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A possible link between kHz quasi-periodic oscillations and the magnetospheric boundary

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Abstract. The quasi-periodic oscillations (QPOs) observed with a 200-1300 Hz frequency range in the X-ray power spectra of low mass X-ray binaries (LMXBs) might be considered as one of the observational clues to the physics at the innermost regions of accretion disks around neutron stars. In a neutron star LMXB, the magnetospheric boundary is likely to be close to the surface of the neutron star because of its presumably weak magnetic dipole field. The kHz QPOs can therefore be interpreted as the modulation of X-ray emission with smallest timescales associated with the dynamics of accreting disk matter at the magnetospheric boundary. As a result of magnetosphere-disk interaction we expect the rotational dynamics of the disk matter in the boundary region to be characterized by either sub-Keplerian or super-Keplerian flow depending on the fastness of the neutron star. We summarize our current understanding of the kHz QPO frequency correlations in terms of the oscillatory modes amplified in the magnetic boundary region and discuss the future prospects related to the possible link between kHz QPOs and the rotational dynamics at the magnetospheric boundary.

1 Introduction

The mass transfer from the normal star onto the compact object in both the neutron star and black hole low mass X-ray binaries (LMXBs) is generally realized via an accretion disk. The release of gravitational energy due to accretion is the main source of high-energy emission from these sources. It is therefore not surprising to observe X-ray variability properties such as broad noise components and quasi-periodic oscillations (QPOs) that are common to both neutron stars and black holes. The existence of similar tight correlations of low- and high-frequency features in the power spectra of both neutron stars and black holes [10, 17] might indicate that QPO production mechanism cannot be directly related to the nature of the compact object [15]. Any difference regarding QPO phenomenology between these two types of sources might originate from different boundary conditions on the accretion disk.

Twin high-frequency QPOs were observed in the kHz range for neutron stars and hectoHz range for black holes [11, 15]. These oscillations are of special interest as they may directly be related to the smallest timescales of accretion flow near the compact object. In addition to kHz QPOs, strong pulsations were observed during X-ray bursts from some of the neutron stars in LMXBs [15]. These millisecond pulsations are also known as burst oscillations with frequency ν_{b}. The first accreting

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millisecond pulsars were discovered in LMXBs with neutron star spin frequency ν_{s} being close to burst oscillation frequency ν_{b} which was also observed in these sources [2, 18]. Burst oscillation frequency was known to be almost stable from one burst to another in a given source [14]. The fact that $\nu_{\mathrm{s}} \approx \nu_{\mathrm{b}}$ at least for a few ms pulsars and that ν_{b} remains almost constant throughout the burst history led to the interpretation of $\nu_{\mathrm{b}} \simeq \nu_{\mathrm{s}}$ for all other neutron stars with burst oscillations in LMXBs.

In neutron star LMXBs, QPO frequencies correlate with the X-ray luminosity of the source [15]. High-frequency QPOs usually appear in pairs as ν_1 and ν_2 for the lower and upper kHz QPO frequencies, respectively ($\nu_2 > \nu_1$). The frequencies of twin kHz QPOs covers $[\nu_1, \nu_2] \approx [200 - 1300]$ Hz range. There is no specific ratio between ν_1 and ν_2 unlike hectoHz QPO pairs in black holes. As it has been revealed by early observations, peak separation frequency $\Delta\nu = \nu_2 - \nu_1$ was close to the burst oscillation frequency ν_{b} or the spin frequency ν_{s} of the neutron star and this fact led to the sonic-point beat frequency model of kHz QPOs [9]. Succeeding observations, however, have suggested for some other sources, particularly for neutron stars with spin frequencies greater than $\sim$ 400 Hz that $\Delta\nu$ is close to half of ν_{b} (or ν_{s}) which is in contradiction with the earliest model of kHz QPOs [15, 18]. Moreover, the analysis of observational data has shown that peak separation frequency $\Delta\nu$ is not constant for a source at all; indeed it decreases as both ν_1 and ν_2 increase [15]. This has motivated the rise of new theoretical interpretations of high frequency QPOs such as relativistic precession model [12, 13] and boundary region model [1, 5]. Early analysis of observations has indicated the possible existence of two seemingly distinct classes of neutron stars in LMXBs: "slow rotators" with $\nu_{\mathrm{s}} < 400$ Hz have $\Delta\nu \approx \nu_{\mathrm{b}} \simeq \nu_{\mathrm{s}}$ and "fast rotators" with $\nu_{\mathrm{s}} \geq 400$ Hz have $\Delta\nu \approx \nu_{\mathrm{b}}/2 \simeq \nu_{\mathrm{s}}/2$ [16]. Recent analysis of all available data has however suggested a more continuous distribution of sources between $\Delta\nu \simeq \nu_{\mathrm{s}}$ and $\Delta\nu \simeq \nu_{\mathrm{s}}/2$ [8]. Almost for half of all sources $\Delta\nu$ deviates from either ν_{s} or $\nu_{\mathrm{s}}/2$. Peak separation frequency takes values between $\Delta\nu > \nu_{\mathrm{s}}$ and $\Delta\nu < \nu_{\mathrm{s}}/2$ as ν_{s} increases over the distribution of sources while $\Delta\nu$ decreases for each source as ν_1 and ν_2 increase [8].

