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# PROTOSTELLAR COLLAPSE OF MAGNETO-TURBULENT CLOUD CORES: FORMATION OF PROTOPLANETARY DISKS AND OUTFLOWS

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## ABSTRACT

We investigate formation of protoplanetary disks and outflows inside collapsing turbulent molecular cloud cores by resistive MHD simulations. By using a self-gravitational adaptive mesh refinement (AMR) code, SFUMATO, the collapse of the cloud core is followed in a wide dynamic range; we resolve both a cloud cores scale and a protoplanetary disk scale. A protostar is modeled with a Lagrangian sink particle. The ohmic dissipation is solved by an implicit scheme. We followed collapse of the turbulent molecular cloud cores and accretion onto the protostars (sink particles) up to ∼ 1000 yr after the protostar formation. The simulations show that weak magnetic fields and strong turbulence promote a relatively rapid growth of a protoplanetary disk around the sink particle. The strong magnetic field models exhibit the cavities in infalling envelopes around the protostars. The protostar accrates the gas while the magnetic fields are decoupled from the gas around the protostar because of the resistivity. The decoupled magnetic fields generate strong filed region, of which magnetic pressure causes the cavity in the infalling envelope. All the models exhibit protostellar outflows irrespective of the initial field strength and the initial turbulent velocity.

*Subject headings:*

## 1. INTRODUCTION

Magnetic fields and interstellar turbulence are believed to play important roles in the gravitational collapse of molecular cloud cores. The measured magnetic fields of molecular clouds and molecular cloud cores are strong and the magnetic energy is approximately equal to the kinetic energy (Crutcher 1999). Moreover, Burkert & Bodenheimer (2000) suggests that the rotation of cloud cores originates in turbulence.

There have been very few theoretical studies of collapse of magnetized turbulent cloud cores in protostars, despite the importance of turbulence and magnetic fields. Although self-gravitational turbulent simulations have been performed by many researchers (e.g., Gammie et al. 2003; Li et al. 2004; Offner et al. 2008; Bate 2009), most investigated large-scale turbulence and focused on cloud core formation.

In this paper, we investigate formation of protoplanetary disks and outflows inside magnetized turbulent cloud cores. In order to achieve a wide spatial dynamic range of the protostellar collapse, a self-gravitational MHD-AMR code is adopted.

## 2. MODELS OF CLOUD CORES

As an initial model of a molecular cloud core, we consider a turbulent, spherical cloud threaded by a uniform magnetic field. The cloud is confined by a uniform ambient gas. The initial central density is set equal to $\rho_0 = 10^{-18}\,\mathrm{g\,cm^{-3}}$, which corresponds to a number density of $n_0 = 2.61 \times 10^5\,\mathrm{cm^{-3}}$ for an assumed mean molecular weight of 2.3.

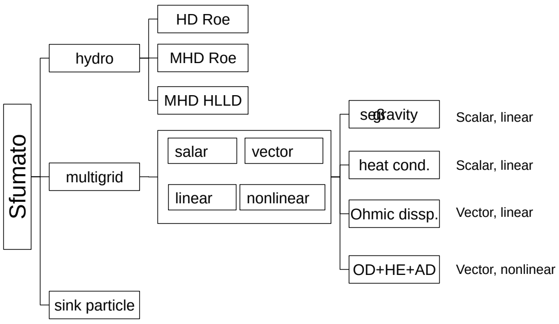

**Figure 1.** Composition of a self-gravitational MHD-AMR code, SFUMATO.

The initial velocity field is an incompressible turbulent flow with a power spectrum of $P(k) \propto k^{-4}$, generated according to Dubinski et al. (1995), where $k$ is the wavenumber. The models are constructed by changing the mean Mach number of the initial velocity field in the range $\mathcal{M} = 0.5 - 3$.

The initial magnetic field is uniform in the $z$-direction. The field strength is given by $B_z = \alpha B_\mathrm{cr}$, where $\alpha$ denotes the non-dimensional flux-to-mass ratio, $B_\mathrm{cr}$ denotes the critical field strength given by $B_\mathrm{cr} = 2\pi G^{1/2}\Sigma$ (Nakano & Nakamura 1978; Tomisaka et al. 1988), and $\Sigma$ denotes the column density at the cloud center.

The barotropic equation of state is assumed where the gas temperature is 10 K below the critical density $\rho_\mathrm{cr} = 2 \times 10^{-13}$ g cm$^{-3}$ ($n_\mathrm{cr} = 5.24 \times 10^{10}$ cm$^{-3}$), and it increases with the adiabatic index $\gamma = 7/5$ above $\rho_\mathrm{cr}$. The model of the resistivity is taken from Machida et al. (2008).

