}$  was implemented. The hot zones arose at the start of the rapid accretion; therefore, resistivity was applied after the central mass grew up about  $10^{-7} M_{\odot}$ . Models of reduced resistivity to  $(\eta = 10^{16} \text{ cm}^2 \text{ s}^{-1} \text{ and } \eta = 0)$  verified that  $\eta = 10^{17} \text{ cm}^2 \text{ s}^{-1}$  is small enough to be insignificant for the sake of numerical improvement.

In an effort to characterize the observable properties of magnetically misaligned protostellar disk systems, Väisälä et al. (2019) identified distinguishable visual features of each model. Especially noteworthy were the spiral patterns. To further quantitatively study them, in this paper, we choose models with various types of spirals and without spiral patterns for comparison. The models of interest are listed in Table 2. Model G, which has robust RSD and clear spiral structure, is specified as the fiducial model.

#### 2.1. Calculating Torques

Analyzing angular momentum transfer of the disk is important for investigating the dynamics of disk formation and its spiral pattern. The key questions are how much the angular momentum is conserved, how the angular momentum is redistributed, and which mechanism dominates in this process.

In an Eulerian frame, conservation of angular momentum in the case of magnetized inviscid flow is given by

$$\frac{\partial \boldsymbol{J}}{\partial t} = -\int_{S} (\rho \boldsymbol{r} \times \boldsymbol{v}) \boldsymbol{v} \cdot d\boldsymbol{S} + \frac{1}{4\pi} \int_{V} \boldsymbol{r} \times ((\nabla \times \boldsymbol{B}) \times \boldsymbol{B})) dV - \int_{V} \boldsymbol{r} \times \nabla p \ dV + \int_{V} \rho \boldsymbol{r} \times \boldsymbol{g} \ dV,$$
(1)

where  $J = \int_V \rho \mathbf{r} \times \mathbf{v} \, dV$  is the angular momentum within a control volume *V*, and  $g = -\nabla \Phi$  is the gravitational force per unit mass per unit volume. The terms on the right-hand side (RHS) are torques due to advection, magnetic field, thermal pressure, and gravity.

To better demonstrate the mechanisms of disk rotation, we calculate in spherical coordinates the *z*-component of the conservation of angular momentum,

$$\frac{\partial J_z}{\partial t} = -\int_{S} (\rho r \sin \theta v_{\phi}) (\mathbf{v} \cdot d\mathbf{S}) + \frac{1}{4\pi} \int_{S} (\rho r \sin \theta B_{\phi}) (\mathbf{B} \cdot d\mathbf{S}) - \frac{1}{4\pi} \int_{V} \frac{\partial}{\partial \phi} \left(\frac{B^2}{2}\right) dV - \int_{V} \frac{\partial p}{\partial \phi} dV - \int_{V} \rho \frac{\partial \Phi}{\partial \phi} dV,$$
(2)

which contains the torques relative to the *z*-axis. The integration control volume *V* and its surface *S* are usually chosen as the volume  $V_{cell}$  and surface  $S_{cell}$  of a grid cell. When torques are calculated locally, the pressure terms cannot be neglected, which is not the case for the integral within a sphere or cylinder. In order to compare local values from cell to cell, we divide the torques by the cell volume.

We also calculate the specific angular momentum defined as  $J_{\text{spc}} = J / \int_{V_{\text{cell}}} \rho dV$ , as well as its *z*-component  $J_{\text{spc},z}$ , and plot its spatial distribution.

#### 2.2. Detecting Gravitational Instability

If a gaseous disk is massive enough, it can be gravitationally unstable. Following Väisälä et al.'s (2019) remarks on the potential influence of self-gravity, here we investigate the role of gravitational effects on substructures.

The parameter describing gravitational instability is  $Q \equiv \frac{a\kappa}{\pi G\Sigma}$ (Lin & Shu 1964; Toomre 1964; Goldreich & Lynden-Bell 1965), where *a* is the sound speed,  $\kappa$  is the epicyclic frequency defined as  $\kappa^2 \equiv 4\Omega^2 + 2R\Omega \frac{\partial\Omega}{\partial R}$  ( $\kappa = \Omega$  for Keplerian rotation), and  $\Sigma = \int_{-z}^{z} \rho dz$  is the disk surface density. In this calculation,  $\Sigma$  will be obtained from PERSPECTIVE<sup>5</sup> by integrating the system along the line of sight via an interpolated ray-tracing method, as in Väisälä et al. (2019).

The modification of the Toomre Q parameter for a magnetized disk can be written as  $Q_M \equiv \frac{a'\kappa}{\pi G\Sigma\epsilon}$  in general (Shu & Li 1997; Lizano et al. 2010), where a' is the isothermal magnetosonic speed, and  $\epsilon = 1 - \lambda^{-2}$  is a function of the mass-

to-flux ratio  $\lambda$ . With the consideration of the magnetic field, the critical limit  $Q_M$  becomes greater than the original Toomre Q (Lizano et al. 2010). When nonideal MHD effects are included, the limit can be reduced to that of the hydrodynamic case (Das & Basu 2021). However, for our simple purposes, we neglect nonideal MHD effects and only take the hydrodynamical case (lower limit). As shown in Section 3.2, it is sufficiently informative for our purposes.

#### 2.3. Shock Identification

Shock waves, such as accretion shocks onto a disk, are salient features and can play a significant role in influencing the dynamics of the accretion flow and thereby the disk (e.g., Yorke et al. 1993, 1995; Yorke & Bodenheimer 1999).

Accurately and completely detecting shocks in numerical simulations can be difficult. In spite of that, when shock properties are not our focus, a simple method to find their location would be adequate. The algorithm for detecting shocks implemented in this paper is based on two threshold conditions: (1) a thermal pressure gradient larger than an empirical threshold and (2) the positive convergence of velocity  $(-\nabla \cdot \mathbf{v})$  larger than another empirical threshold. These thresholds filter out discontinuities that are too weak to detect and artificial jumps due to numerical deviations.

