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Advances in Space Research 38 (2006) 2675–2679
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
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Overview of QPOs in neutron-star low-mass X-ray binaries

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Received 6 June 2005; received in revised form 8 November 2005; accepted 9 November 2005

Abstract

Some aspects of the rapid X-ray variability of low magnetic-field neutron stars in low-mass X-ray binaries are briefly summarized.

Keywords: X-rays; Neutron stars; Low-mass X-ray binaries; Black holes; Pulsars

1. Kilohertz quasi-periodic oscillations and orbital motion

The fastest variability components in X-ray binaries are the kilohertz quasi-periodic oscillations (kHz QPOs; van der Klis et al., 1996; Strohmayer et al., 1996), which occur in a wide variety of low magnetic-field neutron-star systems. The phenomenon is sufficiently characteristic to be considered a neutron-star signature. Two QPO peaks (the 'twin peaks') occur in the power spectrum of the X-ray flux variations (Fig. 1). They move up and down in frequency together in the 300–1200 Hz range in correlation with source state and often, luminosity. The higher-frequency one of these two peaks is called the 'upper kHz QPO', with a frequency ν_u, the lower-frequency one the 'lower kHz QPO' with frequency ν_ℓ. The typicaly 300-Hz peak separation $\Delta\nu \equiv \nu_u - \nu_\ell$ usually decreases by a few tens of hertz when both peaks move up by hundreds of hertz. Weak sidebands to the lower kHz QPO have been reported in a number of sources (Jonker et al., 2000). See van der Klis (2000, 2006) for more extensive reviews of kHz QPOs.

kHz QPOs occur near the expected orbital frequencies in the inner accretion disk. Hence, orbital motion at some preferred radius in the inner disk is an interpretation that underlies nearly all models. If a kHz QPO peak at frequency ν corresponds to stable orbital motion around a neutron-star, one can immediately set limits on neutron-star mass M and radius R (Miller et al., 1998) from the constraints that the orbit must be outside both the star and the innermost stable circular orbit from general relativity (the ISCO, at $6\,GM/c^2$ in a Schwarzschild geometry). Fig. 2 shows these limits in the neutron-star mass-radius diagram for several values of ν. A specific model outlining how orbital motion at the inner edge of the disk could in fact modulate the X-rays was proposed by Miller et al. (1998).

One immediate prediction of the orbital interpretation is that, from GR, assuming general relativity, there should be an upper bound on the observed frequency set by the ISCO. The maximum observed kHz QPO frequencies in well-studied sources are constrained to a relatively narrow range of $\nu_u = 1000$–1250 Hz, with a few outlyers. If this is the ISCO frequency, then the neutron-star masses are near $2M_\odot$ (Zhang et al., 1997).

2. kHz QPOs and neutron-star spin

Burst oscillations, although exhibiting drifts of up to a few hertz, are generally interpreted as due to the neutron-star spin (Strohmayer et al., 1996). Apparently, during the burst, hot spots form on the star's surface which move only slowly relative to the solid surface and hence spin around with approximately the neutron-star rotation. Burst oscillations seem to occur near once or twice the kHz QPO peak separation $\Delta\nu$. However, the correspondence is not exact; discrepancies of several 10% have been

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doi:10.1016/j.asr.2005.11.026

