Contrib. Astron. Obs. Skalnaté Pleso **48**, 476 – 487, (2018)

Rapid X-ray variability and properties of compact stars

G. Török, K. Goluchová and E. Šrámková

Institute of Physics and Research Centre for Computational Physics and Data Processing, Silesian University in Opava, Bezručovo nám. 13, CZ-746 01 Opava, Czech Republic, (E-mail: gabriel.torok@gmail.com)

Received: December 4, 2017; Accepted: March 28, 2018

Abstract. The Rossi X-ray timing explorer, which operated from 1995 to 2012, has provided a large amount of NS data. Timing analysis of the X-ray flux in more than a dozen NS systems reveals remarkable correlations between frequencies of two characteristic peaks present in the high-frequency part of the power-density spectra. We discuss a simple analytic relation that well reproduces these correlations. We outline a possible physical interpretation of the relation's parameters and explore the impact of the obtained results in a broader context.

Key words: X-Rays: Binaries – Accretion, Accretion Discs – Stars: Neutron

1. Introduction

Low-mass X-ray binaries (LMXBs) provide a unique opportunity to probe the effects associated with strong gravity in both black hole (BH) and neutron star (NS) systems (van der Klis, 2006). In the case of NS systems they may serve as a good tool for exploration of the supra-dense matter (Lewin et al., 1997).

The Proportional Counter Array aboard the Rossi X-ray timing explorer (PCA, RXTE Bradt et al., 1993; Jahoda et al., 1996), which operated from 1995 to 2012, has provided observations of NS sources that reveal the existence of two characteristic peaks present in the high-frequency part of the power-density spectra (twin-peak QPOs). In Figure 1a we illustrate correlations between twin-peak QPO frequencies in terms of the upper and lower QPO frequency, ν_U and ν_L, for a group of 14 sources including 8 atoll sources, 5 Z sources, and one milisecond X-ray pulsar. These 14 sources are listed in Table 1. At present there is no commonly accepted model that could explain the observed correlations. Nevertheless, based on various strong arguments, it is usually expected that the twin-peak QPOs are related to orbital motion in the vicinity of NSs. Miscellaneous concepts have been proposed to explain the observed phenomenon (Alpar & Shaham, 1985; Lamb et al., 1985; Miller et al., 1998; Psaltis et al., 1999; Stella & Vietri, 2001; Wagoner et al., 2001; Kluźniak & Abramowicz, 2001; Abramowicz & Kluźniak, 2001; Kato, 2001; Titarchuk & Wood, 2002; Abramowicz et al., 2003; Rezzolla et al., 2003; Kluźniak et al., 2004; Zhang, 2004; Pétri, 2005;

Bursa, 2005; Čadež et al., 2008; Wang et al., 2008; Mukhopadhyay, 2009; Bachetti et al., 2010; Dönmez et al., 2011; Stuchlík et al., 2013; Stuchlík & Kološ, 2014; Huang et al., 2016; Le et al., 2016; Germanà, 2017, and several others).

2. Orbital models

Various attempts to model the individual observed correlations with simple orbital models assuming test particle motion or oscillating pressure-supported fluid structures in the slender torus limit approximation have been rather unsuccessful (see, e.g., Lin et al., 2011; Török et al., 2010, 2012, 2016b, and references therein). In Figure 1a we include an example of correlation predicted by a particular geodesic model, the so-called relativistic precession model (Morsink & Stella, 1999; Stella & Vietri, 1998, 1999, in the following RP model). This correlation is compared to the prediction of a non-geodesic model recently proposed by Török et al. (2016a) to which we in the following refer as the CT (Cusp Torus) model. Both curves in the Figure are drawn for a non-rotating NS with gravitational mass $M = 1.7M_{\odot}$.

2.1. The RP model

The RP model in its usual form incorporates the assumption that the observed rapid X-ray variability originates in the orbital motion of hot inhomogeneities orbiting in the innermost parts of the accretion disc. Within this framework the frequencies of the two observed QPOs are related to the Keplerian frequency ν_K and the relativistic precession frequency ν_P of slightly perturbed circular geodesic motion that occurs at an arbitrary orbital radius r,

$$\nu_U(r) = \nu_K(r), \quad \nu_L(r) = \nu_P(r)\,. \tag{1}$$

The precession frequency equals to a difference between the Keplerian and the radial epicyclic frequency, $\nu_P(r) = \nu_K(r) - \nu_r(r)$.

It has been shown that relation (1) roughly matches the data of NS sources (e.g., Stella & Vietri, 1998, 1999; Belloni et al., 2007; Lin et al., 2011; Török et al., 2012, 2016b). It is however questionable whether the local motion of an individual spot can be responsible for the high amplitudes and coherence times of the observed QPOs (e.g., Barret et al., 2005a; Méndez, 2006; Barret & Vaughan, 2012).

