SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

THE COHERENCE OF KHZ QUASI-PERIODIC OSCILLATIONS IN THE X-RAYS FROM ACCRETING NEUTRON STARS

Didier Barret[1], Jean-Francois Olive[1] and M. Coleman M. Miller.[2]

Abstract. Our examination of archival *Rossi* X-ray Timing Explorer data on neutron star low-mass X-ray binaries has revealed a number of trends in the quality factors of their lower and upper kHz QPOs. We report our analysis of the sources 4U 1636–536, 4U 1608–522, 4U 1735–44, 4U 1728–34, 4U 1820–303 and 4U 0614+09. All the sources except 4U 0614+09 show a precipitous drop in the quality factor of the lower kHz QPO at the highest observed frequencies. In contrast, in all sources except 4U 1728–34, the upper kHz QPO has a quality factor that increases monotonically with increasing frequency. We demonstrate that both observed trends are consistent with generic expectations based on the idea that the region determining the frequencies approaches the innermost stable circular orbit, a feature unique to strong gravity. If this interpretation is correct, it suggests that the neutron stars in several of these systems have masses $\sim 2\,M_\odot$, which has important implications for the equilibrium state of nonrelativistic matter at several times nuclear saturation density.

1 Introduction

The large area, flexible pointing, and rapid timing capability of the *Rossi* X-ray Timing Explorer (RXTE, Bradt et al. 1993) has made possible the detection of kilohertz quasi-periodic brightness oscillations (kHz QPOs) from roughly 25 neutron star low-mass X-ray binaries (NS LMXBs; see van der Klis 2006 and references therein for discussion of the QPOs). The high frequencies of these signals (up to $\sim$ 1300 Hz) require processes close to the neutron star, suggesting that their detailed properties might be useful as probes of general relativity. As a specific example, it has been suggested that a drop in the QPO amplitude and a rapid drop in the quality factor $Q \equiv \nu/\mathrm{FWHM}$ of the QPOs might signal an approach to the innermost stable circular orbit (ISCO; see Miller, Lamb, & Psaltis 1998 for a discussion). The signals could also contain information about the mass and radius of the neutron stars in these systems, which in turn would give valuable hints about the state of matter at the supranuclear densities in their cores.

Our first study of this focused on 4U 1636–536, and in particular on how Q and the rms amplitude depend on frequency (Barret, Olive, & Miller 2005a,b). We find that the upper and lower kHz QPOs for this source follow two different tracks in $Q-\nu$ space. The lower kHz QPO rises steadily to a maximum of $Q \approx 200$ at $\nu \approx 850$ Hz, then drops precipitously at higher frequencies to $Q \sim 50$ at the highest detected frequency, $\nu \approx 920$ Hz. In contrast, the upper kHz QPO has a much lower quality factor of $Q \sim 10$ for most of the range, which shows an increasing trend with frequency and does not display a drop.

Here we apply similar analyses to all low-luminosity NS LMXBs for which RXTE data sample a wide frequency range. The sources are 4U 1636–536, 4U 1608–522, 4U 1820–303, 4U 1735–44, 4U 1728–34, 4U 0614+09 (see van der Klis 2006 for the relevant references).

2 Results

The details of the data analysis are given in Barret et al. (2006a). Figure 1 shows that the trends in quality factors observed for 4U 1636–536 are also seen in the other sources, albeit with fewer details. Note in particular

---

[1] Centre d'Etude Spatiale des Rayonnements, CNRS/UPS, 9 Avenue du Colonel Roche, 31028 Toulouse Cedex 04, France
[2] Department of Astronomy, University of Maryland, College Park, MD 20742-2421, United States

