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kHz quasi-periodic oscillations in the low-mass X-ray binary 4U 0614+09

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ABSTRACT

We report on a comprehensive analysis of the kilohertz (≥300 Hz) quasi-periodic oscillations (kHz QPOs) detected from the neutron star low-mass X-ray binary 4U 0614+09 with the Rossi X-ray Timing Explorer. With a much larger data set than previously analysed (all archival data from 1996 February up to 2007 October), we first investigate the reality of the 1330 Hz QPO reported by van-Straaten et al. This QPO would be of particular interest since it has the highest frequency reported for any source. A thorough analysis of the same observation fails to confirm the detection. On the other hand, over our extended data set, the highest QPO frequency we measure for the upper kHz QPO is at ∼1224 Hz; a value which is fully consistent with the maximum values observed in similar systems. Secondly, we demonstrate that the frequency dependence of the quality factor ($Q = \nu/\Delta\nu$) and amplitude of the lower and upper kHz QPOs follow the systematic trends seen in similar systems. In particular, 4U 0614+09 shows a drop of the quality factor of the lower kHz QPO above ∼700 Hz. If this is due to an approach to the innermost stable circular orbit, it implies a neutron star mass of $\sim 1.9\,M_{\odot}$. Finally, when analysing the data over fixed durations, we have found a gap in the frequency distribution of the upper QPO, associated with a local minimum of its amplitude. A similar gap is not present in the distribution of the lower QPO frequencies, suggesting some cautions when interpreting frequency ratio distributions, based on the occurrence of the lower QPO only.

Key words: accretion, accretion discs – dense matter – gravitation – X-rays: binaries – X-rays: general.

1 INTRODUCTION

Kilohertz quasi-periodic oscillations (kHz QPOs) have been reported from 4U 0614+09 by Ford et al. (1997), van Straaten et al. (2000), van Straaten et al. (2002), Barret et al. (2006) and Méndez (2006). The peculiar properties of its kHz QPOs motivate the present work for three main reasons. First, among kHz QPO sources, 4U 0614+09 holds the record for the highest claimed QPO frequency, 1330 Hz (van Straaten et al. 2000), whereas in most sources the maximum frequency for the upper kHz QPO lies around 1200 Hz. This is of particular importance because it sets the most stringent constraints on the mass and radius of the neutron star (NS), under the assumption that 1330 Hz is an orbital frequency (Miller, Lamb & Psaltis 1998). Unfortunately, 4U 0614+09 tends to have a low count rate and broad QPOs compared to similar sources, hence its QPOs are challenging to characterize.

Secondly, Barret et al. (2006) have performed a systematic study of the quality factor of the lower and upper kHz QPOs in six systems: 4U 1636−536; 4U 1608−522; 4U 1735−44; 4U 1728−34; 4U 1820−303 and 4U 0614+09. Using data available in the Rossi X-ray Timing Explorer (RXTE) archive at the end of 2004, they found that all the sources except 4U 0614+09 showed evidence of a drop in the quality factor of their lower kHz QPOs at high frequency. For 4U 0614+09 only the rising part of the quality factor versus frequency curve was reported. The sudden drop is consistent with what is expected if it is produced by the approach of an active oscillating region to the innermost stable circular orbit (ISCO), a key feature of strong-gravity general relativity (see, however, Méndez 2006 for a different interpretation). With the availability of more data in the RXTE archive, it is now possible to search for a quality factor drop similar to that seen in other sources.

Thirdly, 4U 0614+09 has recently drawn further attention, after the detection of burst oscillations at 414 Hz with the Burst Alert Telescope on board *SWIFT* (Strohmayer, Markwardt & Kuulkers 2008). The latter frequency which is likely to be the neutron star spin frequency (ν_s) is to be compared with the frequency difference $\Delta\nu \sim 320$ Hz between twin kHz QPOs reported so far (van Straaten et al. 2000). Clearly, the ratio $\Delta\nu/\nu_s$ was not consistent with either 0.5 or 1, observed in similar systems. This particular result was consistent with recent suggestions by Yin et al. (2007) and Méndez & Belloni (2007) that the kHz QPO frequency difference may not have a strong connection to the neutron star spin frequency in some

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sources (but see also the discussion in Barret, Boutelier & Miller 2008). A closer inspection of the frequency difference of the twin QPOs over a much larger data set is therefore needed in light of this result, but also because a significant scatter is present in the values reported by van Straaten et al. (2000).

Here, we perform an analysis of more than 11 years of RXTE data on 4U 0614+09. In Section 2, we describe our analysis scheme and present our main results. We discuss the implications of our results in Section 3.

