Magneto-hydrodynamic Simulations of Excitation of Low-Frequency QPOs in Black Hole Candidates

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Abstract

We present the results of global three-dimensional magneto-hydrodynamic simulations of black hole accretion flows. We focus on the excitation mechanism of low frequency quasi-periodic oscillations observed during the state transition of black hole candidates. When a cool gas is supplied, a constant angular momentum inner torus is formed around $4 - 8r_{\rm s}$ where $r_{\rm s}$ is the Schwartzchild radius. This inner torus deforms itself from circle to crescent quasi-periodically. The origin of the torus defomation from circle to crescent is the Papaloizou & Pringle instability. The magnetic energy release by the magnetic reconnection is the reason why the trous deformed to the crescent shape returns to the circle shape. The time interval of these deformation is about 1 day when we assumed a $10^7 M_\odot$ black hole. In this presentation, we show the dependence of numerical results on the gas temperature supplied from the outer region.

Key words: MHD simulations : state transitions — : accretion disks

1. Introduction

Black hole X-ray binaries are suitable for studing accretion disks because they do not have the radiation from the central object. Black hole candidates (BHCs) show transitions between a low/hard state (LHS) and a high/soft state (HSS). LHS is dominated by a hard power-law component and HSS is characterized by the soft black body component. During the transition, BHCs stay in a hard intermediate state. The light curves during LHS show rapid X-ray fluctuations and sometimes show quasi-periodic oscillations (QPOs) in the Fourier Power Spectral Density (PSD). Steady outflows emerge during the LHS. In this state, mass accretes to the black hole as an optically thin, advection dominated accretion flow. The energy spectrum of the hard intermediate state is softer than that in the LHS, but total luminosity is larger than that in the LHS. Low frequency $(1 - 10\text{HZ})$ QPOs are observed in the luminous hard state and in the hard intermediate state. High frequency QPOs (~ 100Hz) are sometimes observed in these states.

These observations indicate that QPOs are associated with the cooling of the disk. By carring out global 3D magneto-hydrodynamic (MHD) simulations including radiative cooling, *Machida et al. (2006)* showed that when the accretion rate exceeds the limit for the onset of the cooling instability, the radiatively inefficient, optically thin disk shows a transition to a magnetically supported, cool, intermediate state. *Oda et al. (2007)* denoted a steady model of the magnetically supported disks and showed that their luminosity can exceed $0.1L_{\rm Edd}$, where $L_{\rm Edd}$ is the Eddington luminosity. When the transition to the cool disk takes place from the outre region, cool gas will be supplied to the inner region.

In this paper, we report the results of global 3D MHD simulatios which produce low-frequency QPOs and discuss their excitation mechanisms.

2. Numerical Method

We solved the resistive MHD equations in a cylindrical coordinate system (ϖ, φ, z) by using a modified Lax–Wendroff scheme with an artificial viscosity. In this calculation, we included the Joule heating term but neglected the radiative cooling term in the energy equation. We assume the anomalous resistivity adopted by solar flare simulations. General relativistic effects are simulated by using the pseudo-Newtonian potential(*Paczynski and Witta 1980*).

The units of length and velocity are the Schwarzschild radius $r_{\rm s}$ and the light speed c, respectively. The unit time is $t_0 = r_{\rm s}c^{-1} = 10^{-4}M/M_\odot$ sec. The unit temperature is given by $T_0 = m_{\rm p}c^2k_{\rm B} = 1.1 \times 10^{13}$ K, where $m_{\rm p}$ is the proton mass and $k_{\rm B}$ is the Boltzmann constant.

The number of grids is $(N_\varpi, N_\varphi, z) = (250, 64, 384)$. The outer boundaries at $\varpi = 132$ and at $|z| = 70$ are free boundaries where waves can be transmitted. We included the full circle ($0 \leq \varpi \leq 2\pi$) in the simulation region, and applied periodic boundary conditions in the azimuthal direction. An absorbing boundary condition is imposed at $r = r_{\rm in} = 2$.