In black hole LMXBs, high-frequency QPOs are relatively weak features with low quality factors as compared to kHz QPOs from neutron stars. For a few black hole sources that exhibit twin high-frequency QPOs, the frequency ratio of the upper hectoHz QPO to the lower one is $\sim$ 1.5 whereas there seems to be no specific ratio at all for twin kHz QPOs from neutron stars. Differences between black hole and neutron star QPO properties can be understood within a single model with different boundary conditions in the innermost region of accretion disk around the compact object [3]. While the radius of the innermost stable circular orbit (ISCO) determines the size of the inner disk around a black hole, the magnetospheric boundary might be the appropriate boundary condition for the inner disk around a neutron star. In Section 2, we discuss the implications of the boundary region model on the frequency correlations of kHz QPOs from neutron star LMXBs. In Section 3, we summarize our current interpretation of kHz QPOs and present our conclusions.

2 High-frequency quasi-periodic oscillations in the boundary region

Boundary region model (BRM) has been proposed to account for the high-frequency QPOs observed in the X-ray power spectra of neutron star LMXBs [1, 5]. The likely origin of high-frequency QPOs, according to recently developed BRM, is the innermost region of accretion disk around the compact object. Most probably high-frequency QPOs correspond to variabilities in accretion flow with smallest timescales. In the presence of a non-Keplerian boundary region at the magnetospheric boundary [4], the degeneracy between radial epicyclic frequency κ and orbital frequency Ω is removed even in the non-relativistic regime and κ becomes the highest dynamical frequency in the inner disk if the boundary region is sub-Keplerian [1]. For neutron stars in LMXBs, the magnetospheric boundary is likely to be close to the surface of the neutron star because of its presumably weak magnetic dipole field.

Any hydrodynamical or magnetohydrodynamical boundary region near the innermost disk radius can potentially harbor the very high-frequency QPOs [5]. For black holes in LMXBs, the relativistic inner disk region near the radius of ISCO might be responsible for the origin of twin hectoHz QPOs [3].

The stability of accretion disks with respect to axisymmetric and non-axisymmetric perturbations in the long wavelength limit has been studied and applied to inner boundary regions of viscous accretion disks to account for the phenomenology of kHz QPOs [5]. This analysis has shown that high-frequency global modes of free oscillations can be excited at a particular radius in the disk with positive growth rates through the dynamical effect of viscosity only if the timescale for radial accretion is finite. Moreover, the frequency bands and growth rates of these modes strongly depend on the global hydrodynamic parameters that define the steady or equilibrium state of the accretion disk [5]. The radial variation of long-wavelength time-dependent perturbations is negligible as compared to that of any time-independent or steady quantity in a boundary region. Any change in the frequency and growth rate of a high-frequency mode is therefore determined by the change in the hydrodynamic parameters that describe the structure of the inner transition zone [5].