## 3. NUMERICAL METHODS

We calculated the collapse of the cloud cores using the AMR code, SFUMATO (Matsumoto 2007), of which the module composition is shown in Figure 1. The code adopts a block-structured grid as the grid of the AMR hierarchy. The HLLD scheme of Miyoshi & Kusano (2005)

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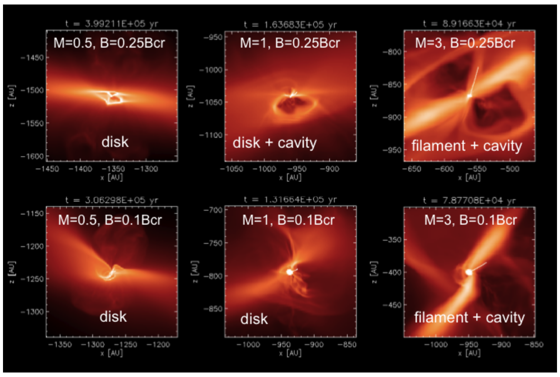

**Figure 2.** Column density distributions in the $x-z$ planes on the scale of the infalling envelopes for all the models. The regions of $(200\ \mathrm{AU})^3$ are plotted for the last stages. The white lines denote the loci of the sink particles.

is adopted as the MHD solver, with the hyperbolic divergence cleaning method of Dedner et al. (2002). The MHD solver achieves second-order accuracy in space and time due to the TVD and predictor-corrector methods. The self-gravity is solved by the multigrid method, exhibiting spatial second-order accuracy. The numerical fluxes are conserved by using a refluxing procedure in both the MHD and self-gravity solvers.

The dissipation term due to resistivity (the ohmic dissipation) in the MHD equations is solved by an operator splitting approach. The dissipation term is solved by an implicit scheme with the multigrid method (Matsumoto 2011). We also adopt a correction proposed by Graves et al. (2008) for acceleration of convergence.

The Lagrangian sink particle is adopted as a sub-grid modeling of a protostar (e.g., Krumholz et al. 2004; Federrath et al. 2010).

## 4. RESULTS

Figure 2 shows infalling envelopes on a 200 AU scale. The strong turbulent models ($\mathcal{M} = 3$) have filamentary envelopes while the weak turbulent models ($\mathcal{M} = 0.5$) have disk envelopes. The shapes of the envelopes reflect the masses of the cloud cores at the initial conditions; the strong turbulent models have higher mass than the weak turbulent models in order to promote the gravitational collapse.

The strong field modes ($B = 0.25B_{\mathrm{cr}}$) exhibit cavities in the envelopes. We confirmed that the cavities are created by the magnetic pressure. The strong magnetic pressure is caused by decoupling of the magnetic field from the accreted gas.

Figure 3 shows the protoplanetary disks on a 20 AU scale. The strong turbulent models and weak magnetic field models tend to have large disks. This implies that the angular momenta of the disks originate in the initial turbulent flow.

Figure 4 shows the growth of the disks qualitatively. The centrifugal radii of disks increase for $\sim$ 1000 yr for all the models except for the weak turbulent models with $\mathcal{M} = 0.5$. The continuous growth of the disk radii implies a larger disks are obtained in the further stages.

All the models exhibit protostellar outflows. Note that the outflows are not responsible to the cavities of the envelopes in the strong field models.

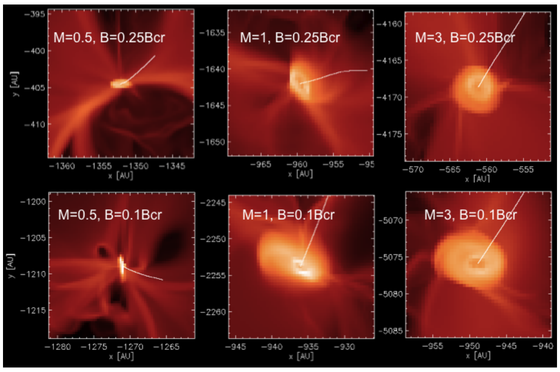

**Figure 3.** Column density distributions in the $x-y$ planes on the scale of the protoplanetary disks. The regions of $(20\ \mathrm{AU})^3$ are plotted for the last stages. The white lines denote the loci of the sink particles.

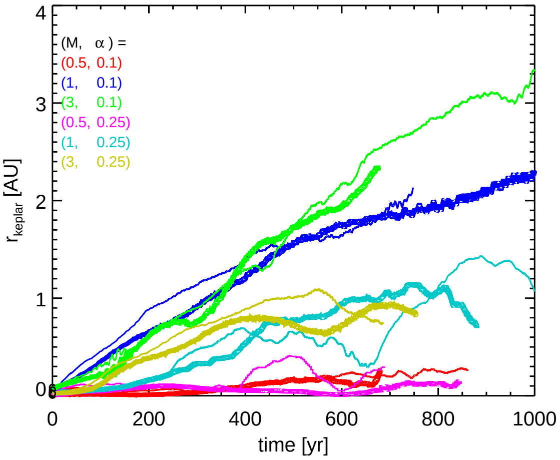

**Figure 4.** Mean centrifugal radii of the disks as a function of elapse time after the protostar formation. Thick and thin lines are for resistive MHD models and ideal MHD models, respectively.

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