2.2. The CT model

The CT model explored recently by Török et al. (2016a) deals with global modes of accreted fluid motion in an oscillating torus (Rezzolla et al., 2003; Abramowicz et al., 2006; Blaes et al., 2006; Šrámková et al., 2007; Ingram & Done, 2010; Fragile et al., 2016; Mishra et al., 2017; Parthasarathy et al., 2017; de Avellar et al., 2017). The torus is assumed to form a cusp by filling up the so-called critical equipotential volume. The upper kilohertz QPO frequency is assigned to the Keplerian frequency of the fluid at the centre of the torus where both the fluid pressure and the density peak, and from which most of the torus radiation emerges. The lower kilohertz QPO frequency is assigned to the frequency of a non-axisymmetric $m = -1$ radial epicyclic mode, $\nu_{\mathrm{r},-1}$. It is expected that the torus at all times keeps its maximal possible size filling the 'Roche-like' lobe, and that its radial oscillations modulate the boundary layer accretion flow (Paczynski, 1987; Horák, 2005; Abramowicz et al., 2007; Parthasarathy et al., 2017).

The QPO frequencies predicted by the CT model are functions of the torus centre location r_0,

$$\nu_{U} \equiv \nu_{K}(r_0), \quad \nu_{L} \equiv \nu_{\mathrm{r},-1}(r_0)\,. \tag{2}$$

Rather long analytic formulae that define $\nu_{\mathrm{r},-1}$ can be found in Straub & Šrámková (2009). Török et al. (2016a) numerically calculated the $\nu_{L}(\nu_{U})$ correlation following from relation (2). Assuming this correlation, they obtained a good match of the data in the case of the atoll source 4U 1636-53 for NS mass of $M = 1.69 M_{\odot}$ (see Figure 1b for illustration).

3. Simple analytical formula

In Török et al. (2017a) we suggested that the $\nu_{L}(\nu_{U})$ frequency relations can be well described by the following formula

$$\nu_{L} = \nu_{U}\left(1 - \mathcal{B}\sqrt{1 - (\nu_{U}/\nu_0)^{2/3}}\right), \tag{3}$$

where ν_0 equals the Keplerian orbital frequency at the innermost stable circular orbit around a non-rotating NS with gravitational mass M_0. This frequency can be expressed in the units of Hz as (e.g., Kluzniak & Wagoner, 1985; Kluzniak et al., 1990),

$$\nu_0 = \nu_{ISCO} = \frac{1}{6^{3/2}}\frac{c^3}{2\pi G}\frac{1}{M} = 2198\,\frac{M_{\odot}}{M} = 2198\,\frac{1}{\mathcal{M}}. \tag{4}$$

For $\mathcal{B} = 1$, relation (3) merges with the frequency relation implied by the RP model while the CT model prediction is well approximated by relation (3) for $\mathcal{B} = 0.8$. We illustrate this property of relation (3) in Figure 1b.

4. Data matching - main results

For 9 sources, namely 4U 1608-52, 4U 1636-53, 4U 1735-44, 4U 1915-05, IGR J17191-2821, GX 17+2, Sco X-1, Cir X-1 and XTE J1807.4-294 we find good agreement between the CT model and data. In all these sources the CT model

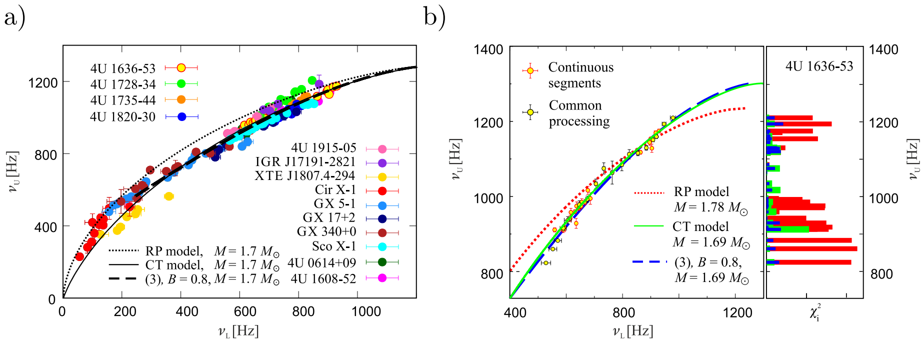

Figure 1. Correlations between the frequencies of twin-peak QPOs. a) The data of 14 sources and examples of the expected frequency relations. Detailed information on the individual sources along with the appropriate references is given in Table 1. b) The data of the atoll source 4U 1636-53 and their best fits. For the sake of clarity, the data-set which corresponds to the individual continuous observations is compared to the data-set associated with the common processing of all observations (see Török et al., 2016a). In both panels the expected frequency relations are drawn for a non-rotating NS.

matches the observed trend better than is done by the RP model (see Figure 2). For the other 5 sources, namely 4U 1728-34, 4U 0614+09, 4U 1820-30, GX 340+0 and GX 5-1, it is not possible to match the data due to the CT model limitations discussed by Török et al. (2016a).

