20PA-053

The Condition of Shock Formation by Cosmic Ray Modified Magnetic Buoyancy Instability

宇宙線を考慮した磁気浮力不安定性による衝撃波生成条件

Yuki Kudoh and Ryoji Matsumoto
工藤祐己, 松元亮治

Graduate School of Science, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
千葉大学

We carried out linear stability analysis and local two-dimensional magnetohydrodynamic(MHD) simulations of the Cosmic-Ray(CR) modified magnetic buoyancy instabilities in magnetized stratified gas disks. In the linear stage, CRs increase the growth rate and critical wave number for the instability by enhancing the buoyancy around the loop top through diffusion of CRs along the magnetic field lines. We call this instability as Magneto-CR instability (MCI). We found that unlike the Parker instability which only drives nonlinear oscillations when the magnetic field is weak, short wavelength magnetic loops buoyantly escape from the disk when MCI grows. Shock waves are formed around the footpoints of these magnetic loops.

1. Introduction

In disk galaxies, magnetic fields can be amplified and maintained by galactic dynamo. Nishikori et al. [1] and Machida et al. [2] showed by three dimensional global magnetohydro-dynamics(MHD) simulations that the mean magnetic fields inside the disk reverse their direction quasi-periodically. This cyclic dynamo is driven by magnetic fields amplification by magneto-rotational instability and the buoyant escape of the magnetic flux by Parker instability.

Parker instability is a magnetic buoyancy instability driven by the buoyancy produced by sliding the gas along undulating magnetic field lines. This instability was studied by Parker as the formation mechanism of interstellar clouds [3]. The nonlinear growth of Parker instability was studied by Matsumoto et al. [4] by two-dimensional MHD simulations. They showed that shock formation is essential for producing quasi-static magnetic loops. When the magnetic field is weak, since the speed of the downflow along the loop is subsonic, shocks are not formed. In such weakly magnetized disks, Parker instability drives nonlinear oscillations.

Cosmic-Ray (CR) or non-thermal particles can be dynamically important, because CR energy density is approximately comparable to magnetic energy density in our galaxy. Here, we present the results of a linear analysis and non-linear simulation of CR modified magnetic buoyancy instability in galactic disk.

2. Initial condition and basic equations

We adopt two dimensional Cartesian coordinate system. We assume that the initial magnetic fields are parallel to the galactic plane, and the magnetized gas layer is stratified by gravity. We ignore the Coriolis force and self-gravity. The external gravitational field [5] is

$$g(z) = 6.8 \times 10^{-9} \tanh\left(\frac{|z|-10}{5}\right) [\mathrm{cm\ s^{-2}}] \quad (1)$$

We solve the MHD equations including CR pressure [6]. We also solve the following CR pressure equation (advection-diffusion equation) derived by the momentum-space integration.

$$\frac{\partial}{\partial t}\left[\frac{P_{CR}}{\gamma_{CR}-1}\right] + \nabla\cdot\left[\frac{\gamma_{CR}}{\gamma_{CR}-1}P_{CR}\mathbf{u}\right] - \mathbf{u}\cdot\nabla P_{CR} = \nabla\cdot\left[\kappa\mathbf{bb}\cdot\nabla\left(\frac{P_{CR}}{\gamma_{CR}-1}\right)\right] \quad (2)$$

We assumed that specific heat ratio of CRs is 4/3, CRs diffusion is assumed to be along magnetic field lines. Here **b** is the unit vector along the magnetic field lines.

3. Linear analysis

We linearized basic equations to study linear stability of the magnetic buoyancy instability with CR. We obtained the growth rate by a method similar to Horiuchi et al. [7] and Kuwabara et al. [8].

Fig.1 shows dispersion relations of the magnetic buoyancy instability for a mode without nodes. When CRs is included (solid lines), the growth rate becomes larger than that of the Parker instability (dashed lines). When the magnetic field is weak (red lines), since the CR diffusion along the magnetic field lines enhances the buoyancy around the loop top of the undulating magnetic field lines, the growth-rate and critical wavenumber increase. We call this mode as Magneto-CR Instability(MCI).

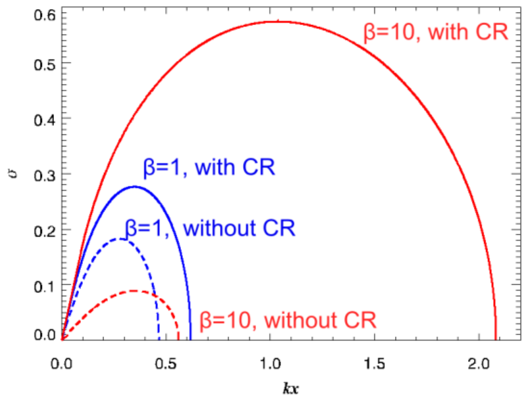

Fig.1. Linear growth rate of the magnetic buoyancy instability. Solid lines show growth rates for the instability including CR, and dashed lines are for pure Parker instability. Blue curve shows the growth rate of Parker instability with β =1, and red curve is for β =10 .

