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Three-Dimensional Global MHD Simulations of Magnetised Accretion Disks and Jets

R. Matsumoto[1]

Department of Physics, Faculty of Science, Chiba University, 1-33 Yayoi-Cho, Inage-ku, Chiba 263, JAPAN

K. Shibata

National Astronomical Observatory, Mitaka, Tokyo 181, JAPAN

Abstract. We carried out three-dimensional global MHD simulations of jet formation from an accretion disk threaded by large-scale magnetic fields. Numerical results show that bipolar jets with maximum speed $v_{jet} \sim v_{Kepler}$ are created. The surface layer of the disk accretes faster than the equatorial part because magnetic braking most effectively affects that layer. Accretion proceeds along spiral channels which correspond to the surface avalanche flow appearing in previous axisymmetric simulations. Spirally shaped low β ($= P_{gas}/P_{mag} < 1$) regions appear in the innermost part of accretion disks where toroidal magnetic fields become dominant.

1. Introduction

When an accretion disk is threaded by large scale poloidal magnetic fields, a bipolar jet can be formed due to the centrifugal acceleration of gas along rigid magnetic field lines (Blandford & Payne 1982). Uchida & Shibata (1985) proposed another type of magnetic mechanism for the acceleration of jets; a bipolar jet is formed due to the accumulation and relaxation of magnetic twists generated by the rotation of the disk. They called this process a "sweeping magnetic twist mechanism" and confirmed this idea by two-dimensional axisymmetric global MHD simulations (Uchida & Shibata 1985; Shibata & Uchida 1986).

Since the torsional Alfvén wave extracts angular momentum from the disk (magnetic braking), the jet formation enhances the accretion of disk gas. As the disk matter rotates faster as they fall toward the central object, they twist the magnetic fields further. This mechanism generates an avalanche-like flow which is a global version of the two-channel flow found in the nonlinear stage of the Balbus & Hawley instability (Balbus & Hawley 1991; Hawley & Balbus 1992). The relation between the magnetic braking and the Balbus & Hawley instability has been discussed by Stone & Norman (1994) and Matsumoto et al. (1996).

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[1] Advanced Science Research Center, JAERI, Naka, Japan

In order to study the effects of non-axisymmetry on the structure and stability of the disk and jets, we carried out global three-dimensional MHD simulations of a torus threaded by large scale magnetic fields.

2. Models and Numerical Methods

We assume that a rotating polytropic torus with constant angular momentum distribution $L = L_0$ is imbedded in a spherical, non-rotating isothermal halo. The gravitational field is assumed to be given by a point mass M. In a cylindrical coordinate (r, φ, z), the dynamical equilibrium of the disk is described by

$$-\frac{GM}{(r^2 + z^2)^{1/2}} + \frac{1}{2}L_0^2 r^{-2} + (n+1)\frac{P}{\rho} = const.$$

where n is the polytropic index. We take the radius of the pressure maximum of the disk $[r = L_0^2/(GM)]$ as the reference radius r_0. The initial magnetic field is assumed to be uniform and vertical ($\mathbf{B} = B_0\hat{z}$). The model parameters for the disk are $A_1 = C_{s0}^2/(\gamma v_{K0}^2)$ and $A_2 = v_{A0}^2/v_{K0}^2$, where γ is the adiabatic index, C_{s0} the sound speed, $v_{A0} = B_0^2/(4\pi\rho_0)$ the Alfvén speed, and $v_{K0} = (GM/r_0)^{1/2}$ is the Keplerian rotation speed at $(r, z) = (r_0, 0)$. We use the normalization $r_0 = v_{K0} = \rho_0 = 1$. The halo parameters are $1/\alpha = C_{sh}^2/(\gamma v_{K0}^2)$ and ρ_h/ρ_0 where C_{sh} and ρ_h are the sound speed and density in the halo at $(r, z) = (0, r_0)$, respectively. We solved the ideal MHD equations in a cylindrical coordinate by using a modified Lax-Wendroff scheme with artificial viscosity.