Relation (3) well describes the data in each of the 14 sources (see Table 1). In some cases one does not achieve $\chi^2 \approx 1$d.o.f, but no clear deviation of data from the expected trend is found. This can be seen from a direct comparison between the expected curves and data, which is for each source included in Török et al. (2017a,b) where we present detailed results.

5. Consideration of models of rotating NSs

In the series of works (Török et al., 2010, 2012, 2016b) the authors explored the implications of several orbital QPO models. They found that the estimation of NS parameters based on these models leads to the effective degeneracy of these parameters. For a given model, each combination of NS mass M, angular momentum j and quadrupole moment q corresponds to a certain value of a single generalized parameter, e.g., non-rotating NS mass. Indeed, Török et al. (2016a) noticed that the NS mass implied by the CT model for the atoll source 4U 1636-53 can be expressed as

$$M = M_0[1 + 0.7(j + j^2)], \quad M_0 = 1.69^{\pm 0.01} M_\odot \,. \tag{5}$$

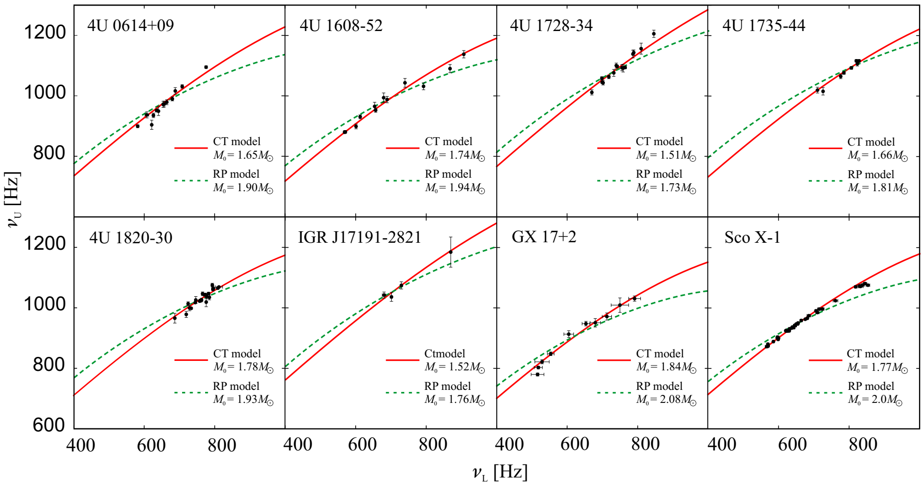

Figure 2. A comparison between the best fits obtained assuming the CT and RP models for data of the individual sources. The best fits for the atoll source 4U 1636-53 are shown in Figure 1b.

5.1. Neutron star spin, radius and equation of state

There is good evidence on the NS spin frequency of 4U 1636–53 based on the X-ray burst measurements (see the reference in Wang et al., 2017). The consideration of the X-ray burst models implies the NS spin to take the value of $\nu_S \doteq 580\,\mathrm{Hz}$. The CT model predictions can therefore be compared to the expectations given by models of rotating NSs.

Figure 3a (after Török et al., 2016a) displays several mass-angular momentum relations expected from the models of rotating NSs for the spin of 580 Hz. Inspecting this Figure one can see that there is an overlap between the relations given by the models of rotating NSs and the relation inferred from the CT model. The required NS mass is $M(580\mathrm{Hz}) \approx 2M_{\odot}$.

Considering the above result, one can expect that similar consideration should also be valid for the other sources listed in Table 1. This is justified in Figure 3b, where we explore the CT model predictions for another atoll source, 4U 1608-52. Table 1 indicates that $\mathcal{M}(\mathcal{B} = 0.8) = 1.74$. The NS spin inferred from the X-ray burst measurements takes the value of $\nu_S \doteq 610\,\mathrm{Hz}$ (see references in Wang et al., 2017). Analyzing Figure 3b one can see that the relation

$$M = M_0[1 + 0.6(j + j^2)], \quad M_0 = 1.74^{\pm 0.01} M_{\odot} \tag{6}$$

describes the CT model model prediction and overlaps with the relations given by the models of rotating NSs around $M(610\mathrm{Hz}) \approx 2.1 M_{\odot}$.

