20PA-049

Nonlinear Evolution of Cosmic Ray Parker instability
宇宙線パーカー不安定性の非線形発展

Takahiro Kudoh, Takaaki Yokoyama, Yuki Kudoh and Ryoji Matsumoto
工藤哲洋(1), 横山央明(2), 工藤祐己(3), 松元亮治(3)

(1) *National Astronomical Observatory of Japan*
(2) *The University of Tokyo, (3) Chiba University*
(1)国立天文台、(2)東京大学、(3)千葉大学

We study the nonlinear evolution of the cosmic-ray Parker instability in the galactic disk by performing two-dimensional MHD numerical simulations with cosmic-ray pressure. In the nonlinear stage of the instability, simulations reveal that the high-density gas layer are formed at the high latitude of the galactic disk through the collision of fast expanding magnetic loops resulting from cosmic ray Parker instability, as long as the initial cosmic-ray pressure is relatively larger than the initial magnetic pressure. These high-density gas layers can be the origin of filamentary structures observed on the galactic plane.

1. Introduction

The Galaxy consists of about 200 billion stars that are mostly distributed on the galactic disk. The space between stars is not a vacuum, but filled with low-density gas, which is called interstellar gas. The average number density of the interstellar gas is about 1 cm^{-3}. The main component of the gas is neutral hydrogen that is partially ionized.

The large-scale magnetic fields along the galactic disk exist in the interstellar gas. The average strength is about 3 μG. Since the diffusion time of the magnetic field is much larger than the dynamical time, the ideal MHD is a good approximation for the interstellar gas.

In the interstellar space, there also exist cosmic rays. The cosmic rays are high-energy particles, which are mostly protons and accelerated by supernova explosions. Since the energy of these particles is comparable to that of the magnetic fields per volume, the pressure of these cosmic rays contributes to the gas dynamics through magnetic fields.

Parker instability [1,2,3] is one of the important instability in the interstellar gas. It occurs in a gravitationally stratified magnetized gas. In this instability, a role of the cosmic ray pressure is considered to be significant. Although there are many studies about the linear analyses of the instability [1,4], the nonlinear evolutions including cosmic rays have not made much progress since Kuwabara et al. (2004) [5]. Here, we will show the nonlinear evolution of the cosmic ray Parker instability in a galactic disk by performing two-dimensional MHD numerical simulations with cosmic-ray pressure.

2. Numerical model

Basic equations are magnetohydrodynamic equations with cosmic ray pressure [5,6]. In this model, the equation of cosmic ray pressure is described as the same equation of the gas pressure, except for including diffusion term. In this diffusion term, the diffusion coefficient is not isotropic, because the cosmic rays (the electric charged particles) are hard to diffuse perpendicular to the magnetic filed lines. We here assume that the diffusion coefficient perpendicular to the magnetic filed is zero in this paper [5, 7].

We perform the two-dimensional numerical simulation in the Cartesian coordinate (x,y). The x-direction is parallel to the galactic disk plane, and the y-direction is perpendicular to the plane. We neglect the rotation of the galaxy for simplicity.

The initial condition is magnetohydrostatic equilibrium under the gravity of the y-direction, assuming the initial magnetic field is parallel to the galactic plane (x-direction). The initial ratio of gas pressure, magnetic pressure and cosmic ray pressure are constant. In this equilibrium gas, the small velocity perturbation is input as a seed for the instability.

We show the case that the initial ratio of gas pressure to magnetic pressure is 1.0 to 0.2 and that of gas pressure to cosmic ray pressure is 1.0 to 0.8 as a representative. The spatial scale of the simulation is 200 times scale height in x-direction, and 140 times scale height in y-direction. The grid size is 0.1 times scale height for both x- and y-direction. We assume a periodic boundary in x-direction and free boundary in y-direction.

3. Results

Figure 1 shows the time evolution of the instability. Color shows normalized gas pressure in logarithmic scale and white lines show magnetic filed lines. The initial condition (t=0) is shown in the top panel. Magnetic loops start to inflate upward as the Parker instability grows (in the middle panel). The gas pressure becomes lower in the magnetic loops because the gas falls down along the magnetic filed. In the nonlinear stage (the bottom panel), the loops come into collisions with nearby loops. This kind of collision is prominent when the initial cosmic ray pressure is larger than the initial magnetic pressure.