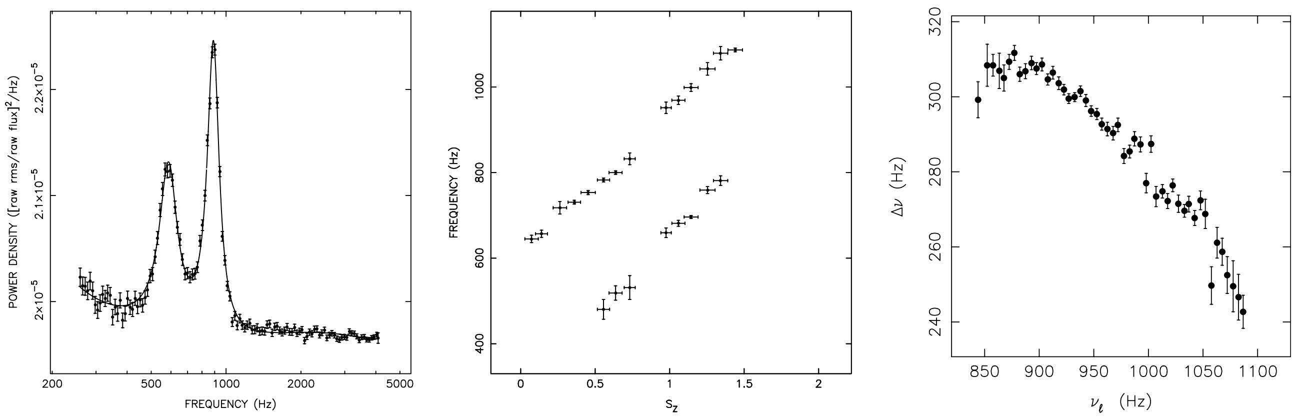

Fig. 1. Left: power spectrum showing twin kHz QPOs in Sco X-1. Middle: twin kHz QPO frequency dependence on S_z, an $\dot{M}$ indicator, in GX 17 + 2. Right: the variation in kHz QPO peak separation as a function of the lower kHz QPO frequency in Sco X-1.

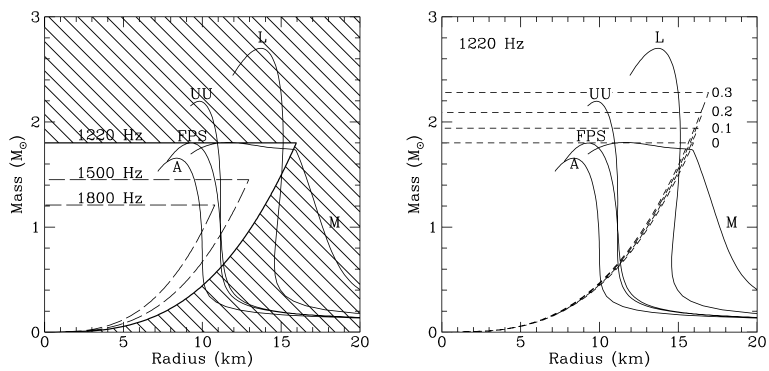

Fig. 2. Constraints on neutron-star mass and radius from orbital motion. Left: for zero spin, orbital frequencies as indicated; the hatched area is excluded. Right: with first order corrections for frame dragging for the values of Kerr parameter *j* indicated. Mass-radius relations for representative EOS are shown. (from Miller et al., 1998).

reported (see van der Klis, 2006 for an overview). Nevertheless, a beat frequency model for kHz QPOs, explaining the presence of the lower kHz QPO as due to a beat of the upper kHz QPO with the spin was explored in some detail (Miller et al., 1998). In this model the orbital frequency $\nu_{\rm orb}$ at the inner edge of the disk interacts with the neutron-star spin $\nu_{\rm spin}$ to produce a third frequency, the beat frequency $\nu_{\rm beat} = \nu_{\rm orb} - \nu_{\rm spin}$; $\nu_{\rm orb}$ is identified with ν_u and $\nu_{\rm beat}$ with ν_ℓ (see Section 1). This model predicts $\Delta\nu = \nu_u - \nu_\ell$ to be constant at $\nu_{\rm spin}$, which is contrary to observations. Lamb and Miller (2001) provided a possible explanation for this within the context of their model. Even with corrections, the model still firmly predicts that $\Delta\nu \approx \nu_{\rm spin}$. That $\Delta\nu$ is sometimes near *half* the burst oscillation frequency $\nu_{\rm burst}$ then implies that in those cases $\nu_{\rm burst} = 2\nu_{\rm spin}$. This could, in principle, result from the presence of two symmetric hot spots on the star.

