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Three-dimensional Magnetohydrodynamic Simulations of Dynamos in Galactic Gas Disks and Accretion Disks

銀河円盤・降着円盤ダイナモの3次元磁気流体数値実験

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Results of three-dimensional global magneto-hydrodynamic simulations of differentially rotating disks are presented. We found that the azimuthal magnetic fields amplified by the magneto-rotational instability (MRI) buoyantly escape from the disk by Parker instability. Numerical results indicate that the azimuthal direction of the buoyantly rising magnetic fields changes quasi-periodically with time scale about 10 rotation period of the disk, and that dipole magnetic fields become more prominent in simulations carried out without assuming symmetry with respect to the equatorial plane. The quasi-periodic dynamo activity can be the origin of low-frequency quasi-periodic oscillations (QPOs) observed in black hole candidates.

1. Introduction

Magnetic fields drive various activities in astrophysical plasmas. Quasi-periodic variation of numbers of sunspots, for example, is attributed to the dynamo activities which amplify the magnetic fields in the convection zone. When the magnetic flux stored inside the sun emerges through the photosphere, active regions and sunspots are formed.

In galactic gas disks, Faraday rotation of polarized electromagnetic waves indicates the presence of magnetic fields whose strength is several μG. In theories of galactic dynamos, the generation of radial magnetic fields from the azimuthal magnetic fields is essential to drive the dynamo. Although such conversion accompanies angular momentum transport by Maxwell stress, the back reactions of magnetic fields to the fluid motion were ignored in conventional theories of galactic dynamos.

2. New Scenario of Disk Dynamos

In differentially rotating gas disks such as accretion disks and galactic gas disks, magnetic fields can be amplified by the magneto-rotational instability (MRI)[1,2]. When rotating cylindrical plasma is threaded by magnetic fields aligned with the rotation axis, inward displacement of the plasma leads to the angular momentum loss, which reduces the centrifugal force. Instability grows when the restoring magnetic tension is small enough (see top panels of Figure 1). MRI also grows when the initial magnetic field is purely azimuthal (see bottom panels of Figure 1).

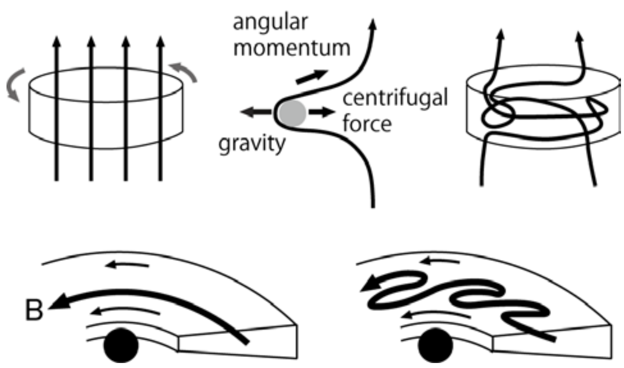

Fig.1. Schematic pictures of the growth of the magneto-rotational instability

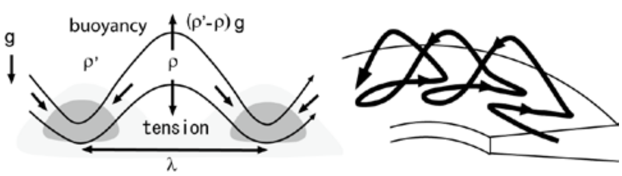

Fig.2. Schematic pictures of the growth of the Parker instability in gravitationally stratified gas disks.

In gravitationally stratified gas disks, Parker instability grows when the buoyancy created by sliding the plasma along the undulating magnetic field lines exceeds the restoring magnetic tension (Figure 2). In differentially rotating gas disks, azimuthal magnetic fields amplified by MRI form magnetic arches, which rise into the disk corona by Parker instability. The buoyant escape of the magnetic flux from the disk limits the strength of the disk magnetic fields. The disk dynamo is governed by MRI and Parker instability.