## 2.4. Characterizing Spiral Structure

As shown in Table 2, spiral structures are present together with RSD in visible features. Li et al. (2013) only explored the two-armed "pseudospirals" (analogously referring to "pseudodisk") that are part of a magnetically induced curtain. By looking into the time evolution of the disk formation, Väisälä et al. (2019) noticed inner spirals through morphology. However, in these two papers, more detailed properties of the spirals were not further studied quantitatively.

To characterize spiral structure, we manually fit the 2D column density map with a simple logarithmic form given by

$$\varphi = b \ln r + \text{const.},\tag{3}$$

where  $(r, \varphi)$  denotes the polar coordinate, and (b, const.) is the parameter space to explore. The corresponding pitch angle would be

$$\alpha = \arctan \frac{1}{b},\tag{4}$$

which does not depend on const.

## 3. Results

In this section, the results of selected models are presented in detail. Spatial distributions of angular momentum and torques, including the dominant torque, are described in Section 3.1; the role of gravitational instability is studied in Section 3.2; the interplay of gravitational and magnetic effects in the spirals is shown in Section 3.3; trends in time for central mass and angular momentum are explored in Section 3.4; the results of the shock detection are shown in Section 3.5; the warped disk and rings present in the precessing model H are studied in Section 3.6; and the dependence on ambipolar diffusion is demonstrated in Section 3.7.

Some of the phenomena were already discovered in Li et al. (2013) and Väisälä et al. (2019). However, due to their

<sup>&</sup>lt;sup>5</sup> PERSPECTIVE is a lightweight radiative transfer code for the purpose of examining observational variables or other integrable quantities based on simulations. For a more complete description of PERSPECTIVE, see Section 3 in Väisälä et al. (2019).



Figure 1. Color map of specific angular momentum and torques of model G in a time sequence. The panels from left to right are the specific angular momentum per unit volume  $J_{spc,z}$ , the total torque  $N_{tot}$ , the advective torque  $N_{adv}$ , the magnetic torque  $N_{mag}$ , the torque due to pressure gradient  $N_{prs}$ , the gravitational torque  $N_{grv}$ , the torque due to magnetic tension  $N_{m,tns}$ , and the torque due to magnetic pressure  $N_{m,prs}$ . The first four rows are the results in the same color scale at different times in sequence. The box size is  $200 \times 200$  au<sup>2</sup>. The last row displays results in the same frame as the fourth row but in different color scale, and the box size is  $2000 \times 2000$  au<sup>2</sup>.

different focus, their analysis was either limited or merely their existence was noted without more quantitative analysis.

## 3.1. Angular Momentum and Torques

Torques and angular momentum transfer play a central role in protostellar disk formation. Figures 1-5 show the angular momentum and torques at midplane<sup>6</sup> within 100 au for their respective models in a time sequence. Figures 1, 2, 3, 4, and 5, respectively, feature models G, H, I, A, and D.

Models G, H, and I have the same misalignment (largest angle) but different mass-to-flux ratios. As the magnetic field is stronger (smaller mass-to-flux ratio), the specific angular momentum is less preserved, and its spatial distribution becomes more chaotic and less azimuthally symmetrical.

Spirals in density and magnetic fields are characteristic features for models with misalignment between the mean magnetic field and the rotation axis. In such models (G, H, and I), shown in Figures 1–3, a spiral structure, as well as a ringlike structure, appears in torques (see the first row of Figures 1–3). The large spirals at early stages correspond to the spirals in density along which the flow is falling in. The total torque along the spirals is positive, which indicates that the flow gains angular momentum through the spirals. As major accretion

begins, the large spirals are interfered with either the rapid rotation with the presence of a disk (models G and H) or the braking of almost all rotation (model I). In contrast, no spiral structure appears in the aligned model (A; see Figure 4), but instead, the disk plane becomes dominated by decouplingenabled magnetic structures (DEMS; Zhao et al. 2011), which manifest as low-density regions evacuated by decoupled magnetic flux near the protostar.

As for the partially misaligned model (D; see Figure 5), the large-scale spiral structure in torques and angular momentum shows up at early stage as well. The low-density "holes," which are magnetically dominated DEMS, have low angular momentum. Though it has the same initial magnetic field strength as model G, partial misalignment cannot completely suppress the formation of DEMS. Also, the symmetric pattern in the thermal pressure gradient torque and gravitational torque in the total misaligned models (G, H, and I) disappears in model D.

Locally, i.e., calculated on a single grid cell, the magnetic pressure gradient torque can be more significant than the magnetic tension torque, so that the former cannot be neglected. Globally, i.e., calculated by integrating over a sphere, the magnetic pressure gradient torque is negligible. For instance, Figure 16 compares each torque to others, which are calculated by adding the local value on each grid cell within a radius. As shown in Figure 16,  $N_{\rm m,prs} + N_{\rm grv} + N_{\rm prs}$ 

<sup>&</sup>lt;sup>6</sup> The first layer of grid points above the midplane.



Figure 2. Same as Figure 1 but for model H.

is negligible at most radii, except that around  $10^{15}$  cm,  $N_{grv}$  is relatively important. This is not inconsistent with neglecting the magnetic pressure term in Li et al. (2013), since the authors analyzed torques integrated over a sphere rather than a grid cell.

Figure 6 shows the dominant torques in the midplane within 100 au of models G, H, D, and A. To examine the forces with physical meaning, only the z-component of torques due to the Lorentz force, thermal pressure gradient, and gravity are compared. Model I has similar results of the dominant terms to model H, and, for simplicity, model I is not demonstrated. In model G, the gravitational torque rather than the magnetic torque dominates at the late stage. It is consistent with the decline in the effect of the magnetic field in this region. Gravity can play its special role within the inner parts, as we will further illustrate in Section 3.2. In model H, where the mass-toflux ratio is smaller, however, the magnetic torque dominates in turn. It implies a stronger effect of magnetic torque on maintaining the angular momentum. In model D, the spiral pattern manifests where the pressure gradient torque is prominent. As mentioned previously, Li et al. (2013) focused the analysis on the global torques so that the gravitational and pressure gradient torques are neglected. According to the dominant terms, however, the local gravitational torque can be prominent.