The initial model is a torus threaded by weak azimuthal magnetic fields. The initial plasma β ($\beta \equiv P_{\rm gas}/P_{\rm mag}$) is 100 at $\varpi = \varpi_{\rm b}$. Here, $\varpi_{\rm b}$ is the radius of the pressure maximum of the initial torus and we assumed $\varpi_{\rm b} = 35$. The initial torus has an angular momentum $L \propto \varpi^a$, where $a = 0.46$. The maximum sound speed of the initial torus is $c_{\rm b} = 0.01$. This sound speed corresponds to the cooler gas than the optically thin advection dominated accretin flows. We adopted $\gamma = 5/3$ where γ is the specific heat ratio.

3. Results

Figure 1 shows the snap shot of the density distribution in $\varpi - z$ plane averaged in the azimuthal direction. Mass accretion takes place due to the magnetic turbulence produced by the magneto-rotational instability, then the initial torus deforms to the disk like shape. The averaged angular momentum transport rate is less than $\alpha < 0.01$ and averaged plasma β is about $\beta \sim 10$.

Figure 2 shows the snap shots of the equatorial density distribution averaged in $|z| < 1$. In this cooler disk model, an inner torus is formed around $\varpi \sim 4 - 8r_{\rm s}$. The inner torus is formed because the angular momentum transport rate decreases when the disk cools down. The inner torus deforms itself to a crescent shape due to the growth of the Papaloizou-Pringle instability.

The top pannel of figure 3 plots the time evolution of the ratio of the Joule heating rate to the magnetic energy averaged in $4 < \varpi < 10$, $|z| < 1$, and $0 \leq \varphi \leq 2\pi$. The ratio increases when magnetic energy is released. Bottom pannel of figure 3 shows the time evolution of the amplitude of the non-axisymmetric $m = 1$ mode of the density where m is the mode number in the azimuthal direction. The amplitude of the azimuthal mode is computed by Fourier decomposing the density contrast. The amplitude of $m = 1$ mode anti-correlates with $\eta J^2/\langle B^2/8\pi \rangle$. It indicates that the magnetic energy is released when the $m = 1$ mode disappears. The amplitude of the $m = 1$ mode also correlates with the magnetic pressure and the angular momentum transport rate.

Figure 4 shows the spatial distribution of time variabilities in mass accretion rate νP_ν in $55000 < t < 61000$. Here P_ν is the Fourier power of the time variation of mass accretion rate. Low frequency QPOs around $4 - 8$Hz appear in $5 < \varpi < 10$, where the inner torus is formed.

Figure 5 shows the Powe Spectral Density (PSD) of time variation of the mass accretion rate averaged in $2.5 < \varpi < 10$ and $|z| < 1$. Black and gray curves show PSD for cooler case and hotter case ($c_{\rm b} = 0.03$), respectively. The PSD for the latter model is similar to the results of *Machdia and Matsumoto (2003)*. The PSD for cooler model has a broad low frequency peak around $4 - 8$Hz. This low frequency peak corresponds to the oscillation involving amplification and release of magnetic energy in the inner torus. The PSD in the cooler model has a slope steeper than that in hotter model in $10 < \nu < 30$Hz.

4. Discussion

In this paper, we studied the structure and time variation of the black hole accretion flows when the cooler gas supplied from the outer region. In such models, an inner torus is formed around $\varpi \sim 4 - 8r_{\rm s}$. Such a torus is formed when the angular momentum transport rate is small enough. Since Maxwell stress decreases due to the decrease of magnetic energy, a nearly constant angular momentum torus is formed in the accretion flow. We found that the inner torus deforms itself into a crescent shape due to the growth of the Papoloizou and Pringle instability. Such non-axisymmetric structures enhance the growth of the MRI. As magnetic energy increases, angular momentum transport rate increases and accretion rate also increases. When the magnetic energy accumulated in the disk is released, the disk returns to circular shape. As the magnetic energy released, it accumulattes again. The frequency of this cycle is about $1000t_0$. It creates a low frequency peak around $4 - 8$Hz in the PSD of the mass accretion rate.

