*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, O-5.066 (2008)*

Magnetohydrodynamic Modeling of the Accretion Disk Corona

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Accretion disks are unique objects in astrophysics [1]. The accretion disks around supermassive black holes are responsible for powering Active Galactic Nuclei (AGNs) and quasars, and they are believed to be responsible for driving jets in these systems. Accretion disks have been observed in stellar binary systems and in Young Stellar Objects (YSOs). The formation and dynamics of a star can not be described without a proper accretion disk model. Angular momentum transport in the disks is a key in understanding of accretion mechanisms. Conservation of angular momentum inhibits accretion. The microscopic viscosity is too small to explain the accretion rate inferred from observations. Turbulent motion has been considered as a mechanism for anomalous transport of angular momentum in accretion disks [2, 3]. Possible mechanisms for angular momentum transport in accretion disks are discussed in this report. In particular, we test the idea that magnetic fields in the corona of an accretion disk may play an important role in the disk angular momentum transport. The evolution of coronal magnetic fields might destabilize differential rotation flows in the disk by leading to the development of a coronal magneto-rotational instability (MRI) and enhancement of angular momentum transport in the disk. The 3D resistive MHD code MAB is used to simulate the evolution of a coronal magnetic loop and the corresponding angular momentum transport in the disk. The MHD equations for the accretion disk and its corona are modeled separately. The azimuthal component of magnetic field and the velocity field in the disk are used as boundary conditions to advance the coronal flows. The toroidal and radial components of magnetic field are computed in the corona simulation and their boundary values are used in turn to advance the accretion disk flows. This provides a coupling between the MHD flows in the accretion disk and its corona.

1. Description of the model

In this study, we consider the evolution of a coronal magnetic loop in 3D corona and accretion disk that rotates around a central object. Since the internal and magnetic energies in the disk are small compared to the rotational energy, the pressure forces in the disk can be neglected

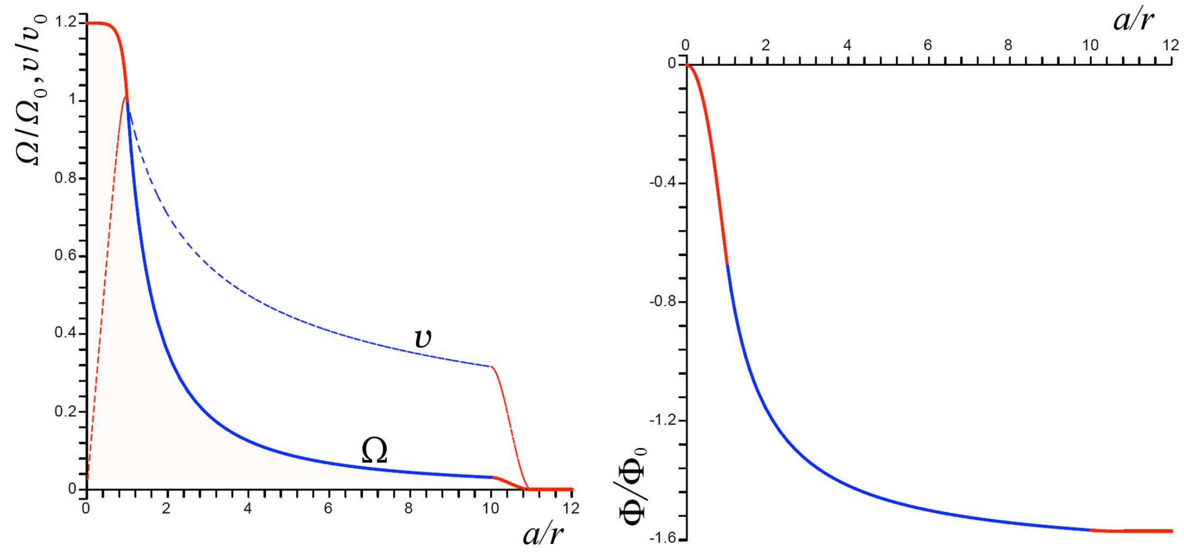

Figure 1: The linear and angular equilibrium velocities (left panel) and corresponding gravitational potential (right panel). Red sections correspond to the modifications to the profiles introduced in order to avoid the singularity at $r = 0$.

