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MHD numerical simulation of clouds and jets in star-forming regions

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Abstract. We review our recent numerical simulations of star formation. First, we show a simulation of magnetic turbulence in a plate-shaped self-gravitating stratified cloud. We find that the cloud is lifted up by the pressure of magnetic turbulence and reaches a steady-state characterized by oscillations about a new time-averaged equilibrium state. Next, we present a numerical simulation of gravitational fragmentation of the plate-shaped magnetized cloud. For strong magnetic field cases, we confirm that the gravitational instability develops gradually on a time scale characteristic of ambipolar diffusion. Finally, a numerical simulation of jet formation is shown. The important factors of jet formation are the magnetic field and rotation of a disk around a star.

1. Introduction

Interstellar molecular clouds, which consist of primarily neutral hydrogen molecules as well as some ionized molecules, contain both turbulence and magnetic fields. The velocity dispersion of the turbulence is up to 10 times larger than the sound speed. It is considered that molecular clouds are in an approximate virial balance between turbulent and gravitational energies. Large-scale magnetic fields are also detected in molecular clouds. The magnetic energy in the cloud is estimated to be comparable in magnitude to the gravitational energy of the cloud. Therefore, the turbulence and magnetic field are important factors for the dynamics of molecular clouds.

Stars are formed inside molecular clouds. We have the following scenario for star formation. As the magnetic Lorentz force does not work along the magnetic field lines, unlike the turbulent pressure and gravity which work along the field lines as well as perpendicular to them, a molecular cloud first contracts along the magnetic field direction. This forms a plate-shaped structure perpendicular to the magnetic field. The plate-shaped cloud is then fragmented by self-gravitational instability, which forms cores (dense regions) in it. Finally, stars are formed in cores with rotating disks around them, since the clouds are expected to have some angular momentum. The interaction between the rotating disk and the magnetic field produces bipolar jets perpendicular to the disk.

In this paper, we present three of our recent studies about clouds and jets, according to this star-formation scenario: (i) nonlinear magnetohydrodynamic (MHD) wave support of a stratified molecular cloud; (ii) fragmentation of a magnetized gaseous plate; (iii) formation of magnetically driven jets.

2. Nonlinear MHD wave support of a stratified molecular cloud

We perform a one-dimensional numerical simulation of nonlinear MHD waves in a stratified molecular cloud in order to study the effect of turbulence on the dynamics of the cloud [1–3]. We continuously input turbulent energy into the magnetized plate-shaped cloud, which is initially in hydrostatic equilibrium between thermal pressure and self-gravity. The initial magnetic field is assumed to be uniform and perpendicular to the plate-shaped cloud. The one-dimensional approximation means that the cloud structure depends only on the direction of this background magnetic field (z-direction).

Figure 1 shows the time evolution of densities and the oscillating part of the y-velocities for different strengths of input energy. (The y-velocity is the component perpendicular to the background magnetic field.) The density plots at various times are stacked with time increasing upwards.

We find that the cloud expands due to the pressure of input MHD waves. Although it is oscillating due to the competing effects of inward self-gravity and the outward wave pressure gradient, the time average of the size of the cloud is increased compared with that of the initial equilibrium cloud. For the various parameters of input MHD waves, the size of the cloud is related to the strength of the velocity dispersion of the cloud (Fig. 2):

$$\sigma \propto Z^{0.5}, \tag{2.1}$$

where σ is the velocity dispersion of the cloud and Z is the size of the cloud. This means that the cloud achieves a time-averaged virial equilibrium between turbulent and gravitational energies. This is consistent with observational results of molecular clouds [4].

3. Fragmentation of a magnetized gaseous plate

A self-gravitationally stratified plate-shaped gas cloud is unstable to gravitational instability. We study the instability of a magnetized gaseous plate by performing a three-dimensional MHD numerical simulation [5] including ambipolar diffusion.

We initially input turbulent velocity into the magnetized plate-shaped cloud which is in hydrostatic equilibrium between thermal pressure and self-gravity. In this paper, we assume that the maximum initial tubulent speed is about 10 times the sound speed. The initial magnetic field is assumed to be uniform and perpendicular to the plate-shaped cloud. This is basically an extension of a previous two-dimensional simulation [6] to three dimensions.

Figure 3 shows the density contours for the case of a magnetic field weaker than the critical value (Fig. 3(a)) and that of a stronger magnetic field (Fig. 3(b)). Upper panels show the density contours on the equator of the cloud and the lower panel shows the contours on a side cut of the cloud.

