# Quasi-Periodic Osicllations and Variable Emissions in Magnetohydrodynamic Accretion Flows

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Abstract

We present our study of oscillations and emissions in three-dimensional (3-D) magnetohydrodynamic (MHD) accretion flows around black holes. It is found that a pair of persistent quasi-periodic oscillations (twin QPOs) is excited at the resonant radius, where the ratio of Keplerian frequency to epicyclic frequency is close to 2:1. The power spectrum density (PSD) shows that the lower peak frequency corresponds to the Keplerian frequency, while the upper peak frequency corresponds to the sum of Keplerian frequency and epicyclic frequency. The results provide the first direct evidence for the excitation of resonant disk oscillation in MHD accretion flows. It is also found that the emergent spectra from radio to gamma-ray of the MHD accretion flows fluctuates in the wide range of frequency and does not always vary coherently.

Key words: accretion, accretion disks — magnetohydrodynamics: MHD — quasi-periodic oscillations — radiation: radiative transfer

## 1. Introduction

Quasi-Periodic X-ray brightness oscillations ranging from 1 mHz to 1 kHz have been observed in some low-mass X-ray binaries. After the discovery of high frequency QPOs (HF-QPOs) whose frequnecy is comparable to the oribital frequency at the innermost stable circular orbit (ISCO), the HF-QPOs are believed to be a footprint of the metric of compact objects such as neutron stars and black holes. Recently, Remillard et al. (2005) pointed out that more than one type of accretion disk can play QPOs and optically thin plasma could be a plausible source of modulated emissions of HF-QPOs. Several models have been proposed by different groups, however, the modualation mechanism of HF-QPOs has been not been settled yet.

Disk oscillations are the most promising mechanism of the HF-QPOs. This is because the disk oscillation model can explain two simultaneous QPOs having a constant ratio of peak frequencies. Recently, magnetohydrodynamic (MHD) simulations have been widely accepted as a standard framework for studying the dynamics of accretion flows, however, the properties of disk oscillations in MHD accretion flows are poorly understood. This is why we motivated to study oscillations and waves in MHD accretion flows. In this proceedings, we introduce our study of the disk oscillations in MHD accretion flows (Kato 2004) and briefly report on the emission properties of the disk oscillations.

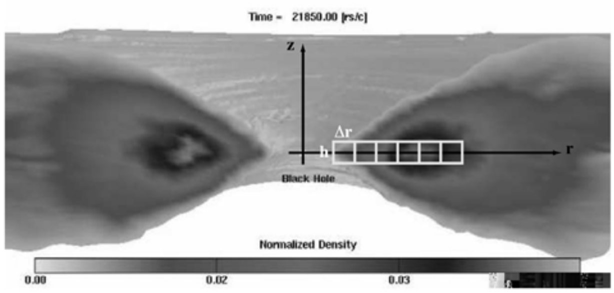


Fig. 1. A perspective view of 3-D MHD accretion flows. Gray-scale indicates the normalized density. A black hole is located at the origin.

## 2. MHD studies on HF-QPOs

The figure 1 shows a snapshot of quasi-steady MHD accretion flows plunging into black holes. We sampled time variation of mass fluxes both in radial and vertical direction at each cells in the equatorial plane ($|z| < h/2 = 5r_s$ where $r_s$ is the Schwartzchild radius). In this study, we assume that emissivity of each cells is proportional to the gravitational energy loss in terms of mass fluxes (see Kato 2004 in detail).

### 2.1. Oscillations and Waves

In the figure 2, radial and vertical oscillations are displayed. The horizontal axis indicates the radius and the vertical axis indicates the time. For a 10 solar mass black hole, sampling is started at 1 sec from the beginning of

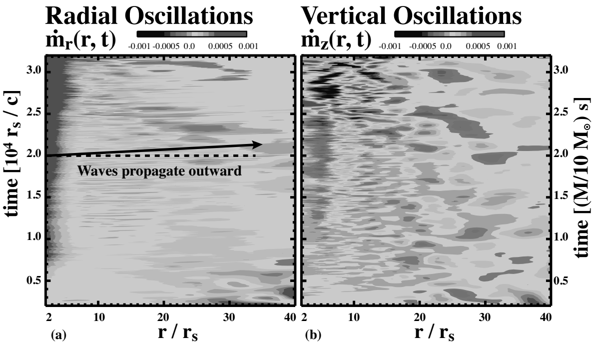


Fig. 2. Radial and vertical oscillations in spact-time diagram. The horizontal axis is the radius and the vertical axis is the time. Gray-scale indicates the mass fluxes at each cells.