The discovery of the first accreting millisecond pulsar, SAX J1808.4–3658 (Wijnands and van der Klis, 1998), followed by several more accreting millisecond pulsar discoveries finally provided the definitive confirmation of the long standing prediction that accretion induced spin up in a low-mass X-ray binary can produce a millisecond spin period neutron-star. Two further breakthroughs came when in 2002 twin kHz QPOs *and* burst oscillations were found in SAX J1808.4–3658. In this object $\nu_{\rm pulse} = 401$ Hz, with an upper limit on the amplitude of the 200.5-Hz subharmonic, obtained from a coherent pulsation analysis, of <0.014% (see Wijnands et al., 2003). So very likely, $\nu_{\rm spin} = 401$ Hz, and the measurement of $\Delta\nu$ at 196 ± 4 Hz admits two important conclusions: (i) $\Delta\nu$ *is* related to $\nu_{\rm spin}$, but (ii) it *can* be $\nu_{\rm spin}/2$. Conclusion (ii) is in direct conflict with the beat-frequency interpretation. This conflict can not be resolved by assuming multiple hot spots on the star or multiple orbiting clumps, all of which only serves to make $\nu_{\rm beat} = n(\nu_{\rm orb} - \nu_{\rm spin})$, where $n = 2, 3, \ldots$ (see Wijnands et al., 2003). The only way to save the model would be that $\nu_{\rm spin} = \nu_{\rm pulse}/2$, i.e., two hot spots exist on the star that are sufficiently symmetric for the amplitude at the pulse frequency subharmonic to be below the very low upper limit quoted above. This led Lamb and Miller (2003) to abandon their original beat-frequency model (where the beat interaction occurs at the inner disk edge with a radiation pattern rotating with the neutron-star spin) and introduce a relativistic disk-spin resonance model instead, where a beat interaction also plays a role, but now occurring at a resonant radius relatively far out in the disk, where a resonant wave traveling around the star at $\nu_{\rm spin}$ interacts with a radiation pattern rotating with the inner disk edge orbital frequency. In another millisecond pulsar, XTE J1807–294, twin kHz QPOs were found that have $\Delta\nu \approx \nu_{spin} = 191$ Hz (Linares et al., 2005); clearly, just as is the case with the burst oscillation frequencies, the pulse frequencies, too, can be either $\Delta\nu$ or $2\Delta\nu$.

Fig. 3 summarizes the current evidence for the $\nu_{spin} - \Delta\nu$ commensurability; the data available now seem to suggest that $\Delta\nu \approx \nu_{spin}$ for $\nu_{spin} \lesssim 400$ Hz and $\Delta\nu \approx \nu_{spin}/2$ for $\nu_{spin} \gtrsim 400$ Hz. This might indicate that at high ν_{spin} some preferred radius in the disk required for generating a kHz QPO falls within the inner disk edge and hence is no longer active (Wijnands et al., 2003). Lamb and Miller (2003) in their spin resonance model provide another explanation, which makes use of the fact that at the 'spin-resonance' radius, where the beat interaction takes place, $\nu_{orb} \approx \nu_{spin}/2$. At this radius a wave pattern propagates around the star in step with ν_{spin}, but the matter itself orbits at $\sim\nu_{spin}/2$ and details in the clumpiness of the flow at the spin resonance radius determine which frequency dominates (at some level both are expected to occur).

