BIMODALITY OF CIRCUMSTELLAR DISK EVOLUTION INDUCED BY THE HALL CURRENT

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ABSTRACT

The formation process of circumstellar disks is still controversial because of the interplay of complex physical processes that occur during the gravitational collapse of prestellar cores. In this study, we investigate the effect of the Hall current term on the formation of the circumstellar disk using three-dimensional simulations. In our simulations, all non-ideal effects, as well as the radiation transfer, are considered. The size of the disk is significantly affected by a simple difference in the inherent properties of the prestellar core, namely whether the rotation vector and the magnetic field are parallel or anti-parallel. In the former case, only a very small disk ($<1$ AU) is formed. On the other hand, in the latter case, a massive and large (>20 AU) disk is formed in the early phase of protostar formation. Since the parallel and anti-parallel properties do not readily change, we expect that the parallel and anti-parallel properties are also important in the subsequent disk evolution and the difference between the two cases is maintained or enhanced. This result suggests that the disk size distribution of the Class 0 young stellar objects is bimodal. Thus, the disk evolution can be categorized into two cases and we may call the parallel and anti-parallel systems Ortho-disk and Para-disk, respectively. We also show that the anti-rotating envelopes against the disk rotation appear with a size of $\geq 200$ AU. We predict that the anti-rotating envelope will be found in the future observations.

Key words: magnetohydrodynamics (MHD) – radiative transfer – stars: formation – stars: low-mass – stars: magnetic field – stars: protostars

1. INTRODUCTION

Circumstellar disks are born around protostars in the course of self-gravitational collapse of molecular cloud cores. The angular momentum evolution during the collapse is critical for the disk formation because the disks are supported by the centrifugal force.

The magnetic field plays a central role for the evolution of the angular momentum. During the gravitational collapse, a toroidal magnetic field is created by the rotation, and the magnetic tension decelerates the rotation, removing the angular momentum. This effect is known as magnetic braking (Mouschovias & Paleologou 1979). Previous studies using ideal MHD simulations have shown that, for a typical magnetic field strength, the disk formation is completely suppressed in the early Class 0 phase (Hennebelle & Fromang 2008; Mellon & Li 2008; Bate et al. 2014).

Meanwhile, the observations of Class 0 young stellar objects (YSOs) showed that a relatively large circumstellar disk ($r \sim 50$ AU) exists around young protostars (Ohashi et al. 2014; Sakai et al. 2014; Tobin et al. 2015). These observations indicate that some very young protostars have relatively large circumstellar disks with sizes of $r > 10$ AU, suggesting a disagreement between previous theoretical works and observations.

Possible physical mechanisms for resolving the discrepancy between theory and observation are Ohmic and ambipolar diffusion (Mellon & Li 2009; Machida et al. 2014; Tomida et al. 2015; Tsukamoto et al. 2015a). Previous works following the formation of protostars showed that a small disk with a size of $r \leq 1$ AU is formed around the protostar when magnetic diffusion is considered (Tomida et al. 2013; Tsukamoto et al. 2015a). However, the formation of a disk with a size of $r \geq 10$ AU in the early phase of protostar formation in a typically magnetized cloud core is still highly difficult even with these effects.

The effect of the Hall current term is the least studied effect in the context of disk formation. The Hall current term generates a toroidal magnetic field from a poloidal magnetic field and directly affects the magnetic tension that determines the magnetic braking efficiency. The Hall current term in MHD equations is not invariant against the global inversion of the magnetic field (Wardle & Ng 1999; Krasnopolsky et al. 2011; Li et al. 2011; Braiding & Wardle 2012) and its effect changes depending on whether the rotation vector and magnetic field of the host cloud core are parallel or anti-parallel. When the Hall diffusion coefficient is negative (this is true for $\rho \lesssim 10^{-11}$ g cm$^{-3}$ in our model, see Figure 4) and the rotation vector and magnetic field are anti-parallel, the Hall current term weakens the magnetic braking. Meanwhile, the Hall current term strengthens the magnetic braking in the parallel case. Despite the possible importance of the Hall current term in disk evolution, it is still unclear how the Hall current term affects the formation of the circumstellar disk as previous numerical studies (Krasnopolsky et al. 2011; Li et al. 2011) neglected the first core evolution phase, which plays an important role in disk formation (Machida & Matsumoto 2011; Dapp et al. 2012; Tomida et al. 2015; Tsukamoto et al. 2015a) and simplifies the radiative transfer. Three-dimensional simulations are also necessary for investigating non-axisymmetric effects.

