Three-dimensional magneto-hydrodynamic simulations of the formation of the inner torus in black hole accretion flows

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Abstract

We present the results of formation of the inner torus in black hole accretion flows obtained from three dimensional magneto-hydrodynamic simulations. We focus on the dependence of numerical results on the gas temperature supplied from the outer region. General relativisitc effects are taken into account using the pseudo-Newtonian potential. We ignore the radiative cooling of the accreting gas. The initial state is a torus threaded by a weak azimuthal magnetic field.

We found that mass accretion rate and the mass outflow rate strongly depend on the temperature of the initial torus. In the cool model, a constant angular momentum inner torus is formed around $4-8r_{\rm s}$ where $r_{\rm s}$ is the Schwarzschild radius. This radius is near the maximum radius of the radial epyciclic frequency. This inner torus deforms itself from a circle to a crescent quasi-periodically. During this deformation, the mass accretion torus returns to a circular shape and starts the next cycle. The time interval of this deformation is caused by the magnetic dynamo activitis driven by MRI. When the magnetic energy released, magnetic pressure driven outflows blow from the inner torus.

Power spectral density (PSD) of the time variation of the mass accretion rate in the coolo model has a low frequency peak around 10Hz when we assumed a $10M_\odot$ black hole. The PSD of the hot model is flat in $1-30$Hz. The slope of the PSD in the cool model is steeper than than in the hot model in $30-100$Hz.

Key words: Accretion disks — MHD — QPOs

1. Introduction

After the RXTE satellite launched, a detailed timing analysis of X-ray binaries has been carried out. During state transition of black hole X-ray binaries, black hole candidates sometimes show the quasi-periodic oscillation (QPO) in its power spectral density. When the disk luminosity exceeds 1% of the Eddington luminosity, broad low frequency QPOs with frequency $1-10$Hz appear. As the disk completes the transition to high/soft state, QPO disappears. Therefore, it seems that the QPOs are associated with the cooling of the disk and state transition. Machida et al. (2006) showed that when the mass accretion rate reached the limit of ADAF solutions, cooling instability growed. Then the transition from the radiatively inefficient, optically thin disk to a magnetically supported, cool, optically thin disk occured. They argued that this magnetically supported disk correspons to the bright hard state.

In this paper, we present the results of global three-dimensional magneto-hydrodynamic (MHD) simulations of the black hole accretion disk whose state corresponds to the bright hard state. This paper is based on Machida and Matsumoto (2008).

2. Initial condition

We solved the resistive MHD equations in a cylindrical coordinate system using a modified Lax-Wendroff scheme with an artificial viscosity. The units of length and velocity were the Schwarzschild radius $r_{\rm s}$ and the light speed, respectively. We used $(N_\varpi, N_\varphi, N_z)$=(250,64,384) meshed. The grid size was $\Delta\varpi = \Delta z = 0.1$ for $0 < \varpi/r_{\rm s} < 10$, and $|z|/r_{\rm s} < 10$.

The initial state of our simulation was an equilibrium torus threaded by a weak toroidal magnetic field. In this paper, we assumed two outer torus. One is the hot torus with a sound speed of $c_{\rm s} = 0.03c$ correspond to the hard state (model HT), and the other is the cool torus with $c_{\rm s} = 0.01c$ corresponds to the bright hard state (model LT).

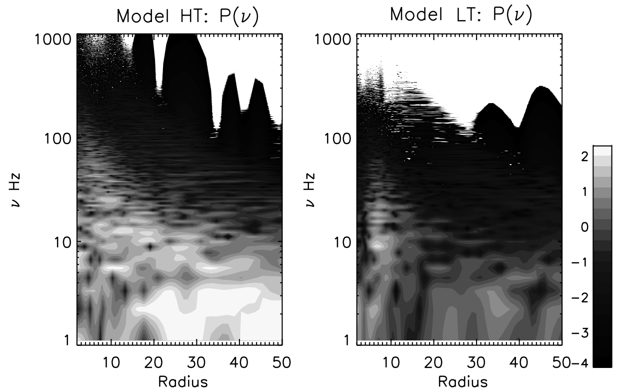

Fig. 1. Radial distribution of the Power Specral Density of the time vaiation of the mass-accretion rate for model HT measured in 23000¡t/t_0¡ 32000(left) and for model LT measured in 55000¡t/t_0¡64000(right)