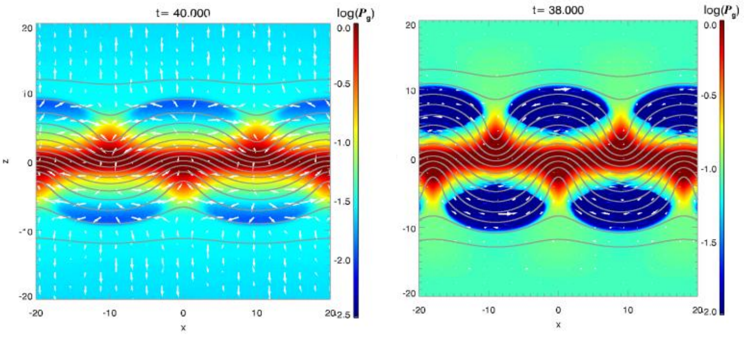

Fig.2. Left panel shows the distribution of gas pressure for pure Parker instability and right panel shows Parker instability modified by CR when plasma beta is 1. The color shows gas pressure in logarithmic scale, arrows are velocity vectors, and black curves are magnetic field lines.

4. Numerical Simulations

We used the modified Lax-Wendroff method to solve the MHD equations and the CR advection and the BiCG-stab method to solve the CR diffusion. The mesh numbers are 1024 in x-direction and 2048 in z-direction. We assumed periodic condition in x-direction and wave-absorbing condition in z-direction.

Fig.2. shows the distribution of gas pressure when plasma beta equal to 1. The height of the magnetic loops increases when CR pressure is included. These results are consistent with Kuwabara et al. [9].

Fig.3. shows the non-linear stage when plasma beta equal to 10. In this case, non-linear oscillation is excited, because Parker instability is linearly unstable but nonlinearly stable (Matsumoto et al. [4]). On the other hand, when the magnetic field is weak, growth of MCI can drive buoyant escape of the magnetic flux from disk and magnetic field lines rise like a balloon by the CR buoyancy. Even if the wavelength of the perturbation is shorter than the critical wavelength of Parker instability in linear stage, the magnetic loops continue to rise, and shock waves are formed at the footpoints of the magnetic loops.

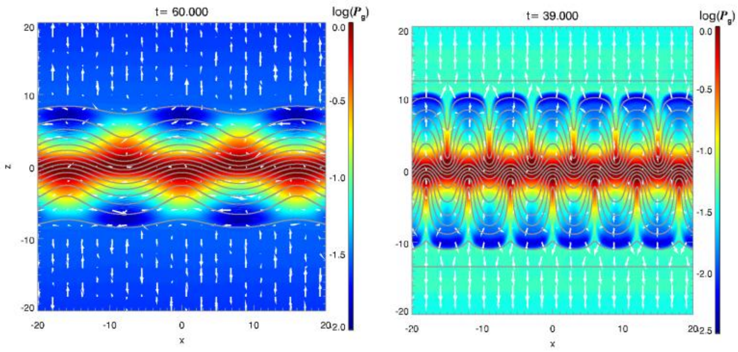

Fig.3. Left panel shows the distribution of gas pressure for pure Parker instability and right panel shows for MCI when plasma beta equal to 10. The color is gas pressure in logarithmic scale, arrows are velocity vectors, and black curves are magnetic field lines.

Acknowledgments

Numerical computations were carried out by XC30 at Center for Computational Astrophysics of National Astronomical Observatory of Japan.

References

[1] Nishikori, H., Machida, M., Matsumoto, R. 2006 ApJ, 641,862
[2] Machida, M., Nakamura, K. E., Kudoh, T., Akahori, T., Sofue, Y., & Matsumoto, R. 2013, ApJ, 764, 81
[3] Parker, E. N., 1966, ApJ, 145, 811
[4] Matsumoto, R., Hanawa, T., Shibata, K., Horiuchi, T. 1990, ApJ, 356, 259
[5] Kim, J., Hong, S.S. 1998, Apj, 507, 254
[6] Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., & Ptuskin, V. S. 1990, Astrophysics of cosmic rays, ed. Berezinskii, V. S., Bulanov, S. V., Dogiel, V. A., & Ptuskin, V. S.
[7] Matsumoto, R., Horiuchi, T., Shibata, K., & Hanawa, T. 1988, PASJ, 40, 171
[8] Kuwabara T, Nakamura K, Ko C.M. 2004, ApJ. 607, 828.