2 OBSERVATIONS AND DATA ANALYSIS

We have retrieved from the High Energy Astrophysics Science Archive Research Center (HEASARC) archive science event mode data recorded by the RXTE Proportional Counter Array. The data set spans over 11 years from 1996 February 26 to 2007 October 17. We consider segments of continuous observation (ObsIDs): 763 ObsIDs were analysed with a typical duration of 3000 s. For each ObsID, we have computed an average power density spectrum (PDS) with a 1 Hz resolution, using events recorded between 2 and 40 keV. The PDS are normalized according to Leahy et al. (1983), so that the Poisson noise level is constant around 2. The PDS is then blindly searched for excess power between 300 and 1400 Hz using a scanning technique, as presented in Boirin et al. (2000). The frequency range searched includes the highest QPO frequency reported so far (van Straaten et al. 2000). We have also verified that no significant excesses were detected between 1400 and 2048 Hz. This justifies the use of the 1400–2048 Hz range to estimate accurately the Poisson noise level in each observation. Each excess (at most the 2 strongest) is then fitted with a Lorentzian with three free parameters: frequency; full width at half-maximum (FWHM; constrained to range from 2 to 1000 Hz) and amplitude (equal to the integrated power of the Lorentzian). The Poisson noise level is fitted separately above 1400 Hz and then frozen when fitting the QPOs. Errors on each parameter are computed with $\Delta\chi^2 = 1$. As in previous papers in this field, our threshold for QPOs is related to the ratio (hereafter *R*) of the Lorentzian amplitude to its 1σ error[1] (*R* was often quoted and used as a significance). In this paper, our threshold for *R* is 3, meaning that we consider only QPOs for which we can measure the power of the Lorentzian with an accuracy of 3σ or more. Such a threshold corresponds to a $\sim 6\sigma$ excess power in the PDS for a single trial, equivalent to $\sim 4\sigma$ if we account for the number of trials of the scanning procedure (van der Klis 1989). Furthermore, as expected we have found that *R* positively correlates with the single trial significance of the excess power in the PDS. It is worth mentioning that the proportionality coefficient is close to 2; i.e. the QPO with the highest *R* ratio $\sim$10 corresponds to a $\sim 20\sigma$ (single trial) excess power in the associated PDS. The integrated power of the Lorentzian is then converted into a rms, expressed as a fraction of the total source count rate. As said above, the QPOs in 4U 0614+09 can be broad. In order to recover properly the parameters of the QPOs in the low-frequency end ($\sim$400–700 Hz), the continuum underneath the QPO must be accounted for. Following van Straaten et al. (2002), the continuum is adjusted with one or two zero centred Lorentzians. An example of such a fit is shown in Fig. 1, showing the decomposition of the PDS into several components.

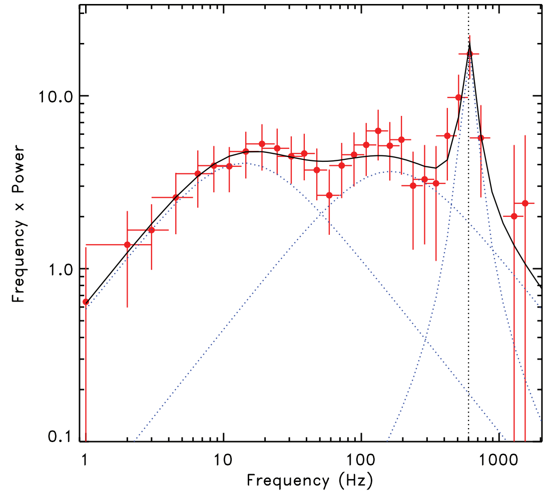

Figure 1. Illustration of the multi-Lorentzian fit of the PDS for the ObsID 10095-01-01-00 recorded on 1996 April 22 at 22:32 pm. The broad zero-centred Lorentzian peaking around 200 Hz must be included in the fit to recover properly the parameters of the kHz QPO at 600 Hz. This was also noted by van Straaten et al. (2002), who adjusted the low-frequency continuum with one or two zero centred Lorentzians.

As a result of this systematic analysis, in 210 ObsIDs we detected a single QPO, and in 24 ObsIDs we found two simultaneous QPOs (in one ObsID, two QPOs were detected but not simultaneously). Tables 1 and 2 summarize all the QPO detections (the full versions of these tables are available in the electronic version of the paper – see the Supporting Information). The remaining ObsIDs, which contained no QPOs, were removed from the subsequent analysis. The quality factor and rms amplitude versus frequency of all detected QPOs are shown in Fig. 2. The patterns identified in other similar systems by Barret et al. (2006) are also seen for 4U 0614+09. In particular, in the quality factor versus frequency plot, lower and upper QPOs occupy two distinct regions: the quality factor of lower QPOs is larger than the quality factor of upper QPOs and the quality factor of the upper QPOs rises steadily with frequency (note that the scatter in the quality factor of the lower QPOs is in part because it is not corrected for the frequency drift within the ObsID). Similarly, there is a clear trend (albeit with some scatter) for the rms amplitude of the upper QPOs to decrease with increasing frequency, whereas the rms amplitude of the lower QPOs increases first to reach a plateau (see below for a full description of the amplitude of the lower QPO). Note also that the rms amplitude of the upper QPO, when its frequency is around 1150–1250 Hz lies above the extrapolation of the blue dashed line, passing through the rms values measured at lower frequencies. Finally, it is worth mentioning that there is a gap in the frequency distribution of the upper QPO, between 1020 and 1130 Hz (this point will be discussed in more detail below).

