THREE-DIMENSIONAL LOCAL MHD SIMULATIONS OF HIGH STATES AND LOW STATES IN MAGNETIC ACCRETION DISKS

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Black hole candidates sometimes show a transition between the high (or soft) state and the low (or hard) state. In the low state, low frequency time variations are much larger than the high state. A possible mechanism of the large-amplitude, sporadic time variabilities in the low-state is the magnetic energy release in low-β (β = \( P_{\text{gas}} / P_{\text{mag}} < 1 \)) disks (Mineshige, Kusunose & Matsumoto 1995). It had been thought that low-β disks cannot exist because buoyant escape of magnetic flux due to the Parker instability may set the lower limit for β inside the disk. Shibata, Tajima & Matsumoto (1990), however, pointed out that in accretion disks, once a low-β disk is formed, it can stay in low-β state partly because the growth rate of the Parker instability decreases when β < 1. They suggested that magnetic accretion disks fall into two types; high-β disks and low-β disks.

We carried out local three-dimensional magnetohydrodynamic (MHD) simulations of a gravitationally stratified, isothermal Keplerian disk initially threaded by azimuthal magnetic field. Since both differential rotation and vertical gravity are included, the magnetorotational (or Balbus & Hawley) instability (Balbus & Hawley 1991) couples with the Parker instability when \( \beta \sim 1 \). Local Cartesian coordinate is used with \( x, y, z \) in the radial, azimuthal, and vertical direction, respectively. The vertical gravity is as-
Figure 1. Time evolution of the mean magnetic field strength $\langle B^2/(8\pi P_0(0)) \rangle$ for various initial $\beta$ (left panel) and the angular momentum transport rate $\alpha_B = -\langle B_x B_y/(4\pi P_0(0)) \rangle$ for a model with $\beta = 1$ (right panel). The unit of time is the rotation time.

assumed to be $g_z = -G M z/(r_0^2 + z^2)^{3/2}$ where $r_0$ is the radius from the gravitating center. We assume that $\beta$ is uniform at the initial state. The size of the simulation box is $(L_x, L_y, L_z) = (1H, 18H, 16H)$, where $H$ is the scale height defined by using the sound speed $C_s$ and Keplerian angular speed $\Omega_K$ as $H = C_s/\Omega_K$. The azimuthal boundaries are periodic. The radial boundaries are treated by using the sliding periodic condition.

The left panel of Figure 1 shows the time evolution of the mean magnetic field strength $\langle B^2/(8\pi P_0(0)) \rangle$ for various initial plasma $\beta$, where $P_0(0)$ is the initial equatorial pressure. Numerical results indicate that in high-$\beta$ disks, the amplification of magnetic fields due to the Balbus-Hawley instability saturates when $\beta \sim 10 - 30$. The disk approaches to a gas pressure dominated, quasi-steady state. The effective value of the viscosity parameter is $\alpha_B = -\langle B_x B_y/(4\pi P_0(0)) \rangle \sim 0.01$. These results are consistent with those reported by Stone et al. (1996). When the initial magnetic energy is comparable to the thermal energy ($\beta \sim 1$), however, the disk stays in the low-\$\beta$ state for time scale longer than the rotation period. In such disks, the amplification of magnetic fields due to the coupling of the Balbus & Hawley instability and the Parker instability overcomes the buoyant loss of magnetic flux. The effective magnetic viscosity in low-\$\beta$ state is the order of 0.1 as shown in the right panel of Figure 1. When the magnetic energy stored in the low-\$\beta$ disk is released, we expect large amplitude sporadic time variations as observed in low-state disks.

References