Three-dimensional MHD simulations of magnetized cloud fragmentation with turbulence and ion-neutral friction

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We perform a 3D-MHD simulation of a self-gravitating isothermal gas layer that is initially penetrated by a uniform magnetic field. The strength of the initial magnetic field is such that the cloud is slightly sub-critical. In this system, we input random super-sonic turbulence initially. Ion-neutral friction is also introduced in the magnetized gas so that the magnetic diffusion allows gas to go across the magnetic field and form self-gravitating cores. We found that the time scale of core formation is on the order of 10^6 years, which is faster than the usual magnetic diffusion time (~ 10^7 years). The result is consistent with that of 2D-MHD simulations by Li & Nakamura (2004).

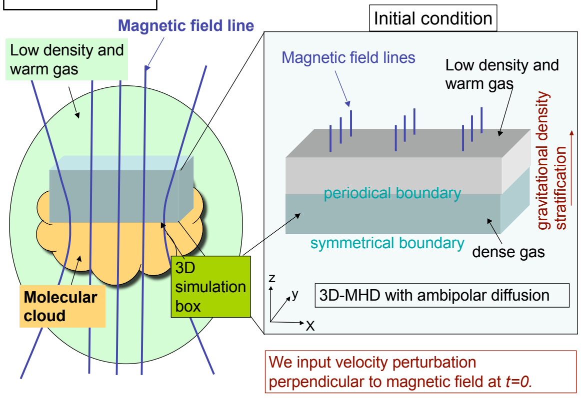
Introduction

When the strength of the magnetic field is weaker than the critical value, the cloud is fragmented by gravitational instability in a free-fall time of the cloud (super-critical). On the other hand, when the magnetic field is stronger than the critical value, the cloud is gravitationally stable because magnetic field prevents the contraction of the cloud (sub-critical). 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 sub-critical (e.g., Basu & Ciolek 2004).

It has been suggested that sub-critical clouds have a time-scale problem: the age spreads of young stars in nearby molecular clouds is often 1-3 x 10^6 years, while the ambipolar diffusion time is typically ~ 10^7 years.

Recently, however, Li & Nakamura (2004) have shown that the time-scale of mildly sub-critical cloud fragmentation is reduced by supersonic turbulence to ~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.

The Model



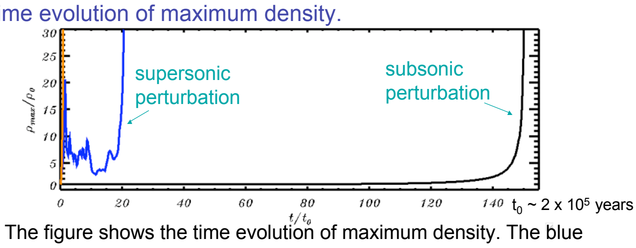
We assume that the initial cloud is a gas layer that is in a self-gravitational equilibrium along uniform magnetic field lines. The initial cloud is assumed to be slightly sub-critical as a typical case. The magnetic field strength is 2 times larger than the critical value.

We also assume that the cold dense gas, which corresponds to molecular cloud, is sandwiched by warm low density gas. Each gas layer is assumed to be isothermal in Lagrangian coordinate. For simplicity, we assume a symmetrical boundary condition at z=0 and solve equations for only half of the sandwiched layer.

In this equilibrium gas layer, we input initial velocity perturbation perpendicular to magnetic field. When the perturbation is super-sonic, we assume $|v| \sim k^{-2}$, where v is velocity and k is wave number.

Results

Time evolution of maximum density.

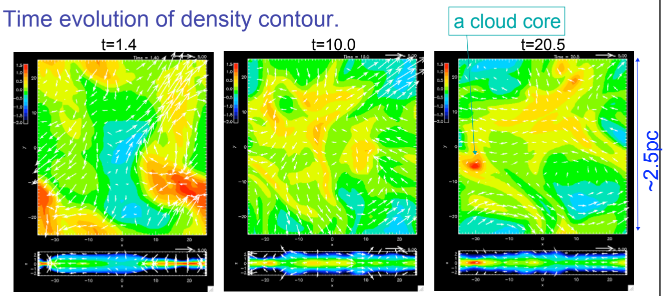


The figure shows the time evolution of maximum density. The blue line shows the case when the initial perturbation is supersonic (3 times sound velocity). The black line shows the case when the initial perturbation is subsonic (0.1 times sound velocity).

The figure shows that the time-scale of cloud fragmentation for supersonic perturbation is much shorter than that of the subsonic perturbation. The time-scale of the fragmentation of sub-critical cloud with supersonic turbulence is ~ 4 x 10^6 years in this case.

The orange line shows the case when the initial magnetic field is weaker than the critical value and perturbation is super-sonic. The fragmentation of super-critical cloud with supersonic turbulence evolves too quickly (~ 2 x 10^5 years).

Time evolution of density contour.



Figures show the time evolution of density contour for a sub-critical cloud with initial supersonic turbulence. Arrows show velocities. Upper panels show the cross section at z=0. Lower panels show the cross section at y=-13.0, y=10.6, and y=-5.9 from left to right, respectively.

The cloud is first strongly compressed by super-sonic turbulence (t=1.4). However, the dense region rebounds and shows oscillations (t=10.0) because the cloud is sub-critical. Finally, ambipolar diffusion allows gravitational collapse and cores to form (t=20.5).

At the final stage (t=20.5), the magnetic field is dissipated enough at the center of the densest core. Then, the core undergoes runaway collapse.

Summary and Discussion

We performed 3D-MHD simulations and confirmed that the time-scale of sub-critical cloud fragmentation is reduced by supersonic turbulence. The result is consistent with Li & Nakamura's 2D simulations. The short time-scale of the fragmentation may be caused by the strong magnetic field gradient created by the super-sonic turbulence.The time scale of the fragmentation is the order of 10^6 years. It may solve the time-scale problem of sub-critical clouds.