

# Drop of coherence of the lower kilo-Hz QPO in neutron stars: Is there a link with the innermost stable circular orbit?

D. BARRET<sup>1</sup>, J.-F. OLIVE<sup>1</sup>, and M. COLEMAN MILLER<sup>2</sup>

<sup>1</sup> Centre d'Etude Spatiale des Rayonnements, CNRS/UPS, 9 Avenue du Colonel Roche, 31028 Toulouse Cedex 04, France

<sup>2</sup> Department of Astronomy, University of Maryland, College Park, MD 20742-2421, USA

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**Abstract.** Using all available archival data from the Rossi X-ray Timing Explorer (RXTE), we follow the frequency of the kilo-Hz QPOs in three low luminosity neutron star low mass X-ray binaries; namely 4U 1636-536, 4U 1608-522, and 4U 1735-44. Following earlier work by Barret et al. (2005a,b), we focus our analysis on the lower kilo-Hz QPO, for which we study the dependency of its quality factor ( $Q = \nu/\Delta\nu$ , where  $\Delta\nu$  is the FWHM) and amplitude as a function of frequency over a range covering from 500 Hz to 1000 Hz. As previously found for 4U 1636-536, we show that the quality factor of the lower kilo-Hz increases with frequency up to a maximum frequency around 800 Hz, beyond which an abrupt drop of its coherence is observed down to a limiting frequency where the QPO disappears completely. Simultaneously the amplitude of the QPOs is almost constant below the peak frequency and starts to decrease smoothly afterwards. The peak frequency is 850 Hz, 820 Hz, 740 Hz whereas the limiting frequency is 920 Hz, 900 Hz and 830 Hz for 4U 1636-536, 4U 1608-522 and 4U 1735-44 respectively. A ceiling of the lower QPO frequencies is also seen clearly in a frequency versus count rate diagram for all sources. This behavior is reproducible within an object and between objects. We suggest here that the drop of coherence of the lower QPO may be a geometry-related effect, which could be related to the last stable circular orbit.

**Key words:** accretion, accretion disk – stars: individual (4U 1636-536, 4U 1608-522, 4U 1735-44) – stars: neutron – X-rays: stars

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## 1. Introduction

Using archival data from the Rossi X-ray Timing Explorer (RXTE), we have studied in a systematic way the variation of the quality factor ( $Q = \nu/\Delta\nu$ , where  $\Delta\nu$  is the FWHM) and amplitude of the lower and upper kilo-Hz quasi-periodic oscillations (QPO) in the low-mass X-ray binary 4U 1636-536. It has been shown that the lower and upper QPO follow two different tracks in a frequency versus quality factor, as represented. The lower QPO is a relatively broad feature with  $Q \sim 20$  at  $\sim 600$  Hz. Its quality factor then increases steadily up to  $Q \sim 200$  at  $\sim 850$  Hz, beyond which it drops precipitously to  $Q \sim 30$  at the highest detected frequencies  $\sim 920$  Hz. The drop of coherence is accompanied by a smooth drop of amplitude. A ceiling of the QPO frequency at the latter frequency is also clearly seen in a frequency-count rate diagram. The behavior of the lower QPO of 4U 1636-536 is summarized in Fig. 1.

On the other hand, the upper QPO shows a clear positive correlation between its quality factor and its frequency, with

*Correspondence to:* barret@cesr.fr

no evidence for a drop when it reaches its highest frequencies. The amplitude of the upper QPO decreases steadily with frequency, bringing the signal down to the sensitivity level of our analysis, and therefore making the measurement of its quality factor difficult and certainly subject to biases (only the narrower signals are seen; see Barret et al. (2005b) for details).

Saturation of frequency and drops of amplitude and coherence of kilo-Hz QPOs were anticipated as possible signatures of the innermost stable circular orbit (ISCO) around a sufficiently compact neutron star (Miller et al. 1998). It was however thought that this should be seen firstly for the upper QPO, which in most models, is associated with orbital motion.

In this paper, we present the results of an analysis of the lower QPO in two additional sources: 4U 1608-522 and 4U 1735-44, using all the publicly available RXTE archival data as of July 2005. We have selected 4U 1608-522 because in a rather limited data set, a loss of coherence of the lower QPO was reported by Berger et al. (1996) and Barret et al. (2005a). The choice of 4U 1735-44 is motivated by the fact

that not much is known about its kilo-Hz QPOs (see however Wijnands et al. 1998 and Ford et al. 1998), while the source has been rather extensively observed with RXTE.

