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Simultaneous observations of a pair of kilohertz QPOs and a plausible 1860 Hz QPO from an accreting neutron star system

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Abstract We report an indication (3.22σ) of ≈ 1860 Hz quasi-periodic oscillations from a neutron star low-mass X-ray binary 4U 1636-536. If confirmed, this will be by far the highest frequency feature observed from an accreting neutron star system, and hence could be very useful in understanding such systems. This plausible timing feature was observed simultaneously with lower ($\approx 585 \,\text{Hz}$) and upper ($\approx 904 \,\text{Hz}$) kilohertz quasi-periodic oscillations. The two kilohertz quasi-periodic oscillation frequencies had a ratio of ≈ 1.5 , and the frequency of the alleged ≈ 1860 Hz feature was close to the triple and the double values of these frequencies. This can be useful for constraining the models of all the three features. In particular, the $\approx 1860 \,\text{Hz}$ feature could be (1) from a new and heretofore unknown class of quasi-periodic oscillations, or (2) the first observed overtone of lower or upper kilohertz quasi-periodic oscillations. Finally, we note that, although the relatively low significance of the $\approx 1860 \, \text{Hz}$ feature argues for caution, even a 3.22σ feature at such a uniquely high frequency should be interesting enough to spur a systematic search in the archival data, as well as to scientifically motivate sufficiently large timing instruments for the next generation X-ray missions.

Key words: accretion, accretion disks — methods: data analysis — relativity — stars: neutron — X-rays: binaries — X-rays: individual (4U 1636–536)

1 INTRODUCTION

Quasi-periodic oscillations (QPOs) are observed from many neutron star low-mass X-ray binary (LMXB) systems (van der Klis 2006). There are several kinds of QPOs, such as millihertz QPOs, horizontal branch QPOs, normal/flaring branch QPOs, hectohertz QPOs, lower kilohertz (kHz) QPOs, upper kHz QPOs, etc. (van der Klis 2006). In this paper we will mostly concentrate on high frequency QPOs, that can currently be observed only with the proportional counter array (PCA) instrument of the *Rossi X-ray Timing Explorer (RXTE)* space mission. kHz QPOs are such high frequency QPOs, and often they appear as a pair. For a given source, their frequencies normally move up and down together in the $\approx 200 - 1200$ Hz range in correlation with the source state. kHz QPOs are scientifically very important for the following reasons: (1) their high frequencies indicate that they originate from regions close to the neutron stars, and hence could be used as a tool to probe the strong gravitational region around these stars, as well as the neutron star properties, and (2) they have been observed from many sources, and repeatedly from a given source, with high significance.

Indeed, there are several models that involve relativistic orbital frequencies and the neutron star spin frequency, as well as beating and resonances among them (Stella & Vietri 1998; Lamb et al. 1985; Miller et al. 1998; Abramowicz & Kluźniak 2001; Török et al. 2008; Wijnands et al. 2003; Lamb & Miller 2003; Zhang 2004; Mukhopadhyay 2009). However, although there are many kHz QPO models available in the literature, none of them can explain all the major properties of this timing feature. Therefore, these QPOs cannot yet be used as a reliable tool to probe strong gravitational regions, or to measure neutron star parameters.

An intriguing aspect of the kHz QPOs is that, so far, they have never been observed with a frequency greater than 1330 Hz (van der Klis 2006), while the PCA can easily detect a feature with a much higher frequency. In fact, even this 1330 Hz QPO was not confirmed by a later analysis (Boutelier et al. 2009). This implies that no timing feature has ever been observed with > 1330 Hz from an accreting neutron star system. In this paper, we report the indication of an ≈ 1860 Hz QPO from the persistent neutron star LMXB 4U 1636–536 (see Altamirano et al. 2008 for the other timing features). This plausible QPO was observed simultaneously with the pair of kHz QPOs, which suggests that the ≈ 1860 Hz QPO could be from a new and previously unknown class of very high frequency QPOs. Note that kHz QPOs from 4U 1636–536 were first discovered by van der Klis et al. (1996), Zhang et al. (1996a,b), and later were reported by many authors (Wijnands et al. 1997; Vaughan et al. 1997; Xaughan et al. 1997; Xaughan et al. 1998; Msira & Shanthi 2004; Kaaret et al. 1999; Psaltis et al. 1999; Markwardt et al. 1999; Jonker et al. 2000; Méndez 2002; Jonker et al. 2002; Di Salvo et al. 2003; Misra & Shanthi 2004; Barret et al. 2007; Belloni et al. 2007; Török et al. 2008).