and the equilibrium angular velocity can be approximated by the Keplerian angular velocity $\Omega = \sqrt{GM/r^3}$. Here, G is the gravitational constant, and M is the mass of the central object. In the special case of barotropic ($p = p(\rho)$) and isothermal ($\gamma = 1$, $c_s =$ const, and $p = c_s^2\rho$) fluid in the corona, the angular velocity does not depend on z and the equilibrium state can be found as a balance between the plasma pressure, p, gravity, and centrifugal force:

$$-\frac{1}{\rho}\nabla p - \nabla\Phi + R\Omega^2\hat{e}_R = 0, \quad (1)$$

where Φ is the Newtonian gravitational potential defined as $g \equiv -\nabla\Phi$, and $\hat{e}_R$ is the unit vector in the radial direction. One can find that the equilibrium plasma density in the corona satisfies the condition $\rho = \rho_0 \exp\left(M_a^2\left(\Phi(r) - \Phi(R)\right)\right)$, where $M_a \equiv v_0/c_s$ and $v_0 \equiv a\Omega_0$. This equilibrium configuration is used as initial condition in the simulations described in the next section.

The gravitational potential and corresponding angular velocity profiles have been modified to avoid the singularity at $r = 0$ and to ensure the Dirichlet boundary conditions for the velocity profile on the disk (see Fig. 1). The initial magnetic loop configuration is chosen in the way to minimize the force imbalance when the coupling between the disk and corona is included.

The equations that describe the horizontal components of velocity in the accretion disk, v_r and v_ϕ, disk surface mass density, Σ, and vertical component of the magnetic field, B_z, are derived from the 3D MHD equations in the approximation of an infinitely thin disk [4]:

$$-2\Omega\tilde{v}_\phi = -c_s^2\frac{\partial \ln\Sigma}{\partial r} + \frac{B_r}{2\pi}\frac{B_z}{\Sigma} \tag{2}$$

$$\left(\Omega r^2\right)' v_r = -c_s^2\frac{\partial \ln\Sigma}{\partial \phi} + r\frac{B_\phi}{2\pi}\frac{B_z}{\Sigma} \tag{3}$$

$$\left[\frac{\partial}{\partial t} + \left(\Omega + \frac{\widetilde{v_\phi}}{r}\right)\frac{\partial}{\partial \phi} + v_r\frac{\partial}{\partial r}\right]\ln\Sigma = -\frac{1}{r}\left[\frac{\partial\,(r v_r)}{\partial r} + \frac{\partial\widetilde{v_\phi}}{\partial \phi}\right] \tag{4}$$

$$\left[\frac{\partial}{\partial t} + \left(\Omega + \frac{\widetilde{v_\phi}}{r}\right)\frac{\partial}{\partial \phi} + v_r\frac{\partial}{\partial r}\right]\frac{B_z}{\Sigma} = \frac{1}{\Sigma}\left(\dot{B}_z + \eta\nabla_h^2 B_z\right) \tag{5}$$

where η is the magnetic diffusivity, and the source $\dot{B}_z$ is introduced to represent the field that can be generated in the disk by a dynamo process. The horizontal components of velocity and vertical component of magnetic field are used as boundary conditions in the 3D resistive MHD equations for the corona:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho v) = 0 \tag{6}$$

$$\frac{\partial p}{\partial t} + \nabla\cdot(p v) = -(\gamma-1)p\nabla\cdot v \tag{7}$$

$$\rho\left(\frac{\partial v}{\partial t} + v\cdot\nabla v\right) = \frac{1}{c}J\times B - \nabla p + \rho g \rho + \nabla\cdot(\nu\rho\nabla v) \tag{8}$$

$$\nabla\times B = \frac{4\pi}{c}J; \qquad \nabla\times E = -\frac{1}{c}\frac{\partial B}{\partial t};\ E + \frac{1}{c}v\times B = \eta J \tag{9}$$

where ν is the plasma viscosity. The horizontal components of magnetic field at the coronal base obtained from these equations are used for the disk equations. This provides a feedback from the corona to the disk.

2. Simulation results

The accretion disk model that is described by Eqs. 2-5 has been implemented as a part of the 3D Cartesian resistive MHD code MAB. The code solves the equations of resistive MHD (Eqs. 6-9) together with the equations for the accretion disk (Eqs. 2-5) using a first-order upwind finite element technique. The MAB code is effectively scaled on a shared-memory platform by including OpenMP support.

The simulation parameters are selected so that the following conditions are satisfied:

$$a << R;\ M_a \equiv v_0/c_s \leq 1;\ M_b \equiv v_0/v_A << 1, \tag{10}$$

where a is the radius of the central object, R is the radius of the accretion disk, and v_A is the Alfvén velocity.

Simulation results indicate that the magnetic field lines become twisted in corona due to strong differential rotation of the disk (see Fig. 2). Such twisting of magnetic field lines might result in dramatic changes of magnetic topology involving the reconnection of magnetic field lines and formation of a plasma jet.

