High Frequency QPOs in Black Holes and Neutron Stars

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Many compact X-ray binaries that contain a black hole or a neutron star exhibit quasi-periodic variability of the X-ray flux in the kHz frequency range. These are the so called kHz QPOs. We suggest that these variations of flux may be caused by axisymmetric perturbations of the inner accretion disk. Two mechanisms of X-ray modulation are known for such perturbations, and are presented here.

1. Twin-peak QPOs

The luminosity of many accreting black holes in transient binaries, and of persistent neutron-star sources in low-mass X-ray binaries is modulated at two different, but related, $\sim$kHz frequencies (for a review see van der Klis [1]). In black holes these frequencies go up to 450 Hz, and are lower than in neutron-stars (up to 1200 Hz). This (rough) inverse proportion of frequency to mass suggests a general-relativistic origin of the phenomenon. Indeed, McClintock and Remillard [2] find that in the three black-hole sources that have two kHz QPOs *and* a known mass, the scaling of frequency is consistent with a $1/M$ dependence.

2. Resonant disk oscillations

The accretion disk is a body of fluid nearly in hydrostatic equilibrium, and its vibrational modes in general relativity have been extensively discussed [3,4]. Several promising non-axisymmetric modes have been identified. However, in the linear regime the results do not fully correspond to the observed properties of the kHz QPOs.

We have previously pointed out that in black hole sources the two frequencies are in a 3:2 ratio [5,6]. McClintock and Remillard [2] have identified four sources in which two kHz QPOs are known, for all four the frequency ratio is 3:2. In neutron star systems, the frequency ratio varies, but in some sources the ratio does cluster about the value 3:2 [7]. The 3:2 ratio can be understood as the result of an internal resonance in an accretion disk placed in a strong gravitational field, e.g., in the Kerr metric [6,8,9,10,11,12].

In black holes the frequencies are fixed, in neutron stars the twin QPOs drift in frequency. The difference can be ascribed to perturbations of the accretion disk by the spinning neutron star. Resonant response of the accretion disk to a fixed perturbing frequency has been investigated in a number of papers, e.g., [13,14,15].

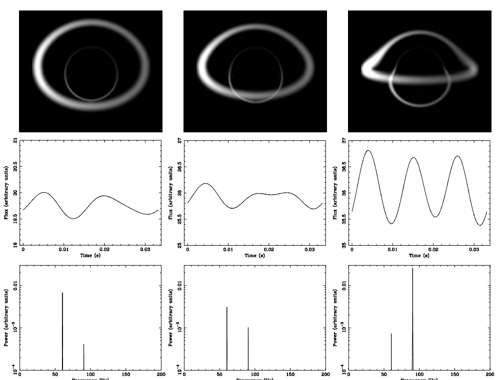

Figure 1: A gravitationally lensed picture of an axi-symmetric, oscillating torus at three different inclinations to the line of sight (top row), the corresponding light curves (middle row) and their power spectra (bottom row). The figure is from Bursa et al. 2004 [16].

3. Modulation of lightcurve

We note that the simplest modes of the accretion disk are axisymmetric. Consider an axisymmetric $m = 0$ vertical motion of the disk. For black holes this will modulate the X-rays by the mechanism of light bending, i.e., variable gravitational lensing at the source, as has been found by Bursa et al. [16], see Fig. 1.

The corresponding calculation for neutron stars has not yet been carried out, however in that case another mechanism of X-ray modulation is possible. If the mass accretion rate is modulated, when the accreting fluid hits the stellar surface the resulting X-ray emission will also be modulated, as pointed out by Paczyński [17].

In neutron stars, as is black holes, the structure of the inner edge of the disk may be determined by effects of strong gravity [18]. The fluid accreting onto the central black hole flows through a nozzle formed by by a self-intersection of one equipotential surface

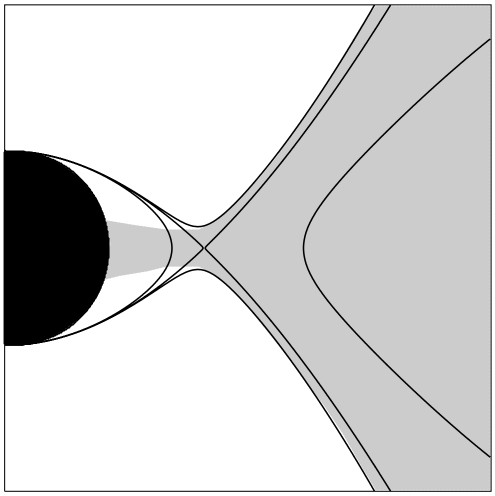

Figure 2: Vertical motion of the inner accretion disk modulates the rate of mass flow through this nozzle (vertical slice through the inner disk is shown).

[19], and this should remain true also for a sufficiently compact neutron star. We have computed the flow rate of fluid through the inner nozzle of the accretion disk, illustrated in Fig. 2, under the assumption of axisymmmetric harmonic vertical displacement of the body of the disk relative to the nozzle. We find that in a disk of height H, the accretion rate varies as square of amplitude, z, of vertical motion in the nozzle

$$\Delta\dot{M}/\dot{M} \propto (\Delta z/H)^2.$$

This follows already from the reflection symmetry of the gravitational potential, but we have performed a detailed calculation to obtain the result. The numerical coefficient will be presented elsewhere.

Acknowledgments

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