2.1 On the 1330 Hz QPO

As can be seen from Fig. 2, the highest QPO frequency detected in our systematic analysis is at about 1220 Hz; hence, we do not detect

[1] The Lorentzian function used in the fit is $\mathrm{Lor}(\nu) = \mathrm{AW}/(2\pi)/[(\nu - \nu_0)^2 + (\mathrm{W}/2)^2]$, where *A* is the integrated power of the Lorentzian from 0 to ∞, *W* its width and ν_0 its centroid frequency. The fitted function is linear in *A*, and therefore its error can be computed using $\Delta\chi^2$ (e.g. Press et al. 1992). The rms amplitude is a derived quantity, computed as $\mathrm{rms} = \sqrt{A/S}$, where *S* is the source count rate (van der Klis 1989). In this paper, we have defined $R = A/\delta A$, from which the error on the rms is estimated as $\delta\mathrm{rms} = 1/2 \times \mathrm{rms} \times R^{-1}$ after neglecting the term δS/S in the derivative of the rms equation.

Table 1. The parameters of the single detected QPOs together with information concerning the observations: the ObsID name (ObsID), the date of the observation (date), the start time of the observation (time, UTC), the observation duration ($T_{\rm obs}$), the source count rate divided by the number of active PCU units (rate), the background count rate (also divided by the number of active PCU units) (Bkg), the frequency (ν), FWHM, fractional rms amplitude (rms, per cent) and the R ratio, which is computed as the Lorentzian integrated power divided by its 1σ error (the larger R., the more significant the QPO: $R \sim 3$ corresponds to a $\sim 6\sigma$ (single trial) excess in the power spectrum, see the text for details). The full table is available online – see the Supporting Information.

ObsID	Date	Time	$T_{\rm obs}$	Rate	Bkg	ν	FWHM	rms	R
10072-02-02-00	1996-03-16	09:10	3456.0	92.8	19.1	725.0 ± 9.3	108.3 ± 24.4	16.3 ± 1.4	6.0
10072-02-02-00	1996-03-16	10:46	1120.0	95.4	19.1	753.3 ± 26.0	154.9 ± 55.1	17.5 ± 2.4	3.6
10095-01-01-00	1996-04-22	20:56	3440.0	89.0	17.9	565.4 ± 18.8	133.1 ± 52.8	15.9 ± 2.6	3.1
10095-01-01-00	1996-04-22	22:32	3456.0	108.5	17.9	601.0 ± 18.4	128.6 ± 37.6	14.1 ± 1.7	4.2
10095-01-02-00	1996-04-24	13:19	2192.0	133.6	20.9	582.8 ± 2.1	16.9 ± 7.3	8.2 ± 1.1	3.7

Table 2. The parameters of the twin QPOs together with information concerning the observations: the ObsID name (ObsID), the date of the observation (date), the start time of the observation (time, UTC), the observation duration ($T_{\rm obs}$), the source count rate divided by the number of active PCU units (rate), the background count rate (also divided by the number of active PCU units) (Bkg), the frequency $\nu_{l,u}$, FWHM$_{l,u}$, fractional rms amplitude (rms$_{l,u}$, per cent) and the $R_{l,u}$ ratio, which is computed as the Lorentzian integrated power divided by its 1σ error, for the lower and upper QPO, respectively. The full table is available online – see the Supporting Information.