As a result of magnetosphere-disk interaction, the matter in the inner disk can be brought into corotation with the neutron star in a boundary region where orbital frequencies deviate from Keplerian test-particle frequencies due to action of viscous and magnetic stresses. The steady-state equation for the angular momentum balance among the material, viscous, and magnetic stresses in a geometrically thin disk with a mass inflow rate $\dot{M}$ can be written as

$$\frac{d}{dr}\left(\dot{M}r^2\Omega + 2\pi\nu\Sigma r^3\frac{d\Omega}{dr}\right) = -r^2 B_\phi B_z, \tag{1}$$

where B_ϕ and B_z are the toroidal and poloidal components of the large-scale magnetic field of stellar origin at the surface of the disk. In equation (1), the origin of B_ϕ is the field-line twisting due to shear between the magnetosphere of the neutron star and the matter in the accretion disk rotating with different rates [4, 6, 7]. The angular velocity Ω of the matter in the disk, except innermost regions, is almost Keplerian, i.e., $\Omega(r) \simeq \Omega_{\rm K}(r) = (GM_*/r^3)^{1/2}$ with M_* being the mass of the neutron star. How fast the neutron star rotates with respect to the Keplerian rate at the innermost disk radius $r_{\rm in}$ is measured by the fastness parameter

$$\omega_* \equiv \frac{\Omega_*}{\Omega_{\rm K}(r_{\rm in})} = \left(\frac{r_{\rm in}}{r_{\rm co}}\right)^{3/2}. \tag{2}$$

The relation between the corotation radius $r_{\rm co}$ in the disk and the spin angular frequency Ω_* of the neutron star is given by $\Omega_* = \Omega_{\rm K}(r_{\rm co})$.

A neutron star is considered as a *slow rotator* if $\Omega_* < \Omega_{\rm K}(r_{\rm in})$, i.e., if $\omega_* < 1$ [5]. Note from equation (2) that $r_{\rm in} < r_{\rm co}$ for a *slow rotator*. For the conservation of angular momentum (equation 1) to be satisfied according to the boundary conditions $\Omega(r_{\rm in}) = \Omega_* < \Omega_{\rm K}(r_{\rm in})$ at the innermost disk radius and $\Omega(r) \simeq \Omega_{\rm K}(r)$ for the outer disk radii $r \geq r_{\rm co}$, the accretion of matter onto the neutron star must be realized through a sub-Keplerian transition zone in the inner disk. The solution of equation (1) for $\Omega(r)$ and the structure of the corresponding boundary region have been obtained together with the self-consistent prescription for the dynamical viscosity $\nu\Sigma$ in a disk threaded by the dipolar magnetic field of a neutron star [4]. The application of the stability analysis to such a boundary region has revealed that the fastest growing modes have frequency bands around $\kappa \pm \Omega$ and κ throughout the sub-Keplerian inner disk and that the highest growth rates are realized near the radius where Ω attains its maximum value $\Omega_{\rm max}$ [5]. The separation between successive frequency bands of the modes such as $\kappa + \Omega$ and κ or κ and $\kappa - \Omega$ is always close to Ω. In a sub-Keplerian boundary region around a *slow rotator*, the separation between consecutive mode frequencies can be estimated as $\Delta\nu \approx \Omega_{\rm max}/2\pi \simeq [1.17-1.27]\nu_{\rm s}$

