GLOBAL SIMULATIONS OF DIFFERENTIALLY ROTATING MAGNETIZED DISKS: FORMATION OF LOW-β FILAMENTS AND STRUCTURED CORONAE

M. MACHIDA
Graduate School of Science and Technology, Chiba University, 1-33 Yayoi-Cho, Inage-ku, Chiba 263-8522, Japan; machida@c.chiba-u.ac.jp

MITSURU R. HAYASHI
National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

AND

R. MATSUMOTO
Department of Physics, Faculty of Science, Chiba University, Chiba, Japan
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ABSTRACT

We present the results of three-dimensional global magnetohydrodynamic simulations of the Parker-shearing instability in a differentially rotating torus initially threaded by toroidal magnetic fields. An equilibrium model of a magnetized torus is adopted as an initial condition. When \( \beta_0 = P_{\text{mag}}/P_{\text{gas}} \approx 1 \) at the initial state, magnetic flux buoyantly escapes from the disk and creates looplike structures similar to those in the solar corona. Inside the torus, the growth of nonaxisymmetric magnetorotational (or Balbus & Hawley) instability generates magnetic turbulence. Magnetic field lines are tangled on a small scale, but on a large scale they show low azimuthal wavenumber spiral structure. After several rotation periods, the system oscillates around a state with \( \beta \approx 5 \). We found that magnetic pressure–dominated (\( \beta < 1 \)) filaments are created in the torus. The volume filling factor of the region in which \( \beta \leq 0.3 \) is 2\%–10\%. Magnetic energy release in such low-\( \beta \) regions may lead to violent flaring activities in accretion disks and in galactic gas disks.

Subject headings: accretion, accretion disks — instabilities — ISM: magnetic fields — MHD — plasmas

1. INTRODUCTION

Magnetic fields in differentially rotating disks play essential roles in angular momentum transport which enable the accretion and various activities such as X-ray flares and jet formation. Motivated by the Skylab observations of the solar corona, Galeev, Rosner, & Vaiana (1979) proposed a model of magnetically structured coronae in accretion disks consisting of X-ray–emitting magnetic loops. The magnetic loops can be created by the buoyant rise of magnetic flux tubes (or flux sheets) from the interior of the accretion disk. Matsumoto et al. (1988) carried out two-dimensional magnetohydrodynamic (MHD) simulations of the Parker instability (Parker 1966) in nonuniform gravitational fields which mimic those in accretion disks. They showed that when \( \beta = P_{\text{mag}}/P_{\text{gas}} \approx 1 \), a plane-parallel disk deforms itself into evacuated undulating magnetic loops and dense blobs accumulated in the valley of magnetic field lines.

Shibata, Tajima, & Matsumoto (1990) carried out two-dimensional MHD simulations of the Parker instability including the effects of shear flow and suggested that magnetic accretion disks fall into two types: gas pressure–dominated (high-\( \beta \)) solar-type disks and magnetic pressure–dominated (low-\( \beta \)) cataclysmic disks. In high-\( \beta \) (\( \beta \geq 1 \)) disks, magnetic flux escapes from the disk more efficiently as \( \beta \) decreases.

These earlier simulations looked at the Parker instability without differential rotation. In differentially rotating disks, magnetorotational instability (Balbus & Hawley 1991) couples with the Parker instability (Foglizzo & Tagger 1995). Differential rotation has been proven to be fundamental to accretion disks and cannot be overlooked in any self-consistent models.

Several authors (Hawley, Gammie, & Balbus 1995; Matsumoto & Tajima 1995; Brandenburg et al. 1995; Stone et al. 1996; Miller & Stone 2000) have reported the results of three-dimensional local MHD simulations of magnetized accretion disks by adopting a shearing box approximation (Hawley et al. 1995). Since Parker instability grows for long-wavelength perturbations along magnetic field lines, nonlocal effects may affect the stability and nonlinear evolution. Global three-dimensional models of differentially rotating disks are essential.

Results of global three-dimensional MHD simulations including vertical gravity were reported by Matsumoto (1999) and Hawley (2000). By adopting an initially gas pressure–dominated torus threaded by toroidal magnetic fields, Matsumoto (1999) showed that magnetic energy is amplified exponentially owing to the growth of the Balbus & Hawley instability and that the system approaches a quasi-steady state with \( \beta \approx 10 \). Matsumoto (1999) assumed \( \beta = \text{constant} \) in the torus at the initial state. When \( \beta_0 \approx 1 \), the deviation from magnetorotational equilibrium introduces large-amplitude perturbations.