ObsID	Date	Time	$T_{\rm obs}$	Rate	Bkg	ν_l	FWHM$_l$	rms$_l$	R$_l$	ν_u	FWHM$_u$	rms$_u$	R_u
10095-01-02-00	1996-04-24	14:57	2080.0	163.2	20.9	560.1 ± 2.1	13.3 ± 6.8	6.2 ± 1.0	3.1	889.4 ± 10.5	86.9 ± 34.2	11.0 ± 1.4	3.8
10095-01-02-00	1996-04-24	16:35	1952.0	166.6	20.9	603.1 ± 6.2	42.1 ± 12.7	9.0 ± 1.1	4.3	932.4 ± 18.0	84.0 ± 0.3	9.4 ± 1.4	3.4
10095-01-02-00	1996-04-25	04:58	3456.0	163.5	20.9	584.2 ± 4.0	29.2 ± 10.8	7.2 ± 0.9	3.8	910.4 ± 8.8	80.3 ± 22.3	10.3 ± 1.0	4.9
10095-01-03-000	1996-08-06	22:29	3456.0	159.5	18.8	680.5 ± 1.6	26.4 ± 4.6	10.3 ± 0.6	8.2	993.7 ± 14.0	85.3 ± 37.3	8.7 ± 1.3	3.3
10095-01-03-000	1996-08-07	00:09	3216.0	151.7	18.8	628.2 ± 6.7	54.9 ± 17.5	9.4 ± 1.1	4.4	944.4 ± 13.3	108.0 ± 36.3	11.3 ± 1.3	4.4
10095-01-03-000	1996-08-07	01:49	2976.0	146.5	18.8	582.9 ± 7.5	36.8 ± 16.4	7.1 ± 1.2	3.0	904.3 ± 12.2	77.7 ± 26.4	9.9 ± 1.2	4.0

any QPOs at frequencies similar to the one reported at 1330 Hz by van Straaten et al. (2000). For the 1330 Hz QPO, note that our detection threshold ($R = 3$) corresponds to a single trial significance of 6σ, much larger than the 3.5σ single trial significance reported by van Straaten et al. (2000). Still, we have repeated the analysis of van Straaten et al. (2000) for the ObsID 40030-01-04-00 in which the later QPO was reported (considering events from 5 to 97 keV). The strongest excess we could fit was at $\nu = 1328.4 \pm 26.5$ Hz, FWHM $= 46.2 \pm 70.2$ Hz, rms $= 4.6 \pm 1.7$ per cent, hence with a ratio R of 1.3, a value far too small to claim a detection. Note that van Straaten et al. (2000) reported a larger ratio $R \sim 2.8$; a value closer to our threshold, but which we failed to reproduce (see Fig. 3).

We have tried to optimize the energy band over which the PDS is computed to determine whether the significance of the above excess could be increased. By looking at the count spectrum of the source, it dominates over the background between 2 and 20 keV. We have thus computed a PDS of this ObsID using only events from 2 to 20 keV. The strongest excess of the PDS is no longer around 1330 Hz (a $R \sim 1$ excess exists at 966 Hz). By initializing

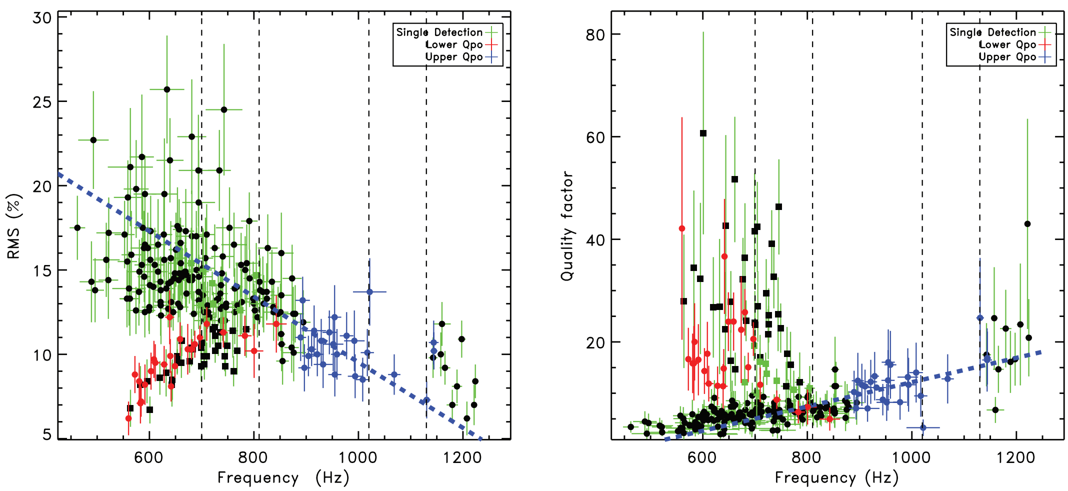

Figure 2. Quality factor (left-hand panel) and rms amplitude (right-hand panel) versus frequency of all QPOs detected in the 2–40 keV range. Each point represents the average over one ObsID. Red and blue filled circles are, respectively, for lower and upper twin QPOs. Black filled squares with green error bars are for single detected QPOs, identified as lower QPOs. Black filled circles with green error bars are for single detected QPOs identified as upper QPOs.

