Trapped Disk Oscillations and Stable QPOs in Micro-quasars

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Abstract. The observed quasi-periodic oscillations (QPOs) in low-mass X-ray binaries have been suggested to be probably related to the characteristic oscillation modes in the inner part of a relativistic accretion disk. In this paper we study the trapped feature of these oscillation modes by considering the radial perturbations and viscosity effects. We find that the trapped oscillations are amplified significantly when the viscosity parameter increases and the trapped size varies when the radial wavenumber and Mach number change. Our results support that the stable hundred-hertz QPOs and their low fractional rms amplitudes found in two Galactic microquasars may be explained by some trapped non-damping oscillation modes in the inner part of accretion disks around rotating black holes.

Keywords: accretion, accretion disks, black hole physics, X-ray: stars

1. Introduction

In recent years, hundred-hertz QPOs have been observed in several black hole X-ray binaries with *RXTE* satellite. These high-frequency QPOs are probably similar to the kilohertz QPOs observed frequently in a dozen neutron star low-mass X-ray binaries. However, the high frequency QPOs in two Galactic microquasars, GRO J1655-40 and GRS 1915+105, are very stable in frequency at 300 Hz and 67 Hz respectively (Morgan, Remillard & Greiner 1997; Remillard *et al.* 1999). These stable QPOs have also very low fractional rms amplitude ($\sim$ 1%). Theoretical models involving frame-dragging (Cui, Zhang & Chen 1998), diskoseismic g-mode (Nowak *et al.* 1997), and periastro precession (Stella, Vietri & Morsink 1999) have been proposed to explain these stable QPOs. But the origin of them is still uncertain.

Recently Psaltis & Norman (2000; hearafter PN) suggested that the observed QPOs in X-ray binaries may be related to the strong resonances peaked at some characteristic oscillation frequencies in the inner part of accretion disks. However, they introduced a simplified term for angular momentum transfer and did not discuss the damping and growth rates of oscillation modes. It is also important to check if some of these modes can be trapped in the inner disk and if the low fractional rms amplitude of QPOs observed in two microquasars can be explained by the trapped feature of oscillation modes.

2. Non-damping Oscillation Modes in Accretion Disk

The basic equations of a geometrically thin accretion disk are the same as those in PN except that the viscosity term in the angular momentum equation is now expressed as: $N_\phi = (1/\rho r)\partial(\nu\rho r^3 d\Omega/dr)/\partial r$. The viscosity is assumed to be described by the usual α prescription, namely, $\nu = \alpha c_{\rm s} H = \alpha c_{\rm s}^2/\Omega$. Like in PN, we consider the general relativistic effects in an approach to specify the the gravitational potential ψ through the dependences of angular velocity (Ω), radial and vertical epicyclic frequencies (κ and $\Omega_\perp$) on the mass, radius and the spin parameter of the central object. We consider small perturbations to all physical quantities in the form of $Q = Q_0 + \delta Q e^{i(\omega t - kr - m\phi)}$, where k and m are radial and azimuthal wavenumbers. We also assume that the perturbations do not alter the local sound speed and the disk is isothermal in the vertical direction. Under the local approximation $kr >> 1$, we can obtain four perturbed equations and derive the dispersion relation as

$$\bar\sigma^4 + \alpha\epsilon^2\bar\sigma^3 + (\bar\kappa^2 + \epsilon^2 + n\bar\Omega_\perp^2)\bar\sigma^2 - \epsilon[m\frac{H}{r}(\frac{\bar\kappa^2}{2} - 2) + 2\alpha\epsilon(\frac{\bar\kappa^2}{2} - 2) - \alpha\epsilon^3 - n\epsilon\bar\Omega_\perp^2]\bar\sigma + n\bar\kappa^2\bar\Omega_\perp^2 = 0. \quad (1)$$

Here we have defined $\bar\sigma = i(\omega - ku_r - m\Omega)/\Omega$, $\bar\kappa = \kappa/\Omega$, $\bar\Omega_\perp = \Omega_\perp/\Omega$, and $\epsilon = kH$. The value of n represents the number of nodes of the oscillations in the vertical direction.

By solving the dispersion relation (1), we found that the characteristic frequencies of oscillation modes depend on the radial wavenumber and radius significantly but are nearly independent of the viscosity. However, the growth (or damping) rates of these modes depend strongly on the viscosity. According to their non-damping feature, we found that the most possible oscillation modes in the disk are the acoustic modes with approximate frequencies of $ku_r \pm \sqrt{\kappa^2 + k^2 c_{\rm s}^2}$ (in the case of $m = 0$ and $n = 0$) and $ku_r + \Omega \pm \sqrt{\kappa^2 + k^2 c_{\rm s}^2}$ (in the case of $m = 1$ and $n = 0$), neutral modes with frequency of ku_r (in the case of $m = 0$ and $n = 0$) and $ku_r + \Omega$ (in the case of $m = 1$ and $n = 0$), and the corrugation modes with approximate frequencies of $ku_r + \Omega \pm \Omega_\perp$ (in the case of $m = 1$ and $n = 1$). In Figure 1 we show the dependences of oscillation frequencies of all non-damping modes on the disk radius and black hole spin parameters. Note that the lower-frequency acoustic modes and the lower-frequency corrugation mode are trapped in the inner part of