The burst oscillation frequency in SAX J1808.4–3658 is ~400 Hz, i.e., approximately equal to the spin frequency, demonstrating that $\Delta\nu \approx \nu_{burst}/2$ does not necessarily imply $\nu_{burst} = 2\nu_{spin}$. Extending the interpretation $\nu_{burst} = \nu_{spin}$ to all observed cases, as had been previously argued on other grounds (Strohmayer and Markwardt, 2002), and including the other accreting millisecond pulsars as well, 17 millisecond spins have now been detected in low-mass X-ray binaries (a further 6 LMXB neutron stars have much slower measured spins and presumably stronger B fields: EXO 0748–676, GRO J1744–28, 2A 1822–371, Her X-1, 4U 1626–67, GX 1+4). From the kHz QPO sources, 10 more spins are under the same assumptions known up to a factor of 2; these are in the range (1 or 2) × (220–410 Hz). See van der Klis (2006) for a list of the frequencies. Inferred spin frequencies are in the range 270–619 Hz, well below the limit set by observational constraints and indicating that a braking mechanism limits ν_{spin} (see Chakrabarty et al., 2003). If the stars spin at the magnetospheric equilibrium spin rates corresponding to their current L_x, this predicts a correlation between L_x and magnetic-field strength B (see White and Zhang, 1997). Another possibility is that gravitational radiation limits ν_{spin} by transporting angular momentum out as fast as accretion is transporting it in; this predicts these sources to be the brightest gravitational-wave sources, with a known ν_{spin} facilitating their detection (Bildsten, 1998). Alternatively, the stars could still be spinning up and not yet have reached equilibrium.

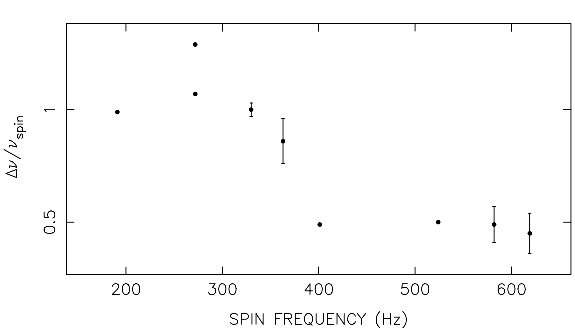

Fig. 3. $\Delta\nu/\nu_{spin}$ vs. ν_{spin}, after van der Klis, 2006.

3. Relation of kHz QPOs with lower frequency phenomena – relativistic precession models

Low-frequency (<100 Hz) QPOs and noise components in the rapid X-ray variability of LMXBs form a complex with several characteristic frequencies in the range 0.1–100 Hz, the 'low-frequency complex'. The components in the low-frequency complex all vary in frequency together, and usually in correlation with the kHz QPO frequencies. These frequency correlations are quite systematic. Fig. 4a displays the frequency correlations of four well-studied intermediate luminosity (atoll) and four weak LMXBs, together covering an order of magnitude in luminosity. Tracks corresponding to the various variability components are clearly recognizable, indicating a scheme of frequency correlations that is to some extent universal. The brightest LMXBs (Z sources) approximately match this scheme (Fig. 4b).

An interesting discrepancy occurs in the frequencies of some millisecond pulsars: in SAX J1808.4–3658 a pattern of correlated frequencies occurs very similar to Fig. 4a, but with relations that are offset from the usual ones. At low frequencies where the relations are clearest, the match can be restored by multiplying the ν_u (and ν_ℓ) values with ~1.45, i.e., close to 1.5 (van Straaten et al., 2005). The millisecond pulsar XTE J1807–294 behaves in a similar way (Linares et al., 2005). This suggests the kHz QPOs form one group of correlated frequencies and the low frequency complex another, independent one.

The observations of frequency correlations (see also Section 4), and the difficulties encountered by the beat-frequency interpretation led to the suggestion that the observed frequencies are general-relativistic orbital, epicyclic, and precession frequencies ("relativistic precession model"; Stella and Vietri, 1998, 1999). The models need additional physics to pick out one or more preferred radii in the disk whose frequencies correspond to those observed.

As one of the lower measured frequencies, ν_h, in this interpretation is the Lense-Thirring precession frequency ν_{nodal}, and ν_u the corresponding orbital frequency, ν_h is predicted to be proportional to ν_u^2, which is indeed sometimes observed (Fig. 5). However, the relation seems to be the same for neutron stars with very different spin frequency, contrary to what the model predicts. Another prediction is that the kHz QPO peak separation $\Delta\nu \equiv \nu_r$, the radial epicyclic frequency. This model does not explain why $\Delta\nu$ is commensurate with the spin frequency. A clear prediction is that $\Delta\nu$ should decrease not only when ν_u increases (as observed) but also when it sufficiently decreases. There are observational indications for this, but the match of observed $\Delta\nu$ vs. ν_u relations to the predictions is not good.

