THE CIRCUMBINARY OUTFLOW: A PROTOSTELLAR OUTFLOW DRIVEN BY A CIRCUMBINARY DISK

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ABSTRACT

Protostellar outflow is a star’s first cry at the moment of birth. The outflows have an indispensable role in the formation of single stars because they carry off the excess angular momentum from the center of the shrinking gas cloud, and permit further collapse to form a star. On the other hand, a significant fraction of stars is supposedly born as binaries with circumbinary disks that are frequently observed. Here, we investigate the evolution of a magnetized rotating cloud using a three-dimensional resistive MHD nested-grid code, and show that the outflow is driven by the circumbinary disk and has an important role even in the binary formation. After the adiabatic core formation in the collapsing cloud core, the magnetic flux is significantly removed from the center of the cloud by the Ohmic dissipation. Since this removal makes the magnetic braking ineffective, the adiabatic core continuously acquires the angular momentum to induce fragmentation and subsequent binary formation. The magnetic field accumulates in the circumbinary disk where the removal and accretion of magnetic field are balanced, and finally drives the circumbinary outflow. This result explains the spectacular morphology of some specific young stellar objects such as L1551 IRS5. We can infer that most of the bipolar molecular outflows observed by low density tracers (i.e., CO) would correspond to circumbinary or circum-multiple outflows found in this Letter, since most of the young stellar objects are supposed to be binaries or multiples.

Key words: binaries: general – ISM: clouds – ISM: jets and outflows – ISM: magnetic fields – MHD – stars: formation

1. INTRODUCTION

Stars are born in molecular clouds, which are magnetized interstellar clouds in our Galaxy. Recent observations with high-angular-resolution measurements of polarized dust emission have shown that the star formation and gas collapsing processes are certainly closely related to the magnetic field (Girart et al. 2006, 2009). The existence of highly collimated outflow/jets has established an indispensable role played by the magnetic field (Cabrit et al. 1988, 2007; Hirano et al. 2006). The realistic process of star formation in a magnetized molecular cloud is fully three-dimensional magnetohydrodynamics (hereafter MHD) with self-gravity. Theoretical astrophysicists now tackle this process by the method of numerical simulations thanks to the recent development of various techniques (Kudoh et al. 1998; Tomisaka 2002; Matsumoto & Tomisaka 2004; Hennebelle & Fromang 2008a). Hydrodynamical calculations of protostellar collapse without magnetic field have shown that initially rotating molecular clouds tend to form binary or higher multiple stars (Goodwin et al. 2007), and the resultant binary stars are externally surrounded by circumbinary disks, which have already been observed in star-forming regions. On the other hand, protostellar collapse calculations with a magnetic field of the observationally inferred strength show spectacular bipolar outflows (Tomisaka 2002; Machida et al. 2004). The outflow is driven by the Lorentz force and removes the angular momentum of the driving object, which suppresses the fragmentation or the binary formation (Hennebelle & Teyssier 2008b; Machida et al. 2008b). Thus, the driving of the MHD outflow and the binary formation have been thought to be incompatible so far, although both the protostellar outflows and circumbinary disks have been observed numerous in star-forming regions. Therefore, understanding of the puzzling link between them seems to require qualitative improvement in theoretical modeling. A clue for possible modifications is found in the evolution of the magnetic field: most of the previous MHD calculations for the evolution of the collapsing cloud were done under the ideal MHD approximation that is valid only in the low-density phase of molecular gas but not in the high-density protostellar phase, which is obviously where the room for improvement exists for theoreticians. Recently we studied the star formation process in resistive MHD calculations that account for the low ionization degree in molecular clouds, and showed that the magnetic field is significantly removed from the center of the collapsing cloud and fragmentation (or binary formation) is actually possible even in a strongly magnetized cloud (Machida et al. 2007, 2008a, 2008b). In this Letter, we show the dramatic relation between the binary formation and outflow in resistive MHD calculations.