Figure 7 demonstrates the connection among torques, column density, magnetic field, and velocity of models G, H, I, and A, respectively. The advective torque has no strict correspondence with the velocity but with the convergence of

velocity. The latter usually relates to shock waves. Utilizing the method mentioned in Section 2.3, we detect shocks to fathom whether the ringlike and spiral structures are formed due to shock waves. The results will be shown in Section 3.5. The torques due to the thermal pressure gradient and gravity are less essential to the ringlike expanding wave surrounding the spirals. The spiral structure of the advective torque follows the column density spirals. The top right panel of Figure 7 shows that the edge of the positive and negative magnetic torque of model G strictly corresponds to the region where the direction of the magnetic field reverses. For models H and I, though the spatial distribution of the magnetic torque looks chaotic, we can always find a pair of symmetric spirals where the magnetic field reverses and the magnetic torque changes its sign across the spirals. Yet model A shows a smaller influential region of magnetic torque.

## 3.2. Role of Gravitational Instability

Since a robust RSD is present in model G, the gravitational instability of the disk can be analyzed for this model, involving the formation of spiral structure. The disk mass and its induced potential well are essential factors of gravitational instability. Thus, the disk-to-star mass ratio  $M_d/M_*$  can be utilized to reflect the underlying physics. For simplicity,  $M_d$  is approximated to the enclosed mass within 100 au, at which the outer edge of the disk for model G is roughly located, and  $M_*$  is regarded as the central mass.



Figure 3. Same as Figure 1 but for model I.

Before efficient accretion begins (about 114.1 kyr), the diskto-star mass ratio is much greater than unity (see Figure 8). It rapidly declines below unity afterward, when the disk starts to form and its mass accumulates. During the process, the ratio decreases slowly, with some temporary increases in the ratio. The mass accretion rate behaves correspondingly. At around 129.9, 136.3, and 154.3 kyr, another three bursts of rapid accretion occur, after an initial buildup of disk mass. They are most likely triggered by a sort of instability in the disk, as disk systems with large mass have a tendency to be gravitationally unstable. Therefore, we calculate the Toomre Q parameter of model G to investigate the possible presence of gravitational instability.

Figure 9 shows the radial distribution of the Toomre Q of frames at which the disk-to-star mass ratio is relatively large. During this period, Toomre Q < 1 within a few tens of au, which suggests that the gravitational instability grows in the disk. It may account for the disk wobbling (see also Figure 7 in Väisälä et al. 2019) around 154.3 kyr. The sharp decrease in the disk-to-star mass ratio after 154.3 kyr agrees with the disk wobbling. At large radii, 1000 au, for instance, though the gas is sparse, it flows inward with little rotation. Then it leads to a relatively low value of Q.

A disk also forms in model H, even though it is porous, as described in Li et al. (2013) and Väisälä et al. (2019), and the disk size is clearly smaller than that in model G. Figure 10 shows that  $M_d/M_*$  is relatively small, and new accretion substantially slows down after about 126 kyr. Then we do the

same analysis on model  $H^7$  as model G. The Toomre Q parameter exceeds unity most of the time (see Figure 11). Meanwhile, the gravitational torque does not dominate other terms (see Figure 6). It indicates that the disk is gravitationally stable in model H with a stronger magnetic field than in model G. It implies that a strong magnetic field suppresses gravitational instability, which is also suggested in Lizano et al. (2010).

The 2D figure at the disk plane illustrates a clearer relation between the spiral structure and Toomre Q. As shown in Figure 12 of model G, the spiral structure in column density correlates with the relatively low value region of Toomre Q. In contrast to model G, no apparent spiral structure in the Toomre Q (see Figure 13) of model H is identified within 100 au. The central disk of model H, whose size is much less than 100 au, is not affected by gravitational instability.

## 3.3. Magnetic Spirals

According to the torque distribution at the midplane (Figure 7) and column density (Figure 14; for more examples, see Väisälä et al. 2019), misalignment models (G, H, I, and D) show large-scale stable two-armed spirals. As shown by Li et al. (2013), a magnetic field is wrapped around like a snail

<sup>&</sup>lt;sup>7</sup> Notice here that in model H, the disk precesses rather than rotating along the fixed *z*-axis. The column density needed for calculating the Toomre Q parameter should be integrated along the rotation axis, so the disk plane should be recognized. See Appendix B for the method used to determine the disk plane.



Figure 4. Same as Figure 1 but for model A.

shell, and the spiral arms are located between two sheets of magnetic fields with opposite signs, where the magnetic field reverses. As the magnetic torque and magnetic field of misaligned models show in Figure 7, the large-scale spirals are always followed by the reversed magnetic field, which is the consequence of misalignment and rotation.

While in principle, the magnetic spirals are the simple results of geometry, in practice, we have to separate the outer and inner spirals. The outer spirals remain, in principle, a coherent structure, whereas the inner spirals are prone to chaotic effects. In model H, we get rings and gaps, further elaborated in Section 3.6. In model G, other forces come to take part.

As a special case, in model G, a small-scale one-armed spiral (Figure 14) is identified, which corresponds to the inner disk. We show in Section 3.2 that gravitational instability can grow in such a magnetized structure. The one-armed spiral corresponds to the mode m = 1 for a hydrodynamic density wave. If we estimate the geometrical properties of the spirals, the logarithmic function fits those spirals well with a slight deviation. The fitting functions have a parameter of b = 6.0 for the one-armed spiral structure. The corresponding pitch angles are about 9° for the inner spiral and 16° for the outer (see Figure 14).

It should be noted that gravitational instability and magnetic spirals are not mutually exclusive effects. Both phenomena can be nonlinearly coupled. Even when gravitational instability becomes significant, the system is still under considerable magnetic force. A potential example of this coupling could be the launching of a blob in model G. There, as a combination of gravitational instability and mass accretion, a blob of gas is launched outward from near the system center. Its launch is likely slowed down by the toroidal magnetic field in the system, making the blob fall back down within an elliptical orbit. Without the magnetic effect, the blob could be expected to propagate farther away—perhaps becoming a genuine fragment.