3. Three-dimensional Magneto-hydrodynamic Simulations of Disk Dynamos

We carried out three-dimensional (3D) magneto-hydrodynamic (MHD) simulations of accretion disks and galactic gas disks by applying a resistive MHD code in cylindrical coordinates. At the initial state, we assume that a differentially rotating, equilibrium disk is threaded by weak azimuthal magnetic fields.

Figure 3 shows results of global 3D MHD simulations of galactic gas disks [3] carried out by assuming a gravitational potential of our galaxy [4] and by imposing symmetric boundary condition at the equatorial plane. Figure 3(b) indicates that the amplitude of the turbulent magnetic fields is comparable to the mean magnetic fields. Figure 3(c) shows that the direction of mean azimuthal magnetic fields reverses with height.

The field reversal is driven by the buoyant escape of the azimuthal magnetic fields (see figure 2). The direction of disk magnetic fields reverses when the azimuthal magnetic fields amplified by MRI escape from the disk. We also found that the direction of disk magnetic fields reverses with time scale comparable to the 10 rotation period of the disk [3].

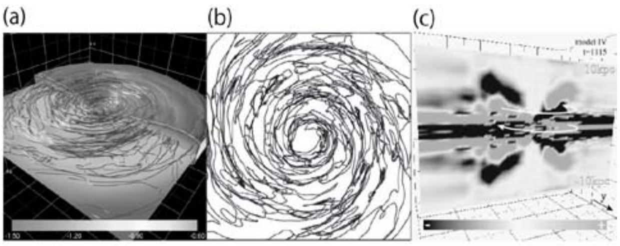

Fig.3. Results of global 3D MHD simulations of galactic gas disks. (a) Distribution of density and magnetic fields, (b) Magnetic field lines projected onto the equatorial plane. (c) Distribution of mean azimuthal magnetic fields. Black and gray show the direction of azimuthal magnetic fields. The upper boundary locates at 10kpc from the equatorial plane.

Figure 4 shows the result of global simulations carried out without imposing the symmetric boundary condition at the equatorial plane [5]. The gray scale shows mean azimuthal magnetic fields. Azimuthal magnetic fields rise into the disk corona quasi-periodically. The direction of rising magnetic fields changes quasi-periodically with time scale of 1Gyr. The amplitude of the azimuthal magnetic fields is comparable to the galactic magnetic fields. These numerical results indicate that quasi-periodic dynamo is excited in galactic gas disks. Although we started simulation with magnetic fields symmetric to the equatorial plane, anti-symmetric mode becomes more prominent in the later stage. It indicates that the galactic magnetic field is approaching a dipole field.

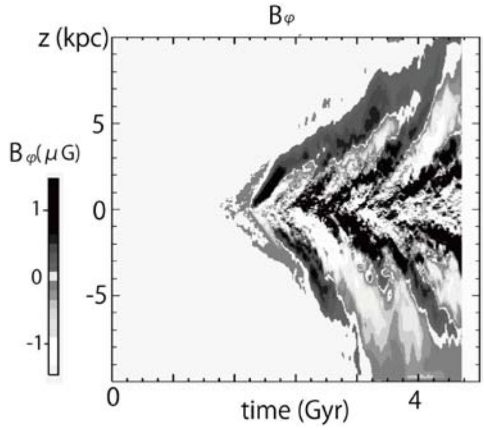

Fig.4. A butterfly diagram of the galactic magnetic fields obtained by global 3D MHD simulations. The gray scale shows azimuthal magnetic fields (black: positive, white: negative).

4. Summary and Discussion

We showed by global 3D MHD simulations that quasi-periodic dynamos accompanying reversal of azimuthal magnetic fields are excited in differentially rotating disks. The time scale of the field reversal is about 10 rotation period of the disk. In black hole accretion disks, since the synchrotron emissivity depends on the strength of magnetic fields, the quasi-periodic dynamo can be the origin of low-frequency quasi-periodic oscillations (QPOs) whose typical frequency is about 10 rotation period of the innermost region of the disk.

Acknowledgment

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