In this Letter, we present the results of three-dimensional MHD simulations starting from an equilibrium MHD torus threaded by initially equipartition strength (\( \beta \approx 1 \)) toroidal magnetic fields.

2. MODELS AND NUMERICAL METHODS

The basic equations we use are ideal MHD equations in the cylindrical coordinate system \((r, \phi, z)\). We assume that the gas is inviscid and evolves adiabatically.

The initial condition is an equilibrium model of an axisymmetric MHD torus threaded by toroidal magnetic fields (Okada, Fukue, & Matsumoto 1989). We assume that the torus is embedded in hot, isothermal, nonrotating, spherical coronal gas. For gravity, we use the Newtonian potential. We neglect the self-gravity of the gas. At the initial state, the torus is assumed to have a constant specific angular momentum \( L \).

We assume polytropic equation of state \( P = K \rho^\gamma \), where \( K \) is a constant and \( \gamma \) is the specific heat ratio. According to Okada
et al. (1989), we assume
\[ v_A^2 = \frac{B_0^2}{4\pi \rho} = H(r^2) \gamma^{-1}, \] (1)

where \( v_A \) is the Alfvén speed and \( H \) is a constant. For normalization, we take the radius \( r_0 \) where the rotation speed \( L/r_0 \) equals the Keplerian velocity \( v_{K0} = (GM/r_0)^{1/2} \) as unit radius and set \( \rho_0 = v_{K0} = 1 \) at \( r = r_0 \). Using these normalizations, we can integrate the equation of motion into the potential form
\[ \Psi = -\frac{1}{R} + \frac{L^2}{2r^2} + \frac{1}{\gamma - 1} v_s^2 + \frac{\gamma}{2(\gamma - 1)} v_A^2 \]

\[ = \Psi_0 = \text{constant}, \] (2)

where \( v_s^2 \) is the square of the sound speed, \( R = (r^2 + z^2)^{1/2} \), and \( v_A \) is the Alfvén speed.

By using equation (2), we obtain the density distribution
\[ \Psi_0 = \Psi(r_0, 0). \]

\[ \rho = \left[ \frac{\max [\Psi_0 + 1/R - L^2/(2r^2), 0]}{K[\gamma/(\gamma - 1)][1 + \beta_0 r^{2(\gamma - 1)}]} \right]^{(\gamma - 1)/\gamma}, \]

where \( \beta_0 = 2K/H \) is the plasma \( \beta \) at \( (r, z) = (r_0, 0) \). The parameters describing the structure of the MHD torus are \( \gamma, \beta_0, L, \) and \( K \). In this Letter, we report the results of simulations for parameters \( \beta_0 = 1, \gamma = 5/3, L = 1, \) and \( K = 0.05 \). The density of the halo at \( R = r_0 \) is taken to be \( \rho_{\text{halo}} = 10^{-3} \). The unit field strength is \( B_0 = \rho_0^{1/2} v_{K0} \).

We solve the ideal MHD equations in a cylindrical coordinate system by using a modified Lax-Wendroff scheme with artificial viscosity. We simulated only the upper half-space \( (z \geq 0) \) and assumed that at the equatorial plane, \( \rho, v_r, v_\phi, B_r, B_\phi, \) and \( P \) are symmetric and \( v_z \) and \( B_z \) are antisymmetric. The outer boundaries at \( r = 6.4r_0 \) and at \( z = 11.8r_0 \) are free boundaries at which waves can transmit. We imposed a periodic boundary
condition in $\phi$ which goes over $0 \leq \phi \leq 2\pi$. The singularity at $R = 0$ is treated by softening the gravitational potential near the gravitating center ($R < 0.2r_0$). The number of grid points is $(N_r, N_\phi, N_z) = (200, 64, 240)$. The grid size is $\Delta r = \Delta \phi = 0.01r_0$ when $0 \leq r \leq 1.2r_0$ and $0 \leq z \leq r_0$ and otherwise increases with $r$ and $z$. To initiate nonaxisymmetric evolution, small-amplitude, random perturbations are imposed at $t = 0$ for azimuthal velocity.