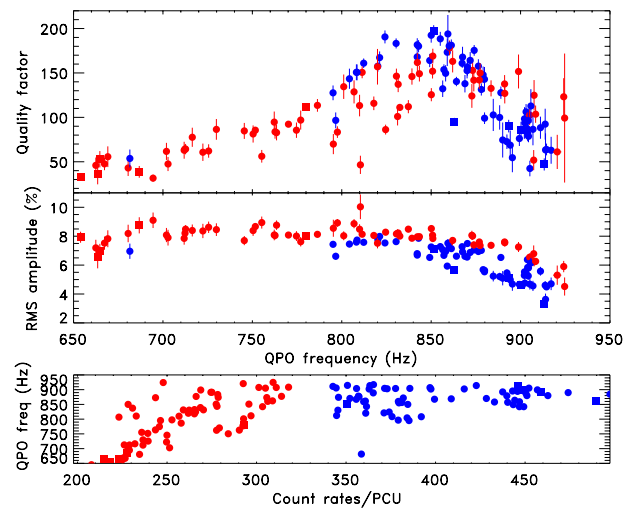
## 2. Data analysis

The analysis is performed the exact same way as in Barret et al. (2005b). We have retrieved all the Proportional Counter Array science event files with time resolution better than or equal to 250 micro-seconds. Only data files with exposure times larger than 600 seconds are considered here. For 4U 1608-522, the data set covers the period from March 1996 to March 2004, whereas for 4U 1735-44 the data cover from August 1997 to September 1999. No filtering on the raw data is performed, which means that all photons are used in the analysis, and only time intervals containing X-ray bursts are removed. We have computed Leahy normalised Fourier power density spectra (PDS) between 1 and 2048 Hz over 8 s intervals (with a 1 Hz resolution).

Because at their lowest end, QPOs are broad features (with  $Q$  of a few), the analysis is restricted to QPOs detected above 500 Hz. The first stage analysis intends to estimate the  $Q$  the strongest QPO by removing as much as possible the long term frequency drift within the segment. This is achieved through a shift-and-add technique performed on the shortest possible timescales permitted by the data statistics. In this analysis, the possible timescales considered are 16, 32, 64, 128, 256, 512 and 1024 seconds. The first product of our analysis is therefore the mean parameters of the strongest QPO, which is fitted with a Lorentzian, above a fitted counting noise level. In some data files, two QPOs can be detected, allowing direct identification of the strongest one. In 4U 1608-522, it is generally the lower QPO which is the strongest of the two. This is not the case for 4U 1735-44. As previously found in Barret et al. (2005b), in those segments where only one QPO is detected, the position of the QPO on a quality factor versus frequency plot allows its identification. For 4U 1636-536, we have shown that QPOs with  $Q$  larger than  $\sim 20$  in the range 650 Hz to 950 Hz are lower QPOs. For 4U 1608-522, lower QPOs have a minimum  $Q$  of  $\sim 50$  between 600 and 900 Hz. For 4U 1735-44 a limiting  $Q$  of  $\sim 30$  is inferred. In Figs. 2 and 3, we show the dependency of the quality factor and amplitude of the identified lower QPOs of 4U 1608-522 and 4U 1735-44. These two figures show that the behavior seen from 4U 1636-536 is also present in these two objects; mostly a drop of coherence at a critical frequency. The properties of the upper QPOs will be described in a forthcoming paper, but as in 4U 1636-536, we have not found clear evidence of a drop of coherence at the highest detected frequencies. Note that the maximum  $Q$  value observed for 4U 1608-522 is remarkably similar to the one of 4U 1636-536 (it is significantly smaller for 4U 1735-44).