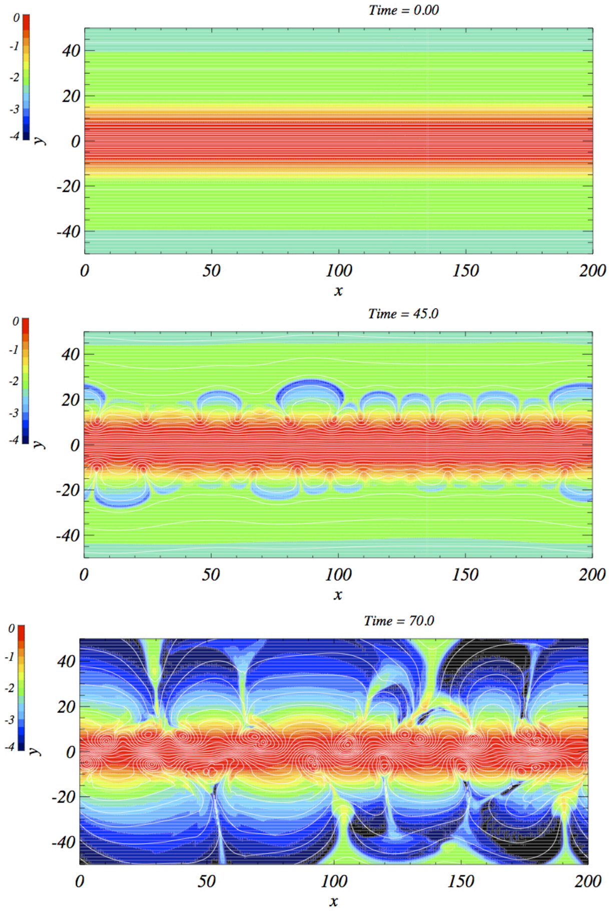

Fig.1. Time evolution of cosmic-ray Parker Instability from random perturbation. Color shows normalized gas pressure in logarithmic scale. White lines show magnetic filed lines.

Figure 2 shows normalized cosmic ray pressure in logarithmic scale. White lines also show magnetic filed lines. Since the cosmic ray pressure only diffuses along the magnetic field lines, the isobaric lines of cosmic ray pressure almost correspond with magnetic field lines.

Figure 3 shows normalized density in logarithmic scale at t=70. High-density filamentary structures are formed between the colliding loops. Around x=140 and y=20, a high-density filamentary structure looks like a loop structure because of the merging of the two filamentary layers. These structures are noticeable as long as the initial cosmic-ray pressure is relatively larger than the initial magnetic pressure. The similar filamentary structures are observed in the Galactic plane [8]. Some of the filamentary structures can be originated from the collisional magnetic loops caused by cosmic ray Parker instability.

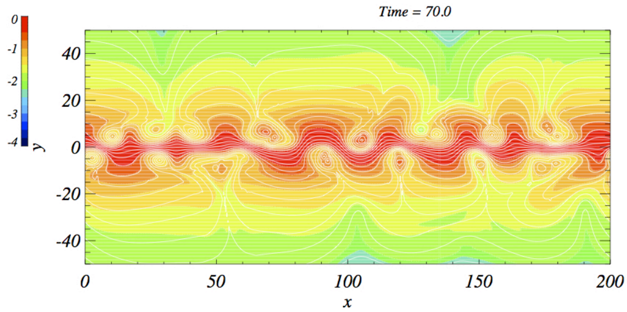

Fig.2. Color contour of normalized cosmic-ray pressure in logarithmic scale. White lines show magnetic field lines.

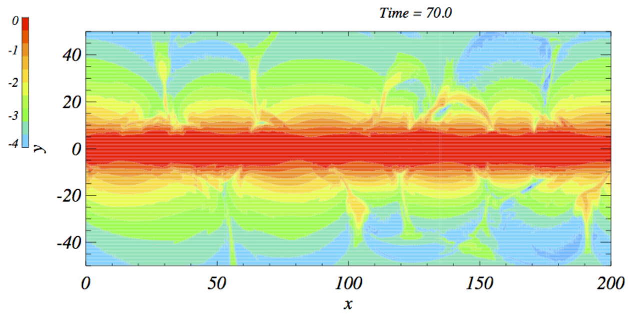

Fig.3. Color contour of normalized density in logarithmic scale.

Acknowledgments

This work is supported by JSPS KAKENHI Grant Number 23540274. Numerical simulations were carried out on PC cluster at the Center for Computational Astrophysics in the National Astronomical Observatory of Japan.

References

[1] E. N. Parker: ApJ **145** (1966) 811.

[2] T. Horiuchi, R. Matsumoto, H. Hanawa and K. Shibata: PASJ **40** (1988) 147.

[3] R. Matsumoto, T. Horiuchi, K. Shibata and H. Hanawa: PASJ **40** (1988) 171.

[4] D. Ryu, J. Kim, S. S. Hong and T. W. Jones: ApJ **589** (2003) 338.

[5] T. Kuwabara, K. Nakamura and C. M. Ko: ApJ **607** (2004) 828.

[6] M. Hanasz and H. Lesch: J. A&A **412** (2003) 331.

[7] T. Yokoyama and K. Shibata: ApJ **549** (2001) 1160.

[8] A. R. Taylor et al.: ApJ **125** (2003) 3145