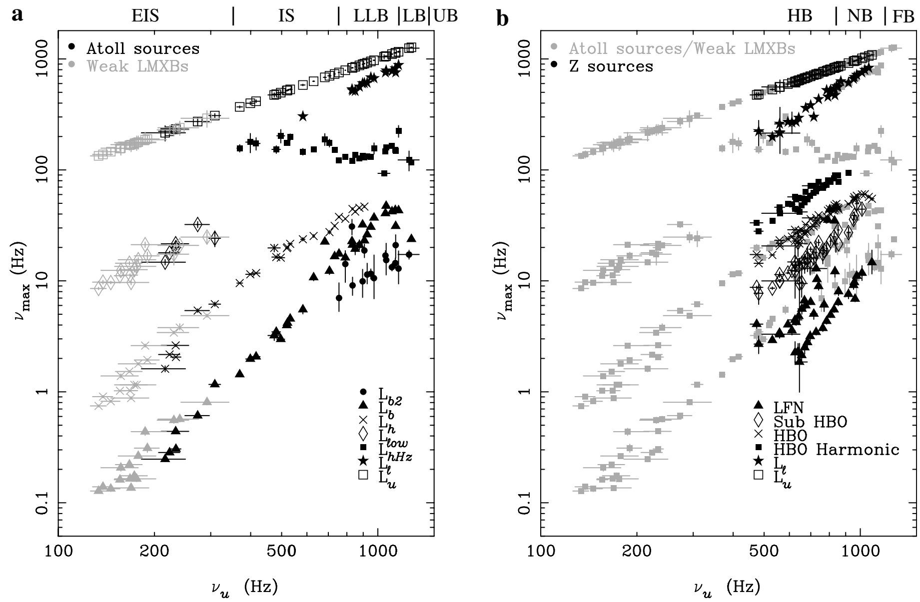

Fig. 4. Frequency correlations. (a) Atoll sources and weak LMXBs, (b) Z sources compared with these objects.

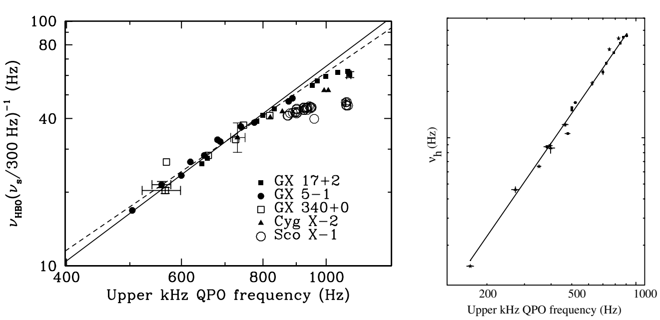

Fig. 5. The relation between upper kHz QPO frequency and, left: HBO frequency in Z sources (scaled between sources by an inferred spin frequency), drawn line is for a quadratic relationship, dashed line is best power-law fit, right: ν_h in atoll sources, line is power law with index 2.01. From Psaltis et al. (1999b) and van Straaten et al. (2003).

4. Relation to black hole timing and states

The power spectra of black holes can be remarkably similar to those of neutron stars, particularly in hard spectral states. Just like in neutron stars, in black holes several different power spectral components are found whose frequencies vary in correlation. Wijnands and van der Klis (1999) noted that in atoll sources and black holes the characteristic frequency of the band-limited noise ν_b and of a hump or QPO often found above this break, ν_h, are correlated over three orders of magnitude (Fig. 6). This 'WK' relation is that between the two lower traces in Fig. 4. Psaltis et al. (1999a) were able to similarly select a set of variability components from neutron stars and black holes, which I shall refrain from fully describing here, that seem to define a common frequency correlation spanning nearly three decades in frequency (Fig. 6). This 'PBK' correlation combines features from different sources with very different Q values with relatively little overlap, and, as Psaltis et al. (1999a) note, although the data are suggestive, they are not conclusive. Further work produced many examples of power spectra confirming these correlations but as there is no direct observation of a gradual transition, the implied identification of the high-Q lower kHz QPO in the more luminous neutron stars with some of the low-Q components in the neutron-star and black hole low states remains conjectural.