## Discussion

The rapid drop seen in the quality factor of the lower QPO in 4U 1636-536, 4U 1608-52, and 4U 1735-44 occurs reproducibly at a particular frequency for each source: the peak



**Fig. 1.** The quality factor of the lower kilo-Hz QPO in 4U 1636-536 showing a smooth rise with frequency up to a critical frequency beyond which a rather abrupt drop is observed. The colors indicate the separation between the observations performed at count rate below (red) and above (blue) the mean count rate of all the observations. The filled squares are those points for which an upper QPO was detected above the  $2\sigma$  level in the same segment. The mid panel shows the dependency of the amplitude of the lower QPO with frequency. The amplitude remains more or less constant up to the critical frequency and then decreases smoothly afterwards. The bottom panel shows the frequency against the mean count rate within a continuous segment of data. Whatever the count rate is, the QPO frequency does not exceed a limiting frequency. This figure shows that the frequency, rather than the count rate, is the governing parameter for the properties of the lower QPO.

frequency is 850 Hz, 820 Hz, and 740 Hz for 4U 1636-536, 4U 1608-522 and 4U 1735-44, respectively. At the same time, the “parallel tracks” phenomenon (e.g. Méndez et al. 2001) means that a given frequency can be reached at many different count rates. We therefore observe a phenomenon that appears to depend primarily on frequency rather than count rate. Indeed, as Figs. 1 to 3 show, the dependence of quality factor on frequency, and of rms amplitude on frequency, is consistent between the high and low count rate samples. In addition, the saturation frequency is the same over a factor of two in count rate. What does this imply about the mechanism that decreases the quality factor?

If the clock that determines the QPO frequencies originates in the disk and is related to orbital, epicyclic, or beat frequencies, then the sharp drop in  $Q$  at a fixed frequency implies that there is some particular radius in the disk inside of which the mechanism that generates QPOs loses coherence. There are several different factors that contribute to the sharpness of the QPO. For example the quality factor depends on (1) the range of radii over which the QPOs are generated, (2) the number of cycles that the QPO lasts, and (3) the amount by which the radius of QPO generation drifts radially during its lifetime. In addition, assuming that most of the energy in the QPO is actually released upon impact with the stellar surface, changes in the dynamics of the boundary layer could affect the quality factor.

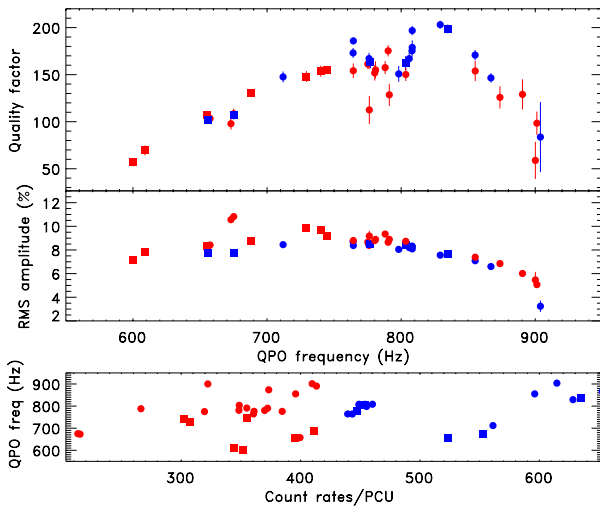


Fig. 2. Same as Fig. 1 for 4U 1608-522.

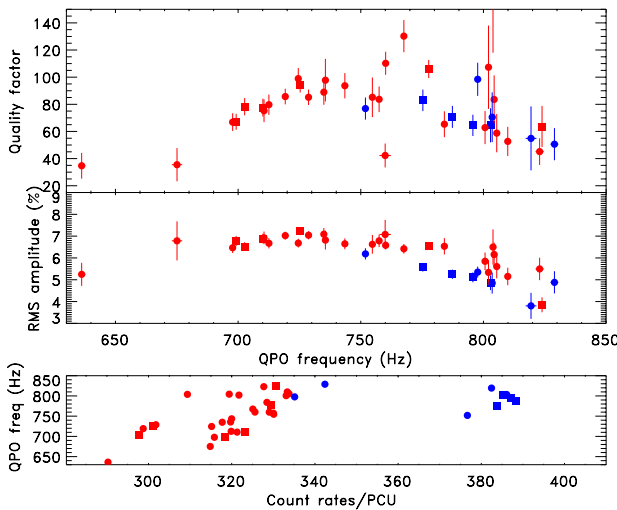


Fig. 3. Same as Fig. 1 for 4U 1735-44.