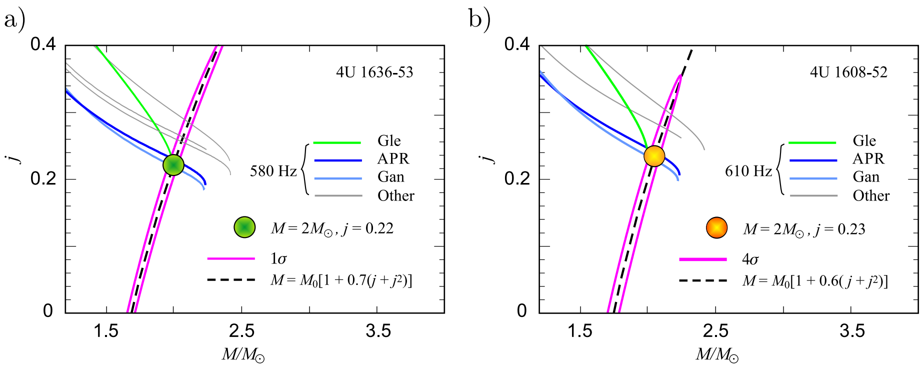

Figure 3. The mass-angular momentum contours obtained from the fitting of datapoints using the CT model vs. the mass-angular momentum relations predicted by models of rotating NSs. These are drawn for several NS EoS and the values of spin inferred from the X-ray burst measurements. For the models of rotating NSs we adopt the approach of Urbanec et al. (2013). The assumed EoS are as follows. Gle - Glendenning (1985); APR - Akmal et al. (1998); Gan - Gandolfi et al. (2010); other - Rikovska Stone et al. (2003); Urbanec et al. (2010). For the QPO model, the σ-confidence levels are calculated in accordance with the method used in Török et al. (2016a,b). a) The atoll source 4U 1636-53. b) The atoll source 4U 1608-52. In both panels the emphasized spot indicates where the QPO model and the EoS relations overlap.

6. Conclusions

The CT model as well as relation (3) for $\mathcal{B} = 0.8$ well reproduce the data of 9 sources. Assuming $\mathcal{B}$ as a free parameter, we obtain good fits for each of the 14 considered sources. We suggest that larger deviations from the case of $\mathcal{B} = 0.8$ are caused by further non-geodesic effects acting on the torus formation. These can be induced by the influence of magnetic field.

The particular consideration of the CT model agrees with the general interpretation, in which the $\mathcal{M}$ parameter represents the main parameter reflecting the spacetime geometry given by the NS mass and spin, while the $\mathcal{B}$ parameter reflects the additional stable factors. Further determination of NS mass and spin is possible when implications of relation (3) are confronted with the results of NS modeling based on NS spin measurements. In the case of the CT model we have already obtained promising results in this research direction.

Acknowledgements.

We would like to acknowledge the Czech Science Foundation grant No. 17-16287S, the internal SU grant No. SGS/15/2016, and the INTER-TRANSFER project No. LTT17003. We are grateful to Marek Abramowicz and Omer Blaes for useful discussions. Last but not least, we would like to acknowledge the hospitality of University of

Table 1. The results of data matching for relation (3) assuming $\mathcal{B} = 0.8$ and $\mathcal{B}$ as a free parameter. The goodness of fits is formally characterized by the χ^2 values. The uncertainties displayed here correspond to standard errors.

Source No./Type	Name	$\mathcal{M}(0.8)$	$\frac{\chi^2}{d.o.f.}$	$\mathcal{M}(\mathcal{B})$	$\mathcal{B}$	$\frac{\chi^2_{\mathcal{M}(\mathcal{B})}}{d.o.f.}$	Data-points
1/A	4U 1608-52	$1.80^{\pm 0.01}$	1.6	$1.79^{\pm 0.04}$	$0.79^{\pm 0.03}$	1.7	12
2/A	4U 1636-53	$1.70^{\pm 0.01}$	2.0	$1.70^{\pm 0.01}$	$0.8^{\pm 0.01}$	2.1	22
3/A	4U 1735-44	$1.69^{\pm 0.01}$	2.1	$1.48^{\pm 0.10}$	$0.61^{\pm 0.06}$	1.0	8
4/A	4U 1915-05	$1.58^{\pm 0.03}$	0.8	$1.65^{\pm 0.03}$	$0.82^{\pm 0.01}$	0.2	5
5/A	IGR J17191	$1.58^{\pm 0.02}$	0.6	$1.63^{\pm 0.20}$	$0.85^{\pm 0.2}$	0.8	4
6/Z	GX 17+2	$1.89^{\pm 0.02}$	1.2	$1.77^{\pm 0.07}$	$0.72^{\pm 0.04}$	0.8	10
7/Z	Sco X-1	$1.82^{\pm 0.01}$	1.0	$1.81^{\pm 0.01}$	$0.8^{\pm 0.01}$	1.0	39
8/Z	Cir X-1	$0.74^{\pm 0.10}$	1.2	$1.42^{\pm 0.5}$	$0.89^{\pm 0.06}$	1.1	11
9/P	XTE J1807.4	$2.61^{\pm 0.11}$	0.8	$2.85^{\pm 0.25}$	$0.86^{\pm 0.07}$	0.8	7
10/A	4U 1728-34	$1.57^{\pm 0.01}$	3.2	$1.35^{\pm 0.12}$	$0.65^{\pm 0.06}$	2.5	15
11/A	4U 0614+09	$1.71^{\pm 0.02}$	5.1	$1.39^{\pm 0.06}$	$0.62^{\pm 0.02}$	1.1	13
12/A	4U 1820-30	$1.81^{\pm 0.01}$	9.3	$1.53^{\pm 0.07}$	$0.58^{\pm 0.03}$	3.2	23
13/Z	GX 340+0	$1.62^{\pm 0.08}$	4.2	$2.23^{\pm 0.10}$	$1.10^{\pm 0.08}$	1.6	12
14/Z	GX 5-1	$1.65^{\pm 0.10}$	16.7	$2.31^{\pm 0.04}$	$1.11^{\pm 0.02}$	1.5	21