# 3.4. Central Mass Growth and Angular Momentum Redistribution

In model G, four significant bursts of central mass growth occur (Figure 8). The first would be the beginning of the insideout collapse. We choose the frames at these four peaks to investigate the torques and angular momentum in detail (114.4, 129.9, 136.6, and 154.3 kyr) and those who are 3.169 kyr before the peaks (111.2, 126.8, 133.4, and 151.2 kyr), at which times the mass accretion rate is relatively low.

As presented in Figure 15, the z-component of angular momentum  $J_z$  redistributes during evolution, while the total amount marginally conserves. In the inner tens of au,  $J_z$  decreases with time, while in the outer thousands of au, the angular momentum rises with time. The enclosed angular momentum of a sphere within around 100 au, for instance, increases first and then drops as the system evolves; the drop is especially significant at the fourth peak of the mass accretion rate. It is accordant with the expectation of the accretion process.



Figure 5. Same as Figure 1 but for model D.

The total torque  $N_{\text{tot}}$  equals the RHS of Equation (2). In the inner 10 au, the total torque is always negative, and in the outer 1000 au, it remains positive. The peak around 1000 au corresponds to the expanding wave shown in the color map of torques (Figure 7). The torque varies significantly in between. At frames of low mass accretion rate, the total torque tends to be positive at most of the radii. Meanwhile, except for the first burst of accretion when the inside-out collapse just begins, the total torque can be negative on a scale of 100 au. It is evident that the burst of accretion accompanies tremendous redistribution of angular momentum.

In order to investigate the mechanisms in detail, we plot each torque at these four peaks of mass accretion rate in Figure 16. The torques due to magnetic pressure and the thermal pressure gradient are zero or negligible due to insignificant numerical deviation, as expected. In addition, we notice that the gravitational torque around 100 au can make minor contributions to angular momentum transfer, even though it is nearly 1 order of magnitude smaller than the advective torque. Moreover, at a late stage, the gravitational torque exceeds the magnetic torque, which is also implied in Figure 6. The trend of its increasing with time suggests that the gravitational torque under favorable conditions.

## 3.5. Locating Shocks

In Figure 17, shown at 144.5 kyr, the noticeable pattern of convergence of velocity and the thermal pressure gradient is an

X-shaped structure on the x-z plane and a spiral structure on the x-y plane. In addition, we see an expanding wave naturally appearing as a ring structure behaving as an inside-out collapse. Viewed on the x-y plane, it shows the clear inner one-armed spiral structure of the compression region. Besides, viewed on the x-z plane, an X-shaped structure exists for a long run. The X-shaped structure represents an inner edge compression layer of the "pseudodisk," as the arms wrap around themselves while spiraling inward, and the outer ring is the expanding wave front of the inside-out collapse. The complex structure along the z-axis may be influenced by boundary conditions, which therefore cannot be fully trusted for conclusions.

The strongest candidates for shocks are seen in the inner disk and identified by the combination of conditions mentioned in Section 2.3. In Figure 18, the shock front is tightly related to the inner spiral. In this sense, we regard this spiral pattern in the shock as the so-called spiral shock driven by the rotation of the system. The X-shaped pattern, on the other hand, does not fulfill equal conditions; therefore, the spiral remains as the most substantial shock.

We have in Figure 18 the presence of a shock front that is associated with both the outer and inner portions of the spiral structure of disk model G. The shock portion located on the outer part of the spiral fulfills the expected role of an accretion shock (being the boundary between fast infalling material and a region of slower accretion with significant rotational support). This role is modified by the break of axisymmetry induced by the presence of spirals in both the accretion channels and the



Figure 6. Colors in panels from top to bottom indicate the dominant terms of models G, H, D and A: magnetic torque in blue gray, pressure gradient torque in light yellow, and gravitational torque in orange. Each panel range extends from -100 to 100 au in both the x- and y-axes. Model I shows similar results to model H, so it is not shown here.

disk structure, so it is not simply a matter of radial location on the midplane but is mediated through the spiral structure. The shock is reported as clearly present, having passed the stringent two-threshold criteria limits given in Figure 18 (less stringent threshold criteria show wider regions as candidates for perhaps weaker shocks). This spiral-associated shock region presents no singly defined centrifugal or accretion shock radius but rather a range that depends on azimuth around the disk spiral structure. We are dealing here with a smoother and more gradual accretion than in the more traditional axisymmetric models, making a less clear boundary between the inner disk and its surroundings. Some of these transition features might represent sharp lines marking the limits of the outer parts of the disk spirals and the inner parts of the accretion channel spirals. It is possible that the magnetized shock structures observed in the simulation are either C- or J-shocks, potentially distinguishable in local or global simulations of very high resolution. Features with strong effects on the observability of shocks, such as heated gas, may be desired in future work along these lines of research.

## 3.6. Warped Disk and Rings

In model H, we notice the disk would evolve to substructures, a warped disk, and rings (see Figure 19). They

are not steady but evolve into each other back and forth. The disk is warped under the influence of precession, while outflow is driven along the *z*-direction. The inner and outer rings have different inclination angles, and they have a gap of about 10 au in between (also see Figure B1).

The magnetic field lines interspersed in the rings show different paths (Figure 20). The inner substructure is more relevant to the toroidal magnetic field; the outer is opposite. In Figure 21, when the inner disk is dense and compact (top left and bottom right panels), the embedded magnetic field reverses inside the disk, but when it is dispersed (top right and bottom left panels), the field direction does not reverse.

In model H, the disk is not rotating with a circular orbit (also suggested in Väisälä et al. 2019). There is a tightly spiraling inward flow.