2. MODEL AND NUMERICAL METHOD

To study the evolution of star-forming cores in a large dynamic range of spatial scale, a three-dimensional nested grid method is used, in which the equations of resistive MHD are solved (see Equations (1)–(5) of Machida et al. 2007). As the initial state, we take a spherical cloud with a critical Bonnor–Ebert (BE) density profile, in which the uniform density is adopted outside the sphere \( r > R_c \). For the BE density profile, we adopt the central density as \( n_c = 10^6 \text{ cm}^{-3} \) and the isothermal temperature as \( T = 10 \text{ K} \). For these parameters, the critical BE radius is \( R_c = 4.6 \times 10^3 \text{ AU} \). To promote the contraction, we increase the density by a factor of \( f = 1.68 \), where \( f \) is the density enhancement factor that represents the stability of the initial cloud. With \( f = 1.68 \), the initial cloud has a (negative) gravitational energy twice as large as the thermal one. Thus, the central density of the initial sphere is \( n_{c,ini} = 1.68 \times 10^6 \text{ cm}^{-3} \), while the ambient density is...


The mass inside $r < R_*$ is 0.8 $M_\odot$. The cloud rotates rigidly with $\Omega_0 = 2.7 \times 10^{-13}$ s$^{-1}$ around the $z$-axis in the region of $r < R_*$, while the uniform magnetic field ($B_0 = 32 \mu G$) parallel to the $z$-axis (or rotation axis) is adopted in the whole computational domain. In the region of $r < R_*$, the ratio of thermal $\alpha_0$, rotational $\beta_0$, and magnetic $\gamma_0$ to gravitational energies are $\alpha = 0.5$, $\beta = 0.04$, and $\gamma = 0.06$, respectively. With these parameters, fragmentation and wide binary formation are expected (Machida et al. 2007).

For a realistic evolution of the magnetic field in the collapsing gas cloud, we adopted the resistivity $\eta$ derived in Machida et al. (2007). Figure 1(a) shows the resistivity $\eta$ and magnetic Reynolds number $Re$ against the central number density (for detailed description see Section 2.2 of Machida et al. 2007). In addition, for gas pressure, the barotropic equation of state derived in Machida et al. 2007), in which the isothermally collapsing gas becomes adiabatic at $n \sim 10^{10}$ cm$^{-3}$ with a minimum Jeans mass of $\sim 0.01 M_\odot$. The gas temperature adopted in this study also plotted by the dotted line in this figure.

To calculate a large spatial scale, the nested grid method is adopted (for details see Machida et al. 2005b, 2005a). Each level of a rectangular grid has the same number of cells (64 × 64 × 32). The calculation is first performed with five grid levels ($l = 1$–5). The box size of the coarsest grid $l = 1$ is chosen to be $2^5 R_*$.

The grid of $l = 1$ has a box size of $\sim 1.5 \times 10^5$ AU. A new finer grid is generated before the Jeans condition is violated. The maximum level of grids is $l_{\text{max}} = 13$ that has a box size of 35 AU and a cell width of 0.54 AU.

We calculate two models: (1) resistive and (2) ideal MHD models. Hereafter, we call the former “resistive model,” and the latter “ideal model.” Both models have the same initial condition shown above. The former includes a resistive term in the induction equation, while the latter does not.

3. RESULTS

As shown in Figure 1(a) (the dotted line), the molecular gas obeys the isothermal equation of state with a temperature of $\sim 10$ K until $n_c \sim 10^{10}$ cm$^{-3}$, then cloud collapses almost adiabatically ($10^{10}$ cm$^{-3} \lesssim n_c \lesssim 10^{16}$ cm$^{-3}$; adiabatic phase), and a quasi-static core (hereafter, first core) forms during the adiabatic phase (Larson 1969; Masunaga & Inutsuka 2000). The first core forms both in resistive and ideal MHD models when the central density reaches $n_c \sim 2 \times 10^{15}$ cm$^{-3}$, and have a radius of $\sim 10$ AU and a mass of $0.017 M_\odot$. By coincidence, the first core formation epoch almost agrees with the epoch at which the Ohmic dissipation becomes effective (i.e., $Re < 1$), as seen in Figure 1(a). Therefore, in the resistive model, the magnetic field dissipates inside or around the first core with time after its formation.