Source type: A - Atoll, Z - Z, P - Pulsar

References: (1)–(3), (10) – (12) - Barret et al. (2005b,c, 2006), (4) - Boirin et al. (2000), (5) - Altamirano et al. (2010), (6) - Homan et al. (2002), (7) - van der Klis et al. (1997), (8) - Boutloukos et al. (2006), (9) - Linares et al. (2005), (13) - Jonker et al. (2000), (14) - Jonker et al. (2002).

California in Santa Barbara, and to express our thanks to concierges of Mlýnská hotel in Uherské Hradiště, Czech Republic for their participation in organizing frequent workshops of Silesian University and Astronomical Institute of the Czech Academy of Sciences.

References

Abramowicz, M. A., Blaes, O. M., Horák, J., Kluźniak, W., & Rebusco, P., Epicyclic oscillations of fluid bodies: II. Strong gravity. 2006, *Classical and Quantum Gravity*, **23**, 1689, DOI: 10.1088/0264-9381/23/5/014

Abramowicz, M. A., Horák, J., & Kluzniak, W., Modulation of the Neutron Star Boundary Layer Luminosity by Disk Oscillations. 2007, *Acta Astron.*, **57**, 1

Abramowicz, M. A., Karas, V., Kluźniak, W., Lee, W. H., & Rebusco, P., Non-Linear Resonance in Nearly Geodesic Motion in Low-Mass X-Ray Binaries. 2003, *PASJ*, **55**, 467, DOI: 10.1093/pasj/55.2.467

Abramowicz, M. A. & Kluźniak, W., A precise determination of black hole spin in GRO J1655-40. 2001, *A&A*, **374**, L19, DOI: 10.1051/0004-6361:20010791

Akmal, A., Pandharipande, V. R., & Ravenhall, D. G., Equation of state of nucleon matter and neutron star structure. 1998, *Phys. Rev. C*, **58**, 1804, DOI: 10.1103/PhysRevC.58.1804

Alpar, M. A. & Shaham, J., Is GX5 - 1 a millisecond pulsar? 1985, *Nature*, **316**, 239, DOI: 10.1038/316239a0

Altamirano, D., Linares, M., Patruno, A., et al., Type I X-ray bursts, burst oscillations and kHz quasi-periodic oscillations in the neutron star system IGRJ17191-2821. 2010, *MNRAS*, **401**, 223, DOI: 10.1111/j.1365-2966.2009.15627.x

Bachetti, M., Romanova, M. M., Kulkarni, A., Burderi, L., & di Salvo, T., QPO emission from moving hot spots on the surface of neutron stars: a model. 2010, *MNRAS*, **403**, 1193, DOI: 10.1111/j.1365-2966.2010.16203.x

Barret, D., Kluźniak, W., Olive, J. F., Paltani, S., & Skinner, G. K., On the high coherence of kHz quasi-periodic oscillations. 2005a, *Mon. Not. R. Astron. Soc.*, **357**, 1288, DOI: 10.1111/j.1365-2966.2005.08734.x

Barret, D., Olive, J.-F., & Miller, M. C., An abrupt drop in the coherence of the lower kHz quasi-periodic oscillations in 4U 1636-536. 2005b, *MNRAS*, **361**, 855, DOI: 10.1111/j.1365-2966.2005.09214.x

Barret, D., Olive, J.-F., & Miller, M. C., Drop of coherence of the lower kilo-Hz QPO in neutron stars: Is there a link with the innermost stable circular orbit? 2005c, *Astronomische Nachrichten*, **326**, 808, DOI: 10.1002/asna.200510417

Barret, D., Olive, J.-F., & Miller, M. C., The coherence of kilohertz quasi-periodic oscillations in the X-rays from accreting neutron stars. 2006, *MNRAS*, **370**, 1140, DOI: 10.1111/j.1365-2966.2006.10571.x

Barret, D. & Vaughan, S., Maximum Likelihood Fitting of X-Ray Power Density Spectra: Application to High-frequency Quasi-periodic Oscillations from the Neutron Star X-Ray Binary 4U1608-522. 2012, *AJ*, **746**, 131, DOI: 10.1088/0004-637X/746/2/131

Belloni, T., Méndez, M., & Homan, J., On the kHz QPO frequency correlations in bright neutron star X-ray binaries. 2007, *Mon. Not. R. Astron. Soc.*, **376**, 1133, DOI: 10.1111/j.1365-2966.2007.11486.x