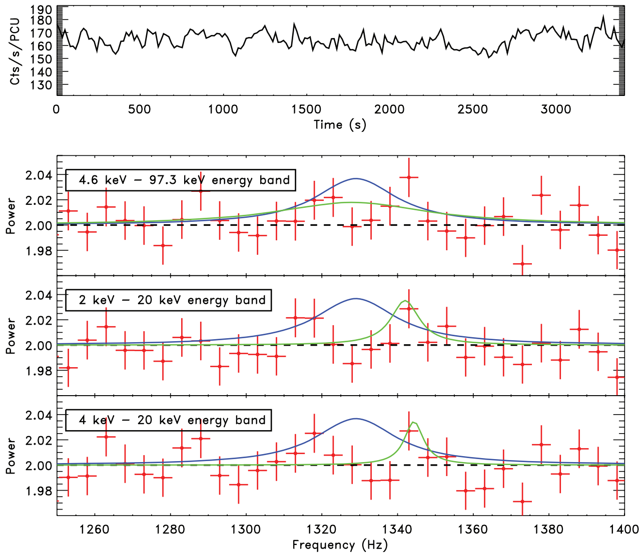

Figure 3. Top panel: light curve of the ObsID 40030-01-04-00 in the energy band 4.6–97.3 keV. Second from the top: PDS in the energy band 4.6–97.3 keV with a 5 Hz resolution, as in van Straaten et al. (2000). Third and fourth from top: PDS in the energy bands 2–20, 4–20 keV with a 5 Hz resolution. The blue curve represents the 1330 Hz QPO with parameters from van Straaten et al. (2000) and the green curve represents our best fit after initialization of the fit parameters with the values of van Straaten et al. (2000).

the parameters of the fit with the values of van Straaten et al. (2000), the Lorentzian parameters are badly constrained (as expected for a non significant excess) and discontinuity in the χ^2 curves prevents us from evaluating the errors. Because it is a general property of QPOs that their rms amplitude increases with energy, we have also restricted the energy range from 4 to 20 keV, but failed to detect any significant excesses. We conclude that the 1330 Hz QPO was likely a statistical artefact, a possibility also implied by van Straaten et al. (2000). A summary plot of the analysis performed is presented in Fig. 3. We also present the X-ray light curve corresponding to the ObsID, indicating no anomalies in the source behaviour along the observation.

2.2 Average properties of kHz QPOs

Following on Barret et al. (2006), we can identify lower and upper QPOs based on their position in the diagrams presented in Fig. 2. One can then align QPOs of similar type (either a lower or an upper) using a shift-and-add technique (Mendez et al. 1998). This allows us to obtain a better description of their average properties; quality factor and rms amplitude. We have therefore aligned all the ObsID averaged PDS, containing a QPO with $R \geq 3$ (either a lower or an upper), within a 50 Hz interval. As stated above, our conservative threshold ensures that we do add real QPOs. Through extensive simulations of PDS with QPO parameters appropriate for 4U 0614+091 and statistics comparable to the real data, we have checked that with our procedure, which leads to averaging a large number of 1 s PDS (several thousands), the QPO parameters (quality factor and rms amplitude) so recovered are not biased by any statistical fluctuations of the signal around the mean QPO profile. The results are presented in Fig. 4. This figure shows for the first time that the quality factor of the lower QPO starts by increasing with increasing frequency and then drops when it reaches a frequency around 700 Hz (the last point for the lower kHz is obtained after aligning all the PDS with an identified upper QPO above 1100 Hz). The maximum frequency averaged value of the quality factor of the lower QPO is only about 25, while in one observation it reaches 60 albeit with large error bars. The low values reported can be explained in part by the fact that no correction for the frequency drift is applied within the ObsIDs. At the same time, the quality factor of the upper QPOs increases steadily. The behaviour of the rms amplitude of the lower QPO is consistent with other sources: it increases, saturates and then decreases sharply with increasing frequency. On the other hand, for the upper QPO, its rms amplitude decreases up to a minimum around 1100 Hz, after which a second maximum is observed at 1150 Hz. Although the minimum was not completely sampled by the data presented in van Straaten et al. (2002), a similar trend could be inferred.

2.3 A constant frequency difference of twin QPOs

As said above, in 24 ObsIDs, we detect simultaneous twin QPOs. Their frequency difference is plotted against the frequency of the lower QPO in Fig. 5. This figure shows that albeit with large error bars, the frequency difference is consistent with being constant