2 DATA ANALYSIS AND RESULTS

The LMXB 4U 1636–536 was observed with the RXTE PCA on 2007 September 28. We analysed the data from the event file FS4f_19d86be0-19d8c749 (time: 16:17:36 to 22:47:38, i.e., 23.402 ks duration) of the obsID 93091-01-01-000, and searched for QPOs. We excluded the data gaps and a burst, as well as the time intervals in which the number of used proportional counter units (PCU) was changed, and divided the 21.85 ks of data into M (= 2185) equal segments of 10 s duration. We performed a fast Fourier transform on each time segment for the entire PCA energy range, and the resulting power spectra (up to 2048 Hz) were averaged in order to reduce the noise. By combining W (= 4) consecutive frequency bins (making the frequency resolution 0.4 Hz), we found a tentative peak at the frequency 1861.45 Hz (see the upper panel of Fig. 1). Before exploring this peak further, we binned the power spectrum more in order to search for kHz OPOs. This gave clear evidence of two kHz QPOs at ≈ 585 Hz and ≈ 904 Hz (see the lower panel of Fig. 1). For probing the properties of these QPOs, we fitted the power spectrum with a model and minimized the corresponding χ^2 to get the best-fit parameter values. This model was the sum of a "constant" (to account for the Poisson noise level including the effect of deadtime), a "powerlaw" (to describe the red noise or broad-band feature at lower frequencies), and two Gaussians (to fit the kHz QPO pair). Then, we divided the power spectrum with the continuum part of the best-fit model (see, for example, the lower panel of Fig. 1) and multiplied by 2, in order to have the noise distributed as χ^2 with 2MW degrees of freedom (van der Klis, 1989; Bhattacharyya et al., 2006). The peak powers of the 585 Hz and 904 Hz QPOs were 2.00669 (for W = 1024) and 2.00959 (for W = 2048) respectively, which gave the respective single trial significance of 2.87×10^{-7} and 2.20×10^{-24} . Therefore, multiplying by the number of trials (20 and 10), we got a significance of 5.74×10^{-6} (i.e., 4.5σ) and 2.20×10^{-23} respectively. These numbers show that both of the kHz QPOs were very significant. The Gaussian modeling gave the RMS amplitudes $\approx 4.5\%$ and $\approx 7\%$, and the quality factors ≈ 5.6 and ≈ 7.3 for the lower and the upper kHz QPOs respectively.

In order to estimate the significance of the observed peak at ≈ 1860 Hz, we followed the same procedure as mentioned in the previous paragraph. After having the noise distributed as χ^2 with



Fig. 1 Power spectrum (averaged over 2185 spectra; each from a 10 s time segment) of the 21.85 ks *RXTE* PCA data from the source 4U 1636–536 (see text). *Upper panel* (power spectrum with 0.4 Hz frequency resolution): a peak near 1860 Hz is clearly seen. *Lower panel* (same power spectrum with 51.2 Hz frequency resolution): two kHz QPOs (near 585 Hz and 904 Hz) are clearly seen. 1 σ error bars and a model (*solid line*; describing the continuum part of the power spectrum) are shown. The vertical dotted lines mark the frequency of the narrow ≈ 1860 Hz peak of the upper panel, and its half and one-third frequencies. Note that the latter two pass through the upper and lower kHz QPOs respectively.

