§26. Sawtooth-like Oscillations of Accretion Disks

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Accretion disks formed around a gravitating object efficiently extract the gravitational energy of the accreting matter and drive activities such as X-ray emission and jets. We are studying the evolution of such rotating disks by global three-dimensional magnetohydrodynamic (MHD) simulations. We found that when an inner torus is formed, the disk shows sawtooth-like oscillation with period about 10 rotation time of the torus. Magnetic energy is released quasi-periodically by magnetic reconnection.

We are especially interested in quasi-periodic oscillations (QPOs) of X-ray luminosity observed in black hole candidates because they enable us to measure the spacetime near the black hole. Low frequency QPOs (1-10Hz in stellar mass black holes) appear when the disk is in optically thin, X-ray hard state. Its frequency increases with the disk luminosity. In luminous disks, high frequency QPOs (50-200Hz in stellar mass black holes) are sometimes observed. High frequency QPOs accompany low-frequency QPOs.

We numerically solved resistive MHD equations in cylindrical coordinates (ϖ, φ, z). We assumed anomalous resistivity $\eta = \eta_0[\max(v_d/v_c - 1, 0)]^2$ where $v_d = j/\rho$ is the electron-ion drift speed and v_c is the threshold above which the anomalous resistivity sets in. Here j and ρ are current density and matter density, respectively. General relativistic effects are simulated by using the pseudo-Newtonian potential $\psi = -GM/(r - r_s)$ where M is the mass of the black hole, $r = (\varpi^2 + z^2)^{1/2}$, and r_s is the Schwarzschild radius. The initial state is a disk with angular momentum $L \propto \varpi^{0.46}$ threaded by weak toroidal magnetic fields. The initial strength of magnetic field is parameterized by $\beta_0 = P_{\rm gas}/P_{\rm mag}$ at the pressure maximum of the disk. We take $\beta_0 = 100$.

We assume the magnetic Reynolds number $R_{\rm m} = cr_s/\eta_0 = 2000$ and take the threshold for the anomalous resistivity $v_c = 0.9c$. The number of grid points is 250 in radial direction, 32 in azimuthal direction and 384 in vertical direction. We imposed absorbing boundary condition at $r = 2r_s$. Outer boundaries are free boundary where waves can be transmitted.

As the magnetorotational instability (MRI) grows in the weakly magnetized disk, the disk matter infalls by losing angular momentum and forms an inner torus around $\varpi = 8r_s$. Figure 1 shows that the inner torus is deformed into a crescent shape. Figure 2 shows the time evolution of the magnetic energy (solid curves) and the Joule heating rate (dashed curves) integrated in the inner torus. They show sawtooth-like oscillation with period $\sim 2500r_s/c$. This time scale is determined by the growth time of MRI ($\sim$ 10 rotation period) and comparable to that of low-frequency QPOs.

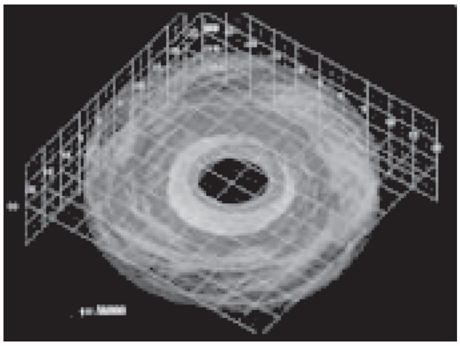

Figure 1: Isosurface of density at $t = 58000r_s/c$.

Sawtooth-like oscillations are excited in nonlinear system when an instability and dissipation coexists. When the dissipation is small, the energy accumulated by the growth of the instability is released sporadically. Numerical results indicate that magnetic energy is released by magnetic reconnection. As the disk is heated by magnetic energy release, sawtooth-like oscillation disappears because the enhanced angular momentum transport prohibits the formation of the inner torus. We are carrying out simulations including radiative cooling to avoid such disk heating.

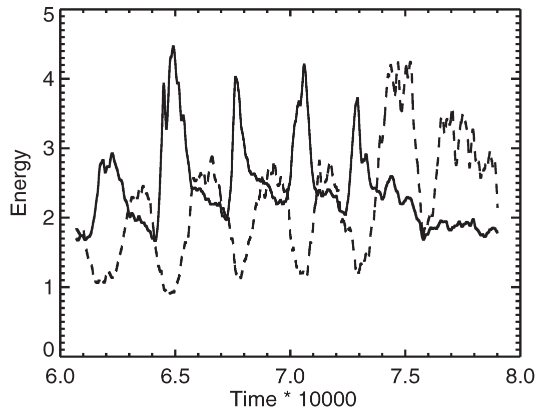

Figure 2: Time evolution of the magnetic energy (solid curve) and the Joule heating rate (dashed curve).

We found that when the large-amplitude sawtooth-like oscillation appears, two high frequency QPOs with frequency ratio 2:3 appear around 100Hz [1]. The large amplitude sawtooth-like oscillation excites high frequency oscillations in the inner torus.

Reference

1) Matsumoto, R., Machida, M., Proceedings of IAU symposium 238, Cambridge University Press, (2007) 37