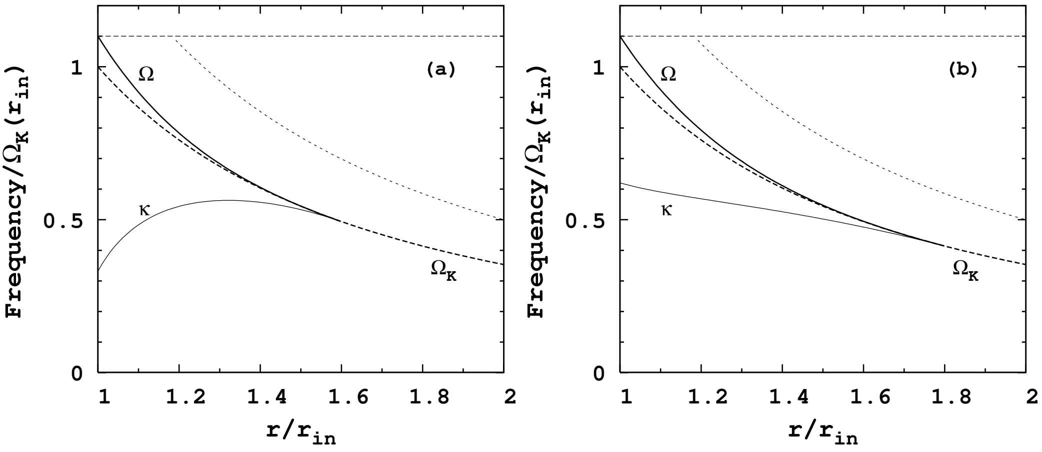

Figure 1. Characteristic frequencies in a super-Keplerian boundary region of a disk around a neutron star of fastness $\omega_* = 1.1$ (dashed horizontal line) together with escape velocity limit (dotted curve)

at the radius where Ω is maximum and as $\Delta\nu \approx \Omega_*/2\pi \simeq \nu_s$ at the innermost disk radius for all typical transition zones that have been discussed so far [4, 5]. These model estimations are in agreement with the observed distribution of slowly rotating sources with $\nu_s < 400$ Hz among others [8].

Unlike slow rotators, the peak separation frequency $\Delta\nu$ for the neutron star sources with $\nu_s > 400$ Hz is always $\lesssim \nu_s/2$. As compared to a slowly rotating neutron star, the difference in the relation between $\Delta\nu$ and ν_s for a *fast rotator* might arise from the peculiar characteristic of rotational dynamics in the inner regions of accretion disk around the neutron star. A neutron star can be depicted as a *fast rotator* if $\Omega_* > \Omega_K(r_{in})$, i.e., if $\omega_* > 1$ [5]. Note from equation (2) that $r_{in} > r_{co}$ for a *fast rotator*. For the angular momentum balance (equation 1) to be satisfied according to the boundary conditions $\Omega(r_{in}) = \Omega_* > \Omega_K(r_{in})$ at the innermost disk radius and $\Omega(r) \simeq \Omega_K(r)$ for the outer disk radii $r \geq r_m$, we expect the rotation of the accretion flow in the transition zone to be super-Keplerian for the matter in the inner disk to overcome the centrifugal barrier and accrete onto the neutron star. For the outer radii beyond the critical radius r_m in the accretion disk, the dynamical effect of magnetic stresses on the rotation of the disk matter is negligible. For the disk radii $r < r_m$, both magnetic and viscous stresses lead to deviation of angular velocity Ω of the matter in the inner disk from its Keplerian value (equation 1). The rotation rate of the magnetosphere for a *fast rotator* is higher than the rotation rate of the disk matter. The efficient angular momentum transfer from the magnetosphere of the neutron star to the inner disk forces the neutron star to spin down while speeding up the rotation of the matter in the inner disk. In order for the neutron star to accrete the disk matter instead of flinging it as a propeller, a super-Keplerian boundary region with $\Omega_K \leq \Omega \leq \sqrt{2}\Omega_K$ is formed in the inner disk ($r_{in} \leq r \leq r_m$). Here, the escape velocity determines the upper limit for the orbital velocity. The fastness parameter cannot have arbitrarily large values for a *fast rotator* in the accretion regime, i.e., the range of interest is given by $1 \leq \omega_* \leq \sqrt{2}$. In figure 1, we illustrate profiles of characteristic frequencies in a typical super-Keplerian boundary region of a disk around a neutron star of fastness $\omega_* = 1.1$. Note that $r_m = 1.6 r_{in}$ in figure 1(a) and $r_m = 1.8 r_{in}$ in figure 1(b). The degeneracy between the radial epicyclic frequency κ and orbital frequency Ω disappears as the orbital frequency Ω begins to deviate from Ω_K at $r = r_m$ (figure 1). Apart from relativistic effects, the degeneracy between κ and Ω is also removed in a sub-Keplerian boundary region [1, 5]. The main difference, however, is that