Spirals are present in this flow, and, through mechanisms of angular momentum change, the spiraling inflows largely circularize their orbit and form rings. For instance, at 154.3 kyr, two salient rings at radii of 20 (inner ring) and 50 (outer ring) au are observed to feed from the inflowing spirals. As the first row in Figure 2 shows, ripples in the radial direction exist in the torques. Such ripples in the torques result in the local increases in angular momentum at the radii of some rings, as well as decreases at their surroundings. Migration of gas



Figure 7. Color map of advective torque (left panels) overlaid by velocity (arrows) and column density (yellow contours) and magnetic torque (right panels) overplotted by magnetic field (arrows) and column density (yellow contours) on the midplane of model G at frame 429, model H at frame 456, model I at frame 525, and model A at frame 400.

takes place according to these variations in the content of angular momentum at different radii, redistributing the gas. Rings and gaps then form during this angular momentum redistribution.

When the inner disk is formed, the field is heavily curved. Then, when the removal of angular momentum due to polar outflow driven by a possible magnetic tower jet results in both accretion and ejection of surrounding matter, the rings are dispersed. In such a case, the magnetic field would play a dominant role in angular momentum transfer.

Loss of mass and angular momentum in outflows is then a possible cause of weakening and potentially destroying transient disk structures, as seen here in model H. While model D has a different structure, its transient disk is destroyed at least in part due to outflows. The transient outflows observed in this set of simulations are to be distinguished from mature outflows, such as those presented in Shang et al. (2020); these mature outflows start from a long-duration magnetocentrifugal wind (such as the steady-state flow in Shu et al. 1995) and are largely governed by their interaction with the ambient medium. By contrast, the outflows presented here are transient structures of various origins connected to the processes of disk formation; however, they have in common that both kinds of outflows are channels for mass loss and angular momentum transport.

#### 3.7. Dependence on Ambipolar Diffusion

With regard to the existing data set, our focus has been on an ideal MHD scenario, and nonideal MHD effects have been excluded. However, previous literature suggests that nonideal MHD effects are crucial for disk formation during core collapse, at least in the first core phase (e.g., Duffin & Pudritz 2008; Mellon & Li 2009; Tsukamoto et al. 2015; Marchand et al. 2016; Masson et al. 2016; Hennebelle et al. 2016; Wurster et al. 2016; Zhao et al. 2016; Vaytet et al. 2018). To address the influence of nonideal MHD effects, we examine preliminary results at this point by considering ambipolar diffusion as a case of weak ionization. The formula of drag force per unit volume exerted on the neutrals by the ions reads

$$\boldsymbol{f}_{\mathrm{d}} = \gamma \rho_{\mathrm{n}} \rho_{\mathrm{i}} \boldsymbol{v}_{\mathrm{d}}, \tag{5}$$

where  $\gamma = \frac{\langle \omega \sigma_{in} \rangle}{m_n + m_i}$  is the drag coefficient, with  $\langle \omega \sigma_{in} \rangle$  being the momentum transfer rate coefficient for ion-neutral collisions;  $v_d$  is the drift velocity defined as  $v_d \equiv u_i - u_n$ ; and  $\rho$ , m, and u are the density, mass, and velocity with subscripts n and i denoting the neutrals and ions, respectively. We utilize the practical drag coefficient  $\gamma = 3.5 \times 10^{13} \text{ cm}^3 \text{ g}^{-1} \text{ s}$  and  $\rho_i = C \rho_n^{1/2}$  with  $C = 9 \times 10^{-16} \text{ cm}^{-3/2} \text{ g}^{1/2}$  (three times the value from Shu 1992 but well within the expected range of variation of *C*). Since the drag force on ions  $-f_d$  equals a negative Lorentz force exerted on ions under the assumption of small fractional ionization, the drift velocity can be rearranged as  $v_d = \frac{1}{4\pi\gamma\rho_n\rho_i}(\nabla \times B) \times B$ . With the strong coupling limit, a single fluid is an adequate approximation. Thus, the equations remain closed.

We visualize the column density and drift velocity  $v_d$  in Figure 22 to investigate the role that ambipolar diffusion plays in the emergence of the spiral structure. The significant change in column density of model Galpha compared to model G is that the small-scale spiral structure stays two-armed and



Figure 8. Central mass growth (top), disk-to-star mass ratio (middle), and mass accretion rate (bottom) of model G.

symmetric in the inner disk. The large-scale magnetic spirals are unaffected in their morphology.

The drift velocity tends to vanish within  $r \sim 200$  au, mainly due to high density. In the outer region, the drift velocity coincides with the spiral structures. The evolution of the drift velocity corresponds to the inside-out collapse, and the influential region expands. The interface between positive and negative values of  $v_d$  goes along where the magnetic field reverses. Specifically, the positive radial drift velocity (reddish color in the right panel of Figure 22) represents where the drag force accelerates the neutrals outward.



Figure 9. Integrated Q parameter in model G at frames between the first and last bursts of rapid accretion. Here R is the cylindrical radius on the disk plane.

The angular momentum and torques of model Galpha are shown in Figure 23. Compared to model G, the major change observed in model Galpha would be the absence of one-armed spirals in torques at a later stage, but two-armed spirals appear instead, similar to the structure in column density. What remains the same in principle is that at a later stage in most of the inner disk, the gravitational torque is prominent, and the pressure gradient torque dominates along the spiral edge (see Figure 24).

Influences of other aspects on the magnetic spirals magnetic flux, for instance—are beyond the scope of this paper and might be investigated in future work.

## 4. Discussion

# 4.1. Gravitational Instability Affects the Magnetic Field

Comparing model G with model A, misaligned magnetic fields make it possible for both gravitational torque and pressure gradient torque to play a role in redistributing angular momentum. A stronger field (model H) or less misalignment (model D), however, leads to less disk mass, which is below the threshold of disk mass for gravitational instability to occur. Therefore, both the misalignment of the magnetic field and the strength of the field are relevant factors for allowing gravitational instability to grow.

In model G, the wobbling disk leads to both a high mass accretion rate and redistribution of mass. Once the rate of mass accumulation is higher than that of magnetic flux, the disk mass is large enough to trigger gravitational instability, delaying magnetic field gathering. Due to the motions driven by the gravitational instability, the gas in the disk becomes more evenly spread alongside the azimuthal magnetic field in the disk, effectively slowing down field gathering around the central sink.

