Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
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Three-dimensional MHD simulations of molecular cloud fragmentation regulated by gravity, ambipolar diffusion, and turbulence

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Abstract. We find that the star formation is accelerated by the supersonic turbulence in the magnetically dominated (subcritical) clouds. We employ a fully three-dimensional simulation to study the role of magnetic fields and ion-neutral friction in regulating gravitationally driven fragmentation of molecular clouds. The time-scale of collapsing core formation in subcritical clouds is a few $\times 10^7$ years when starting with small subsonic perturbations. However, it is shortened to approximately several $\times 10^6$ years by the supersonic flows in the clouds. We confirm that higher-spacial resolution simulations also show the same result.

Keywords. MHD – stars: formation – ISM: magnetic fields

1. Introduction

When the gravitational energy is larger than the magnetic energy (supercritical), the cloud is fragmented by gravitational instability in a free-fall time of the cloud ($\sim 10^6$ years). On the other hand, when the gravitational energy is smaller than the magnetic energy (subcritical), the cloud is gravitationally stable because magnetic field prevents the contraction of the cloud. However, because the molecular cloud contains a lot of neutrals as well as some ions, magnetic diffusion induced by ion-neutral friction (amibipolar diffusion) occurs in the cloud. Due to this effect, gravitational instability develops gradually over the diffusion time even when the cloud is subcritical.

It has been suggested that subcritical clouds have a time-scale problem: the age spreads of young stars in nearby molecular clouds is often $\sim 10^6$ years, while the ambipolar diffusion time is typically $\sim 10^7$ years. Recently, however, Li & Nakamura (2004) have shown that the time-scale of mildly subcritical cloud fragmentation is reduced by supersonic turbulence to $\sim 10^6$ years by performing 2D simulations in the thin-disk approximation. In this paper, we study the 3D extension of the model by including the self-consistent calculation of vertical structure of the cloud.

2. Results

The initial cloud is a gas layer that is in a self-gravitational equilibrium along uniform magnetic field lines. The initial cloud is assumed to be slightly subcritical (the magnetic field strength is 2 times larger than the critical value). An initial random velocity perturbation (v_a) is input perpendicular to the magnetic field. 3D-MHD simulation with

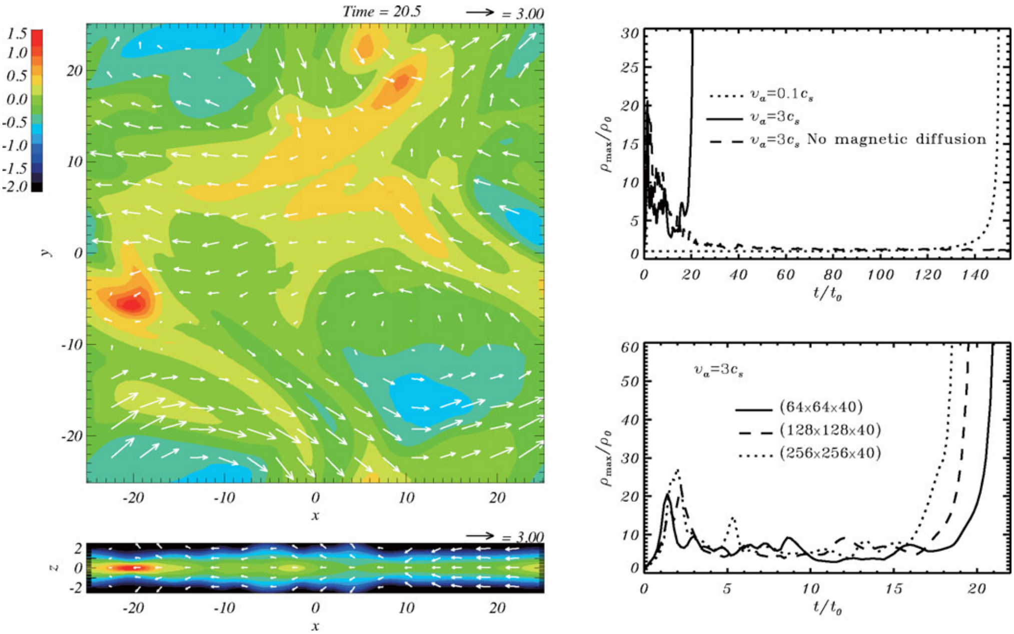

Figure 1. (Left panel) Logarithmic density image. It shows at $t = 20.5t_0$ ($\sim 4\times10^6$ years) for the case of initially supersonic perturbation ($v_a = 3c_s$), where c_s is initial sound speed. A collapsing core is located in the vicinity of $x = -20H_0$ and $y = -6H_0$, where H_0 is the scale height of the gas layer ($H_0 \sim 0.05$pc). ; (Right upper panel) Time evolution of the maximum density for the different strength of the perturbation. The unit time (t_0) is $t_0 = H_0/c_s \sim 2 \times 10^5$ year. The timescale of collapsing core formation for the supersonic perturbations case ($v_a = 3c_s$) is much shorter than that for the subsonic perturbation case ($v_a = 0.1c_s$). The dashed line shows that there is no collapsing core formation in the subcritical cloud without ambipolar diffusion; (Right lower panel) Time evolution of the maximum density for the different spatial resolutions of numerical simulations. (The left and right upper panels corresponds to the results of $(N_x, N_y, N_z) = (64 \times 64 \times 40)$ grid sizes.) Each line shows the evolution for an initially supersonic perturbation ($v_a = 3c_s$). Higher resolution simulations confirm the same result.

ambipolar diffusion is performed (see details in Kudoh *et al.* 2007 and Kudoh & Basu 2008).

Results are summarized in figure 1. Our three-dimensional MHD simulations have shown that the supersonic nonlinear flows significantly reduce the timescale of collapsing core formation in subcritical clouds. It is of order several $\times10^6$ years for typical parameters, or ~ 10 times less than found in the linear initial perturbation studies. The short timescale of the core formation is caused by the small ambipolar diffusion time when the turbulent compression creates structure with small scale length (Kudoh & Basu 2008).

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