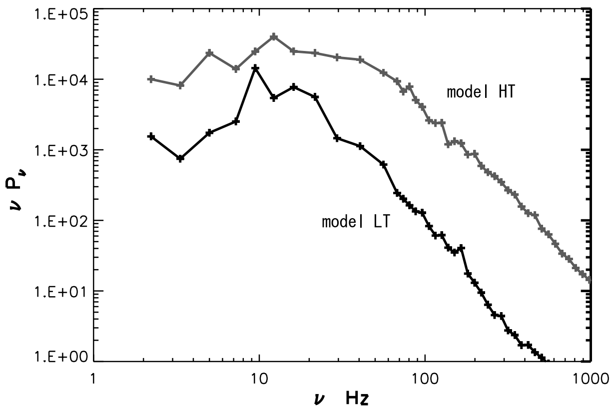

Fig. 2. Power spectrum, νP_ν where P_ν is the Fourier power of the time variation of the mass-accretion rate averaged in $2.5 < \varpi/r_s < 29$ and $|z|/\varpi_s < 1$ for model LT (black) and for model HT(gray).

3. Numerical Results

In both model, the disks become the magnetic turbulence by the magneto-rotational instability (MRI). The averaged plasma β where plasma β is the ratio of the gas pressure to magnetic pressure becomes about 10. The angular momentum transport rate α in model HT is saturated around $\alpha \sim 0.05$. The disk gas accretes to the black hole through dense, spiral channels. In model LT, however, the averaged α becomes less than 0.01. Therefore, the inner torus is formed around $\varpi \sim 5 - 10r_s$. This result indicates that the angular momentum transport rate strongly depends on the temperature of the gas supplied from the outer region.

The inner torus in model LT deforms itself from the circular shape to the crescent shape, respectively. The deformation of the inner torus takes place due to the growth of the Papaloizou-Pringle instability. Inside the torus, magnetic fields are amplified by the MRI. As the local plasma β approaches $\beta \sim 1$, magnetic energy is suddenly released by magnetic reconnection. Subsequently, the torus returns to the circular shape. When the torus returns to the circular shape, the large mass accretes to the central black hole and the outflow blows from the inner torus. The outflow rate is 1-10% of the mass accretion rate.

Figure 1 shows the spatial distribution of the Fourier amplitude νP_ν of the time variation of the mass accretion rate. Left panel shows the model HT, and right panel is the model LT. Horizontal axis shows the radius and the vertical axis shows the frequency. Here, we assumed the $10M_\odot$ black hole. In model HT, various peaks appear at various radius. On the other hand, in model LT, low-frequency QPOs around 10Hz appear in $5 < \varpi/r_s < 10$, where the inner torus is formed.

Figure 2 shows the Power Spectral Density (PSD) of the time variation of the mass accretion rate averaged in $3 < \varpi/r_s < 29$ and $|z|/r_s < 1$. Black and gray curves show PSD for model LT and model HT, respectively. The PSD for model LT has a broad low-frequency peak around 10Hz. This low-frequency peak corresponds to the oscillation of the inner torus caused by the magnetic activities. The PSD for model HT becomes flat in 1-30 Hz. The slope of the PSD in the model LT is steeper than in the model HT.

4. Summary

We carried out global three-dimensional MHD simulation of the black hole accreton disk. In this paper, we studied the dependence of the structure and the time variation of the black hole accretion flows on the gas temperature supplied from the outer region. In such cool accretion disk, the averaged angular momentum transport rate becomes less than 0.01, although plasma β inside the disk is comparable to that of radiatively inefficient hot accretion flows ($\beta \sim 10$). Since the angular momentum transport becomes inefficient, the inner torus is formed around $4 - 10r_s$. This inner torus deforms itself from circle to crescent, repeatedly. Such deformation takes place due to the growth of a non-axisymmetric instability in geometrically thick tori. As the magnetic energy enhanced in the inner torus by MRI is released by magnetic reconnection, the crescent-shaped inner torus returnes to a weakly magnetized, axisymmetric torus. The PSD of the mass accretion rate has a broad pead around 10Hz. This frequency corresponds to the time scale of the amplification and release of the magnetic energy in the inner torus.

References

Machida et al. 2006, PASJ., 58, 193
Machida and Matsumoto, 2008, PASJ., 59, 613