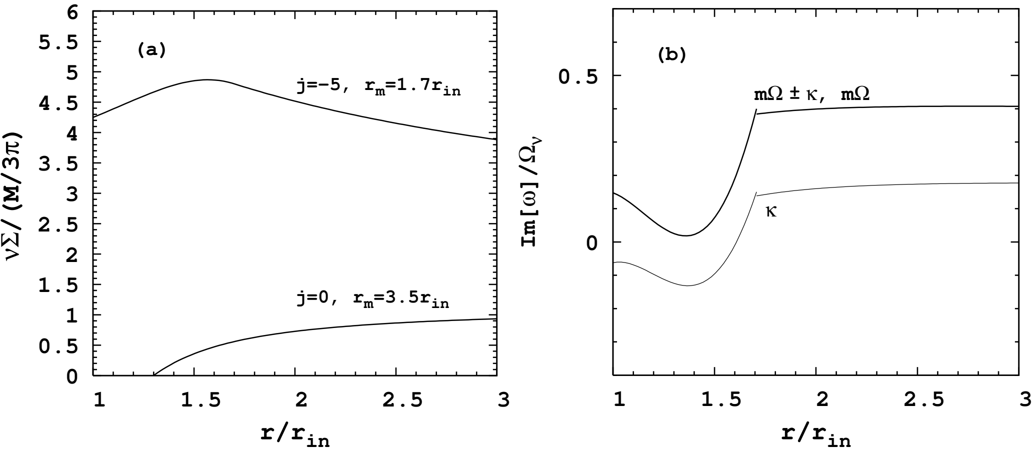

Figure 2. Profiles of dynamical viscosity $\nu\Sigma$ for different values of the dimensionless torque j on the neutron star and the critical radius r_{m} (panel (a)) and growth rates of global modes of free oscillations with different frequency bands in the super-Keplerian boundary region with $r_{\mathrm{m}} = 1.7 r_{\mathrm{in}}$ and $j = -5$ (panel (b))

κ becomes smaller than Ω in a super-Keplerian boundary region whereas it is greater than Ω if the boundary region is sub-Keplerian.

To have a physically plausible super-Keplerian transition region (figure 1), κ must be real and $\nu\Sigma > 0$ must be satisfied throughout the disk radii $r \geq r_{\mathrm{in}}$. While the first condition is necessary for disk orbits to be rotationally stable, the second one guarantees the existence of a possible viscous flow in the accretion disk. In figure 2(a), we present two different solutions of equation (1) for the dynamical viscosity $\nu\Sigma$ as functions of both the dimensionless torque j acting on the neutron star and the critical radius r_{m} where Ω starts to exceed Ω_{K}. For both solutions (solid curves in figure 2(a)), the fastness is $\omega_* = 1.1$. The dimensionless torque j is the net torque acting on the neutron star in units of $\dot{M}\sqrt{GM_* r_{\mathrm{in}}}$. As a result of the interaction of its magnetosphere with the disk, the neutron star may either spin up ($j > 0$) or spin down ($j < 0$). Note that the super-Keplerian boundary regions for sufficiently high values of j and r_{m} are not physically realizable as $\nu\Sigma$ becomes negative at certain disk radii $r \geq r_{\mathrm{in}}$ as shown in figure 2(a). The physically acceptable profile of dynamical viscosity in figure 2(a) corresponds to a super-Keplerian boundary region with $r_{\mathrm{m}} = 1.7 r_{\mathrm{in}}$ for a spinning-down neutron star with $j = -5$. In figure 2(b), we display the growth rates of global modes of free oscillations with different frequency bands in the super-Keplerian boundary region with physically acceptable dynamical viscosity, i.e., with $r_{\mathrm{m}} = 1.7 r_{\mathrm{in}}$ and $j = -5$. The growth rates of the modes in figure 2(b) are obtained in the limit of small hydrodynamic corrections [5]. As shown in figure 2(b), the non-axisymmetric modes with frequencies $m\Omega \pm \kappa$ and $m\Omega$ grow while the axisymmetric mode with frequency κ decays in amplitude for $r < r_{\mathrm{m}}$. The difference frequency between two successive bands of the growing modes is κ. In a super-Keplerian boundary region around a *fast rotator*, the separation between consecutive mode frequencies at the innermost disk radius can be estimated as $\Delta\nu \approx \kappa/2\pi \lesssim 0.5\nu_{\mathrm{s}}$ (figure 1). This is in accordance with the peak separation frequency of twin kHz QPOs from relatively fast rotating neutron stars in LMXBs [8, 16].