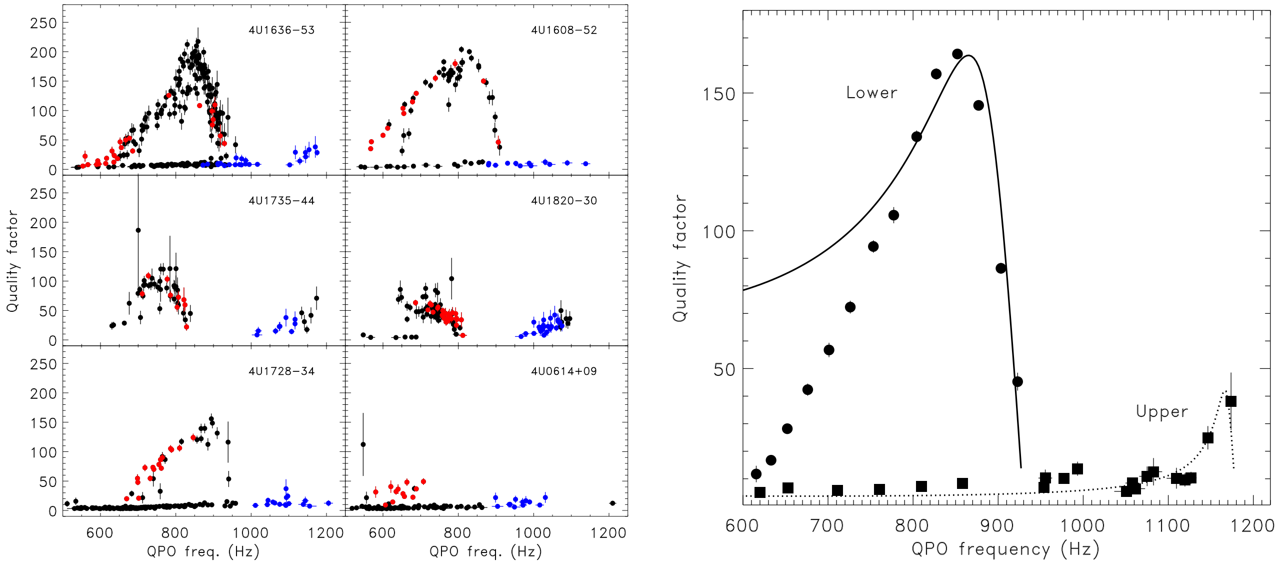

Fig. 1. *left* Quality factor versus frequency of all fitted QPOs: red circles identify fitted lower QPOs, blue circles identify fitted upper QPOs, black circles correspond to single QPOs. Each data point represents the average over a continuous data segment, after having removed the long term frequency drift using a shift-and-add technique (see Barret et al. 2006a for details). *right)* Measured quality factor of the lower and upper kHz QPOs of 4U 1636–536, compared to the quality factor estimated with the toy model for the lower (solid line) and for the upper (dashed line). Original figures and captions as in Barret et al. (2006a).

that the sharp drop in Q for the lower kHz QPO is clear in the data for 4U 1608–522, 4U 1728–34, and 4U 1735–44, and might also be present in 4U 1820–303. On the other hand, 4U 0614+09 shows only a rise in Q, not a drop; this is, in fact, a consistency check, because van Straaten et al. (2000) detected a 1330 Hz QPO from this source, and hence the ISCO frequency cannot be less than this. It is therefore not expected that ISCO-related effects could be seen at the frequencies probed by the data we analyzed. In all of the sources, Q for the upper kHz QPOs increases monotonically for the entire analyzed range.

3 Discussion

In all QPO models put forward so far, none provides a satisfactory explanation for the high quality factor observed, its dependence on frequency, and the significantly different behaviours of the quality factors of the upper and lower QPOs. This means that caution is needed when interpreting the above results. However, as we have already emphasized in Barret et al. (2005a,b), the evidence in 4U 1636–536 for a frequency ceiling independent of count rate and a sharp drop in the quality factor at a fixed frequency is consistent with prior expectations for effects due to the ISCO. If the ISCO is indeed responsible for the trends observed in the data, one can discuss the implications in terms of neutron star masses and elaborate a simple model involving the ISCO and compare its prediction with the data. This is the scope of the next two subsections.

