Sidebands to the lower kilohertz quasi-periodic oscillation in 4U 1636–53

P. G. Jonker,1,2* M. Méndez2,3 and M. van der Klis4
1Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
2SRON, National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, the Netherlands
3Astronomical Institute, Utrecht University, PO Box 80000, 3508 TA Utrecht, the Netherlands
4Astronomical Institute ‘Anton Pannekoek’, University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, the Netherlands

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ABSTRACT

In this paper we report on further observations of the third and fourth kilohertz quasi-periodic oscillations (QPOs) in the power spectra of the low-mass X-ray binary (LMXB) 4U 1636–53. These kilohertz QPOs are sidebands to the lower kilohertz QPO. The upper sideband has a frequency 55.5 ± 1.7 Hz larger than that of the contemporaneously measured lower kilohertz QPO. Such a sideband has now been measured at a significance >6σ in the power spectra of three neutron-star LMXBs (4U 1636–53, 1728–34 and 1608–52). We also confirm the presence of a sideband at a frequency ∼55 Hz less than the frequency of the lower kilohertz QPO. The lower sideband is detected at a 3.5σ level only when the lower kilohertz QPO frequency is between 800 and 850 Hz. In that frequency interval, the sidebands are consistent with being symmetric around the lower kilohertz QPO frequency. The upper limit to the rms amplitude of the lower sideband is significantly lower than that of the upper sideband for lower kilohertz QPO frequencies >850 Hz. Symmetric sidebands are unique to 4U 1636–53. This might be explained by the fact that lower kilohertz QPO frequencies as high as 800–850 Hz are rare for 4U 1728–34 and 1608–52. Finally, we also measured a low-frequency QPO at a frequency of ∼43 Hz when the lower kilohertz QPO frequency is between 700 and 850 Hz. A similar low-frequency QPO is present in the power spectra of the other two systems for which a sideband has been observed. We briefly discuss the possibility that the sideband is caused by Lense–Thirring precession.

Key words: accretion, accretion discs – binaries: general – stars: individual: 4U 1636–53 – stars: neutron – X-rays: binaries.

1 INTRODUCTION

One of the important discoveries made with the Rossi X-ray Timing Explorer (RXTE) satellite is that of the kilohertz quasi-periodic oscillations (QPOs) in the power spectra of ~20 accreting neutron-star low-mass X-ray binaries (LMXBs; see van der Klis 2000, for a review). Kilohertz QPOs are caused by the motion of matter in regions of space–time within a few kilometres of the surface of accreting neutron stars, where strong-field gravity is required to describe such motion. They potentially allow one to detect strong-field effects and to constrain the neutron-star mass–radius relation. Although there is as yet no agreement about the precise physical mechanism underlying kilohertz QPOs, most models agree that the frequency of one of the observed kilohertz QPOs reflects the frequency of orbital motion at the inner edge of the accretion disc.

The basic phenomenology of kilohertz QPOs consists of two kilohertz QPO peaks, which are separated by Δν = 200–360 Hz and move in frequency by up to 700 Hz in general correlation with mass accretion rate indicators (again, see van der Klis 2000, for a review). The highest observed frequency is ∼1330 Hz (van Straaten et al. 2000), corresponding in the case of a 1.4 M⊙ neutron star to an orbital radius as tight as 15 km. Some of these sources also show X-ray bursts, in which burst oscillations are seen which last for a few seconds and have frequencies between 270 and 620 Hz (see Strohmayer & Bildsten 2004, for a review). These oscillations usually drift by 1–2 Hz but are near the neutron-star spin frequency in each source (Chakrabarty et al. 2003). In the millisecond pulsar SAX J1808.4–3658, the value of Δν has been found to be equal to half the spin frequency, which disproves spin–orbit beat-frequency models (Wijnands et al. 2003) and suggests instead that the neutron-star spin induces resonances in the disc flow, perhaps involving the general relativistic epicyclic frequencies (Abramowicz et al. 2003; Wijnands et al. 2003; Lamb & Miller 2003).