3 Summary and conclusions

The recently developed analysis of global hydrodynamic modes has been applied to magnetospheric boundary regions with sub-Keplerian flows to improve our current understanding of kHz QPO frequency correlations [5]. The formation of a sub-Keplerian region near the magnetospheric boundary is possible if the neutron star is a *slow rotator* with fastness $\omega_* < 1$. The global modes with frequency bands around $\kappa \pm \Omega$ and κ grow in amplitude throughout the sub-Keplerian zone in the inner disk around a *slow rotator*. The frequency difference between two successive bands of growing modes and its relation with the frequency of either of these two bands are in agreement with the observed correlations of kHz QPO frequencies. The accretion of matter from the inner disk onto the neutron star as a *fast rotator* with $\omega_* > 1$ can be possible if a super-Keplerian region is formed near the magnetospheric boundary under appropriate conditions. The preliminary analysis in the limit of small hydrodynamic corrections has revealed that the modes with frequencies $m\Omega \pm \kappa$ and $m\Omega$ grow in amplitude throughout the super-Keplerian zone in the inner disk around a *fast rotator*. The difference frequency between two consecutive bands of growing modes is determined by κ, which indeed is always less than the rotation rate of the neutron star, throughout the super-Keplerian boundary region. This behavior is also in reconciliation with the peak separation frequency of twin kHz QPOs observed in the power spectra of sufficiently fast rotating neutron stars with spin frequency $\nu_{\rm s} \gtrsim 400$ Hz. As a future prospect, the analysis of the long wavelength global modes in a super-Keplerian boundary region beyond the limit of small hydrodynamic corrections can be useful to identify the modes that are responsible for the origin of kHz QPOs. The high-frequency QPOs are common to both neutron stars and black holes. The future studies concerning the similarities and differences of high-frequency QPOs from neutron stars and black holes can serve to determine the appropriate boundary conditions for accretion onto compact objects [3].

References

[1] Alpar, M.A., Psaltis, D., MNRAS **391**, 1472 (2008)

[2] Chakrabarty, D., Morgan, E.H., Muno, M.P., Galloway, D.K., Wijnands, R., van der Klis, M., Markwardt, C.B., Nature **424**, 42 (2003)

[3] Erkut, M.H., ApJ **743**, 5 (2011)

[4] Erkut, M.H., Alpar, M.A., ApJ **617**, 461 (2004)

[5] Erkut, M.H., Psaltis, D., Alpar, M.A., ApJ **687**, 1220 (2008)

[6] Ghosh, P., Lamb, F.K., ApJ **232**, 259 (1979)

[7] Lovelace, R.V.E., Romanova, M.M., Newman, W.I., ApJ **437**, 136 (1994)

[8] Méndez, M., Belloni, T., MNRAS **381**, 790 (2007)

[9] Miller, M.C., Lamb, F.K., Psaltis, D., ApJ **508**, 791 (1998)

[10] Psaltis, D., Belloni, T., van der Klis, M., ApJ **520**, 262 (1999)

[11] Remillard, R.A., McClintock, J.E., ARA&A **44**, 49 (2006)

[12] Stella, L., Vietri, M., ApJ **492**, L59 (1998)

[13] Stella, L., Vietri, M., Phys. Rev. Lett. **82**, 17 (1999)

[14] Strohmayer, T.E., Zhang, W., Swank, J.H., Lapidus, I., ApJ **503**, L147 (1998)

[15] van der Klis, M., ARA&A **38**, 717 (2000)

[16] van der Klis, M., Advances in Space Research **38**, 2675 (2006)

[17] Wijnands, R., van der Klis, M., ApJ **514**, 939 (1999)

[18] Wijnands, R., van der Klis, M., Homan, J., Chakrabarty, D., Markwardt, C.B., Morgan, E.H., Nature **424**, 44 (2003)