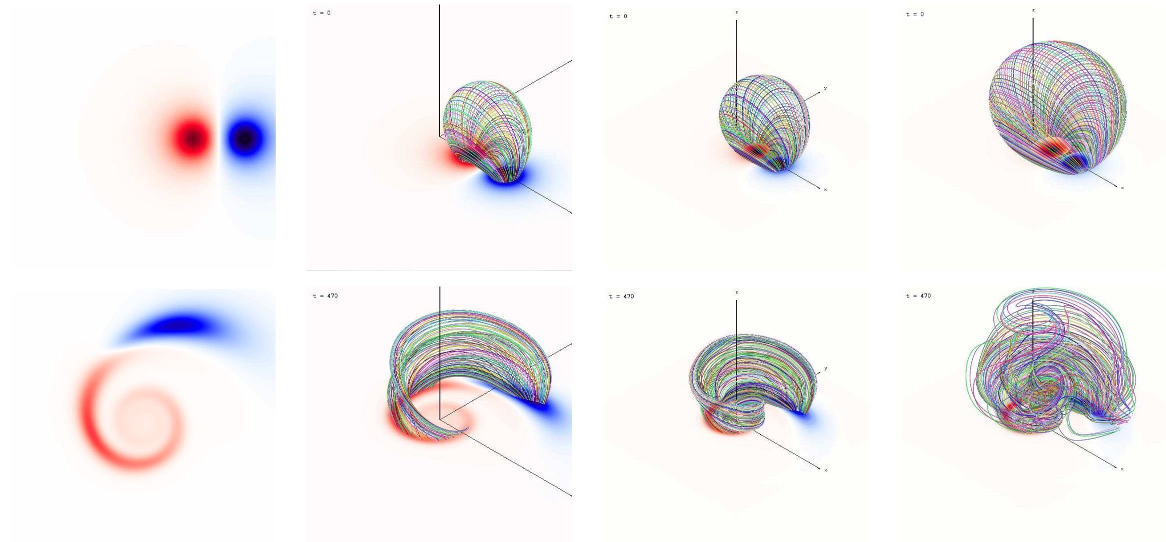

Figure 2: Contour plots of the horizontal component of magnetic field on the disk (left panels) and field lines with the launch points corresponding to $B_z = 0.50B_z^{max}$, $B_z = 0.25B_z^{max}$, and $B_z = 0.10B_z^{max}$ (second, third, and fourth panels, correspondingly). The upper panels show the initial states at the beginning of the simulation; the lower panels show the final states at the end of the simulation.

The main focus of the current study is to demonstrate that the model introduced in Sec. 1 can provide a mechanism for the enhanced angular momentum transport through coronal MRI. The resulting transport of the angular momentum can be estimated from the evolution of magnetic torque density in the disk $K \equiv RB_\phi B_z/2\pi$. The magnetic torque density profiles averaged over azimuthal angle,

$$< K >_\phi = \frac{r}{2\pi^2} \int_0^{2\pi} B_\phi B_z d\phi$$

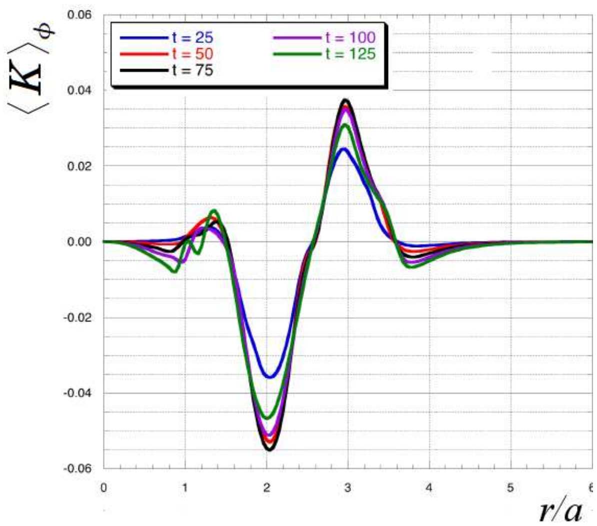

Figure 3: The simulation results for the magnetic torque density profiles averaged over azimuthal angle at different simulation times.

at different times are shown in Fig. 3. There is a clear indication that the angular momentum of the inner footprint of magnetic loop decreases, while the angular momentum of the outer footprint increases. Thus, our preliminary results support the basic idea that the angular momentum in the disk can be redistributed via its nonlocal interaction with the coronal magnetic loops.

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