The issue of whether we are seeing the same phenomena in neutron-star and black hole systems is a very important one, as a phenomenon occurring in both types of system can not rely on a property unique to either type, such as a solid surface or a horizon. This leaves essentially only phenomena in the accretion(/ejection) flow for their explanation.

The relations of Fig. 6 suggest that physically similar phenomena cause the frequencies plotted there. If so, then these phenomena are extremely tunable, in some cases over nearly three orders of magnitude in frequency, and occur in neutron stars as well as black holes, which as mentioned above probably means they arise in the disk. The relativistic precession models already discussed above are one possible way to do this. However, to actually match the observed frequencies for reasonable compact object parameters seems difficult with these models.

These frequency–frequency correlations may even extend to accreting white dwarfs (in cataclysmic variables), as proposed by Warner and Woudt (2002). If so, then by similar reasoning as above this would seem to exclude GR effects as a viable mechanism for the timing phenomena involved. It is important to note, however, that even if black holes, neutron stars, and white dwarfs all follow the same correlations, meaning that the same physics underlies the *correlations*, this does not strictly require that all *frequencies* participating in the correlations have similar

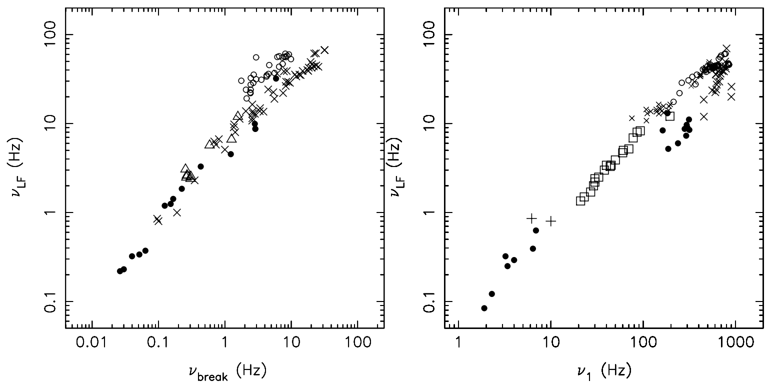

Fig. 6. Left: WK relation (after Wijnands and van der Klis, 1999); right: PBK relation (after Psaltis et al., 1999a). Filled circles represent black hole candidates, open circles Z sources, crosses atoll sources, triangles the millisecond pulsar SAX J1808.4–3658, pluses faint burst sources and squares Cir X-1.

physical origins. It could, e.g., be that accretion disks, given one oscillation frequency, are able to produce a second one matching the correlation. The common frequency–frequency correlations would then derive from this accretion-disk property, which is not unique to any compact object type, while unique compact object properties (e.g., strong-field gravity effects in neutron stars and black holes) might well be involved in generating the original disk oscillation in the first place (cf. Abramowicz et al., 2004).

References

Abramowicz, M.A., Kluźniak, W., Stuchlik, Z., Torok, G., 2004, The orbital resonance model for twin peak kHz QPOs, astro-ph/0401464, 8 pp.

Bildsten, L. Gravitational radiation and rotation of accreting neutron stars. ApJ 501, L89–L93, 1998.

Chakrabarty, D., Morgan, E.H., Muno, M.P., Galloway, D.K., Wijnands, R., van der Klis, M., Markwardt, C.B. Nuclear-powered millisecond pulsars and the maximum spin frequency of neutron stars. Nature 424, 42–44, 2003.

Jonker, P.G., Méndez, M., van der Klis, M. Discovery of a new, third kilohertz quasi-periodic oscillation in 4U 1608-52, 4U 1728-34, and 4U 1636-53: sidebands to the lower kilohertz quasi-periodic oscillation? ApJ 540, L29–L32, 2000.