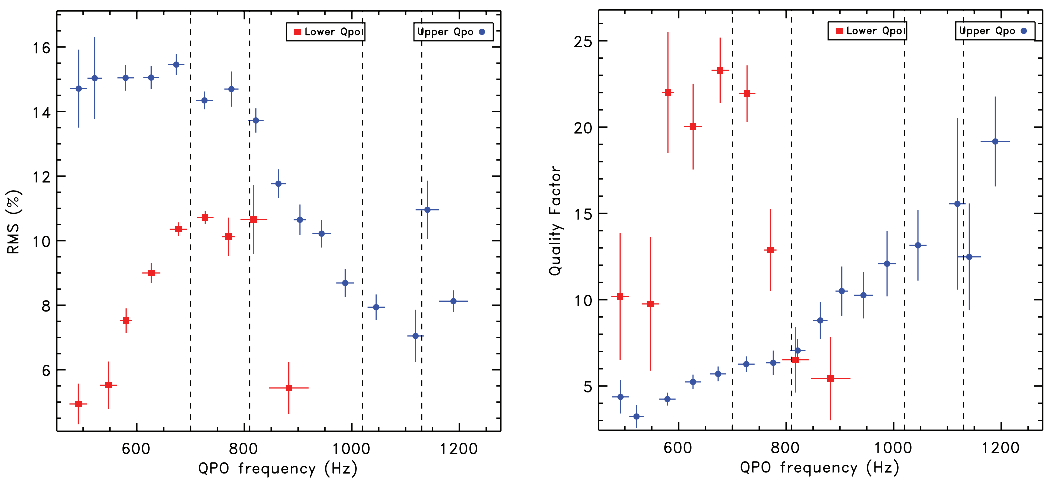

Figure 4. Quality factor (left-hand panel) and rms amplitude (right-hand panel) versus frequency after grouping the ObsIDs with QPOs of similar type and frequency (within a 50 Hz interval). Red filled squares are for lower QPO. Blue filled circles are for upper QPO. An abrupt drop of coherence of the lower QPO around 700 Hz is now revealed.

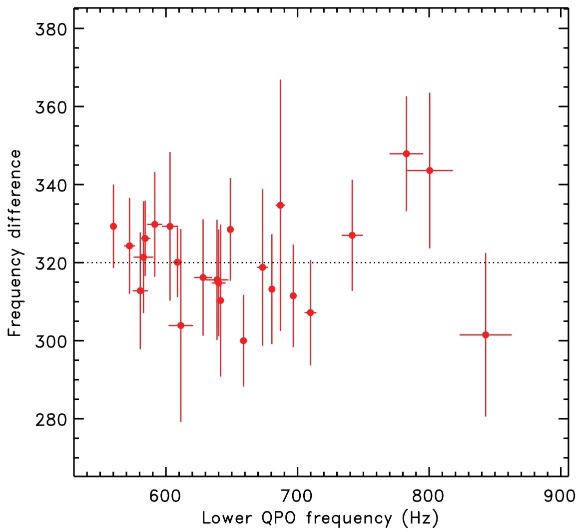

Figure 5. Frequency difference of the 24 simultaneous twin QPOs detected in our analysis. The frequency difference is consistent with being constant around 320 Hz.

around 320 Hz. A similar conclusion was reached by van Straaten et al. (2000) using a reduced data set, but with a rather large scatter, with values ranging from 250 to 380 Hz. This value is indeed significantly different from the neutron star spin frequency at 414 Hz (Strohmayer et al. 2008). Note also that the drop towards higher frequencies seen in other sources is not observed in 4U 0614+09, and our result is consistent with findings of Ford et al. (1997) and van Straaten et al. (2000).

2.4 On the distribution of twin QPO frequencies

We have started to investigate how the dependence of the QPO quality factor (or width) and rms amplitude with frequency influences their detectability in time intervals of fixed durations, hence affects the observed distribution of frequency ratios. This is an important issue, because such distributions have been shown to be peaked around small integer ratios in some sources, e.g. 3:2 in the case of Sco X-1 (Abramowicz et al. 2003) and 4U1636-536 (Török et al. 2008). This has been used as an argument in favour of resonance based models (but see the discussion in Belloni, Méndez & Homan 2005). Following this idea, Barret & Boutelier (2008) have shown that in the case of 4U1820-303 a gap in the frequency distribution was present, together with a cluster of frequency ratio. They showed that the lack of twin QPOs within the gap could not be due to a lack of sensitivity for QPO detection, provided that the parameters of the QPOs (rms and width) could be interpolated within the gap, using values measured before and after. Their result implied a sudden change of the QPO properties within the gap, most likely a loss of coherence of the upper QPO.

As said above, there is a gap in the frequency distribution of the twin upper QPOs, between 1020 Hz and 1130 Hz. The histograms of occurrence of single and twin upper kHz QPOs are shown in Fig. 6.

Between 1020 and 1130 Hz, there is only one detection of a twin upper QPO and no single upper QPO detected. It is possible to evaluate the probability of having such a gap of 110 Hz width, with one QPO inside, assuming that the 24 twin upper QPO frequencies are uniformly distributed over their 250 Hz frequency span. This probability is less than 3.7×10^{-4} (3.4σ), giving us confidence that the gap is significant. As shown in Fig. 6, single upper kHz QPOs are detected over a much wider range of frequencies and show a highly non-uniform and peaked distribution of frequencies; single upper kHz QPOs are detected predominantly below the gap, but some are also detected above.