Homan et al. (2005) pointed out that during the transition from the LHS to HSS, GX339$-$4 shows a subtransition from a hard intermediate state dominated by power-law X-ray radiation to soft intermediated state dominated by radiation from optically thick disk. They also showed that the low frequency QPOs appear when the X-ray spectrum stays in the hard intermediate state and soft intermediate state and sometimes in LHS.

Homan (2008) also pointed out that the root mean square of the PSD of hard intermediate state when the QPO appears in its PSD is smaller than that of LHS. The rms. of the PSD obtained from numerical simulations also shows the same tendancy in figure 5. In the LHS when the QPO does not appear PSD is wider than the cooler case. Therefore, our model can explain that rms. becomes smaller when the low frequency QPO appears.

References

Homan J. et al. 2005, ApJ, 624, 295

Homan J 2008, MAXI proceedings

Machida M. and Matsumoto R. 2003, ApJ, 585, 429

Machida M., Nakamura K.E., and Matsumoto R. 2006, PASJ, 58, 193

Machida M. and Matsumoto R. 2008, PASJ, 60, 613

Oda et al. 2007, PASJ, 59, 457

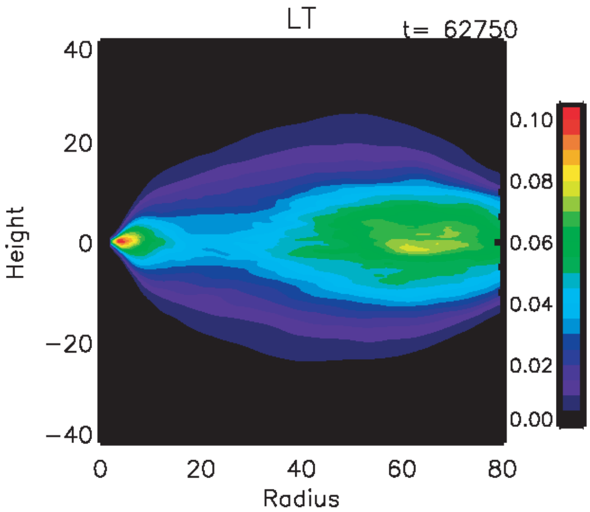

Fig. 1. The snap shot of the density distribution averaged in the azimuthal direction.

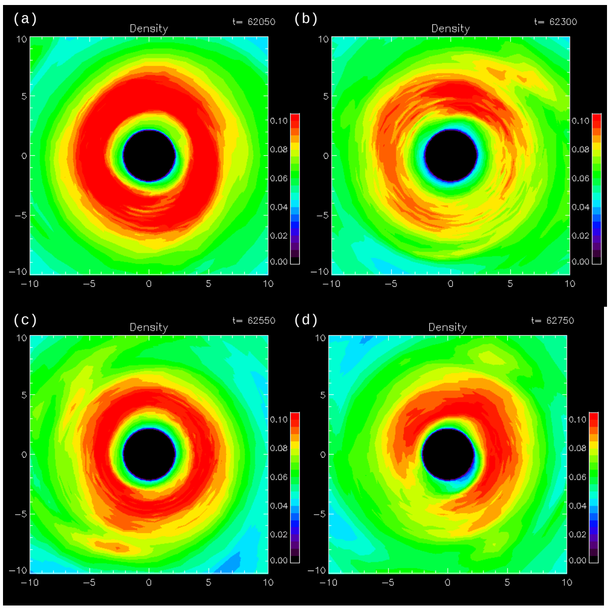

Fig. 2. Snap shots of the density distribution in $\varpi - \varphi$ plane. The time evolution is a,b,c and d.