Blaes, O. M., Arras, P., & Fragile, P. C., Oscillation modes of relativistic slender tori. 2006, *MNRAS*, **369**, 1235, DOI: 10.1111/j.1365-2966.2006.10370.x

Boirin, L., Barret, D., Olive, J. F., Bloser, P. F., & Grindlay, J. E., Low and high frequency quasi-periodic oscillations in 4U1915-05. 2000, *Astronomy and Astrophysics*, **361**, 121

Boutloukos, S., van der Klis, M., Altamirano, D., et al., Discovery of Twin kHz QPOs in the Peculiar X-Ray Binary Circinus X-1. 2006, *APJ*, **653**, 1435, DOI: 10.1086/508934

Bradt, H. V., Rothschild, R. E., & Swank, J. H., X-ray timing explorer mission. 1993, *ApJ Supp.*, **97**, 355

Bursa, M., High-frequency QPOs in GRO J1655-40: Constraints on resonance models by spectral fits. 2005, in *RAGtime 6/7: Workshops on black holes and neutron stars*, ed. S. Hledík & Z. Stuchlík, 39–45

de Avellar, M. G., Porth, O., Younsi, Z., & Rezzolla, L., The kilo Hertz quasi-periodic oscillations in neutron star low-mass X-ray binaries as tori oscillation modes. I. 2017, *ArXiv e-prints* [arXiv: 1709.07706]

Dönmez, O., Zanotti, O., & Rezzolla, L., On the development of quasi-periodic oscillations in Bondi-Hoyle accretion flows. 2011, *Mon. Not. R. Astron. Soc.*, **412**, 1659, DOI: 10.1111/j.1365-2966.2010.18003.x

Fragile, P. C., Straub, O., & Blaes, O., High-frequency and type-C QPOs from oscillating, precessing hot, thick flow. 2016, *MNRAS*, **461**, 1356, DOI: 10.1093/mnras/stw1428

Gandolfi, S., Illarionov, A. Y., Fantoni, S., et al., Microscopic calculation of the equation of state of nuclear matter and neutron star structure. 2010, *MNRAS*, **404**, L35, DOI: 10.1111/j.1745-3933.2010.00829.x

Germanà, C., Upper-twin-peak quasiperiodic oscillation in x-ray binaries and the energy from tidal circularization of relativistic orbits. 2017, *ArXiv e-prints* [arXiv: 1711.01626]

Glendenning, N. K., Neutron stars are giant hypernuclei? 1985, *ApJ*, **293**, 470, DOI: 10.1086/163253

Homan, J., van der Klis, M., Jonker, P. G., et al., RXTE Observations of the Neutron Star Low-Mass X-Ray Binary GX 17+2: Correlated X-Ray Spectral and Timing Behavior. 2002, *The Astrophysical Journal*, **568**, 878, DOI: 10.1086/339057

Horák, J., A possible mechanism for QPOs modulation in neutron star sources. 2005, *Astronomische Nachrichten*, **326**, 845, DOI: 10.1002/asna.200510425

Huang, C.-Y., Ye, Y.-C., Wang, D.-X., & Li, Y., A model for 3:2 HFQPO pairs in black hole binaries based on cosmic battery. 2016, *Mon. Not. R. Astron. Soc.*, **457**, 3859, DOI: 10.1093/mnras/stw226

Ingram, A. & Done, C., A physical interpretation of the variability power spectral components in accreting neutron stars. 2010, *MNRAS*, **405**, 2447, DOI: 10.1111/j.1365-2966.2010.16614.x

Jahoda, K., Swank, J. H., Giles, A. B., et al., In-orbit performance and calibration of the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA). 1996, in Proc. SPIE, Vol. **2808**, *EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VII*, ed. O. H. Siegmund & M. A. Gummin, 59–70

Jonker, P. G., van der Klis, M., Homan, J., et al., Low- and high-frequency variability as a function of spectral properties in the bright X-ray binary GX 5-1. 2002, *MNRAS*, **333**, 665, DOI: 10.1046/j.1365-8711.2002.05442.x

Jonker, P. G., van der Klis, M., Wijnands, R., et al., The Power Spectral Properties of the Z Source GX 340+0. 2000, *The Astrophysical Journal*, **537**, 374, DOI: 10.1086/309029

Kato, S., Basic Properties of Thin-Disk Oscillations. 2001, *PASJ*, **53**, 1, DOI: 10.1093/pasj/53.1.1

Kluźniak, W. & Abramowicz, M. A., The physics of kHz QPOs—strong gravity's coupled anharmonic oscillators. 2001, *ArXiv Astrophysics e-prints* [arXiv: astro-ph/0105057]

Kluźniak, W., Abramowicz, M. A., Kato, S., Lee, W. H., & Stergioulas, N., Nonlinear Resonance in the Accretion Disk of a Millisecond Pulsar. 2004, *AJ*, **603**, L89, DOI: 10.1086/383143