When the strength of the magnetic field is weaker than the critical value, the gaseous plate is fragmented by the instability in a free-fall time of the cloud (approximately $2.7t_0 \sim 10^6$ years). On the other hand, when the magnetic field is stronger than the critical value, the gaseous plate is gravitationally stable in the

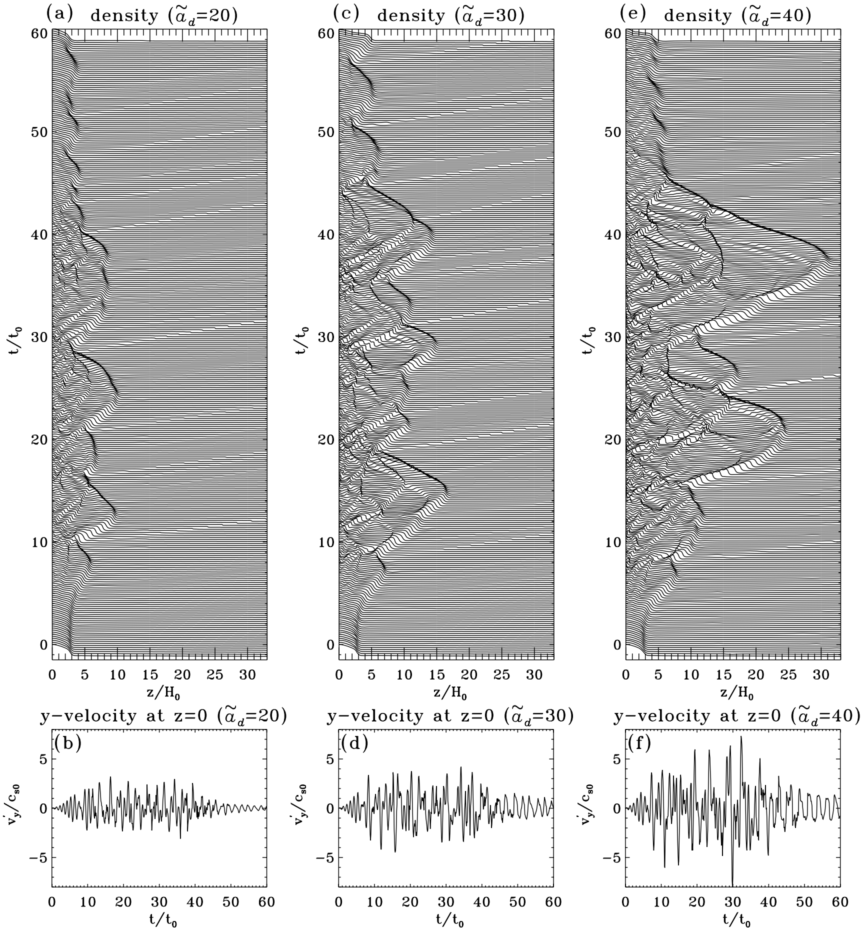


Figure 1. Evolution of clouds with different driving forces parameterized by $\tilde{a}_d$ (see [1] for a definition). A larger $\tilde{a}_\mathrm{d}$ means a larger driving force. (a) Time evolution of densities for $\tilde{a}_\mathrm{d} = 20$. (b) The oscillating part of y-velocity at $z = 0$, v'_y, as a function of time for $\tilde{a}_\mathrm{d} = 20$. (c) Time evolution of densities for $\tilde{a}_\mathrm{d} = 30$. (d) The oscillating part of y-velocity at $z = 0$, v'_y, as a function of time for $\tilde{a}_\mathrm{d} = 30$. (e) Time evolution of densities for $\tilde{a}_\mathrm{d} = 40$. (f) The oscillating part of y-velocity at $z = 0$, v'_y, as a function of time for $\tilde{a}_\mathrm{d} = 40$. The density plots at various times are stacked with time increasing upward in uniform increments of $0.2t_0$, where $t_0 = H_0/c_\mathrm{s0}$, H_0 is the scale height of the cloud, and c_s0 is the isothermal sound speed in the cloud. The driving force is increased gradually until $10t_0$. The constant driving force is input from $10t_0$ to $40t_0$. The driving is stopped at $t = 40t_0$.

ideal MHD limit because the magnetic field prevents contraction. However, because the molecular cloud contains a lot of neutrals as well as some ions, ambipolar diffusion occurs within the cloud. Due to this effect, the gravitational instability develops gradually in the diffusion time (approximately $21.7t_0 \sim 10^7$ years). For both cases, the cloud is fragmented and forms cores. In the simulation, we find that the spatial distribution of plasma β in the fragmented cloud strongly depends on whether the magnetic field is stronger than the critical value or not: the cores have a higher β than the surroundings for the strong field case, and *vice versa* (Fig. 4).