In this paper, we performed three-dimensional simulations starting from prestellar cloud cores. Our numerical simulations include all non-ideal MHD effects as well as radiative transfer. The simulations were conducted until the birth of the protostar.
We did not use any sink technique for the center and hence our simulations do not suffer from numerical artifacts introduced by the sink particle or the inner boundary, which may artificially change the formation and evolution of the disk (Machida et al. 2014).

2. NUMERICAL METHOD AND INITIAL CONDITIONS

In this study, we solved the non-ideal radiation magnetohydrodynamics equations with self-gravity. The numerical method, except for the Hall current term, is the same as that used in our previous study (Tsukamoto et al. 2015a). The ideal MHD part was solved using methods proposed by Iwasaki & Inutsuka (2011; 2013). The radiative transfer was treated with methods of Whitehouse & Bate (2004) and Whitehouse et al. (2005). We treated the Ohmic and ambipolar diffusion with the method described by Tsukamoto et al. (2013a) and Wurster et al. (2014), respectively. Both diffusion processes were accelerated by super time stepping (Alexiades et al. 1996).

For this study, we newly implemented the Hall current term according to Wurster et al. (2014). The Hall current term couples with the ideal terms and changes the phase velocity. Thus, it is unclear that the sub-cycle method, which is often used for the diffusion terms (Machida et al. 2011b; Tsukamoto et al. 2015a), is valid for the Hall current term. Therefore, in our simulations, the ideal MHD term and the Hall current term are updated with the same time step. The smaller time step of either the ideal term or the Hall current term, $\Delta t_{\text{ideal}} = C_{\text{ideal}} h^2 / (4 \pi \sqrt{n_0})$ (Sano & Stone 2002) is used for the update. Here, $C_{\text{ideal}} = 0.4$ is the Courant–Friedrichs–Levy number for the Hall term, and $h$ is the smoothing length.

We conducted numerical tests for the Hall current term and confirmed that the scheme can correctly calculate the whistler mode in the linear wave propagation test. Furthermore, we conducted gravitational collapse tests of non-rotating cloud cores and confirmed that the rotation amplitude induced by the Hall current term does not depend on the direction of the magnetic field. We adopted the equation of state (EOS), dust, and gas opacity tables from Tomida et al. (2013), Semenov et al. (2003), and Ferguson et al. (2005), respectively. We employed the resistivity table used in our previous works (Okuzumi 2009; Tsukamoto et al. 2015a) in which a fixed dust grain size of $a = 0.035$ μm and fixed cosmic-ray ionization rate of $\xi_{\text{CR}} = 10^{-17}$ s$^{-1}$ are assumed.

We modeled the initial cloud core with an isothermal uniform gas sphere using about $3 \times 10^5$ particles. The mass and temperature of the initial core are $1 M_\odot$ and 10 K, respectively. Initially, the core had a radius of $R = 3.0 \times 10^3$ AU and was rigidly rotating with an angular velocity of $\Omega_0 = 2.2 \times 10^{-13}$ s$^{-1}$. The initial magnetic field is uniform and parallel or anti-parallel to the rotation ($z$)-axis with a magnitude of $B_0 = 1.7 \times 10^2$ μG. The corresponding initial mass-to-flux ratio relative to the critical value is $\mu = (M / \Phi) / (M / \Phi)_{\text{crit}} = 4$ where $\Phi_0 = \pi R^2 B_0$ and $(M / \Phi)_{\text{crit}} = (0.53 / 3 \pi) (5 / G)^{1/2}$ (Mouschovias & Spitzer 1976).

We conducted three simulations, Model Para, Ortho, and NoHall. The magnetic field and the rotation vector are initially perfectly parallel in Model Ortho and NoHall, and anti-parallel in Model Para. The model NoHall does not include the Hall current term. Other parameters are the same in the models. The runtime of Models Para, Ortho, and NoHall was about $3.7 \times 10^5$, $1.4 \times 10^5$, and $1.6 \times 10^4$ CPU hours, respectively with XC30 in NAOJ.