Kluzniak, W., Michelson, P., & Wagoner, R. V., Determining the properties of accretion-gap neutron stars. 1990, *ApJ*, **358**, 538, DOI: 10.1086/169006

Kluzniak, W. & Wagoner, R. V., Evolution of the innermost stable orbits around accreting neutron stars. 1985, *ApJ*, **297**, 548, DOI: 10.1086/163550

Lamb, F. K., Shibazaki, N., Alpar, M. A., & Shaham, J., Quasi-periodic oscillations in bright galactic-bulge X-ray sources. 1985, *Nature*, **317**, 681, DOI: 10.1038/317681a0

Le, T., Wood, K. S., Wolff, M. T., Becker, P. A., & Putney, J., Standing Shock Instability in Advection-dominated Accretion Flows. 2016, *Astrophys. J.*, **819**, 112, DOI: 10.3847/0004-637X/819/2/112

Lewin, W. H. G., van Paradijs, J., & van den Heuvel, E. P. J. 1997, *X-ray Binaries* (Cambridge University Press), 674

Lin, Y.-F., Boutelier, M., Barret, D., & Zhang, S.-N., Studying Frequency Relationships of Kilohertz Quasi-periodic Oscillations for 4U 1636-53 and Sco X-1: Observations Confront Theories. 2011, *The Astrophysical Journal*, **726**, 74, DOI: 10.1088/0004-637X/726/2/74

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. 2005, *The Astrophysical Journal*, **634**, 1250, DOI: 10.1086/497025

Méndez, M., On the maximum amplitude and coherence of the kilohertz quasi-periodic oscillations in low-mass X-ray binaries. 2006, *MNRAS*, **371**, 1925, DOI: 10.1111/j.1365-2966.2006.10830.x

Miller, M. C., Lamb, F. K., & Psaltis, D., Sonic-Point Model of Kilohertz Quasi-periodic Brightness Oscillations in Low-Mass X-Ray Binaries. 1998, *AJ*, **508**, 791, DOI: 10.1086/306408

Mishra, B., Vincent, F. H., Manousakis, A., et al., Quasi-periodic oscillations from relativistic ray-traced hydrodynamical tori. 2017, *MNRAS*, **467**, 4036, DOI: 10.1093/mnras/stx299

Morsink, S. M. & Stella, L., Relativistic Precession around Rotating Neutron Stars: Effects Due to Frame Dragging and Stellar Oblateness. 1999, *ApJ*, **513**, 827, DOI: 10.1086/306876

Mukhopadhyay, B., Higher-Order Nonlinearity in Accretion Disks: Quasi-Periodic Oscillations of Black Hole and Neutron Star Sources and Their Spin. 2009, *AJ*, **694**, 387, DOI: 10.1088/0004-637X/694/1/387

Paczynski, B., Possible relation between the X-ray QPO phenomenon and general relativity. 1987, *Nature*, **327**, 303, DOI: 10.1038/327303a0

Parthasarathy, V., Kluzniak, W., & Cemeljic, M., MHD simulations of oscillating cusp-filling tori around neutron stars – missing upper kHz QPO. 2017, *ArXiv e-prints* [arXiv: 1703.05036]

Pétri, J., An explanation for the kHz-QPO twin peaks separation in slow and fast rotators. 2005, *A&A*, **439**, L27, DOI: 10.1051/0004-6361:200500151

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. 1999, *AJ*, **520**, 763, DOI: 10.1086/307460

Rezzolla, L., Yoshida, S., & Zanotti, O., Oscillations of vertically integrated relativistic tori - I. Axisymmetric modes in a Schwarzschild space-time. 2003, *MNRAS*, **344**, 978, DOI: 10.1046/j.1365-8711.2003.07023.x

Rikovska Stone, J., Miller, J. C., Koncewicz, R., Stevenson, P. D., & Strayer, M. R., Nuclear matter and neutron-star properties calculated with the Skyrme interaction. 2003, *Phys. Rev. C*, **68**, 034324, DOI: 10.1103/PhysRevC.68.034324

Šrámková, E., Torkelsson, U., & Abramowicz, M. A., Oscillations of tori in the pseudo-Newtonian potential. 2007, *A&A*, **467**, 641, DOI: 10.1051/0004-6361:20065979

Stella, L. & Vietri, M., Lense-Thirring Precession and Quasi-periodic Oscillations in Low-Mass X-Ray Binaries. 1998, *ApJ lett.*, **492**, L59, DOI: 10.1086/311075

Stella, L. & Vietri, M., kHz Quasiperiodic Oscillations in Low-Mass X-Ray Binaries as Probes of General Relativity in the Strong-Field Regime. 1999, *Phys. Rev. Lett.*, **82**, 17, DOI: 10.1103/PhysRevLett.82.17