On the other hand, in model H, we do not see the presence of gravitational instability. There, the flux is able to sufficiently accumulate to create what we suspect to be a magnetic tower jet, removing angular momentum in that way. This is why we see a momentary burst of outflow in model H but not in model G.

## 4.2. Properties of Magnetic Spirals

In misalignment models, a large spiral structure forms at the beginning of accretion due to initial rotation and reversed magnetic field lines. At a late stage, the central region is disrupted by accumulation of mass and magnetic flux, while the outer spirals sustain their structure. The formation of RSD essentially highlights the magnetic spirals as a feature of the infalling envelope.

Along the outer magnetic spirals, the total torque keeps positive so as to maintain the angular momentum of inflows. Since the evolution in the central region is complex, the magnetic spirals most effectively affect the accretion of mass downstream along the spiral arms. In contrast to the small-scale spirals, the large-scale spirals do not produce shocks. They are merely features of magnetic inflow, reasonably coherent in their large length scale and independent of the disk downstream.



Figure 10. Same as Figure 8 but for model H.

#### 4.3. Implications for Observations: Streamers

In principle, the large-scale magnetic spirals, described in Section 4.2 above, are very visible features in ideal conditions. In practice, however, they are likely easily missed. As sparser features, their emission can be relatively weak and therefore remain unresolved. There are, however, some promising observations.

Magnetic torques can be relevant with the streamer-like objects such as observed by Pineda et al. (2020; Per-emb-2) and Grant et al. (2021; MGM 2012 512). Also, the HH 211 observations of Lee et al. (2019) indicate a magnetic streamer arm. If the magnetic field is strong enough to be dynamically

significant, it will make the most sense that such inflows are aligned with the magnetic field. As such, magnetic torques as explored in this study could become a significant factor of their behavior during their collapse downward.

To explain this further, the idea of magnetic spiral inflow is not limited to cases of spirals directly and primarily caused by the magnetic field. The idea also includes cases in which the magnetic field efficiently couples with the inflowing gas. Therefore, even if the spiral-like inflow is caused by some other phenomenon, a dynamically important magnetic field is still crucial.

So there are two primary options: either the magnetic field is dynamically significant, or it is not. If it is not dynamically significant (unlikely), then we do not need to care about any of this. However, as it is likely that the magnetic field is dynamically significant, we have to look into the effects to reach a complete understanding.

If a streamer is to propagate in a perpendicular direction with respect to the magnetic field, it will not be able to maintains it elongated structure. In the case of a magnetically aligned streamer, however, it would naturally follow the inspiraling form. Therefore, it would be reasonable to state the hypothesis that the streamers of Pineda et al. (2020), Grant et al. (2021), and Lee et al. (2019) are aligned with the field and that the mean magnetic field of the object will be generally aligned perpendicular to the rotation axis of the system.

#### 4.3.1. IRAS 18089-1732

In the domain of high-mass star formation, there is the case of the object IRAS 18089–1732 (Sanhueza et al. 2021), which demonstrates, very visibly, magnetic field alignment with the inflowing gas. In their ALMA observations, Sanhueza et al. (2021) depicted a site of massive star formation where rotational flows are collapsing toward the center in a whirlpool-like manner. In their estimates, gravity dominates the process, with rotational and magnetic energies being significantly weaker. Sanhueza et al. (2021) estimated based on a magnetic model and observations that the mass-to-flux ratio is  $\lambda \sim 3.61$  and 3.2, respectively. These would be values between our models I and H, though those are not directly comparable, as our models do not examine massive star formation, and the basis for computing values of  $\lambda$  is different.

Sanhueza et al. (2021) showed that IRAS 18089–1732 consists of one spiral streamer and two inflow filaments. Based on polarization estimates, the magnetic field is following the spiral geometry of the streamers/filaments and is substantially toroidal. Based on the seeming alignment of the field, streamers of IRAS 18089–1732 can be a case of magnetic spirals.

The magnetic field model of Sanhueza et al. (2021) assumes an hourglass poloidal field with an added toroidal component, but our magnetic spiral model is dominated by toroidal features. However, choosing the basic large-scale field model is a choice that will bias the estimate with its assumptions. The depth of the system is not obvious; therefore, either model assumption can, in principle, be attempted.

The basis for magnetic spirals has two main arguments. First, the field geometry is appropriate, with density and magnetic structures similarly aligned. Second, despite gravity dominating the system globally, magnetic forces can still play a role locally, e.g., by maintaining the relative coherence of the inflow spirals. This is possible because, by the estimates of Sanhueza et al. (2021), the magnetic, turbulent, and rotational energies



Figure 11. Integrated Q parameter in model H at selected frames when an inner disk is clearly distinguished. Thus, the column density is derived along the disk rotating axis. Same as in Figure 9, R is the cylindrical radius on the disk plane.



Figure 12. Toomre Q at the midplane of model G at 149.9 kyr. The right panel is a zoom-in of the panel on the left. White represents Q = 1.

are roughly equal. Therefore, within the inflow frame, the magnetic field could clearly affect secondary types of motions, as happens with magnetic inflow spirals in our collapse models.

## 4.4. Implications for Observations: Rings and Spirals

A couple of spiral structures within the protostellar disk of HH 111 VLA 1 with ALMA observations of thermal emission

have been reported by Lee et al. (2020). They subtracted the continuum map of HH 111 VLA 1 by its annular mean and fitted the residual map in logarithmic and Archimedean form, respectively. Their corresponding pitch angles are  $\sim 16^{\circ}$  for one arm and  $\sim 13^{\circ}$  for the other. In our simulations, the most promising model to demonstrate the spiral structures in HH 111 VLA 1 is model Galpha, since it has a proper length scale (tens of au) and number of arms (m = 2). To compare with the



Figure 13. Same as Figure 12 but at the disk plane for model H at 154.3 kyr.