3.1 Implication for neutron star masses

If the ISCO frequency $\nu_{\rm ISCO}$ can be inferred, then the neutron star gravitational mass is

$$M \approx 2.2\, M_\odot (1000~{\rm Hz}/\nu_{\rm ISCO})(1+0.75j) \tag{3.1}$$

where $j \equiv cJ/GM^2$ is the dimensionless angular momentum, $j \sim 0.1$ for observed spins and plausible masses and equations of state. How, then, can we infer $\nu_{\rm ISCO}$? Despite uncertainty in details, currently viable models suggest that the upper kHz QPO is close to an orbital frequency (e.g., Miller et al. 1998; Lamb & Miller 2001, 2003) or a vertical epicyclic frequency (e.g., Stella & Vietri 1998; Stella, Vietri, & Morsink 1999; Psaltis &

Norman 2000; Abramowicz et al. 2003; Lee, Abramowicz, & Kluźniak 2004; Bursa et al. 2004; Kluźniak & Abramowicz 2005), which for orbits around a neutron star is at most a few Hertz different from the orbital frequency (Marković 2000). Our primary inference about the ISCO, however, comes from the *lower* kHz QPO, not the upper. Fortunately, in the sources we study, as well as in many others, the separation between the two QPOs remains close to either the spin frequency or half the spin frequency. Therefore, to a good approximation, we can add the spin or half the spin to the frequency at which $Q_{\rm lower}$ would project to zero, and use this as an estimate of the ISCO orbital frequency. For the three of our sources with known spin frequency, this gives $\nu_{\rm ISCO} \approx 1220$ Hz for 4U 1636–53, $\nu_{\rm ISCO} \approx 1230$ Hz for 4U 1608–52, and $\nu_{\rm ISCO} \approx 1310$ Hz for 4U 1728–34.

The inferred masses of these neutron stars are in the $1.8 - 2.1\,M_\odot$ range. This is greater than the masses in double neutron star binaries (see, e.g., Cordes et al. 2004 for a recent review). Howver, it is comparable to the masses determined for Vela X-1 (Quaintrell et al. 2003) and PSR J0751, which has a detached low-mass companion (Nice et al. 2005). These masses are also consistent with modern equations of state for cold high-density matter, which accommodate maximum masses for slowly rotating ($j \ll 1$) stars of $\sim 1.8 - 2.3\,M_\odot$ (Akmal, Pandharipande, & Ravenhall 1998; Lattimer & Prakash 2001; Klähn et al. 2006).

3.2 Advection based toy model

Some insight into how an approach to the ISCO can affect Q quantitatively can be obtained through a simplified toy model. Suppose, as in most currently viable models, that the observed QPO frequencies are determined by some process that operates in a region at $r_{\rm orb}$ of width $\Delta r_{\rm orb}$ in the disk. We note that simple energy arguments suggest that most of the energy has to be released at the stellar surface even if the observed frequencies are established in the disk. Let us assume that the oscillation lasts $N_{\rm cycles}$ cycles, and that it is advected with the accreting matter, assumed to have an inward radial speed v_r. The finite lifetime, radial drift, and finite width of the region then all contribute to the observed frequency width. In contrast, if the spin interaction is resonant, this is not expected to broaden the QPO significantly. The frequency width of the lower peak is then governed by the following factors:

1. $\Delta\nu_{\rm drift}$, which is the frequency width produced by radial drift.
2. $\Delta\nu_{\rm orb}$, which is the frequency width at a given instant due to the finite width of the active region.
3. $\Delta\nu_{\rm life}$, which is the frequency width produced by the finite lifetime of the oscillation.

If we assume that these widths add in quadrature, then the total width of the QPO is $\Delta\nu_{\rm total}$ as

$$\Delta\nu_{\rm total} = \sqrt{(\Delta\nu_{\rm drift})^2 + (\Delta\nu_{\rm orb})^2 + (\Delta\nu_{\rm life})^2}\ , \tag{3.2}$$

and the quality factor is $Q_{\rm lower} = \nu_{\rm lower}/\Delta\nu_{\rm total}$.

In Barret et al. (2006a, which should be consulted for details, in particular for an estimate of each of the three contributions), we describe a simple model in which we assume that $N_{\rm cycles}$ is constant with radius and that the radial drift and its gradient are described generically by a rate of loss of specific angular momentum of the inspiralling gas (caused, e.g., by interaction of the gas with the stellar radiation field or magnetic field). The overall frequency scale is set by an assumption of $\nu_{\rm ISCO}$ and the spin frequency. The right hand panel of Fig. 1 shows a fit to the data for 4U 1636–536 for this model, showing that it reproduces the rapid drop of Q for the lower QPO at high frequencies. As shown in Barret et al. (2006a), at the lowest frequencies, the main contribution to the total width is $\Delta\nu_{\rm orb}$, whereas at frequencies above 850 Hz, it is $\Delta\nu_{\rm drift}$ which dominates. Additional broadening mechanisms would be necessary to explain the lower Q at low frequencies (to increase $\Delta\nu_{\rm orb}$), but there are many such mechanisms available.

