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Formation of Dense Filaments by Parker Instability in Galactic Gas Disks
銀河ガス円盤におけるパーカー不安定性による高密度フィラメントの形成

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We performed two dimensional numerical simulations of Parker instability taking into account the cooling and heating functions of the interstellar medium. We found that when magnetic pressure exceeds the gas pressure, long dense filaments are formed at the valley of magnetic field lines by Parker instability. Shock compression of the spurs formed by Parker instability triggers the cooling instability, which forms cold (T < 100K), dense (n > 150cm^{-3}) filaments. The length of the filaments can exceed 200pc. Initially vertical dense filaments are deformed into inclined filaments when the Ram pressure at the left and right hand side of the filament is different. These results indicate that filamentary high galactic latitude molecular clouds can be formed by Parker instability.

1. Introduction

NANTEN CO observations found molecular loops with large velocity gradient along the loop in Galactic center region [1]. These molecular loops can be formed by Parker instability [2], which grows in gravitationally stratified gas layer, such as disk of galaxies. To explain the formation processes of molecular loops, it is necessary to include physical processes such as cooling and heating. Koyama and Inutsuka summarized several thermal processes in the interstellar gas [3], and Inoue et. al obtained the cooling and heating function taking into account these effects [4]. Mouschovias et al. simulated the Parker instability including the cooling and heating function and found that cold, dense cloud can be formed at the valley of magnetic field lines. They showed that Parker instability can trigger thermal instability [5]. We carried out 2D MHD simulations including cooling/heating to study whether the loop-like structure near the Galactic center can be formed by Parker instability by using magnetohydrodynamic code "CANS+" which adopts HLLD Riemann solver [6].

2. Numerical Methods

2.1 *Basic equations*

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla P + \rho \boldsymbol{g} + \frac{(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi} \tag{2}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) \tag{3}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P + \frac{B^2}{8\pi})\boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{B}\cdot\boldsymbol{v})}{4\pi}] = \rho \boldsymbol{v} \cdot \boldsymbol{g} - \rho L \tag{4}$$

$$E = \frac{P}{\gamma - 1} + \frac{\rho v^2}{2} + \frac{B^2}{8\pi} \tag{5}$$

Cooling/heating function [4]

$$\rho L = n(-\Gamma + n\Lambda) \tag{6}$$

$$\Gamma = 2 \times 10^{-26} \mathtt{erg\ s}^{-1} \tag{7}$$

$$\Lambda = 7.3 \times 10^{-21} \mathtt{exp}(\frac{-118400}{T + 1500}) + 7.9 \times 10^{-27} \mathtt{exp}(-92/T) \mathtt{erg\ cm}^3\ \mathtt{s}^{-1} \tag{8}$$

Gravitational field model [7]

$$\boldsymbol{g} = -\nabla \phi \tag{9}$$

$$\phi = \Sigma \frac{GM_i}{(r^2 + (a_i + (z^2 + b_i^2)^{0.5})^2)^{0.5}} \tag{10}$$

$$M_1 = 2.05 \times 10^{10} \mathtt{M}_{sun} \tag{11}$$

$$a_1 = 0.0\mathtt{kpc},\ b_1 = 0.495\mathtt{kpc} \tag{12}$$

$$M_2 = 25.47 \times 10^{10} \mathtt{M}_{sun} \tag{13}$$

$$a_2 = 7.258\mathtt{kpc},\ b_2 = 0.52\mathtt{kpc} \tag{14}$$

here r is the distance from Galactic Center, which is assumed as 1kpc, and other symbols have their usual meanings.

2.2 *Initial condition*

The initial condition (ρ, p, T) is determined by solving the equations of the magnetohydrostatic balance by assuming the thermal equilibrium in the warm disk where T < 20000K. Isothermal corona (T=200000K) is assumed to exist below and above the disk. We examined the dependence on initial plasma beta by taking $\beta = p_{gas}/p_{mag}$ as 1, 0.2 and 0.04 (named as model B1, B02 and B004). Figure 1 shows the initial condition of density and temperature for model B1.

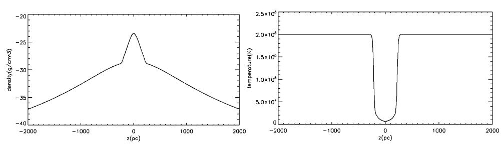

Fig. 1 Vertical distribution of ρ and T for model B1.