2MW degrees of freedom, the peak power 2.1094 gave the single trial significance of 2.47×10^{-7} . We considered the number of trials to be equal to the number of frequency bins (= 5120) in the power spectrum. This is because, (1) we applied no cuts to the data (e.g., based on energy bands), apart from the standard filtering for burst and gaps; and (2) we did not search for QPOs in any other data set of 4U 1636–536. Note that we chose this particular data set in connection with research on broad iron lines, and we happened to find the feature at ≈ 1860 Hz. Furthermore, since the frequency of high frequency QPOs evolves with time (van der Klis 2006), it is unlikely that a feature with the *same* frequency will appear in another observation. Therefore, it should be reasonable to consider only the current data set in order to estimate the number of trials. Hence, considering that the number of trials = 5120, we found that the plausible QPO at ≈ 1860 Hz was 3.22σ significant. The RMS amplitude of this feature was $\approx 1\%$, and it had an extremely high quality factor ($Q \approx 4650$), as this QPO was observed with 0.4 Hz resolution.

In order to find out whether the plausible $\approx 1860 \text{ Hz}$ QPO was stronger in a part of the dataset, we examined the power spectra of nine unequal data segments. This division was naturally done in order to exclude the data gaps, bursts, etc. (see the first paragraph of Sect. 2). We searched for a plausible timing feature at the known frequency of $\approx 1860 \text{ Hz}$ in the power spectrum of each of these data segments. Although we found the indication of such a feature in several segments, it was strong in the power spectrum of only one segment (hereafter segment 1; time: 19:20:06 to 20:53:26,



Fig. 2 Power spectrum (averaged over 560 spectra; each from a 10 s time segment) of the 5.6 ks *RXTE* PCA data from the source 4U 1636–536 (see Sect. 2). *Upper panel* (power spectrum with 3.2 Hz frequency resolution): a peak near 1860 Hz is clearly seen. *Middle panel* (same power spectrum with 51.2 Hz frequency resolution): two kHz QPOs (at the same frequencies shown in Fig. 1) are clearly seen. A tentative broad peak near 1860 Hz is also seen. 1 σ error bars and a model (*solid line*; describing the continuum part of the power spectrum) are shown. The vertical dotted lines mark the frequency of the narrow \approx 1860 Hz peak of the upper panel, and its half and one-third frequencies. Note that the latter two pass through the upper and lower kHz QPOs respectively. *Lower panel* (same power spectrum with 12.8 Hz frequency resolution): the narrow part (marked with a vertical dotted line) and the broad part (suggested from the powers of several adjacent frequency bins above the average power) of the plausible \approx 1860 Hz QPO are visible.

i.e., 5.6 ks duration). This power spectrum was calculated by averaging the spectra of M (=560) equal segments of 10 s duration. By combining W (=32) consecutive frequency bins (making the frequency resolution 3.2 Hz), we found a peak at the frequency 1860.85 Hz (see the upper panel of Fig. 2). After having the noise distributed as χ^2 with 2MW degrees of freedom (see the first paragraph of Sect. 2), we got a peak power of 2.07. Therefore, for the search at a known frequency in this particular power spectrum, the \approx 1860 Hz QPO had a significance of 1.82×10^{-6} (i.e., 4.8σ). The RMS amplitude of this QPO was 2.4%. Therefore, this QPO was stronger in segment 1 than in the whole data set. Here we note that even for segment 1, the \approx 1860 Hz QPO occurred simultaneously with the lower and the upper kHz QPOs (see the middle panel of Fig. 2).

The very high Q-value of the plausible $\approx 1860 \text{ Hz}$ QPO is somewhat unusual. We, therefore, searched for a broader feature at the known 1860 Hz frequency in the power spectrum of segment 1, and indeed we found a tentative peak with the centroid frequency of 1868.85 Hz (middle panel of Fig. 2). After having the noise distributed as χ^2 with 2MW degrees of freedom, the peak power 2.0109 gave a significance of 1.82×10^{-3} (i.e., 3.1σ). This tentative broad feature had the RMS amplitude of $\approx 3.7\%$, and a more usual quality factor of ≈ 35 . Note that, although such a broad

feature is not significant in the power spectrum of the whole dataset, the lower panel of Figure 1 does show a small broad peak at the frequency of the plausible narrow ≈ 1860 Hz QPO. Therefore, while the evidence of a broad feature is weak, we still explored the data a little more in order to see whether the plausible narrow QPO could be a part of a broad QPO. The upper and the middle panels of Figure 2 exclusively show the plausible narrow QPO and the plausible broad QPO respectively. Therefore, in the lower panel of the same figure, we used an intermediate frequency resolution of 12.8 Hz, and found both the plausible narrow QPO (marked with a dotted vertical line) and the plausible broad QPO (suggested from the powers of several adjacent bins above the average power). This indicates that the narrow QPO at ≈ 1860 Hz could be a part of a broader QPO.