Figure 14. Density overlaid by fitted spirals. The one-armed spiral in the inner region (blue curve) and the two-armed spiral in a more outer region (red curve) are fitted as shown in Section 3.3 using the method of Section 2.4.



Figure 15. The *z*-component of angular momentum (left) and total torque (right) within spheres of a given radius *r*. Different colors and line styles depict quantities at different time frames. The angular momentum is plotted in units of g cm<sup>2</sup> s<sup>-1</sup> and torques in dyn cm. The left panel is plotted in logarithmic scale and the right in symmetrically logarithmic scale with a linear scale within  $\pm 0.2$ .



Figure 16. Left panel: advective (solid lines), magnetic tension (dotted-dashed lines), magnetic pressure (dotted lines) torque. Right panel: gravitational (solid lines) and pressure gradient (dotted-dashed lines) torque. The lines in different color denote the torques at 114.4 kyr (black), 129.9 kyr (purple), 136.6 kyr (magenta), and 154.3 kyr (yellow). The left panel is displayed in symmetrically logarithmic scale with a linear scale within  $\pm 0.2$ , and the right panel is in linear scale. Torques are given in dyn cm.

observed value, we estimate the pitch angle with the 2D discrete Fourier transform (2DDFT; e.g., Kalnajs 1975; Iye et al. 1982; Krakow et al. 1982; Yu et al. 2018, 2019; for details, see Appendix C) method more accurately than by hand. We processed the map of column density for model Galpha subtracted by its annular mean (Figure 25). The pitch angle remains reasonably close from frame to frame. As a result, the dominant mode  $(p, m) \approx (6, 2)$  corresponds to a pitch angle

 $\alpha = \arctan(\frac{2}{6}) \approx 18^{\circ}$ , which is consistent with the observed value for HH 111 VLA 1, as long as it can be assumed that the spiral will persist for a longer duration than the numerical collapse simulation has shown.

In model H, the magnetic rings appear within a warped disk, as two rings are tilted from each other with respect to their inclinations. This gives us a clue for where to find a system with such rings. We found that IRAS 04368+2557 could be an



**Figure 17.** Cut of convergence of velocity (upper row) and thermal pressure gradient (lower row) at the *x*-*z* (left column) and *x*-*y* (right column) planes of model G at 144.5 kyr. White represents  $-\nabla \cdot \mathbf{v} = 0$  (upper row) and  $|\nabla p| = 10^{-20}$  g cm<sup>-2</sup> s<sup>-2</sup> (lower row).

interesting one. Sakai et al. (2019) reported evidence of a warped structure in their disk candidate, analogous to two differently aligned rings. It is indicative that disks can be warped and not constricted into a flat plane. The follow-up observations of the nearly edge-on disk L1527 IRS around the protostar, IRAS 04368+2557, suggest that the disk could potentially embed rings in the disk-forming stage (Nakatani et al. 2020). The observed three clumps in the 7 mm radio continuum observations are closely located and symmetric and are resolved in the inner part of the disk (r < 50 au). Nakatani et al. (2020) speculated that it is a projected dust ring or spiral arms. The magnetic field provides one natural mechanism for

how the disk could be warped. With continuing modeling work, we can better characterize the magnetic rings and provide more detailed estimates for observations.

#### 5. Summary

In this work, we performed studies of spiral structure in simulations focused on the details of physics. Magnetic spirals in different scales are identified by their morphologies and torques in misaligned models. In some cases with relatively weak magnetic fields, small-scale spirals for which gravitational instability might play a role can be noticed as well. The main results are summarized as follows.



Figure 18. Density (color map) overlaid with the shock (region within contours) at the midplane of model G. To locate the shock, the threshold is set to  $10^{-20} \text{ s}^{-1}$  for convergence of velocity and  $10^{-21} \text{ g cm}^{-2} \text{ s}^{-2}$  for the thermal pressure gradient. The contours encircle the region that meets the conditions of both thresholds.



Figure 19. Column density of model H at 148.3 (left panel) and 154.3 (right panel) kyr. The color map displays the log<sub>10</sub> of the column density in units of g cm<sup>-2</sup>.

- 1. Magnetic spirals are triggered by initial rotation where the magnetic inflow aligns itself with the wrapped-around magnetic field geometry, as is most optimal for the flow.
- 2. In the misaligned case with a relatively high mass-to-flux ratio (model G), the magnetic torque is the main reason for angular momentum transfer at an early stage. In the central region of the disk, the gravitational torque softens the effects of magnetic torques at a late stage. With an increased magnetic field (model H), the gravitational torque becomes insignificant.
- 3. Rings and gaps can form in the inner disks when a relatively strong magnetic field wraps itself in the misaligned model with an intermediate mass-to-flux ratio (model H). The local gains and losses of angular momentum are local torques that have ripples in the radial direction; these ripples in the torques may be the cause of such rings and gaps.
- 4. Ambipolar diffusion as explored in this work has shown a slight influence on the small-scale spirals but not the main morphologies of magnetic spirals.

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Figure 20. Density (isosurfaces) with two embedded magnetic field lines (gray curves) whose start points are selected within the inner and outer disks for each. The box size is  $133.69^3$  au<sup>3</sup> in Cartesian coordinates. The density isosurfaces are logarithmically selected by 10 levels between  $3.0 \times 10^{-14}$  and  $1.0 \times 10^{-12}$  g cm<sup>-3</sup>.



Figure 21. Density on the disk plane overlaid by magnetic field arrows for model H at different frames: 136.9 (upper left), 154.3 (upper right), 161.3 (lower left), and 167.6 (lower right) kyr. Each panel has a different viewing angle, which is demonstrated by the triad rotation axis in the bottom left corner of each panel.



**Figure 22.** Left: face-on view of  $\log_{10}$  of column density for model Galpha at 135.0 kyr. Right: radial drift velocity in units of cm s<sup>-1</sup> on the equatorial plane for model Galpha at 135.0 kyr. The viewing phase angle of the right panel is rotated by 126°.



Figure 23. Same as Figure 1 but for model Galpha.