2.3 *Perturbation*

Symmetric perturbation

$$v_z = 0.002 \times C_s \times \mathtt{sin}(2\pi x/l) \tag{15}$$

Asymmetric perturbation

$$v_z = \begin{cases} 0.002 \times C_s \times \mathtt{sin}(2\pi x/l) & 0 < x < l/2 \\ 0.01 \times C_s \times \mathtt{sin}(2\pi x/l) & otherwise \end{cases} \tag{16}$$

here C_s is sound speed and l is half of the box size in x-direction.

2.4 *Grid points and boundary condition*

We used uniform grid size in x-direction. The grid size in vertical direction (dz) increases with |z| when 40pc < |z| < 80pc. dz = 0.4pc when |z| is smaller than 40pc and dz = 4pc when |z| larger than 80pc, The number of grid points is 800×1280

We applied periodic boundary condition in x-direction. The top and bottom boundaries are absorbing boundaries.

3. Numerical Results

3.1 *Dependence on the magnetic field strength*

Figure 2, 3, 4 show the simulation results of density with initial plasma beta β as 1, 0.2, 0.04 respectively. White curves show magnetic field lines. We found that vertical long dense filaments are formed when initial magnetic pressure exceeds the gas pressure. The dense filaments can extend higher from disk when β is smaller. The length of the filaments can exceed 100pc when the disk is strongly magnetized.

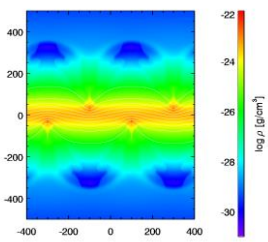

Fig. 2 Distribution of density at 60Myrs for model B1.

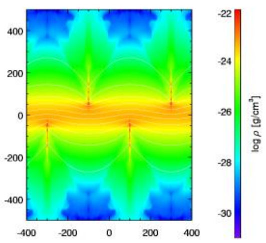

Fig. 3 Distribution of density at 40Myrs for model B02.

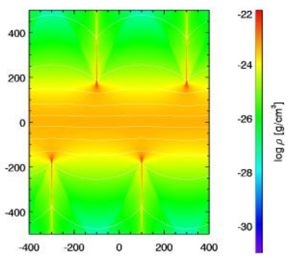

Fig. 4 Distribution of density at 30Myrs for model B004.

3.2 *Bent spurs*

Figures 5 shows the simulation results of density for model B004. Since the asymmetric perturbation is imposed, the Ram pressure at left and right hand of filaments are different. The vertical dense filaments are deformed into inclined filament.

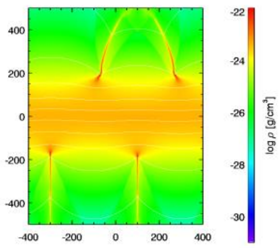

Fig. 5 Distribution of density at 30Myrs for model B004 for asymmetric perturbation

4. Summary

We performed 2D numerical simulations of Parker instability taking into account the cooling and heating functions of the interstellar medium by adopting realistic gravitational potential. We found that when magnetic pressure exceeds the gas pressure, long dense filaments are formed at the valley of magnetic field lines. Shock compression of the spurs formed by Parker instability triggers the cooling instability, which form cold (T < 100K), dense (n > 150cm^{-3}) filaments. The length of the filaments can exceed 100pc. These results indicate that long-length filamentary and high galactic latitude molecular clouds can be formed by Parker instability when the magnetic pressure exceeds the gas pressure. Initially vertical dense filaments are deformed into inclined filaments when the Ram pressure at the left and right hand side of the filament is different and we speculate that the inclined filament may have chance to be deformed into loop-like dense clouds.

References

[1] Y. Fukui, H. Yamamoto, M. Fujishita, N. Kudo, K. Toroii, S. Nosawa, K. Takahashi, R. Matsumoto, M. Michida, A. Kawamura, Y. Yonekura, N. Mizuno, T. Onishi and A. Mizuno: Science, 314, 2006, 106-109.

[2] E.N. Parker: ApJ, 145, 1996, 811.

[3] H. Koyama and S. Inutsuka: ApJ, 532, 2000, p980.

[4] T. Inoue, S. Inutsuka and H. Koyama: ApJ, 652, 2006, 1331-1338

[5] T. Ch. Mouschovias, M. W. Kunz and D. A. Christie: MNRAS, 397, 2009, 14-23.

[6] T. Miyoshi and K. Kusano: J. Comput. Phys., 208, 2005, 315-344.

[7] M. Miyamoto and R. Nakai: 1975, PASJ, 27, 1975, 533.