A boundary condition was imposed at $R_{\text{out}} = 0.995R$, and the particles with $r > R_{\text{out}}$ rotate with an initial angular velocity. Thus, the gas was confined in a rigidly rotating shell. This boundary is very similar to that used in Matsumoto & Tomisaka (2004) and Machida et al. (2007), and also used in our previous work (Tsukamoto et al. 2015a). In addition, a boundary condition for radiative transfer was introduced by fixing the gas temperature to be 10 K when $\rho < 2.0 \times 10^{-17}$ g cm$^{-3}$.

3. RESULTS

In Figure 1, we show the structure at the center of the cloud core. The left and right panels show the result of Models Para and Ortho, respectively. The central densities are $10^{-5}$ g cm$^{-3}$ for the left panels, which correspond to slightly before the protostar formation, and $10^{-2}$ g cm$^{-3}$ for the right panels, which is immediately after the protostar formation.

When the rotation vector and magnetic field are in the anti-parallel configuration, a large disk with a size of $r \sim 20$ AU is formed (Model Para; top left panel). The disk is so massive that spiral arms are created by the gravitational instability. We confirmed that the Toomre’s $Q$ value, $Q = \kappa_{\text{ep}} c_g / (\pi G \Sigma)$ is $Q \sim 1$ in the entire disk region ($5 \lesssim r \lesssim 20$ AU). In the top panel of Figure 2, we show the force balance between the pressure gradient force, the centrifugal force, and the radial gravitational force on the $x$-axis. The gas is mainly supported by the centrifugal force. Therefore, a rotationally supported massive disk is formed in Model Para. On the other hand, when the rotation vector and magnetic field are in the parallel configuration, no large disk ($r \gtrsim 10$ AU) appears (Model Ortho; top right panel) because the magnetic braking is strengthened by the Hall current term and the angular momentum is efficiently removed from the central region. The dense region ($\rho > 10^{-11}$ g cm$^{-3}$) at the center, which has a radius of $r \sim 5$ AU, is the remnant of the first core and is not a rotationally supported disk. Although a rotationally supported disk with $r \lesssim 0.6$ AU is also formed in Model Ortho around the protostar, as shown in the bottom panel of the Figure 2; the difference of the disk size of Model Para and Model Ortho is remarkable.

The plasma $\beta$ in the disk regions ($r \lesssim 20$ AU) of Model Para is large ($\beta > 100$) because the magnetic flux is largely removed due to the magnetic diffusion. In this high $\beta$ region, the magnetic field and the gas are almost decoupled and the magnetic braking is no longer important. The disk is sufficiently massive and develops gravitational instability. Thus, gravitational instability may play an important role for angular momentum transfer in the subsequent evolutionary phase. Furthermore, in such a massive extended disk, disk fragmentation, which is a promising mechanism for the formation of binaries or wide-orbit planets (Marois et al. 2010), possibly occurs in the subsequent evolution (Boss 1997; Inutsuka et al. 2010; Machida et al. 2011a; Tsukamoto & Machida 2011, 2013; Tsukamoto et al. 2013b, 2015b). Thus, the parallel or anti-parallel property of the cloud core would play a crucial role for the formation of the binary or wide-orbit planets.

To quantify the strength of the rotation at the center of the cloud core, we show the mean specific angular momentum of regions with $\rho > 10^{-12}$ g cm$^{-3}$ as a function of the central density in Figure 3. The figure shows that the specific angular momentum in Model Para is about an order of magnitude larger than that of Model Ortho. The specific angular momentum in Model Ortho (Para) is about three times smaller (larger) than
that in Model NoHall. The combination of the spin-up effect (weakening of the magnetic braking) in the anti-parallel case and the spin-down effect (strengthening of the magnetic braking) in the parallel case causes the large difference.

The mass and the absolute value of the magnetic flux $|\mathbf{B}| = |\int \mathbf{B} d\mathbf{S}|$ of regions with $\rho > 10^{-12}$ g cm$^{-3}$ in model Para, Ortho, and NoHall at the beginning of the second collapse ($\rho_c = 10^{-3}$ g cm$^{-3}$), was $(M(M_\odot), |\mathbf{B}| \text{ G cm}^2) = (1.9 \times 10^{-1}, 3.7 \times 10^{28}), (7.5 \times 10^{-2}, 4.1 \times 10^{27})$, and $(1.1 \times 10^{-1}, 8.0 \times 10^{27})$, respectively. Here, $d\mathbf{S}$ is defined at the $z = 0$ and is parallel to the $z$-axis. Thus, the mass-to-flux ratio of the region normalized by its critical value $(M_\text{crit} = (0.53/(3\pi))(S/G)^{1/2})$ is $\mu = 21, 74, \text{ and } 56$, respectively. These values are much larger than the initial mass-to-flux ratio $\mu = 4$.