With this in mind, it could in principle be that when the radius of QPO generation reaches some critical point, interactions with the stellar magnetosphere or the properties of the boundary layer change suddenly and the quality factor drops. However, one would expect that if the mass accretion rate were to change significantly, the details of the plasma interactions would also change, leading to a significant variation in the quality factor with mass accretion rate. The current evidence is that the QPO properties do not correlate well with countrate, but countrate is not a reliable measure of mass accretion rate (e.g. Méndez et al. 2001). If it is demonstrated that the dependence of quality factor on frequency is roughly independent of mass accretion rate, then these scenarios would be less likely.

An attractive option would then be that the root cause of the drop in quality factor has to do with the geometry of the spacetime, because this would depend directly on the radius of QPO generation and only secondarily on details of plasma interactions. This would also explain the consistency of the saturation frequency and rms vs. frequency curves over many

countrates. A natural candidate for a mechanism is one related to the flattening of the specific angular momentum curve with radius near the innermost stable circular orbit (ISCO). The gas orbiting around the neutron star is subjected to a number of stresses that remove angular momentum, hence close to the ISCO the inward radial speed will tend to increase. This can help define a narrow range of radii in which the QPO is generated, which will tend to increase the quality factor as the radius decreases (see Miller et al. 1998). This could explain the gradual rise in  $Q$  with frequency at low frequencies. However, if the range of radii covered during the lifetime of the QPO becomes too large, the range of frequencies sampled during its lifetime is also large, hence the quality factor drops sharply when the radius is too close to the ISCO. Because the upper QPO has a lower quality factor than the lower QPO, the crossover point (where radial drift becomes dominant) would be at smaller radius, hence in this scenario it makes sense that the higher  $Q$  oscillation would show a drop in  $Q$  at a lower frequency, whereas the upper QPO would not necessarily show a clear drop.

If this interpretation is correct then one may use the sharp drop in coherence to estimate the frequency of the ISCO. We assume that  $Q = 0$  corresponds to the ISCO. The frequency at which this will occur is somewhat uncertain, because of the lack of a fundamental theory to predict the functional dependence of  $Q$  on frequency. We will use a linear extrapolation, which appears to fit the data adequately. This gives us a maximum frequency  $\nu_{\text{low,max}}$  for the lower QPO. We then assume, as in most models, that the upper QPO is at approximately the orbital frequency at some radius in the disk and the lower QPO is less than this by approximately the spin frequency or half the spin frequency, depending on the source (Wijnands et al. 2003; see Lamb & Miller 2005 for a theoretical discussion). We therefore estimate the orbital frequency at the ISCO by adding the difference frequency between the upper and lower QPOs, so  $\nu_{\text{ISCO}} \approx \nu_{\text{low,max}} + \Delta\nu$ . Using this approach, we estimate  $\nu_{\text{ISCO}} \approx 1200 - 1300$  Hz in these three sources. The mass then follows from

$$M/M_{\odot} = (\nu_{\text{ISCO}}/2200 \text{ Hz})(1 + 0.75j) \quad (1)$$

(Miller et al. 1998), where  $j \equiv cJ/GM^2$  is the dimensionless angular momentum, with  $j \approx 0.1$  a typical value. Therefore,  $\nu_{\text{ISCO}} \approx 1200 - 1300$  Hz implies  $M \sim 1.8 - 2.0 M_{\odot}$ . This is higher than inferred for double neutron stars but consistent with modern equations of state for matter beyond nuclear density (Lattimer & Prakash 2001).

The ISCO interpretation of the sharp drop in quality factor is subject to falsification in at least two ways. First, the interpretation is obviously incorrect if in a given source a QPO is observed above the putative ISCO frequency. The uncertainty in extrapolation to  $Q = 0$  means that there is some leeway, but not more than a few tens of Hertz. The second possibility is that a source shows behavior similar to that described here, but at a frequency low enough that the implied mass is higher than plausible for a neutron star. From Lattimer & Prakash (2001),  $M < 2.8 M_{\odot}$  is required even for mean field theories, so if the inferred  $\nu_{\text{ISCO}} < 800$  Hz for any source then this interpretation is called into question. However, if neither of these falsifications occur and additional sources

show a sharp drop in  $Q$  that depends only on frequency, the data may indeed be showing evidence for the innermost stable circular orbit.

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