Lamb, F.K., Miller, M.C. Changing frequency separation of kilohertz quasi-periodic oscillations in the sonic-point beat-frequency model. ApJ 554, 1210–1215, 2001.

Lamb, F.K., Miller, M.C., 2003. Sonic-Point and Spin-Resonance Model of the Kilohertz QPO Pairs, astro-ph/0308179, 10 pp.

Linares, M., van der Klis, M., Altamirano, D., Markwardt, C.B. Discovery of kilohertz quasi-periodic oscillations and shifted frequency correlations in the accreting millisecond pulsar XTE J1807-294. ApJ 634, 1250–1260, 2005.

Miller, M.C., Lamb, F.K., Psaltis, D. Sonic-point model of kilohertz quasi-periodic brightness oscillations in low-mass X-ray binaries. ApJ 508, 791–830, 1998.

Psaltis, D., Belloni, T., van der Klis, M. Correlations in quasi-periodic oscillation and noise frequencies among neutron star and black hole X-ray binaries. ApJ 520, 262–270, 1999a.

Psaltis, D., Wijnands, R., Homan, J., et al. On the magnetospheric beat-frequency and lense-thirring interpretations of the horizontal-branch oscillation in the Z sources. ApJ 520, 763–775, 1999b.

Stella, L., Vietri, M. Lense-thirring precession and quasi-periodic oscillations in low-mass X-ray binaries. ApJ 492, L59–L62, 1998.

Stella, L., Vietri, M. kHz quasiperiodic oscillations in low-mass X-ray binaries as probes of general relativity in the strong-field regime. Phys. Rev. Lett. 82, 17–20, 1999.

Strohmayer, T.E., Zhang, W., Swank, J.H., et al. Millisecond X-ray variability from an accreting neutron star system. ApJ 469, L9–L12, 1996.

Strohmayer, T.E., Markwardt, C.B. Evidence for a millisecond pulsar in 4U 1636-53 during a superburst. ApJ 577, 337–345, 2002.

van der Klis, M., Swank, J.H., Zhang, W., et al. Discovery of submillisecond quasi-periodic oscillations in the X-ray flux of Scorpius X-1. ApJ 469, L1–L4, 1996.

van der Klis, M. Millisecond oscillations in X-ray binaries. ARA&A 38, 717–760, 2000.

van der Klis, M. Rapid X-ray variability, in: Compact stellar X-ray sources, in: Lewin, Walter H.G., Van der Klis, Michiel (Eds.), Cambridge Astrophysics Series, ISBN 0521826594, pp. 39–100, 2006.

van Straaten, S., van der Klis, M., Méndez, M. The atoll source states of 4U 1608-52. ApJ 596, 1155–1176, 2003.

van Straaten, S., van der Klis, M., Wijnands, R. Relations between timing features and colors in accreting millisecond pulsars. ApJ 619, 455–482, 2005.

Warner, B., Woudt, P.A. Dwarf nova oscillations and quasi-periodic oscillations in cataclysmic variables – II.A low-inertia magnetic accretor model. MNRAS 335, 84–98, 2002.

White, N.E., Zhang, W. Millisecond X-ray pulsars in low-mass X-ray binaries. ApJ 490, L87–L90, 1997.

Wijnands, R., van der Klis, M. A millisecond pulsar in an X-ray binary system. Nature 394, 344–346, 1998.

Wijnands, R., van der Klis, M. The broadband power spectra of X-ray binaries. ApJ 514, 939–944, 1999.

Wijnands, R., van der Klis, M., Homan, J., Chakrabarty, D., et al. Quasi-periodic X-ray brightness fluctuations in an accreting millisecond pulsar. Nature 424, 44–47, 2003.

Zhang, W., Strohmayer, T.E., Swank, J.H. Neutron star masses and radii as inferred from kilohertz quasi-periodic oscillations. ApJ 482, L167–L170, 1997.