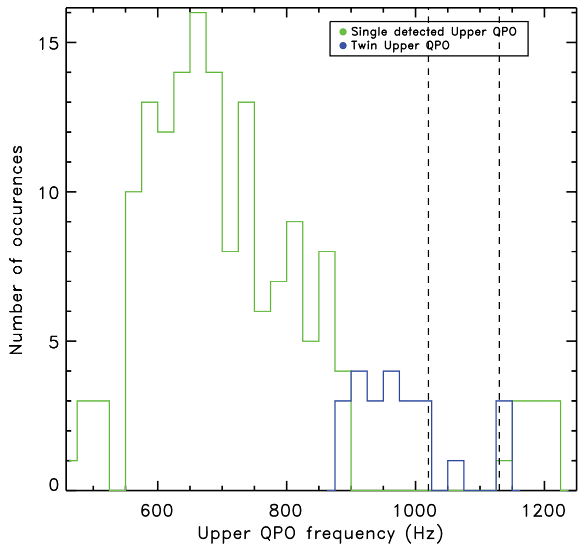

Figure 6. Histograms of occurrence of single and twin upper QPOs showing a frequency gap between 1020 and 1130 Hz in the distribution of frequencies. A frequency bin of 20 Hz has been used. The gap is indicated for twin upper QPOs as vertical dashed lines.

There is no such a gap in the frequency distribution of the lower QPOs, 320 Hz below (there are more than 10 single lower QPOs). In fact, it is the frequency range in which both the quality factor and the amplitude of the lower QPO reach a maximum, hence where lower QPOs are easy to detect. After recovering the upper QPO parameters within the gap through the shift-and-add technique, Fig. 4 shows that the gap corresponds to the region where the rms amplitude of the upper QPO reaches a minimum. This leads to the conclusion that the absence of twin QPOs within the gap is linked to a localized drop of the amplitude of the upper QPO, unlike in 4U1820-303 for which the gap was more likely related to a local minimum of the quality factor of the upper QPO. This result suggests some cautions when estimating frequency ratios based on the detection of single lower QPOs and computing the frequency of the upper QPO through the linear function that links the two QPO frequencies (Belloni et al. 2005, 2007). Clearly in sensitivity-limited observations (as is the case here, where the data are analysed over comparable integration times), the histogram of ratios computed from simultaneous twin QPOs will differ from the one computed from the distribution of single lower QPOs. The study of the histogram of frequencies and frequency ratios, resulting from the frequency dependency of the QPO rms and width (see Fig. 4), will be the subject of a forthcoming paper.

3 CONCLUSIONS

The main results of our systematic analysis of all archival RXTE data for 4U 0614+09 are as follows.

(i) We do not confirm the previous claim of a QPO at 1330 Hz. This is based on a thorough reanalysis of the observation from which the QPO was reported, and the fact that in our analysis the highest frequency detected is at ~1220 Hz. This value is fully consistent with maximum frequencies observed in similar systems.

(ii) We observe for the first time a drop of the quality factor of the lower QPO. Such a drop has been interpreted as being related to the oscillating region, crossing the ISCO, and our detection is consistent with that idea.

(iii) The frequency difference between the lower and upper kHz QPOs is consistent with being constant, around 320 Hz, a value significantly different from the neutron star spin frequency (414 Hz) or half its value.

(iv) If the drop in quality factor for the lower kHz QPO is due to the ISCO, one can estimate the orbital frequency there, given the constant frequency difference. To do this, we compute the maximum frequency of the lower QPO by extrapolating its quality factor to zero. This yields a limiting frequency of ∼920–930 Hz, corresponding to an orbital frequency of 1250 Hz at the innermost stable orbit ($\nu_{\rm ISCO}$). As a safety check, we note that the maximum QPO frequency detected for the upper QPO is indeed lower than $\nu_{\rm ISCO}$. From this, we can estimate the mass of the NS following the equation $\frac{M}{\rm M_{\odot}} \approx 2200\,{\rm Hz} \times (1 + 0.75 j)/\nu_{\rm ISCO}$ where $j = \frac{cJ}{GM^2} \sim 0.1$–$0.2$ is the dimensionless angular momentum of the star. This leads to a gravitational mass for the neutron star of $1.9\,{\rm M_{\odot}}$, i.e. a relatively massive NS, but still consistent with realistic modern equations of state, which predict maximum masses for slowly rotating ($j \ll 1$) stars of $\sim$1.8–2.3 $\rm M_{\odot}$ (Akmal, Pandharipande & Ravenhall 1998; Lattimer & Prakash 2001; Klähn et al. 2006).