3. NUMERICAL RESULTS

Figure 1a shows the initial conditions. The color scale denotes the density distribution, and the red curves depict magnetic field lines. Figure 1b shows density distribution and velocity vectors at $t = 6.2t_0$, where $t_0$ is the orbit time $t_0 = 2\pi r_0/\dot{v}_K$. As the matter that lost angular momentum accretes to the central region, the MHD torus becomes disklike. Velocity vectors indicate that matter flows out from the disk.

After the nonaxisymmetric Balbus & Hawley instability grows, the inner region of the torus becomes turbulent. Figure 1c shows the magnetic field lines projected onto the equatorial plane and the density distribution at $z = 0$. The turbulent motions tangle magnetic field lines in small scale and create numerous current sheets (or current filaments). In large scales, magnetic field lines and density distribution show low azimuthal wavenumber spiral structure. Figure 1d shows that magnetic loop structures similar to those in the solar photosphere develop in the disk.

4. DISCUSSION

We showed by three-dimensional global MHD simulations that when a differentially rotating torus is threaded by equipartition-strength toroidal magnetic fields, magnetic loops emerging from the disk continue to rise and form coronal magnetic loops similar to those in the solar corona. Inside the disk, magnetic turbulence drives dynamo action which maintains magnetic fields and keeps the disk in a quasi-steady state with $\beta \approx 5$. We successfully reproduced the formation process of the “solar-type” disk with magnetically structured coronae (Shibata et al. 1990) by three-dimensional direct MHD simulations.

Numerical results indicate that in differentially rotating disks, magnetic field lines globally show spiral structure with low azimuthal wavenumber, but locally fluctuating components create numerous current sheets inside the disk (see Fig. 1c). We
Figure 3.—(a) Time development of the mean magnetic energy averaged in the region in which \(0.7 \leq r/r_0 \leq 1.3\) and \(0 \leq z/r_0 \leq 0.3\). The dashed curve \((BP)\), dash-dotted curve \((B)\), and solid curve \((A)\) show \(\log ([B^2/8\pi\rho]/P)\), \(\log ([B^2/8\pi\rho_0]/P)\), and \(\log (-B\cdot B/(4\pi\rho_0))\), respectively. (b) Time development of accretion rate \((AR)\) at \(r = 0.3r_0\) and outflow rate \((OR)\) at \(z = 3.0r_0\). (c) Poynting flux which goes through the plane \(z = 1.0r_0, 2.0r_0, 3.0r_0\). (d) Volume filling factor of the region in which \(\beta < 0.3\) in \(0.7 \leq r/r_0 \leq 1.3\) and \(0 \leq z/r_0 \leq 0.7\).

We expect that magnetic reconnection taking place in current sheets generate hot plasmas which emit hard X-rays. When the disk is optically thin, such reconnection events may be observed as large-amplitude sporadic X-ray time variations characteristic of low states in black hole candidates (Kawaguchi et al. 2000). Current sheets are also created in the corona. The plasma \(\beta\) in the corona is \(\beta = 0.1–1\) (see Fig. 2).

We found that inside the torus, filamentary-shaped, locally strongly magnetized, low-\(\beta\) regions appear. Even when \(\beta \sim 5\) on average, low-\(\beta\) regions in which \(\beta \leq 0.3\) occupy 2%-10% of the total volume. The low-\(\beta\) filaments are embedded in high-\(\beta\) plasma. Such an intermittent structure is common in magnetized astrophysical plasmas. Numerical results indicate that low-\(\beta\) filaments are regenerated after they disappear around \(t/t_0 = 8–10\).

Although we assumed point gravity suitable for accretion disks, numerical results can qualitatively be applied to galactic gas disks. Our numerical results suggest that although \(\beta \geq 1\) on average, low-\(\beta\) filaments exist in galactic gas disks. Magnetic reconnection taking place in such low-\(\beta\) regions may heat the interstellar gas and create hot, X-ray-emitting plasmas. Tanuma et al. (1999) proposed a model that magnetic reconnection in strongly magnetized \((\sim 30 \mu G)\) regions in our Galaxy creates hot plasma which emit the 7 KeV component of Galactic ridge X-ray emission. The low-\(\beta\) filaments can also confine the hot plasma and prevent it from escaping from the Galaxy.

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