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High frequency oscillations of a slim disk undergoing a limit-cycle outburst

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ABSTRACT

We numerically investigate thermally unstable accretion discs around non-spinning and fast-spinning black holes. We adopt an additional evolutionary viscosity equation, based on the results of recent MHD simulations, which replaces the standard α-prescription. We find oscillations which arise from the sonic point and propagate outwards. By directly integrating the cooling flux on each radius we obtain light-curves, calculate their PSD, and find a series of harmonics with base frequency very close to the predicted frequency of a p-mode in QPO theory.

Keywords: accretion, accretion disks – gravitation – relativistic processes – stars: black holes – X-rays: bursts

1 INTRODUCTION

High-frequency quasi-periodic oscillations (HFQPOs) have been observed in some black hole (BH) X-ray binaries. They appear only in the "steep power law" state at high luminosities ($L > 0.1\,L_{\text{Edd}}$) and are in range of 40 to 450 Hz. These frequencies are comparable to the orbital frequency of the innermost stable circular orbit (ISCO) of a stellar-mass BH. It is believed that the mechanism behind them are closely related to the dynamics of inner regions of BH accretion disks (see Remillard and McClintock, 2006; Kato et al., 2008; Belloni et al., 2012, for reviews).

In order to study oscillations of thermally unstable accretion disks, we solve their evolution using a non-stationary, 1+1 dimensional, general relativistic spectral code, and implement a new prescription for viscosity, motivated by recent MHD simulations. Our work is similar to Chen and Taam (1995), who used the standard α-prescription, and a comparison between our model and theirs will be given in Section 3.

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2 EVOLUTIONARY VISCOSITY

In our previous paper (Xue et al., 2011), we have described a code and relevant equations for the axisymmetric relativistic accretion flows around spinning black holes. The viscosity in that code is described by the standard α-prescription (Shakura and Sunyaev, 1973). The viscous stress (only $r\phi$-component is non-vanishing) can be written as (The asterisk denotes the standard α-prescription)

$$S^*_{r\phi} = -\frac{\nu \Sigma A^{3/2}\gamma^3}{2r^3 \Delta^{1/2}} \frac{\partial \Omega}{\partial r} \, , \tag{1}$$

$$\nu = \frac{2}{3}\alpha H \sqrt{\frac{p}{\rho}} \, , \tag{2}$$

where Σ, p, ρ and Ω are the mass surface density, total pressure, mass density and rotating angular velocity of accreted gas respectively, and γ, A and Δ are the relativistic factors whose detailed definitions can be found in Xue et al. (2011). This famous prescription has been used extensively since 1973. It is perfectly simple but may not closely accord with actual accretion flows. The MHD shearing box simulation of Hirose et al. (2009) implied that there is certain time-delay between the viscous stress and total pressure. Penna et al. (2013), relying on several relativistic MHD global simulations, pointed out that the parameter α is a function of radius, and is not constant in the inner disk region. Therefore, following Hirose et al. (2009) and Penna et al. (2013), we update the code by adopting an additional time-dependent stress equation instead of the α-prescription. This time-dependent equation can be written as

$$n\tilde{\tau}\frac{\partial S_{r\phi}}{\partial t} = S^*_{r\phi} - S_{r\phi} \, , \tag{3}$$

$$\tilde{\tau} = -\left(\frac{\gamma^2 A \Omega}{r^4}\frac{\partial \ln \Omega}{\partial \ln r}\right)^{-1} \, , \tag{4}$$

where $\tilde{\tau}$ is the typical time-delay (in practice, we scale it up with the n factor in Eq. (3). When $n \to 0$, Eq. (3) implies $S_{r\phi} = S^*_{r\phi}$, which is equivalent to Eq. (1). It means that the α-prescription is a trivial case of Eq. (3).

To mimic the radial dependence of the parameter α observed by Penna et al. (2013), we apply the following α-profile:

$$\alpha = \alpha_0 \left(\frac{1 - 2Mr^{-1} + a^2 r^{-2}}{1 - 3Mr^{-1} + 2aM^{1/2}r^{-3/2}}\right)^6 \, , \tag{5}$$

where M and a are the mass and spin of black hole, respectively. The radial factor, including the exponent 6, was suggested by Penna et al. (2013). Under this profile, α is almost a constant α_0 in outer disc region with large r and increases to higher value radially inwards. We set $\alpha_0 = 0.1$ and fix the mass supplying rate $\dot{M}_\mathrm{S} = 0.06\,\dot{M}_\mathrm{Edd}$ at the outer boundary in this work. These settings are sufficient to make the disc thermally unstable since we observe the limit-cycle outbursts from running code. The impact of viscous time-delay on the thermal instability may be unremarkable since we always observe the similar outbursts on the models with different time-delay parameters n in the range 0 to 4. This confirms the analysis of Lin et al. (2011) and Ciesielski et al. (2012) on this kind of delay. However, we find that this time-delay may determine the appearance of the oscillation in the discs (detailed paper in preparation).

3 RESULTS AND DISCUSSION

In Figure 1 we show the power spectral densities (PSDs) of oscillating light-curves for two typical models (around non-spinning and fast-spinning $\sim 10\,M_{\odot}$ black holes). The fundamental frequency (the lowest frequency of harmonics) is ~ 74.9 Hz for the non-spinning model and ~ 285.6 Hz for the fast-spinning model, which are both close to 71.3 Hz and 300 Hz predicted by the p-mode theory (see below).