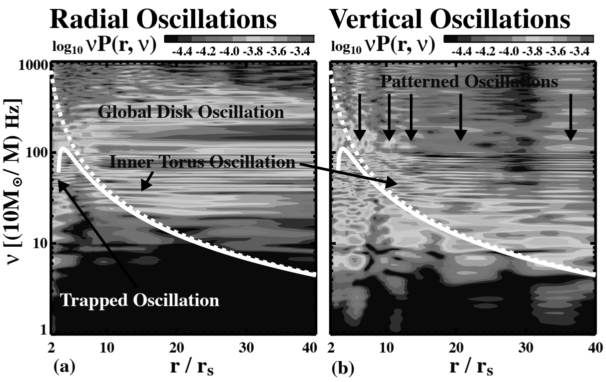


Fig. 3. Power Spectrum Density (PSD) of the radial and the vertical oscillations. The horizontal axis is the radius and the vertical axis is the time. Gray-scale indicates the mass fluxes at each cells.

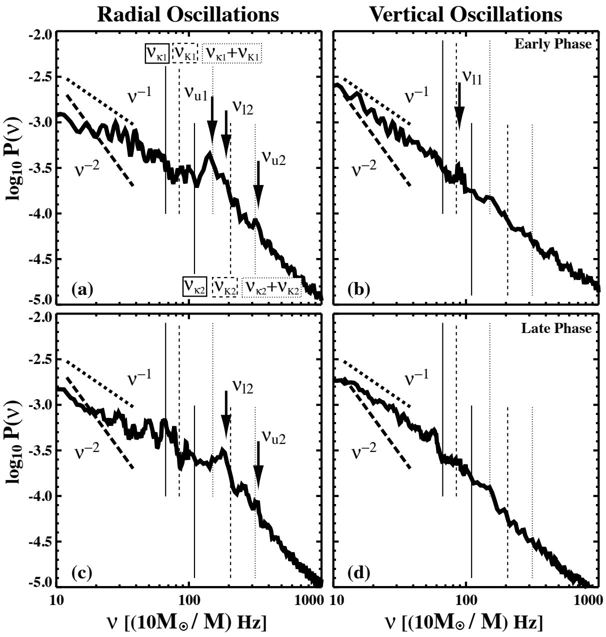


Fig. 4. Integrated PSD of the radial and the vertical oscillation.

the simulation and is ended 3 sec and the sampling duration is 2 sec in total. The first 1 sec is called as the early phase and the last 1 sec is called as the late phase in this study. The mass fluxes are displayed in gray-scale.

## 2.2. Global disk oscillations

The figure 3 shows PSDs of the radial and the vertical oscillations as a function of radius. The power of oscillations is shown by gray-scale. A dashed line and a solid line indicate Keplerian frequency and epicyclic frequency as a function of radius, respectively. In radial oscillations, we found some global oscillations. In vertical oscillations, we found several patterned oscillations. One of them is located at $6r_s$. In addition, we found weak trapped oscillations inside the radius where the epicyclic frequency become maximum and also weak oscillations of inner torus located around $10r_s$.

## 2.3. Twin HF-QPOs

Integrated PSD over the radius is shown in figure 4. We found two twin QPOs. One is transient twin QPOs only in early phase and theother is persistent twin QPOs in both early and late phase of MHD accretion flows.

In twin QPOs in radial oscillations, the lower peak frequency corresponds to the Kepler frequency and the higher peak frequency corresponds to the sum of Keper frequency and epicyclic frequency at the resonant radius where the ratio of Kepler and epicyclic frequency is close to 2 in the Schwartzchild black hole. Radial oscillation is excited at the resonant radius and it propagate the accretion disk globally. We have discovered for the first time resonant global disk oscillations in magnetized accretion disks.

## 2.4. Short Summary

We have found twin QPOs in the integrated PSD of variabilities in the magnetized accretion flows. Frequencies of QPOs corresponds to the resonant frequencies at the resonant radius. These QPOs are likely to be excited at the resonant radius where the ratio of the Kepler frequency and the epicyclic frequency is 2:1. This may be caused by the wave-warp resonance (see S. Kato 2004 in detail; see also Abramowicz 2003, Rebusco 2004). The ratio of resultant upper and lower frequencies of QPOs is close to 3:2 which is consistent with the observed ratio (Remillard et al. 2002).

