Radiative corrections to the neutron star mass inferred from QPO frequencies

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Received Month Day, Year

ABSTRACT

The frequencies of kHz QPOs are widely interpreted as being indicative of the values of characteristic frequencies related to orbital motion around neutron stars, e.g., the radial epicyclic frequency. In regions directly exposed to the radiation from the luminous neutron star these frequencies change with the luminosity. Including radiative corrections will change the neutron star mass value inferred from the QPO frequencies. Radiative forces may also be behind the puzzling phenomenon of parallel tracks.

Key words: Stars: neutron — accretion disks — X-rays: binaries — QPOs

1. Introduction

“Twin peak” QPOs with a pair of physically connected frequencies $\nu_U, \nu_L$ are observed in several X-ray binaries (e.g., van der Klis 2000). Physical models involve characteristic frequencies related to orbital motion, either directly (e.g., Morsink & Stella 1999), or indirectly through their effect on disk oscillation properties (e.g., Wagoner 1999, Kato 2001). The values of these frequencies depend on the mass of the central neutron star or black hole.

The frequency ratio in all black hole sources in which the twin peak QPOs have been detected is $\nu_U/\nu_L = 3/2$ exactly. In several neutron star X-ray binaries the ratio has approximately the same value, $\nu_U/\nu_L \approx 3/2$. Kluźniak & Abramowicz (2000), Abramowicz & Kluźniak (2001), and Kluźniak & Abramowicz (2002),
proposed that the twin peak QPOs may be explained by a non-linear 3:2 resonance in the epicyclic oscillations of accretion disks around the compact object in these sources. The resonance occurs because of properties of strong gravity in general relativity and hence the model predicts that the QPO frequencies scale inversely with the gravitational mass of the object,

\[ \nu \sim \frac{1}{M}. \] (1)

However, Abramowicz, Bulik, Bursa & Kluzniak (2003) pointed out that when this model is applied to the atoll and Z sources, where \( \nu_U \approx 900 \text{ Hz} \), a rather low value for the neutron star mass is obtained \( M \leq 1.2M_\odot \). In the case of Sco X-1 those authors found that the epicyclic resonance model predicts the mass to be \( M = 1M_\odot \). A similar problem occurs for most of the neutron star sources, as exhaustively discussed in a recent paper by Urbanec et al. (2010). Note that the black hole QPOs have lower frequencies, and accordingly the implied masses can be much higher, and for particular values of the Kerr parameter can be made to correspond to the measured black hole masses.

Discussing this problem, Urbanec et al. (2010) concluded that the epicyclic resonance model cannot explain the QPO phenomenon in neutron star sources, unless the oscillating accretion disks around neutron stars experience some “fairly non-geodesic” effects, i.e., when there are strong non-gravitational forces acting on the disk matter.

In this Note we suggest a natural origin for such “fairly non-geodesic” effects. We expand on an idea already suggested by Yu (2008, 2011) that radiation force affects the orbital frequencies in QPO sources, and show (in Section 3) that when the illumination of the accretion disk by the radiation emitted by the neutron star is properly included, the 3:2 epicyclic resonance model implies higher neutron star masses. The main point is that radiation forces reduce the effective gravity. The observed frequencies \( \nu_U \approx 1 \text{ kHz} \) may then be consistent with the canonical mass value \( M_* \sim 1.4M_\odot \), and even higher ones. We note that Orosz & Kuulkers (1999) measured a mass of \( 1.78 \pm 0.23M_\odot \) for the neutron star Cyg X-2, which is known to be a high luminosity twin kHz QPO source (Wijnands et al. 1998).

2. Illuminated epicyclic oscillator

Figure 1 illustrates the effect discussed here, for the epicyclic resonance model. The interior of a geometrically thin accretion disks around a neutron star is affected by radiation of the luminous boundary layer only in a very small region near the inner edge \( r_{\text{in}} \). This is because the optical depth in the radial direction is very large, and the disk is self-shadowing. This has two obvious consequences. Firstly, the radiative drag (Poynting-Robertson effect) discussed by Walker & Mészáros (1989), and others, cannot affect motion of matter inside the disk at the location of the 3:2 resonance radius \( r_{3:2} \approx 2r_{\text{in}} \). Secondly, the vertically oscillating part
of the disk (shown in Figure 1 as a toroidal ring) periodically emerges from the disk shadow, and hence, is illuminated by the boundary layer. If the oscillating torus is optically thin (as will be the case when the disk is optically thin in the vertical direction) the emergent ring will briefly be subjected to a radiative force proportional to the mass of the ring that is momentarily outside the shadow of the disk. Thus, the effective gravity on the ring is reduced by a factor proportional to the luminosity of the boundary layer.