Can a slight modification of this idea account for the different trends visible for the upper QPO? Barret et al. (2006a) show that, indeed, the overall lower Q can be explained if there is one extra broadening mechanism (e.g., if the way the gas falls onto the surface tends to produce a spread in the observed frequencies), which we model as $\Delta\nu_{\rm orb,upper} = x_{\rm upper}\Delta\nu_{\rm orb,lower}$ where in the simplest picture $x_{\rm upper}$ is a radius-independent free parameter. As the right hand panel of Fig. 1 shows, $x_{\rm upper} = 20$ does remarkably well for 4U 1636–536.

4 Conclusions

The RXTE data are consistent with the picture that the sharp drop in Q is caused by an approach to the ISCO. If correct, this is an exciting and profound conclusion, as it implies that we are seeing the result of a predicted strong-gravity effect. In addition, the implication of masses $\sim 2\,M_\odot$ for several neutron stars has important consequences for the properties of very dense matter. Because of the importance of these conclusions, we are pursuing additional avenues of analysis to determine whether the quality factor could be instead driven by factors such as the mass accretion rate (see Méndez 2006), or whether, as seems demanded by the data for 4U 1636–536, it is in fact the frequency that governs the quality factor. If the latter, the ISCO is a strong candidate for why Q drops sharply. This will be the scope of a forthcoming paper (Barret, Olive, Miller, 2006b).

References

Abramowicz M. A. et al. 2003 PASJ, 55, 467

Akmal A., Pandharipande V. R., Ravenhall D. G. 1998, PhRvC, 58, 1804

Barret D., Olive J. F., Miller M. C. 2006b, MNRAS, submitted

Barret D., Olive J. F., Miller M. C. 2006a, MNRAS, 370, 1146

Barret D., Olive J. F., Miller M. C. 2005a, MNRAS, 361, 855

Barret D., Olive J. F., Miller M. C. 2005b, AN, 326, 808

Barret D., Kluźniak W., Olive J. F., Paltani S., Skinner G. K. 2005c, MNRAS, 357, 1288

Bradt H. V., Rothschild R. E., Swank J. H. 1993, A&AS, 97, 355

Bursa M., Abramowicz M. A., Karas V., Kluźniak W. 2004 ApJ, 617, L45

Cordes J. M. et al. 2004 NewAR, 48, 1413

Klähn T. et al., 2006 Phys. Rev. C, submitted (nucl-th/0602038)

van der Klis M. 2006, in Compact stellar X-ray sources, ed. W. H. G. Lewin, & M. van der Klis (Cambridge: Cambridge Univ. Press), in press (astro-ph/0410551)

Kluźniak W., Abramowicz M. A. 2005, Ap & SS, 300, 143

Lamb F. K., Miller M. C. 2001, ApJ, 554, 1210

Lamb F. K., Miller M. C. 2003, ApJ, submitted (astro-ph/0308179)

Lattimer J. M., Prakash M., 2001 ApJ, 550, 426

Lee W. H., Abramowicz M. A., Kluźniak W. 2004, ApJ, 603, L93

Marković D. 2000 (astro-ph/0009450)

Méndez M., et al. 1998, ApJ, 494, L65

Méndez M. 2006, MNRAS, 371, 1925-1938.

Miller M. C., Lamb F. K., Psaltis D. 1998, ApJ, 508, 791

Nice D. J. et al. 2005, ApJ, 634, 1242

Psaltis D., Norman C. 2000, astro-ph/0001391

Quaintrell H. et al. 2003, A&A, 401, 313

van Straaten S. et al. 2000 ApJ, 540, 1049

Stella L., Vietri M. 1998, ApJ, 492, L59

Stella L., Vietri M., Morsink S. 1999, ApJ, 524, L63