The evolutions of the magnetic field $B_{z,c}$ and the angular momentum $J$ after the first core formation $t_c$ both in ideal and resistive models are plotted in Figure 1(b). The figure shows that $B_{z,c}$ and $J$ have the same evolution track in both models for $t_c \lesssim 100$ yr but different tracks for $t_c \gtrsim 100$ yr. In the ideal model, the magnetic field continues to increase to reach $B_{z,c} \sim 1$ G at $t_c \sim 1000$ yr, while the angular momentum decreases to have $J \sim 7 \times 10^{47}$ cm$^2$ s$^{-1}$ at the same epoch. The decrease in the angular momentum for the ideal model owes to the magnetic braking which transfers the angular momentum outward along the magnetic field lines (Basu & Mouschovias 1994; Tomisaka 2002). The first core is formed around the center of the cloud after the gas becomes adiabatic. Since the first core collapses very slowly due to large thermal pressure, the rotation timescale becomes shorter than the collapsing timescale inside and around the first core. As a result, the magnetic field lines are strongly twisted and the angular momentum is considerably transferred owing to the amplified field. On the other hand, in the resistive model, the magnetic field begins to decrease at $t_c \sim 300$ yr, while the angular momentum continues to increase. Since the density of the first core exceeds $n_c \gtrsim 10^{12}$ cm$^{-3}$, the magnetic field is effectively removed from the first core by the Ohmic dissipation as shown in Figure 1(a). Thus, the region around and inside the first core has a weak field that little contributes to the magnetic braking, and thus, the first core in the resistive model has a larger angular momentum than that in the ideal model. As shown in Figure 1, the magnetic field in the resistive model is about two orders of magnitude weaker than that in the ideal model, while the angular momentum in the resistive model is about two orders of magnitude larger than that in the ideal model.
structure (Figures 3(a)–(c)) with a centrally peak density profile (Figures 2(a)–(c)). On the other hand, the magnetic field has a peak at the edge or outside of the first core: the peak of the magnetic field has a ring-like structure as shown in Figures 2(b) and (c). This is because the magnetic flux is removed from the region inside the first core by the Ohmic dissipation. Figures 2(b) and (c) indicate that the first core has a density of \( n = 10^{12} - 10^{14} \text{ cm}^{-3} \) where the magnetic Reynolds number is below unity \( Re < 1 \) (see, Figure 1(a)), thus the magnetic field dissipates effectively. Since the first core increases in size with times, the decoupled region (i.e., the region with \( Re < 1 \)) also expands. Therefore, the peak of the magnetic field strength moves outward as shown in Figures 2(f) and (g). In the resistive model, since the magnetic braking is not so effective owing to the weak field, the first core continues to spin up (see, Figure 1(b)). In general, when the first core has a large angular momentum, the fragmentation occurs (e.g., Goodwin et al. 2007). The fragmentation occurs \( \sim 800 \text{ yr} \) after the first core formation (Figure 2(d)) only in the resistive model.

Both in ideal and resistive models, the outflow appears \( \sim 100 \text{ yr} \) after the first core formation. This kind of outflow was already reported in many past studies (e.g., Tomisaka 2002; Banerjee & Pudritz 2006; Hennebelle & Fromang 2008a). In Figures 3(a)–(d), the outflowing region is represented by the white-dotted line inside which the gas outflows from the center of the cloud. The outflow continues to be driven near the first core in the ideal model. On the other hand, in the resistive model, the driving point of the outflow moves outward with time as seen in Figures 3(a)–(d), because the decoupled region of \( Re < 1 \) expands outward. In the resistive model, the magnetic field is too weak to drive outflow in the region near the first core where the magnetic dissipation is effective. Figure 4 (left panel) shows the configuration of the outflow for the resistive model, which indicates that the outflow is driven by the circumbinary disk, not by the protostar (or protobinary). Figure 4 (upper right panel) shows the configuration of magnetic field lines that are strongly twisted by the rotation of the circumbinary disk. The circumbinary disk has a density of \( n < 10^{12} \text{ cm}^{-3} \) and is well coupled with the magnetic field that can drive the outflow. On the
other hand, the magnetic field is too weak to drive the outflow in the region around the protobinary where the magnetic field is significantly dissipated by the Ohmic dissipation. Figure 4 (lower right panel) shows the strength of the vertical component of the magnetic field ($B_z$) on the $z = 0$ plane with the same scale of the left panel, and indicates that the magnetic field is weak around protobinary but strong in the circumbinary disk.