(v) 4U 0614+09 is the second object in which a gap in the frequency distribution of the upper QPO is observed, after 4U1820-303. This gap is likely associated with a local minimum of the rms amplitude of the upper QPO. This is the first time such a minimum is so clearly identified, although it was suggested in previous work (van Straaten et al. 2002). Similar trends will be searched in similar systems, because frequency gaps are present in the data analysed by Barret et al. (2006) in sources like 4U1636-536. This result motivates caution when estimating frequency ratios based on the detection of single lower QPOs.

We note two additional consequences of our work. First, our conclusion that the proposed 1330 Hz QPO in 4U 0614+09 is not likely to be real means that no kHz QPO source has a confirmed frequency significantly above ∼1200 Hz. This is surprising a priori, because for a neutron star of canonical mass $M = 1.4\,{\rm M_{\odot}}$ and a spin parameter of $j = 0.1$ the orbital frequency at the ISCO is 1690 Hz. Such frequencies should have been detected with RXTE, hence the wide gap relative to the maximum actually observed suggests a physical cause. One possibility is that these stars tend to have higher masses, consistent with accretion of several tenths of a solar mass, but other explanations should also be explored.

Secondly, 4U 0614+09 is an important source to test the suggestion by Barret, Olive & Miller (2005); Barret, Olive & Miller (2006); Barret, Olive & Miller (2007) that the rapid drop in coherence of the lower QPO is caused by the approach of the oscillating region to the ISCO. In their proposal, the orbital frequency at the ISCO can be very roughly estimated by adding the separation frequency $\Delta\nu$ between the twin kHz QPOs to the maximum frequency seen from the lower QPO after a sharp drop in quality factor. If the 1330 Hz QPO were real, it would contradict this interpretation because the maximum inferred lower frequency is ∼900 Hz and the separation is ∼320 Hz. However, the maximum significant upper QPO frequency is actually ∼1220 Hz, which is consistent with the ISCO interpretation. This is encouraging, but other sources must also be analysed carefully to look for potential disproofs of our hypothesis.

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REFERENCES

Abramowicz M. A., Bulik T., Bursa M., Kluźniak W., 2003, A&A, 404, L21
Akmal A., Pandharipande V. R., Ravenhall D. G., 1998, Phys. Rev. C, 58, 1804
Barret D., Boutelier M., 2008, New Astron. Rev., 51, 835
Barret D., Olive J.-F., Miller M. C., 2005, MNRAS, 361, 855
Barret D., Olive J.-F., Miller M. C., 2006, MNRAS, 370, 1140
Barret D., Olive J.-F., Miller M. C., 2007, MNRAS, 376, 1139
Barret D., Boutelier M., Miller M. C., 2008, MNRAS, 384, 1519
Belloni T., Méndez M., Homan J., 2005, A&A, 437, 209
Belloni T., Homan J., Motta S., Ratti E., Méndez M., 2007, MNRAS, 379, 247
Boirin L., Barret D., Olive J. F., Bloser P. F., Grindlay J. E., 2000, A&A, 361, 121
Ford E. et al., 1997, ApJ, 475, L123
Klähn T. et al., 2006, Phys. Rev. C, 74, 035802
Lattimer J. M., Prakash M., 2001, ApJ, 550, 426
Leahy D. A., Darbro W., Elsner R. F., Weisskopf M. C., Kahn S., Sutherland P. G., Grindlay J. E., 1983, ApJ, 266, 160
Méndez M., 2006, MNRAS, 371, 1925
Méndez M., Belloni T., 2007, MNRAS, 381, 790
Mendez M. et al., 1998, ApJ, 494, L65
Miller M. C., Lamb F. K., Psaltis D., 1998, ApJ, 508, 791
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Numerical Recipes in FORTRAN: The Art of Scientific Computing. Cambridge Univ. Press, Cambridge
Strohmayer T. E., Markwardt C. B., Kuulkers E., 2008, ApJ, 672, L37
Török G., Abramowicz M. A., Bakala P., Bursa M., Horák J., Rebusco P., Stuchlik Z., 2008, Acta Astron., 58, 113
van der Klis M., 1989, in Ögelman H., van den Heuvel E. P. J., eds, Proc. NATO Advanced Study Institute, Timing Neutron Stars. Kluwer, New York, p. 27
van Straaten S., Ford E. C., van der Klis M., Méndez M., Kaaret P., 2000, ApJ, 540, 1049
van Straaten S., van der Klis M., di Salvo T., Belloni T., 2002, ApJ, 568, 912
Yin H. X., Zhang C. M., Zhao Y. H., Lei Y. J., Qu J. L., Song L. M., Zhang F., 2007, A&A, 471, 381

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. The parameters of the single detected QPOs together with information concerning the observations.
Table 2. The parameters of the twin QPOs together with information concerning the observations.