Stella, L. & Vietri, M., Quasi-Periodic Oscillations from Low-Mass X-ray Binaries and Strong Field Gravity. 2001, in Astronomical Society of the Pacific Conference Series, Vol. **234**, *X-ray Astronomy 2000*, ed. R. Giacconi, S. Serio, & L. Stella, 213

Straub, O. & Šrámková, E., Epicyclic oscillations of non-slender fluid tori around Kerr black holes. 2009, *Classical and Quantum Gravity*, **26**, 055011, DOI: 10.1088/0264-9381/26/5/055011

Stuchlík, Z. & Kološ, M., String loops oscillating in the field of Kerr black holes as a possible explanation of twin high-frequency quasiperiodic oscillations observed in microquasars. 2014, *Phys. Rev. D*, **89**, 065007, DOI: 10.1103/PhysRevD.89.065007

Stuchlík, Z., Kotrlová, A., & Török, G., Multi-resonance orbital model of high-frequency quasi-periodic oscillations: possible high-precision determination of black hole and neutron star spin. 2013, *A&A*, **552**, A10, DOI: 10.1051/0004-6361/201219724

Titarchuk, L. & Wood, K., On the Low and High Frequency Correlation in Quasi-periodic Oscillations among White Dwarf, Neutron Star, and Black Hole Binaries. 2002, *AJ*, **577**, L23, DOI: 10.1086/344147

Török, G., Bakala, P., Šrámková, E., Stuchlík, Z., & Urbanec, M., On Mass Constraints Implied by the Relativistic Precession Model of Twin-peak Quasi-periodic Oscillations in Circinus X-1. 2010, *AJ*, **714**, 748, DOI: 10.1088/0004-637X/714/1/748

Török, G., Bakala, P., Šrámková, E., et al., Mass-Angular-momentum Relations Implied by Models of Twin Peak Quasi-periodic Oscillations. 2012, *ApJ*, **760**, 138, DOI: 10.1088/0004-637X/760/2/138

Török, G., Goluchová, K., Horák, J., et al., Twin peak quasi-periodic oscillations as signature of oscillating cusp torus. 2016a, *MNRAS*, **457**, L19, DOI: 10.1093/mnrasl/slv196

Török, G., Goluchová, K., Urbanec, M., et al., Constraining Models of Twin-Peak Quasi-periodic Oscillations with Realistic Neutron Star Equations of State. 2016b, *The Astrophysical Journal*, **833**, 273, DOI: 10.3847/1538-4357/833/2/273

Török, G., Goluchová, K., Šrámková, E., et al., On one-parametric formula relating the frequencies of twin-peak quasi-periodic oscillations. 2017a, *ArXiv e-prints* [arXiv: 1710.10901], accepted for publication in MNRAS

Török, G., Goluchová, K., Šrámková, E., et al., A one-parametric formula relating the frequencies of twin-peak quasi-periodic oscillations. 2017b, in *RAGtime 17, 18, 19: Workshops on black holes and neutron stars*

Urbanec, M., Běták, E., & Stuchlík, Z., Observational Tests of Neutron Star Relativistic Mean Field Equations of State. 2010, *Acta Astron.*, **60**, 149

Urbanec, M., Miller, J. C., & Stuchlík, Z., Quadrupole moments of rotating neutron stars and strange stars. 2013, *MNRAS*, **433**, 1903, DOI: 10.1093/mnras/stt858

Čadež, A., Calvani, M., & Kostić, U., On the tidal evolution of the orbits of low-mass satellites around black holes. 2008, *A&A*, **487**, 527, DOI: 10.1051/0004-6361:200809483

van der Klis, M. 2006, *Rapid X-ray Variability* (Cambridge University Press), 39–112

van der Klis, M., Wijnands, R. A. D., Horne, K., & Chen, W., Kilohertz Quasi-Periodic Oscillation Peak Separation Is Not Constant in Scorpius X-1. 1997, *APJL*, **481**, L97, DOI: 10.1086/310656

Wagoner, R. V., Silbergleit, A. S., & Ortega-Rodríguez, M., "Stable" Quasi-periodic Oscillations and Black Hole Properties from Diskoseismology. 2001, *AJ*, **559**, L25, DOI: 10.1086/323655

Wang, D.-H., Zhang, C.-M., Qu, J.-L., & Yang, Y.-Y., Correlations between the frequencies of twin kHz QPOs and spins of neutron stars in LMXBs. 2017, *ArXiv e-prints* [arXiv: 1710.09128]

Wang, D.-X., Gan, Z.-M., Huang, C.-Y., & Li, Y., Association of the 3:2 HFQPO pairs with the broad Fe K line in XTE J1550-564 and GRO J1655-40. 2008, *Mon. Not. R. Astron. Soc.*, **391**, 1332, DOI: 10.1111/j.1365-2966.2008.13965.x

Zhang, C., The MHD Alfven wave oscillation model of kHz Quasi Periodic Oscillations of Accreting X-ray binaries. 2004, *A&A*, **423**, 401, DOI: 10.1051/0004-6361:20035808