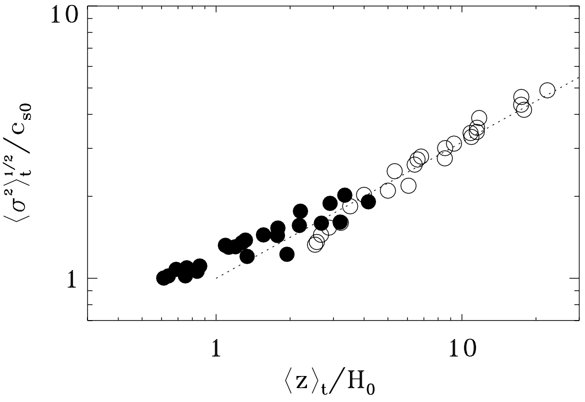
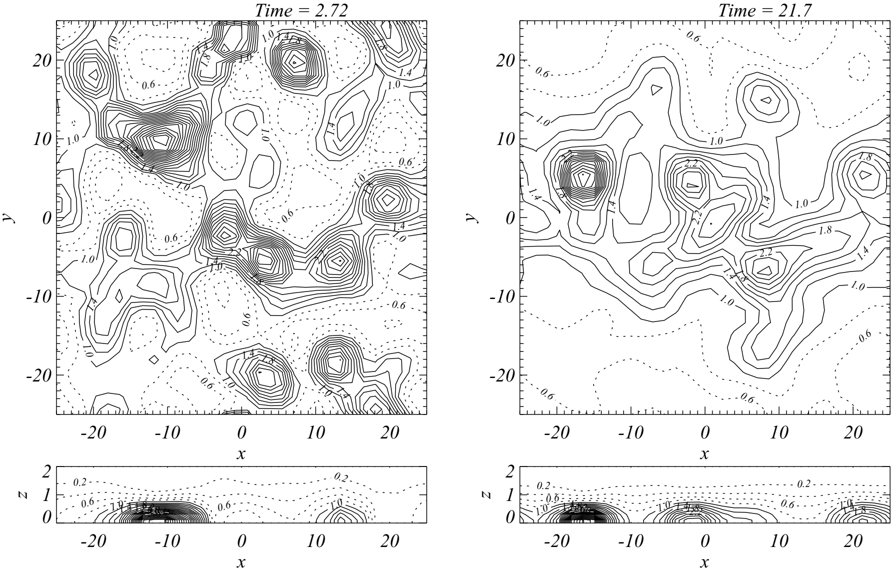


Figure 2. Time-averaged velocity dispersions of different Lagrangian fluid elements for different parameters, as a function of time-averaged positions. The open circles correspond to Lagrangian fluid elements whose initial positions are located at $z/H_0 = 2.51$, which is close to the edge of the cold cloud. The filled circles correspond to Lagrangian fluid elements whose initial positions are located at $z/H_0 = 0.61$, which is approximately the half-mass position of the cold cloud. The dotted line shows $\langle\sigma^2\rangle_t^{1/2} \propto \langle z\rangle_t^{0.5}$.



(a) (b)

Figure 3. Density contours for the case of a weaker magnetic field than the critical value (a) and that of a stronger magnetic field (b). Upper panels show the contours on the equator of the cloud. Lower panels show the contours on the side of the cloud: (a) $y \approx 10$ and (b) $y \approx 5.5$. The density is normalized by the initial value (ρ_0) on the equatorial plane. The calculations are stopped when the maximum density becomes 10 ρ_0. The dotted lines identify the region where the contour values are lower than the initial value. The time and spatial units are t_0 and H_0, respectively. The data are smoothed for the contours.