Finally, the vertical dotted lines of the figures show that the frequency of the plausible $\approx 1860 \text{ Hz}$ QPO is close to the double value of the upper kHz QPO frequency and triple value of the lower kHz QPO frequency. Therefore, the $\approx 1860 \text{ Hz}$ QPO could be the first overtone of the upper kHz QPO or the second overtone of the lower kHz QPO.

3 DISCUSSION

In this paper, we report the detection of a pair of kHz QPOs from a neutron star LMXB 4U 1636–536. The ratio of these QPO frequencies is roughly 1.5, which is somewhat consistent with the resonance model described in Abramowicz et al. (2003) (but see Boutelier et al. 2009; see also Zhang et al. 2006). It is generally observed that the separation of the twin kHz QPO frequencies clusters around the neutron star spin frequency, or half of that. Models have been proposed in order to explain this aspect. However, for the kHz QPOs reported in this paper, the separation is ≈ 319 Hz, which is quite different from half of the stellar spin frequency (see also Méndez & Belloni 2007; Yin et al. 2007). Note that the neutron star of 4U 1636–536 spins with a rate of 582 Hz (Strohmayer & Markwardt 2002).

Apart from the kHz QPOs, we have found an indication of a QPO at ≈ 1860 Hz. This is by far the highest frequency feature observed from an accreting neutron star system, and hence could be extremely useful in understanding such systems. Moreover, this plausible QPO was observed simultaneously with the lower and the upper kHz QPOs, which means that the ≈ 1860 Hz QPO could be from a new class of QPOs.

We will now briefly discuss the plausible origin of this QPO using general arguments, and without going into specifics. In some of the models, the lower and upper kHz QPO and some other QPO frequencies are thought to be one or more of the following frequencies (for equatorial circular orbits in Kerr spacetime; van der Klis 2006):

(1) Keplerian orbital frequency

 $\nu_{\phi} = \nu_{K} [1 + j(r_{q}/r)^{3/2}]^{-1} = (2\pi)^{-1} (GM/r^{3})^{1/2} [1 + j(r_{q}/r)^{3/2}]^{-1};$

(2) radial epicyclic frequency

$$\nu_r = \nu_{\phi} [1 - 6(r_g/r) + 8j(r_g/r)^{3/2} - 3j^2(r_g/r)^2]^{1/2};$$

(3) vertical epicyclic frequency

$$\nu_{\theta} = \nu_{\phi} [1 - 4j(r_g/r)^{3/2} + 3j^2(r_g/r)^2]^{1/2};$$

(4) periastron precession frequency

$$\nu_{\rm peri} = \nu_{\phi} - \nu_r$$

and

(5) nodal precession frequency

$$\nu_{\rm nodal} = \nu_{\phi} - \nu_{\theta}$$

Here, the last four frequencies are for infinitesimally tilted and eccentric orbits, M is the neutron star mass, $r_q = GM/c^2$, $j = Jc/GM^2$, J is the total angular momentum of the neutron star, and r is the distance of an orbit from the center of the neutron star. For a sample of radio pulsars, M was found to be distributed around $1.35 M_{\odot}$ in a narrow Gaussian ($\sigma = 0.04 M_{\odot}$; Thorsett & Chakrabarty 1999). Therefore, considering $M = 1.35 M_{\odot}$, we find that only ν_{ϕ} or ν_{θ} can be the frequency of the plausible $\approx 1860 \, \text{Hz}$ QPO, and also that for relatively large angular momentum parameter values (as far as a neutron star is concerned) and for orbits very close to the innermost stable circular orbit (ISCO; see Fig. 3). As the neutron star mass increases due to accretion, M is expected to be greater than $1.35 M_{\odot}$ for accreting neutron stars (such as the one in 4U 1636–536). Moreover, since $\nu_K = (c^3/2\pi G)(r/r_q)^{-3/2}(1/M)$, ν_K decreases as M increases for a given r/r_q . Therefore, it is unlikely that any of the above mentioned five frequencies can be the frequency of the plausible ≈ 1860 Hz QPO. Besides, since the spin frequency of the neutron star in 4U 1636–536 is $\nu_{\rm spin} = 582 \,{\rm Hz}$, the beating of $\nu_{\rm spin}$ with any of ν_{ϕ} , ν_r or ν_{θ} cannot explain the frequency of this QPO. However, the ≈ 1860 Hz QPO could be an overtone of any of ν_{ϕ} , ν_{r} , ν_{θ} or ν_{peri} , or the beating between an overtone and a fundamental of these frequencies. This plausible QPO could also be an overtone of one of the kHz QPOs (see Sect. 2).