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Figure 24. Same as Figure 6 but for model Galpha.



Figure 25. The left panel shows the residual column density  $\delta N_{\rm H}$  by subtracting the annular mean from the column density of model Galpha at 128.0 kyr. The cutoff inner and outer radii in pure blue are 25 and 125 au, respectively. The right panel shows the amplitude of the residual column density by 2DDFT. Curves in different colors represent different modes with a value of m.

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Software: Astropy (Astropy Collaboration et al. 2013, 2018), Jupyter notebook (Kluyver et al. 2016), Matplotlib (Hunter 2007), Numpy (Harris et al. 2020), SciPy (Virtanen et al. 2020), VisIt (Visualization Tool; Childs et al. 2012).

## Appendix A Notes on Cell Integrations

Many of the data presented here are in the form of integrals of quantities inside a volume of a computational cell. Due to grid staggering, we performed our integrals in a cell-centered manner with the help of interpolation.

The center of the cell is numbered as (i, j, k), with the centers of the cell faces at points called  $(i - \frac{1}{2}, j, k), (i + \frac{1}{2}, j, k)$ , and so on, with *i*, *j*, and *k* in the *r*,  $\theta$ , and  $\phi$  directions. This amounts, in terms of the variables of the Zeus codes, to labeling the

b-grid with integer numbers and the a-grid with half-integer numbers. We keep to this convention while acknowledging that the converse notation (integers for the a-grid) is also used for other works.

Using this convention, when we compute integrals in a cell-centered manner, we are integrating inside a computational volume  $V_{i,j,k}$ , centered at the point (i, j, k), and extending in the r,  $\theta$ ,  $\phi$  directions to the range  $[i - \frac{1}{2}, i + \frac{1}{2}], [j - \frac{1}{2}, j + \frac{1}{2}], [k - \frac{1}{2}, k + \frac{1}{2}]$ . A face-centered point is located at a place such as  $(i - \frac{1}{2}, j, k)$ , and the corresponding volume  $V_{i-\frac{1}{2},j,k}$  extends to the range [i - 1, i],  $[j - \frac{1}{2}, j + \frac{1}{2}]$ ,  $[k - \frac{1}{2}, k + \frac{1}{2}]$ . We can start from the torque term

$$N_{\rm prs} = -\int \frac{\partial P}{\partial \phi} \, dV$$



Figure B1. Contours of column density in model H at 154.3 kyr viewed at a position angle of (88°, 288°).

where the pressure *P* can be seen as either the thermal pressure *p* or the total pressure  $p + p_{mag}$ . We assume that the pressure *P* is given to us defined at the cell centers (i, j, k) and that we want to compute the cell-centered integral over the volume  $V_{i,j,k}$ .

#### A.1. Point Value Approximation

While our r and  $\theta$  grids are nonuniform, our  $\phi$  grid is uniform. That allows a quick computation of the point value of the partial derivative at the cell center as

$$\frac{\partial P}{\partial \phi}\Big|_{i,j,k} = \frac{P(i,j,k+1) - P(i,j,k-1)}{2\,\Delta\phi} + O(\Delta\phi^{\text{order}}),$$

using the familiar centered-difference formula for the partial derivative. The point value approximation consists of just multiplying this point value at the center of V by the volume of V. This neglects the variations of the force inside V. Such approximation is expected to give results in the correct order of magnitude nearly everywhere, with some inaccuracy in regions where the force undergoes rapid variations.

## Appendix B Disk Plane in Model H

An edge-on view of column density provides the tilt angle of the disk. In model H, the disk has noticeable tilting. Figure B1 shows the contours of column density in model H at the same frame as Figure 19. The viewing angle ( $\theta$ ,  $\phi$ ) is an input parameter for PERSPECTIVE to provide the column density. When the contour of the largest column density (e.g., red curve) becomes the thinnest, its corresponding viewing angle is chosen to find the normal direction to the disk plane. The slope of the red contour is denoted by  $\arctan(y, x)$ . Thus, the normal direction to the disk plane is given by  $(\theta + \arctan(y, x), \phi)$ .

## Appendix C 2DDFT

To characterize spiral structure, we implement 2DDFT to extract the mode and pitch angle of spirals. The Fourier component AMP(p, m) can be derived by the Fourier transform of column density  $N(r, \varphi)$  as

$$\begin{aligned} \text{AMP}(p, m) \\ = & \frac{1}{2\pi} \int_0^{2\pi} \int_{-\infty}^{\infty} N(\ln r, \varphi) \\ & \times \exp[-i(p \ln r + m\varphi)] d(\ln r) d\varphi. \end{aligned} \tag{C1}$$

For discretely sampled N, the normalized discrete Fourier transform for AMP(p, m) can be obtained as

$$AMP(p, m) = \frac{1}{\sum_{n=1}^{M} N_n} \times \int_{\ln r_{in}}^{\ln r_{out}} \int_{\pi}^{-\pi} \sum_{n=1}^{M} N_n(r_n, \varphi_n) \delta(\ln r - \ln r_n) \delta(\varphi - \varphi_n) \times \exp[-i(m\varphi + p \ln r)] d\varphi d(\ln r)$$
(C2)

$$=\frac{1}{\sum_{n=1}^{M}N_n}\sum_{n=1}^{M}N_n(r_n,\,\varphi_n)\exp[-i(m\varphi_n+p\ln r_n)],\qquad(C3)$$

where  $N_n(r_n, \varphi_n)$  is the column density of the *n*th grid cell at  $(r_n, \varphi_n)$ ,  $r_{in}$  and  $r_{out}$  are the inner and outer boundaries of the spiral structure, and *M* is the number of grids between  $r_{in}$  and  $r_{out}$ . The mode in the  $\varphi$ -direction is sampled as m = [1, 2, 3, 4],

and in the *r*-direction, *p* is a sample of 100 evenly spaced points between -20 and 20. The pitch angle  $\alpha$  can be written in a function of dominant mode (p, m) as  $\alpha = \arctan(|\frac{m}{n}|)$ .

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