In Figure 4, we show the evolution of the Ohmic, Hall, and ambipolar diffusion coefficients, $\eta_O$, $\eta_H$, and $\eta_A$, at the center of model Para as a function of the central density. The evolution of model Ortho and NoHall were almost the same. In $\rho_c < 10^{-14}$ g cm$^{-3}$, $\eta_H$ is larger than $\eta_A$ and $\eta_O$, and the gas rotation is significantly affected by the Hall current term in this region. The value of $\eta_H$ is much larger than the “critical value” for disk formation (thin black line) suggested by Krasnopolsky et al. (2011) in this region. Although the $\eta_H$ decreases in $\rho_c \gtrsim 10^{-13}$ g cm$^{-3}$, the Ohmic and ambipolar diffusion alternatively play a role in $\rho_c \gtrsim 10^{-13}$ g cm$^{-3}$, and the rotation is maintained in the high density region without magnetic braking. Note that Krasnopolsky et al. (2011) only considered the Hall term and neglected other non-ideal effects. We remark that $\eta_A$ does not strongly depend on $|\mathbf{B}|$ around $\rho \sim 10^{-14}$ g cm$^{-3}$ although $\eta_A \propto |\mathbf{B}|^2$ in low density regions.

Because of the conservation of angular momentum, the spin-up due to the Hall term at the center causes spin-down of the outer region, eventually, causing anti-rotation against the disk. In Figure 5, we show the cross-section of the rotation velocity distribution of Model Para in the $x-z$ plane at the same epoch of Figure 1. This figure clearly shows an anti-rotating envelope surrounding the forward rotating inner region. Since the anti-rotation of envelope is driven by torsional Alfvén waves, the anti-rotating region expands with time and will propagate to the...
outside of the parental core. Thus, the angular momentum of the direction opposite to the disk would eventually be cast away to the interstellar medium.

4. CONCLUSIONS AND DISCUSSION

In this study, we investigated the effect of the Hall current term on the formation of circumstellar disks. All non-ideal effects, as well as the radiative transfer, are considered. To our knowledge, this is the first study that simultaneously includes these physical processes in a three-dimensional simulation. We found that the disk evolution can be categorized into two cases depending on whether the magnetic field and the rotation vector are parallel or anti-parallel. In the anti-parallel case, a relatively large ($r \approx 10$ AU) and massive disk forms simultaneously with protostar formation; however, a disk with $r \approx 1$ AU does not form in the parallel case. Thus, the parity of the magnetic field significantly changes the disk formation process, which has not been paid much attention to so far. Since

Figure 2. Solid lines show the ratio of the sum of the centrifugal force and the pressure gradient force to the radial gravitational force, $q_1 = |\frac{\partial^2 \Phi}{\partial r^2} + \frac{p}{\rho} / \frac{\partial^2 F}{\partial r^2}|$. The dashed lines show the ratio of the centrifugal force to the radial gravitational force, $q_2 = |\frac{\partial^2 \Phi}{\partial r^2}|$. The dash–dotted lines show $q = 0.5$. In the regions where the dashed lines are larger than the dash–dotted lines, the gas is mainly supported by the centrifugal force. The top and bottom panels show the results of Models Para and Ortho, respectively. The epochs of each model are the same as those in Figure 1.

Figure 3. Time evolution of the mean specific angular momentum of the inner region with $\rho > 10^{-12}$ g cm$^{-3}$ as a function of the central density. The solid, dashed, and dotted lines show the results of Model Para, Ortho, and NoHall, respectively.

