Restrictions to neutron star models based on twin-peak quasi-periodic oscillations

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Abstract. In a series of works - Török *et al.* (2010, 2012a) and Urbanec *et al.* (2010a) - we explored restrictions to neutron star properties that are implied by various models of twin-peak quasi-periodic oscillations. Here we sketch an attempt to confront the obtained mass–angular-momentum relations and limits on neutron star compactness with the parameters estimated by assuming various equations of state and the spin frequency of the atoll source 4U 1636-53.

Keywords. X-rays: binaries; stars: neutron; stars: fundamental parameters; stars: rotation
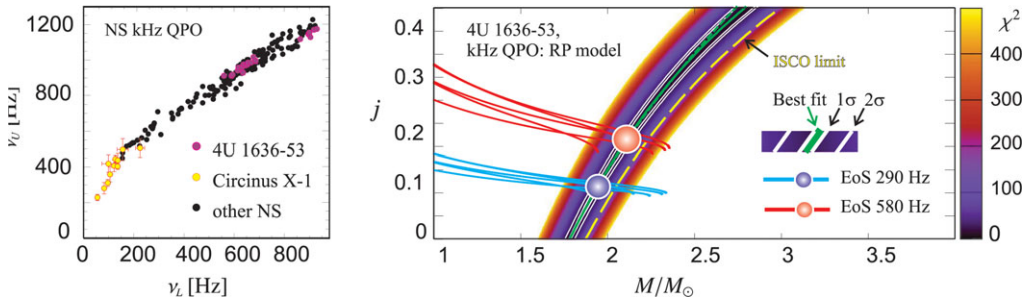
1. Introduction

Twin-peak quasi-periodic oscillations (kHz QPOs) appear in the X-ray power-density spectra of several accreting low-mass neutron star (NS) binaries. Frequencies of these QPOs follow correlations specific for a given source (see the left panel of Figure 1 for illustration). Most QPO models relate the observed frequencies to frequencies of the orbital motion inside an inner part of the accretion disc.

The consideration of various orbital QPO models for the NS sources data results in specific mass–angular-momentum (M–j) relations rather than in preferred combinations of M and j (e.g., Török *et al.* 2012b). For the atoll source 4U 1636-53, there is a good evidence on the NS spin frequency based on the X-ray burst measurements, Strohmayer & Markwardt (2002). Thus, one can in principle infer the angular momentum j and remove the $M - j$ degeneracies related to the individual twin-peak QPO models.
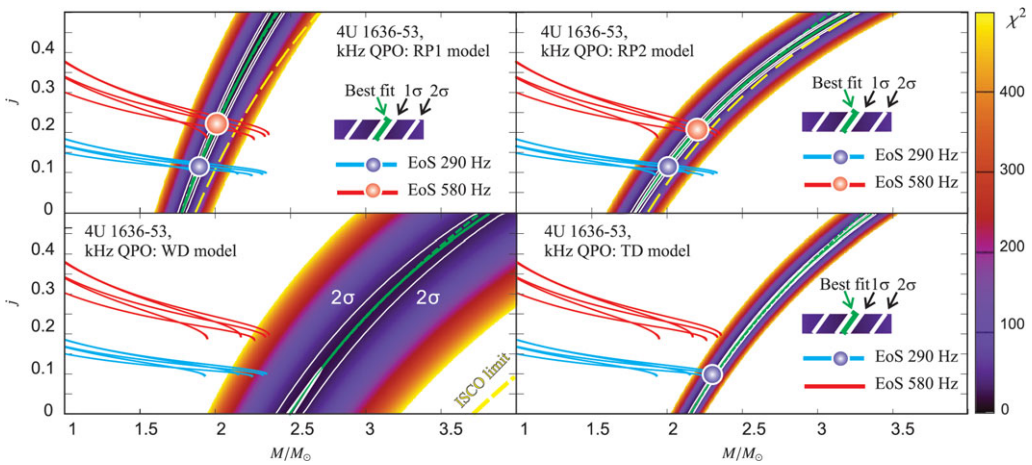
2. Our approach

We calculate χ^2 maps resulting from the fitting of the 4U 1636-53 data for various twin-peak QPO models (RP - Stella & Vietri, 1999, Stella *et al.*, 1999; RP1 - Bursa, 2005; RP2 - Török *et al.*, 2010; WD - Kato, 2001; TD - Čadež *et al.*, 2008). These maps are compared to the $M - j$ relations calculated from several NS equations of state (EoS) assuming that the spin frequency is either 290Hz or 580Hz (from one or two hot-spot models for the X-ray bursts).