## 3. Radiation Transfer Calculations

We compute radiation properties of our 3-D MHD simulation data and compare our result with the spectral energy distribution (SED) of the Galactic center source, Sgr A*. For a radiative transfer calculation, there are three parameters, normalization density, black hole mass, and electron temperature. The normalization density is leave as a free parameter in order to fit the observed SED and the electron temperature is estimated by the gas temperature in the MHD simulation. The black hole mass is fixed as $3.6 \times 10^6 M_\odot$ (Eckert et al. 2005). For radiative process, Synchrotron emision/absorption, inverse-Compton scattering, and Bremsstrahlung emission/absorption by thermal electrons (e.g., Narayan & Yi 1995; Manmoto 2000) are taken into consideration in this study.

### 3.1. Emergent SED

In figure 5, we plot SEDs of MHD accretion flows. The emergent SED is consistent with the observed SED of Sgr A* from radio to gamma-ray in quiescent state. Radio band consist of self-absorbed synchrotron emission. From submillimeter to optical band consist of synchrotron self-compton emission. Above X-ray band consist of Bremsstrahlung emission.

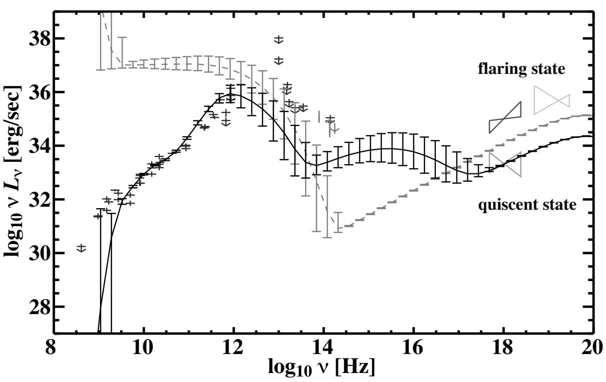


Fig. 5. Spectral Energy Distribution (SED) of MHD accretion flows ranging from radio to gamma-ray. Solid and dashed lines indicate the emergent spectra and the emitted spectra, respectively. Bars indicate the time variation. Cross points and "bow ties" indicate the observed spectra in the Galactic center (Narayan et al. 1998; Eckart et al. 2006; Baganoff 2001; Belandger et al. 2005)

### 3.2. Synthesis Images

We created images of centimeter, submillimeter, and infrared bands by using the ray-tracing calculation displayed in figure 6. We found that the size of a core emission region in the centimeter and the submillimeter bands is about 30 $r_s$ around a black hole. In the infrared band, we found that a disk like emission region extends more than 100 $r_s$. Direction of magnetic vectors in centimeter and submillimeter bands is similar but that of infrared band is different from the others.

### 4. Future Prospects

Radiation transfer studies of MHD data will be a keystone between theory and observation. Intensive timing analysis both on variable emissions in MHD accretion

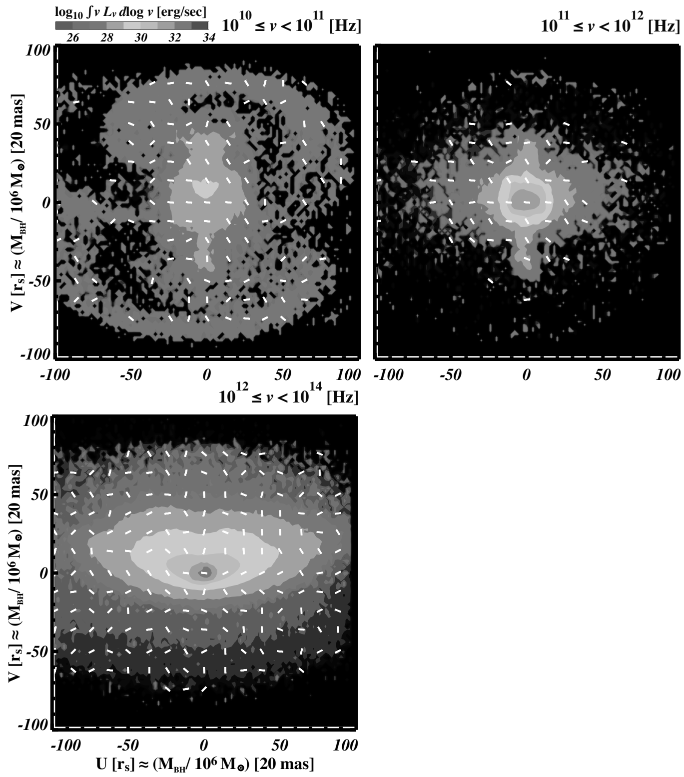


Fig. 6. Synthesis images in centimeter, submillimeter, and infrared bands. White arrows indicate the magnetic vector which is perpendicular to the polarization vector.

flows and on X-ray brightness oscillations in X-ray binaries will provide a crucial information on the origin of QPOs.

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