Figure 4. Magnetic diffusion coefficients, $\eta_H$, and $\eta_A$ at the center as a function of the central density in Model Para. The red line shows $\eta_H$, the green line shows $\eta_A$ where the dashed line shows the region of $\eta_H < 0$, and the solid line shows the region of $\eta_H > 0$, and the blue dash–dotted line shows $\eta_A$. The black thin line shows the “critical value” of $\eta_H$, $3 \times 10^{20}$ $B_c$ (cm$^2$ s$^{-1}$) suggested by Krasnopolsky et al. (2011) above which the disk is formed in their simulations. Here, $B_c$ is the central magnetic field.

Figure 5. Cross-section of $v_f$ in the $x$–$z$ plane in Model Para. The epoch of the snapshot is the same as that in Figure 1.

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the parallel and anti-parallel properties are inherent and do not readily change in time, we expect that the spin-up (the magnetic braking weakening) and spin-down (the magnetic braking strengthening) effects due to the Hall current term are also important in the subsequent disk evolution and the difference between the two cases is maintained or enhanced. Therefore, we suggest that the disk evolution can be categorized into two cases. We may call the resultant parallel and anti-parallel systems as Ortho-disk and Para-disk, respectively.

Our results predict that the bimodality in the disk size distribution spontaneously arises due to the Hall current term in typically magnetized molecular clouds. We tend to think that the disk size has an unimodal distribution according to the strength of the rotation and the magnetic field of the cloud cores. However, as we have shown above, the Hall term changes the disk size according to the parallel or anti-parallel property of the cores. It is expected that about half of the molecular cloud cores have parallel configuration and the others have anti-parallel configuration, as the Hall term would not play a role during cloud core formation (Wardle 2004) and there is no physical mechanism that distinguishes the parallel and anti-parallel configurations. On the other hand, during the gravitational collapse of the cloud core, the Hall term becomes effective and strengthens or weakens the magnetic braking. Therefore, the bimodality of the disk size distribution spontaneously arises from the unimodal distributions of the rotation and the magnetic field strength of the cores.

An observational signature predicted from our results is the anti-rotating envelope in Class 0 YSOs. At the end of the simulations, the anti-rotating envelope had a size of $r \gtrsim 200$ AU and a rotation velocity of $v_\phi \sim 1$ km. Because the anti-rotation of the envelope stems from torsional Alfvén waves, the anti-rotating region expands with time. We predict future observations will find an anti-rotating envelope against disk rotation in the Class 0 YSOs. These observations will provide clear evidence that the Hall current term plays an important role for the evolution of circumstellar disks.

In this paper, several simplifications were adopted and their influences should be investigated in future works. We employed a fixed dust grain size of $a = 0.035 \mu m$ and a fixed cosmic-ray ionization rate of $Q_{cr} = 10^{-17} s^{-1}$. The magnetic resistivities are sensitive to the models of dust and cosmic-ray (Dapp et al. 2012; Padovani et al. 2014). Furthermore, the drift velocity of the magnetic field induced by the Hall term that characterizes the strength of the Hall term, linearly depends on $n_{fi}$. Thus, the simulations with different models are necessary to confirm our results. The misalignment between the magnetic field and the rotation vector is another important issue. In our simulations, the initial rotation vector and the magnetic field are in perfectly parallel or anti-parallel configurations. However, it is expected that they are mutually misaligned in realistic cloud cores (Hennebelle & Ciardi 2009; Joos et al. 2012). Its effect on disk formation with non-ideal effects should also be investigated. We used a rigidly rotating shell as the outer boundary condition. Because of the angular momentum out-flux at the boundary, the total angular momentum is a non-conserved quantity in our simulations. At the end of the simulations, the total angular momentum of Models Para, Ortho, and NoHall within the boundary shell were 97%, 94.3%, and 95.5% of the initial angular momentum, respectively. Note that the difference of the angular momentum between models is expected because the Hall current term changes the angular momentum transfer rate near the boundary. Similar phenomena are also observed in previous works. Previous simulations starting from the non-rotating core with the Hall term and outgoing boundary have a finite angular momentum at the end of the simulations (Krasnonskolsky et al. 2011; Li et al. 2011). We expect the treatment of the outer boundary condition would not change our results significantly because the crossing time of an Alfvén wave $t_{\text{cross}} = R/v_A$ is larger than the free-fall time $t_f$ (in our initial condition, $t_{\text{cross}}/t_f = 2.5$) and the boundary mainly influences the relatively outer region within our simulation time $t_{\text{sim}} \gtrsim 1.1 t_f$. However, more sophisticated boundary conditions are desired.

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