Although it is unlikely that the $\approx 1860 \,\text{Hz}$ QPO frequency is a Keplerian frequency ν_{ϕ} , it is still instructive to examine what constraints $\nu_{\phi} = 1860 \,\text{Hz}$ can impose on the neutron star parameter values. This is because the measurement of neutron star parameters provides the only way to constrain the theoretically proposed equation of state (EoS) models of neutron star cores, and hence to understand the nature of supranuclear core matter (Lattimer & Prakash 2007; Bhattacharyya et al. 2000, 2001). Various authors suggested ways to constrain the neutron star parameters assuming one



Fig. 3 Radial profiles of various frequencies (*color coded*) of equatorial circular orbits in Kerr spacetime (see Sect. 3). Two angular momentum parameters (j = 0.0 (*solid*) and j = 0.3 (*dotted*)), and neutron star mass $= 1.35 M_{\odot}$ are used. The dashed horizontal line exhibits the 1860 Hz frequency. This figure shows that these frequencies, that are often used to explain kHz and some other QPOs, cannot possibly explain a ≈ 1860 Hz QPO.

of the kHz QPO frequencies is a Keplerian frequency (Kaaret et al. 1997; Miller et al. 1998; Zhang et al. 2007; Zhang 2009). For example, this assumption, and the following two reasonable conditions can constrain the mass (M) and the radius (R) of a neutron star (Miller et al. 1998):

$$R \le r,\tag{1}$$

where r is the radius of the orbit associated with the kHz QPO via the expression of ν_{ϕ} ; and

$$r_{\rm ISCO} \le r,$$
 (2)

where $r_{\rm ISCO}$ is the radius of the ISCO. This is because the first condition gives a mass-dependent upper limit on R via the expression of ν_{ϕ} ; and the second condition gives an upper limit on M: $M < c^3/(2\pi 6^{3/2}G\nu_{\phi}|_r)$ (for Schwarzschild spacetime). Therefore, if 1860 Hz were a Keplerian frequency, then the upper limit of neutron star mass and radius would be $\approx 1.2 M_{\odot}$ and ≈ 10.5 km respectively. Such upper limits would support the strange star EoS models (Cheng et al. 1998; Bhattacharyya et al. 2001), although the less exotic neutron star EoS models could not be completely ruled out.

The unique high frequency of the plausible ≈ 1860 Hz QPO and its coexistence with both of the kHz QPOs make it extremely interesting. Furthermore, although no such high frequency signal was claimed previously, van der Klis (2006) mentioned, "the distinct impression of the observers is that there is still much hiding below the formal detection levels." It should, therefore, be worthwhile to report this feature, which will spur a systematic search of such high frequency features in the archival *RXTE* PCA data, as well as in the large area xenon proportional counters (LAXPC) instrument data of the upcoming *Astrosat* space mission. Moreover, next generation X-ray timing instruments, such as the high timing resolution spectrometer (HTRS; proposed for the *International X-ray Observatory*) and the proposed Si pixel detector of the *Advanced X-ray Timing Array*, will have much better capability to detect weak QPOs (see, for example, fig. 2 of Barret et al. 2008; Chakrabarty et al. 2008). The plausible ≈ 1860 Hz QPO will therefore motivate future X-ray timing instruments.

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