3. Numerical Results

In figure 1, we show a result of 3D MHD simulations for a typical model ($n = 3$, $\gamma = 5/3$, $\alpha = 1$, $A_1 = 0.05$, $A_2 = 10^{-3}$, $\rho_h/\rho_0 = 10^{-3}$). The initial plasma β at the pressure maximum of the disk is $\beta_0 = 100$. The plasma β in the halo is $\beta_h = 2.0$ at $(r, z) = (0, r_0)$. We initiate the non-axisymmetric evolution by imposing perturbation for azimuthal velocity as $\delta v_\varphi = 0.01 v_\varphi \sin(2\varphi)$. The number of grid points is $(n_r, n_\varphi, n_z) = (101, 32, 101)$.

We confirmed the results of previous 2D axisymmetric simulations (Matsumoto et al. 1996) that the surface layer of the disk accretes faster than the equatorial part (see magnetic field lines at $t = 6.0$). This inflow creates the radial component of magnetic fields which is further twisted by the differential rotation of the disk. When the accumulated magnetic twist relaxes along the large-scale magnetic fields, it entrains matter in the surface layer of the disk and form bipolar jets ($t = 12.3$). The maximum speed of the jet is the order of the Keplerian rotation speed. Due to the self-pinching effect of the toroidal magnetic field, the outflow is collimated along the rotational axis. The magnetic field lines at $t = 12.3$ indicate that toroidal magnetic field dominates inside the disk. The magnetic field lines are bunched into helical bundles in the jet. A helical filamentary structure can also be seen in the density distribution of the jet.

Figure 2 shows the projection of magnetic field lines and the isocontours of β near the equatorial plane ($z = 0.14$) at $t = 11.4$. The dashed curves show

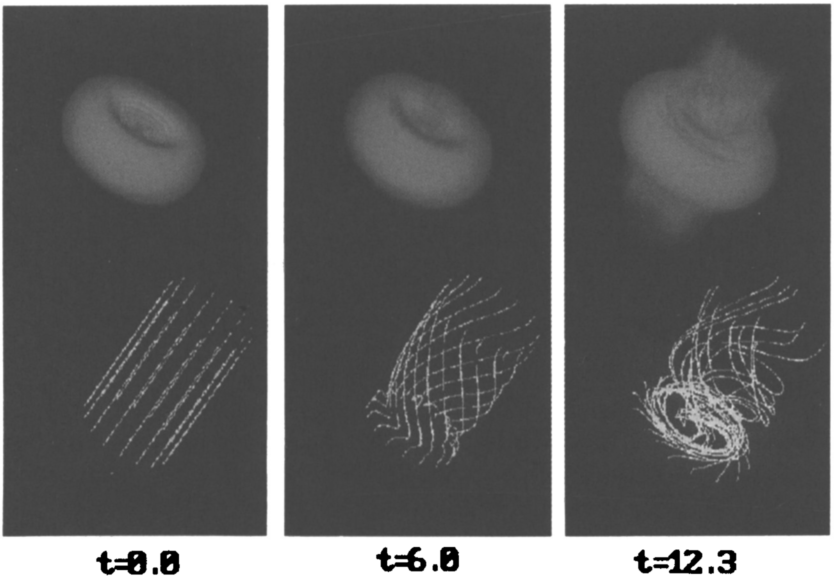

Figure 1. Results of 3D MHD simulation for a typical model. Top panels show volume rendered image of density distribution. The bottom panels show magnetic field lines above the equatorial plane.