4. DISCUSSION AND SUMMARY

In this Letter, we show that the outflow can be driven by the circumbinary disk. We calculated the evolution of the outflow 1762 yr after its emergence, in which the outflow continues to be driven by the circumbinary disk and reach 427 AU from the center of the cloud with a maximum speed of $8.4 \text{ km s}^{-1}$. At the end of the calculation, each fragment (i.e., each protobinary) has the only mass of $\sim 0.03 \text{ M}_\odot$. During calculation, the protobinary revolves about the center of the cloud (i.e., a common center of gravity) $\sim 20$ times, keeping a separation of about $\sim 5–10$ AU. It is expected that the size and speed of the outflow increase with time, because the mass of the protobinary and circumbinary disks continues to increase in the gas accretion phase.

Previous studies about the evolution of a rotating cloud showed that fragmentation frequently occurs only after the gas becomes optically thick (i.e., after the first core formation) and the binary system is possible to form when the molecular cloud has a certain amount of the angular momentum (Bodenheimer et al. 2000; Goodwin et al. 2007). On the other hand, the study about a collapsing magnetized-rotating cloud showed that the magnetic field suppresses fragmentation and a single star tends to form in a strongly magnetized core, because the rotation (or angular momentum) to promote fragmentation is transferred by the magnetic effect such as the magnetic braking and outflow (Machida et al. 2004, 2005a; Price & Bate 2007; Hennebelle & Teyssier 2008b). However, these studies adopted an ideal MHD approximation. In reality, the magnetic field dissipates in the high-density region in the collapsing cloud (Nakano et al. 2002). Note that although the ambipolar diffusion and the Hall term effect can also be important for the magnetic dissipation, the Ohmic dissipation dominates in the high-density gas region (Machida et al. 2007).

We calculated the magnetized rotating cloud including the magnetic dissipation, and found the following:

1. After the first core formation, the magnetic field is significantly reduced by the Ohmic dissipation, and a weak field is realized inside and around the first core.
2. Fragmentation occurs by the rapid rotation and the protobinary is formed, since a weak magnetic field makes the magnetic braking ineffective. In addition, such a weak field cannot drive outflow from the protobinary itself.
3. A strong outflow is driven by the circumbinary disk, because the magnetic field accumulates in the circumbinary disk where the removal and accretion of the magnetic field are balanced, and thus a strong field is realized in the circumbinary disk.

The binary system often shows a single outflow that may be driven by the circumbinary disk, not by one protostar in the binary system. For example, a single molecular outflow in L1551 IRS5, in which the binary system is embedded, may be driven by this mechanism.
In the present Letter, we adopted the most plausible value for the resistivity $\eta$. The resistivity adopted in this study is originally taken from Nakano et al. (2002), in which they adopted abundances for various charged particles. However, the resistivity depends on the size distribution and the abundance of dusts. The resistivity is closely related to the magnetic dissipation. The magnetic field is related to the most fundamental phenomena of the star formation: the angular momentum and magnetic flux problem, fragmentation and binary formation, and outflow driving. Thus, it is crucial to determine the resistivity for resolving major problems in star formation. Since the strength and driving point of the outflow are directly related to the resistivity as shown in this Letter, we can determine it with future higher-resolution observations such as ALMA.

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