The spectrum shows harmonics with frequencies in a regular integer series 1:2:3, . . . The relative strength between harmonics for the fast-spinning model looks much more irregular than the non-spinning one. If there were some background noise in those spectrum of Fig. 1, one might see the losing of some harmonics. For example, in the right panel of Fig. 1, the peak C would be easier to be overwhelmed by noise than peak D. These interesting features are potentially useful for explain the observational QPO pairs. However, direct comparison would require more careful treatment. One should carefully consider the gravitational redshift and ray-bending of the emitted photons. However, for convenience, we only construct the lightcurves by directly integrating the radiation cooling flux at each radius in this work. In order to roughly demonstrate the effects of gravitational red-shift or other blocking effects on radiation emitted from the inner disk region, we show, in Fig. 2, four PSDs made from the light-curves without the radiation contribution from a certain inner cutting region. It is remarkable that the fundamental harmonic (inside the rectangle in all four panels) can not be easily removed from PSDs because of the outward propagation of the oscillation from ISCO. It implies that the measurement of black hole spin with QPO will be very robust even in a case when modulation of the innermost disk is not visible.

Similar oscillations were observed by Chen and Taam (1995) who used the regular viscosity prescription with $S_{r\phi} \propto \alpha p_{\mathrm{gas}}$. Perhaps this difference in the treatment of viscosity leads to the different PSDs of our models and theirs. In our models multiple harmonics of the base frequency are observed.

We argue that the oscillations observed in our models could be the trapped p-modes, which are excited by the sonic-point instability in a transonic accretion flow across ISCO (Kato, 1978; Kato et al., 2008). Kato (1978) and Kato et al. (2008) point out that the sonic-point instability requires large α. The α-profile implemented in our code implies that the effective α in the inner disk region is large enough to trigger the sonic-point instability.

We directly inspect the numerical light-curves and their PSDs obtained from our code. We observe oscillations only in the limit-cycle outburst state ($L \gtrsim 0.2\,L_{\mathrm{Edd}}$) when the inner disk region has switched to slim disk mode. On the contrary, there are no oscillations observed in the limit-cycle quiet state ($L \sim 0.01\,L_{\mathrm{Edd}}$). This is consistent with the QPO observations (Kato et al., 2008), but not with the sonic-point instability theory which does not discriminate between accretion rates. Recently, the shearing box simulation of Hirose et al. (2014) implied that the effective α is enhanced by the vertical convection during the

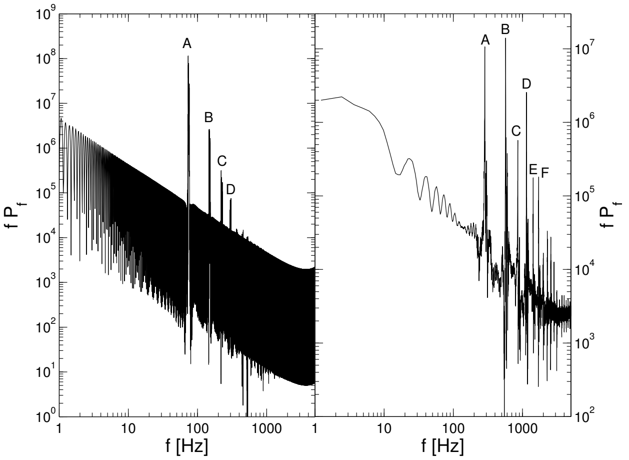

Figure 1. PSDs of light-curves. The left panel is for the disk around a non-spinning black hole ($a_* = 0$, $M = 10\,M_\odot$, $n = 1$). The right panel is for the disk around a fast-spinning black hole ($a_* = 0.947$, $M = 7.02\,M_\odot$, $n = 4$). In left panel, the frequencies of peaks A to D are 74.9 Hz, 149.5 Hz, 224.0 Hz, and 299.2 Hz respectively. In the right panel, the frequencies of peaks A to F are 285.6 Hz, 570.1 Hz, 855.7 Hz, 1140 Hz, 1427 Hz, and 1711 Hz respectively.

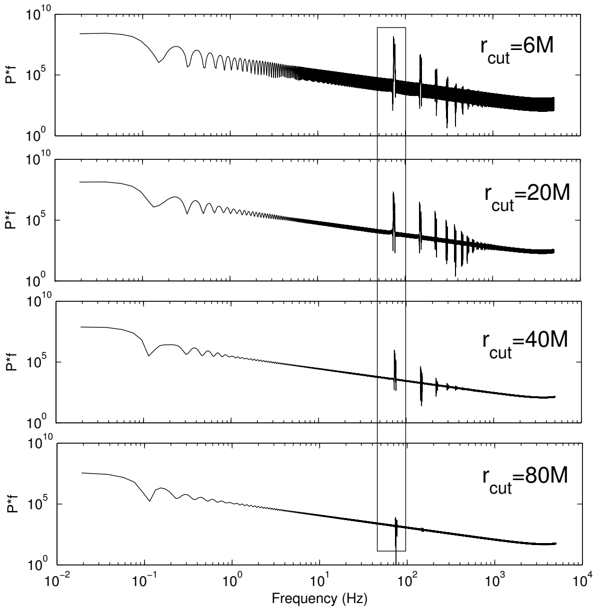

Figure 2. PSDs of light-curves. From upper to lower, the radius $r_{\rm cut}$ of the cut out region increases from 6 M to 80 M for the same non-spinning model.

outburst, which is similar to the conception of Milsom et al. (1994). Thus, large α required by the HFQPO may be caused by the outburst, explaining why HFQPOs are observed only in high luminosity state.

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