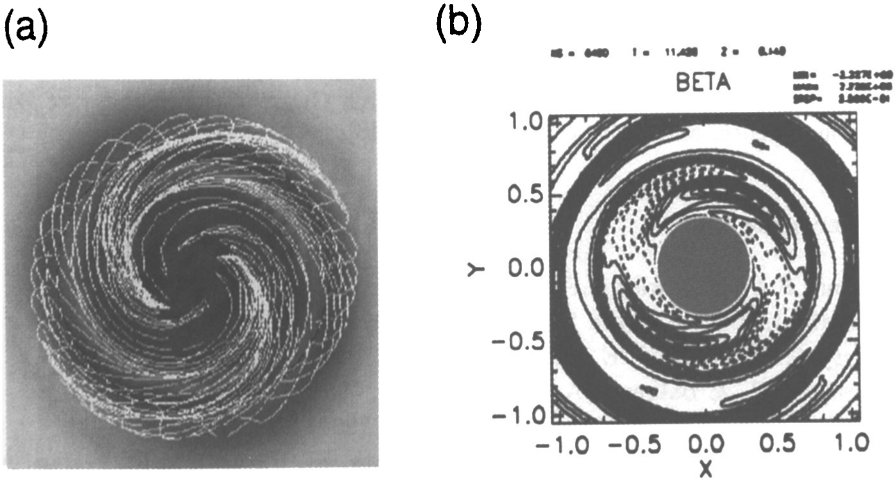

Figure 2. (a) Projection of magnetic field lines onto the equatorial plane at $t = 11.4$. Gray scale shows density distribution near the equatorial plane (dark area is denser), (b) Isocontours of β at $z = 0.14$. Dashed curves show low-β region.

low-β ($\beta < 1$) region. Accretion proceeds along two spiral channels. In the innermost region of the disk where toroidal magnetic field becomes dominant, spiral-shaped low-β region appears.

4. Discussion

Through three-dimensional global MHD simulations, we showed that a bipolar jet is formed from an accretion disk threaded by large scale magnetic fields.

The surface avalanche generated by magnetic braking corresponds to the two channel flow which appears in the nonlinear stage of the Balbus & Hawley instability. Hawley, Gammie, & Balbus (1995) showed by 3D local MHD simulations that the two channel flow breaks up and generates turbulence in accretion disks. The simulation results we presented here indicate that the avalanche flow breaks up into spiral channels due to the growth of non-axisymmetric modes. Recently, Ogilvie & Pringle (1996) and Curry & Pudritz (1996) carried out global linear analysis of non-axisymmetric instabilities in magnetized disks. They found growing eigenmodes confined between one of the boundaries and the Alfvén resonance point. This mode is a magnetic analogue of the Papaloizou & Pringle instability (Papaloizou & Pringle 1984). The spiral structure which appeared in our 3D simulation may be due to the growth of this mode.

In addition to the global instabilities, magnetized accretion disks are locally unstable against the Balbus & Hawley instability (Balbus & Hawley 1991). By carrying out simulations with higher resolution ($> 256^3$ grids), we will be able to study the growth and saturation of such local instabilities by global simulation.

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References

Balbus, S.A., & Hawley, J.F. 1991, ApJ, 376, 214

Blandford, R.D., & Payne 1982, MNRAS, 199, 883

Curry, C & Pudritz, R.E 1996, MNRAS, 281, 119

Hawley, J.F., & Balbus, S.A. 1992, ApJ, 400, 595

Hawley, J.F., Gammie, C.F., & Balbus, S.A. 1995, ApJ, 440, 742

Matsumoto, R., Uchida, Y., Hirose, S., Shibata, K., Hayashi, M.R., Ferrari, A., Bodo, G., & Norman, C. 1996, ApJ, 461, 115

Ogilvie, G.I., & Pringle, J.E. 1996, MNRAS, 279, 152

Papaloizou, J.C.B., & Pringle, J.E. 1984, MNRAS, 208, 721

Shibata, K., & Uchida, Y. 1986, PASJ, 38, 631

Stone, J.M., & Norman, M.L. 1994, ApJ, 433, 746

Uchida, Y., & Shibata, K. 1985, PASJ, 37, 515

Discussion

C. Curry: If I understand correctly, the ratio of Alfvén speed to Keplerian speed at the disk surface is of order unity. How does one get such a strong field there?

R. Matsumoto: The Alfvén speed in the disk surface becomes large because density decreases in that region. The magnetic field is not necessarily strong.

P. Hartigan: What is the ratio of V_ϕ to V_z along the jet?

R. Matsumoto: Within our simulation region, V_ϕ and V_z are comparable.

H. Zinnecker: Is this a general result (and if so, why) that the jet mass loss rate is 10% of the disk accretion rate? Where in your 3D MHD simulations does most of the ejected mass originate: from near the disk star boundary layer or further out in the accretion disk?

R. Matsumoto: In the parameter range I surveyed in 2D simulation the jet mass is about 10% of the accreting mass. The jet mass loss rate is related to the accretion rate because accretion proceeds due to magnetic braking whose efficiency is related to the jet mass flow rate. In our 3D simulation the ejected mass comes from the surface layer of the disk.