In passing, we note that the radiation force caused by this illumination is a function of the vertical displacement, \( f = f(\delta z) \). This leads to a coupling between the vertical and radial oscillations that can be described by a forced oscillator equation,

\[
\delta \ddot{r} + \omega_r^2 \delta r = f_r(|\delta z|),
\]

where \( \omega_r \) is the radial epicyclic frequency corresponding to pure gravity (absence of illumination), and the form of the forcing function is to be calculated from the exact geometry of illumination. Such a coupling is a desirable feature in the QPO resonance model.
3. Corrections to the mass estimated from the oscillatory frequencies

Observations of the response of the twin kHz QPOs to the flux of the normal branch oscillations (NBOs) in the manner of an anti-correlation between the upper kHz QPO frequency and the NBO flux in Sco X-1 provided evidence that radiation force affects the frequency of the orbital signal on sub-second time scales (Yu, van der Klis & Jonker 2001). More solid evidence is found for this anti-correlation in the atoll source 4U 1608-52 (Yu & van der Klis 2002). Yu (2008 and 2011) suggested that the radiation force can cause the apparent QPO coherence difference between Z and atoll sources and the apparent coherence drop in several well-observed atoll sources (Barret et al. 2005, 2008), and that the radiation force effect can be used to constrain neutron star masses and radii if both radiation force and orbital frequency can be measured. For a clear positive correlation between luminosity and QPO frequency see e.g., Fig. 1 of van der Klis (2001).

The radiation force effects that are suggested by the correlated behavior of the kHz QPO frequency and the X-ray flux in both atoll sources and Z sources provide a natural origin of the “fairly non-geodesic” effects invoked by Urbanec et al. (2010). This is because radiation leads to a reduced “effective gravity” and consequently the mass $M$ that appears in (1) is not identical with the true gravitational mass of the star $M_\ast$, but instead it is the smaller “effective mass” $M = M_\ast \left(1 - \epsilon \frac{L_\ast}{L_{\rm Edd}}\right)$.

Here, $L_\ast$ is that part of the total observed luminosity $L$ that influences the disk oscillations, and the part that does not will be $L_i = L - L_\ast$, while $L_{\rm Edd}$ is the Eddington luminosity, and $\epsilon < 1$ is a factor that depends on details of the radiation field geometry and of the radiation transfer in the accretion disk. Accordingly, the mass of the neutron star predicted by the epicyclic model when radiative corrections are included is,

$$\frac{M_\ast}{M_\odot} \approx f_{3:2} \left(\frac{\nu_U}{\nu_{3:2}}\right) \left[1 - \epsilon \left(\frac{L - L_i}{L_{\rm Edd}}\right)\right]^{-1}.$$

(4)

Here $f_{3:2} \approx 900\text{Hz}$ for the 3:2 resonance in Schwarzschild metric. For different orbital resonances (discussed by several authors) the value of this coefficient will be different.

One may estimate values of $\epsilon$ and $L_i$ from observations. From (4) it follows, in the case of small $\epsilon L_i$, that

$$\nu_U = f_{3:2} \left(\frac{\epsilon M_\odot}{L_{\rm Edd} M_\ast}\right) L + f_{3:2} \frac{M_\odot}{M_\ast} \left(1 - \frac{\epsilon L_i}{L_{\rm Edd}}\right).$$

(5)

If the values of $\epsilon$ and $L_i$ do not change much during the observation period, and $L_i$ changes from one observation to another (indicated by the $i$ label), then
\[ \nu = aL + b_i. \] In this case one may estimate \( \varepsilon \) and \( L_i \) from the observable parameters \( a = a(\varepsilon, M_i) \) and \( b_i = b_i(\varepsilon, M_i, L_i) \). Thus, Eq. (5) may explain the observed parallel tracks (Méndez et al. 1999), in which the QPO frequency is proportional to the luminosity on short timescales, but for successive observations the lines on a luminosity-frequency plot are displaced in frequency by different offsets.

4. Conclusions

In conclusion we want to stress three points:

- The radiation force from the luminous neutron star will affect the orbital, and related frequencies, most strongly at the inner disk edge.

- In all previous estimates of the neutron star mass based on the 3:2 epicyclic resonance QPO model it was assumed that \( \varepsilon = 0 \), and this implied masses that were too low. The inclusion of radiation force effects will lead in a natural manner to an increased mass prediction. The brighter the neutron star source is, the more the inferred mass will be raised, since the mass was underestimated in the original models by an amount proportional to the strength of the radiation force effect. For Sco X-1, if \( \varepsilon L = 0.5 L_{\text{Edd}} \), the mass estimate would double, yielding a mass up to 2 solar masses. For atoll sources, the mass estimate would be raised by 10-20%, e.g., by \( 0.1 - 0.4 M_\odot \), assuming \( L \) is about 10-20\% \( L_{\text{Edd}} \).

- The inclusion of the radiation force may provide an explanation for the parallel tracks phenomenon.

Acknowledgements. Research supported in part by the Polish Ministry of Science (grant NN203 381436). WK acknowledges the hospitality of the Shanghai Astronomical Observatory. MAA acknowledges the support of the Czech grant MSM 4781305903

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