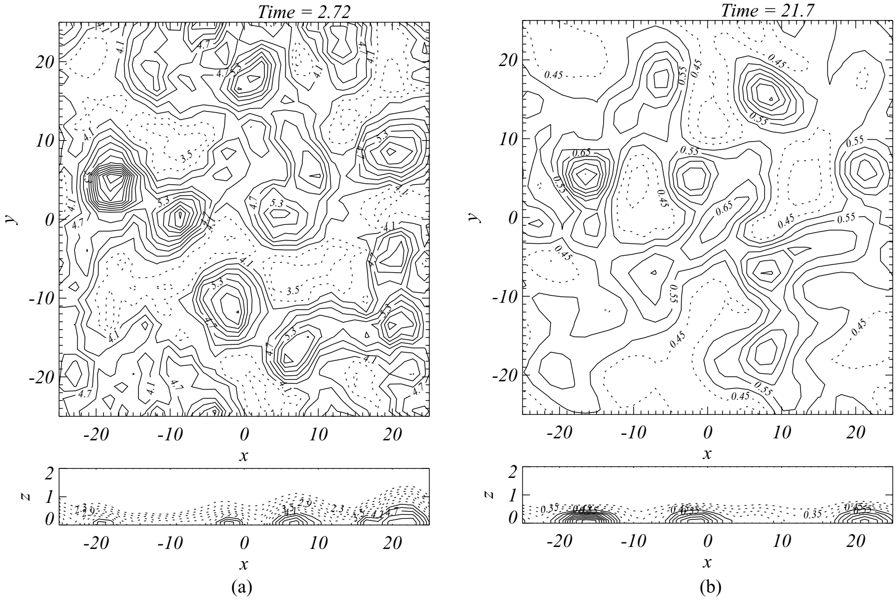


Figure 4. The contour of plasma β for the case of a weaker magnetic field than the critical value (a) and that of a stronger magnetic field (b). Upper panels show the contours on the equator of the cloud. Lower panels show the contours on the side of the cloud: (a) $y \approx 10$ and (b) $y \approx 5.5$. The dotted lines identify the region where the contour values are lower than the initial value. The time and spatial units are t_0 and H_0, respectively. The data are smoothed for the contours.

4. Formation of magnetically driven jets

Finally, we present a 2.5-dimensional MHD numerical simulation of magnetically driven jets [7]. We assume that a star has already formed in the center of a cloud core with a rotating disk that is threaded by magnetic field lines. As the angular momentum of the disk is transferred by the magnetic field, material in the rotating disk starts falling onto the central star. During this process, a part of the disk surface obtains angular momentum from the disk through the magnetic field and blows off along the field lines.

Figure 5 shows the poloidal cross section of the density (Fig. 5(a)) and plasma β (Fig. 5(b)). The white lines of the left panel are magnetic field lines, those of right panel are lines of poloidal current density. The outflow material ejected from the disk surface is collimated by the twisted magnetic field lines, which are created by the rotation of the disk. The twisted magnetic field (B_ϕ) creates the poloidal current (J_p). The magnetic Lorentz force produced as $J_\mathrm{p} \times B_\phi$ accelerates and collimates the outflow.

The typical speed of the outflow is of the order of the Keplerian speed of the disk at the location where the outflow is ejected, and does not strongly depend on the strength of the magnetic field [8]. Observations show that the speeds of the jets are of the order of the escape speeds of the stars. This means that the jets are being ejected from the disk regions which are very close to the stars.

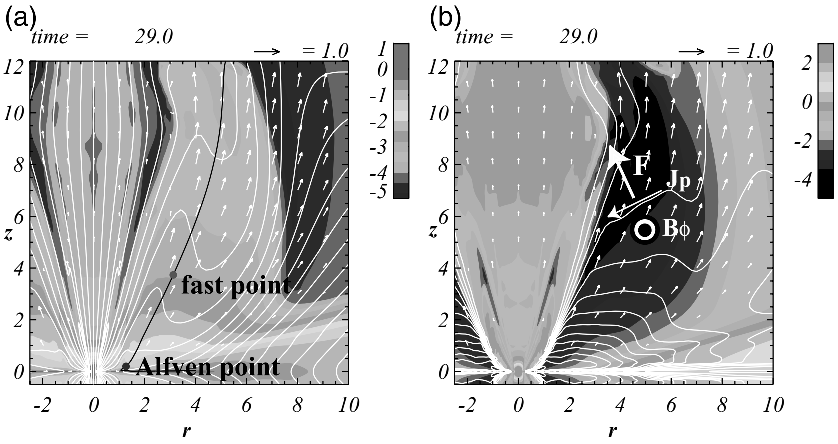


Figure 5. (a) The grayscale shows the density on a logarithmic scale. White lines show the poloidal magnetic field lines. A black line shows one of the stream lines. The arrows show the poloidal velocity. On the stream line, the fast magnetosonic point and Alfvén point are denoted. The spatial unit is r_0 that is the radius where the density is maximum value ρ_0 in the disk. The unit of density is ρ_0, and the unit of time is $r_0/V_{\rm K0}$, where $V_{\rm K0}$ is the Kepler velocity at $r = r_0$. The unit of velocity is $V_{\rm K0}$. (b) The gradient shows the ratio of gas pressure to magnetic pressure on a logarithmic scale. White lines show the lines of poloidal current density ($J_{\rm p}$). The arrow shows the poloidal velocity. B_ϕ is the toroidal component of the magnetic field, which is perpendicular to the r–z plane. F shows the Lorentz force generated by $J_{\rm p} \times B_\phi$.

5. Conclusions

We have presented three of our recent studies about clouds and jets, which form part of a star formation scenario. In each process, the magnetic field has played an important role: (1) The magnetic field is coupled to the turbulence in the cloud, and the effective pressure of the turbulence increases the scale height of the gravitationally stratified cloud; (2) The magnetic field retards star formation and may contribute to the low star-formation efficiency in star-forming regions; (3) The magnetic field produces a collimated jet from a rotating disk around a star.

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