For the QPO models we (yet) assume that the influence of the NS oblateness related to the quadrupole moment q is low and it is $q/j^2 \sim 1$. In the calculations of the NS models we use the geometry of the Hartle-Thorne spacetime (Hartle & Thorne, 1968) and utilize the set of various EoS. These are namely: SLy 4 - Rikovska-Stone *et al.* (2003); APR - Akmal *et al.* (1998); AU-WFF1, UU-WFF2 and WS-WFF3 - Wiringa *et al.* (1988), Stergioulas & Friedman (1995). Related details and further references are given in Urbanec *et al.* (2010a,b).

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Figure 1. Frequencies of the twin-peak QPOs in various NS sources. Right: The χ^2 map of the RP model vs. the NS EoS. The χ^2 map results from the fits of the RP model to the kHz QPO data of 4U 1636-53. The NS EoS are assumed for the rotational frequency inferred from the X-ray burst measurements. The green line indicates the best QPO χ^2 for a fixed M. The white lines indicate the corresponding 1σ and 2σ confidence levels. The dashed-yellow line indicates a simplified estimate on the upper limits on M and j assuming that the highest observed upper QPO frequency in 4U 1636-53 is associated to the innermost stable circular orbit (ISCO).

Figure 2. Mass–angular-momentum relations and limits on the NS compactness (the same as in the right panel of Figure 1, but for several other models).

In the right panel of Figure 1 we illustrate the potential of such approach in the case of the relativistic precession (RP) QPO model. Several other models are considered in Figure 2. The inferred NS parameters are summarized in Table 1.

3. Conclusions

The presented partial results come from the work in progress and the final assessment requires to complete a fully self-consistent consideration of the quadrupole moment influence. Nevertheless, each application of the concrete EoS clearly removes the degeneracy in mass and angular momentum determined from the QPO models. Moreover, the applied NS EoS seems to be compatible only with some of the considered QPO models and vice versa.

Table 1. Results for geodesic QPO models. Symbols ν_K, ν_r and ν_θ denote the Keplerian and the epicyclic orbital frequencies.

	Atoll Source 4U 1636-53			
Model	$M\,(290\,\mathrm{Hz})$	$j\,(290\,\mathrm{Hz})$	$M\,(580\,\mathrm{Hz})$	$j\,(580\,\mathrm{Hz})$
RP: $\nu_L = \nu_K - \nu_r$, $\nu_U = \nu_K$. Modes of relativistic epicyclic motion of blobs at various radii r in the accretion disc.	$1.9 M_\odot$	0.11	$2.1 M_\odot$	0.21
TD: $\nu_L = \nu_K$, $\nu_U = \nu_K + \nu_r$. The QPOs generated by a tidal disruption of large accreting inhomogeneities.	$2.3 M_\odot$	0.10	–	–
RP1: $\nu_L = \nu_K - \nu_r$, $\nu_U = \nu_\theta$. Non-axisymmetric disc-oscillation modes whose frequencies are similar to the frequencies predicted by the RP model when $j \sim 0$.	$1.8 M_\odot$	0.11	$2.0 M_\odot$	0.21
RP2: $\nu_L = \nu_K - \nu_r$, $\nu_U = 2\nu_K - \nu_\theta$. Non-axisymmetric disc-oscillation modes whose frequencies are similar to the frequencies predicted by the RP model when $j \sim 0$.	$2.0 M_\odot$	0.11	$2.2 M_\odot$	0.20
WD: $\nu_L = 2(\nu_K - \nu_r)$, $\nu_U = 2\nu_K - \nu_r$. Another specific non-axisymmetric modes of accretion disc-oscillations.	–	–	–	–

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