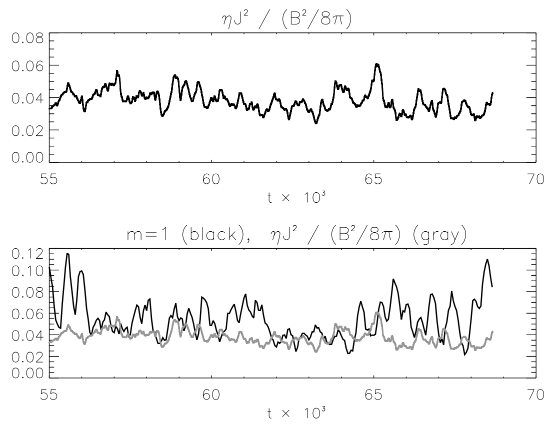

Fig. 3. (top) Time evolution of the ratio of the Joule heating rate to magnetic energy. (bottom) Time evolution of the Fourier amplitude of the non-axisymmetric mode with the azimuthal mode number $m = 1$ computed from the density distribution. Gray curve depicts the same curve as that in the top pannel.

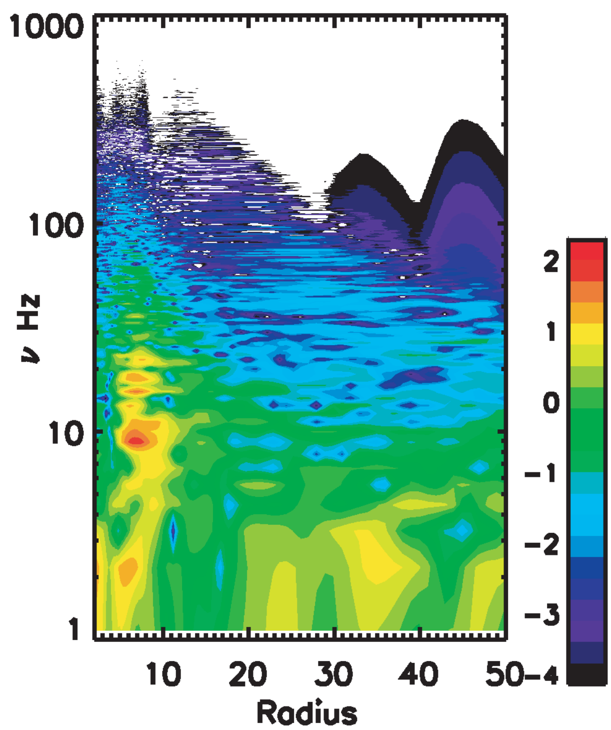

Fig. 4. Radial distribution of the PSD of the time variation of mass accretion rate measured in $55000 < t < 61000$.

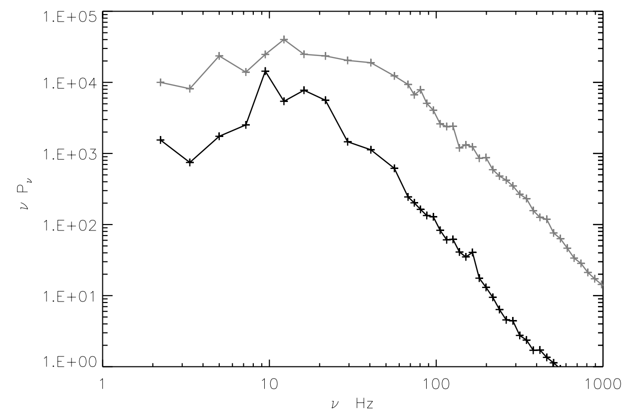

Fig. 5. Power spectrum νP_ν averaged in $2.5 < \varpi < 29$ and $|z| < 1$. Black curve shows the cooler case and gray one shows the hot accretion flow.