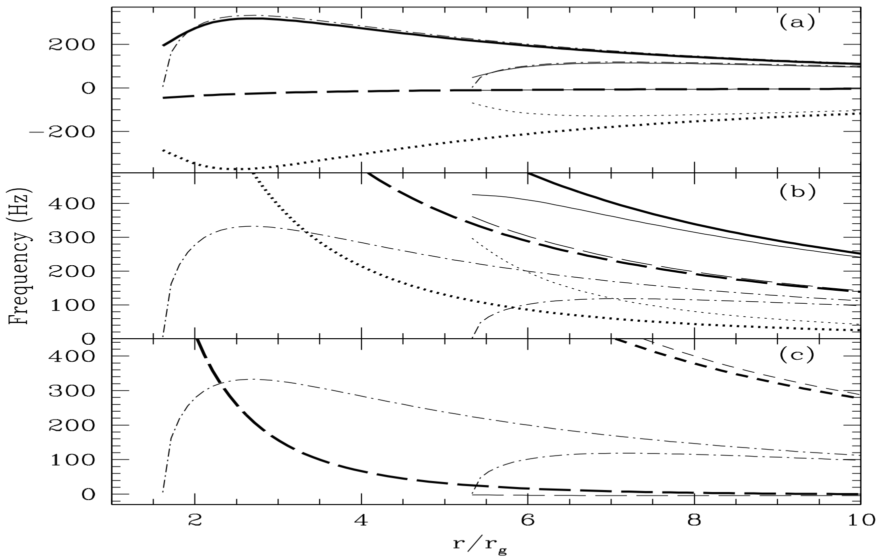

Figure 1. Oscillation frequencies of non-damping modes when $kH = 0.1$ and $|u_r|/c_s = 0.3$. The weighted and light lines represent the cases with black hole spin parameter $a_* = 0.98$ and 0.2. The panel (a), (b) and (c) correspond to (m, n)=(0, 0), (1, 0) and (1,1). In (a) and (b) the solid, dotted and dashed lines represent two acoustic modes and the neutral mode. In (c) the long and short dashed lines represent two corrugation modes. The dot-dashed lines show the radial epicyclic frequencies. The black hole mass was taken to be $7M_\odot$and r_g was defined as GM/c^2.

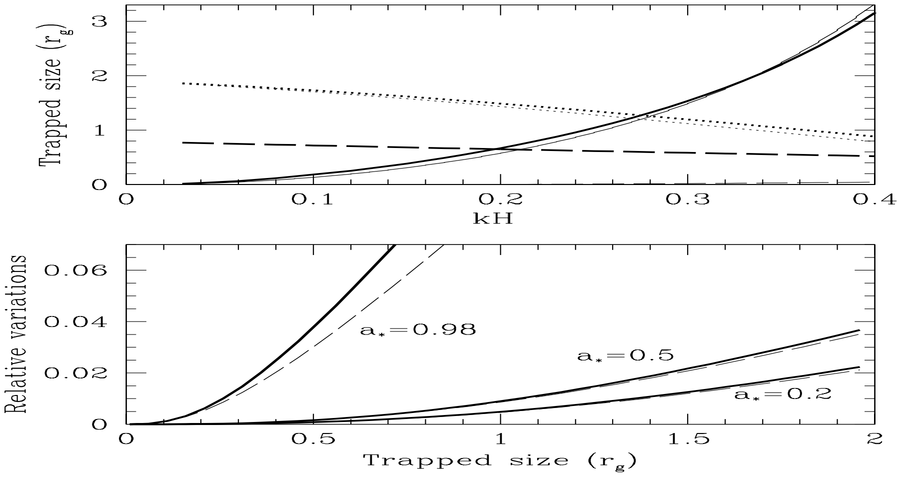

Figure 2. Upper panel: Trapped sizes of three oscillation modes. The solid, dotted and dashed lines represent the lower-frequency acoustic modes in the cases of (m, n) =(0,0) and (1,0), and the lower-frequency corrugation mode in the case of (m, n)=(1,1). The weighted and light lines correspond to the cases with $a_* = 0.98$ and 0.2. Lower panel: Relative variations caused by the trapped oscillations. The solid and dashed lines correspond to the cases with accretion rate of $10^{17} g/s$ and $10^{18} g/s$.

accretion disks since $\omega^2 > \kappa^2$. The trapped sizes of these modes depend significantly on the radial wavenumber, Mach number and black hole spin parameter. The relative luminosity variations caused by the oscillations in the trapped area may be estimated using the expression of local flux emitted from a relativistic accretion disk. These relative variations may be comparable to the observed fractional rms magnitudes if the X-ray luminosity variations are caused by the disk oscillations in the trapped area. In Figure 2 we show the trapped sizes of the oscillation modes and the relative luminosity variations.

3. Conclusion

RXTE observations on GRO J1655-40 have shown 300 Hz QPOs with $\sim 1\%$ rms magnitude. If this stable QPO originates from the trapped disk oscillations, from Figures 1 and 2 we see that it may be explained by either the lower-frequency acoustic mode in the case of $m = 1$ and $n = 0$ or the lower-frequency corrugation mode in the case of $m = n = 1$ and $a_* \sim 0.9$. However, the rapidly spinning black hole is more favored to explain the high QPO frequency. The unambiguous determinations of the inner disk radius and the black hole spin are still needed to confirm this explanation. Further studies on the origin of low-frequency QPOs and their correlation with high-frequency QPOs, as well as the correlation between spectral and temporal properties, will help us to understand more clearly the origin of stable QPOs in microquasars.

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