After extensive searches for additional kilohertz QPO peaks at theoretically predicted frequencies that remained unsuccessful (e.g. in Sco X-1; Méndez & van der Klis 2000), Jonker, Méndez & van der Klis (2000) discovered sidebands at a frequency 50–65 Hz above
the lower kilohertz QPO in 4U 1608–52, 1728–34 and 1636–53. Magnetospheric modulation of the lower kilohertz QPO, a beat phenomenon taking place inside the marginally stable orbit as well as Lense–Thirring precession are all possible explanations for these sidebands (Jonker et al. 2000). Psaltis (2000) demonstrated that the hydrodynamic disc mode model (Psaltis & Norman 2000) naturally produces a sideband at a frequency near that observed plus several other, as yet unobserved, peaks; no other models have so far been able to accommodate the sideband explicitly. The 50–65 Hz frequency difference between the lower kilohertz QPO and the sideband frequency, the ‘sideband separation’ $\Delta v_{SB}$, is different in each source and not identical to any of the other QPO frequencies simultaneously observed in the 10–100 Hz frequency range (Jonker et al. 2000).

In this paper we find evidence for symmetric sidebands to the lower kilohertz QPO in the atoll source 4U 1636–53.

2 OBSERVATIONS, ANALYSIS AND RESULTS

We used all the proportional counter array (PCA) data from RXTE observations of 4U 1636–53 available to us at the beginning of 2004. Hence, we included the data used by Jonker et al. (2000). The analysis we performed was the same as that done by Jonker et al. Below, a condensed description of the analysis steps is given; more details can be found in Jonker et al. (2000).

Using 128 s long segments of high time resolution PCA data (122 µs resolution), we calculated power spectra up to a Nyquist frequency of 4096 Hz in an energy band of 2–60 keV. The power spectra were searched for lower kilohertz QPOs that are narrow [full width at half-maximum (FWHM) less than $\sim 10$ Hz] and are detected in 128 s at a significance larger than $2\sigma$. This resulted in a selection of 244 ks of data.

The lower kilohertz QPO was traced using a dynamical power spectrum (e.g. see plate 1 in Berger et al. 1996) to visualize the time evolution of the QPO frequency. For each power spectrum, the lower kilohertz QPO peak was fitted in a range of 200 Hz centred on the traced frequency using a function consisting of a constant plus a Lorentzian. This provides us with a lower kilohertz QPO frequency measurement for each 128 s power spectrum. We used the shift-and-add technique described by Méndez, van der Klis & van Paradijs (1998b) to shift each lower kilohertz QPO to a reference frequency. Next, the shifted, aligned, power spectra were averaged. The average power spectrum was finally fitted in the range 512–2048 Hz so as to exclude the edges, which are distorted due to the shifting. The fitting function consisted of a constant to fit the noise and three or four Lorentzians representing the QPOs. The fitted average power spectrum is displayed in Fig. 1. Errors on the fitting parameters were calculated using $\Delta \chi^2 = 1.0$ ($1\sigma$, single parameter).

We clearly detected the two kilohertz QPOs and the sideband to the lower kilohertz QPO. The sideband was detected at a significance of $3\sigma$, confirming our previous $3\sigma$ detection of the sideband in 4U 1636–53 (Jonker et al. 2000). The frequency difference between the frequency of the lower kilohertz QPO and that of the sideband was $\Delta v_{SB} = 55.5 \pm 1.7$ Hz. The average kilohertz QPO frequency separation, $(\Delta v = v_{\text{upper}} - v_{\text{lower}})$, is $283 \pm 5$ Hz. The FWHMs of the sideband, the lower kilohertz QPO and the upper kilohertz QPO are $12.7 \pm 2.7, 4.86 \pm 0.04$ and $130 \pm 11$ Hz, respectively. Because we have combined data with either three, four or five active proportional counter units (PCUs), we cannot determine the fractional rms amplitude of the QPO peaks from the combined data. Therefore, we selected data where only three, four or five PCUs were active; we fitted those data sets separately. In those separate fits, we fixed

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The average power density spectrum of 4U 1636–53 showing the lower kilohertz QPO (the peak is off-scale), the upper kilohertz QPO, and the upper sideband to the lower kilohertz QPO. Owing to the shift-and-add method applied in the analysis, only the frequency differences are meaningful (see text and references therein). The drawn line represents the best fit of a function consisting of a constant and three Lorentzians. The power in the y-axis is given in Leahey units.

FWHM and the frequency of the QPOs to the values found using the complete data set. The fractional rms amplitude of the sideband is consistent with what was found before (see Table 1 and Jonker et al. 2000).

In order to search for changes in the sideband separation frequency $\Delta v_{SB}$, we averaged shifted power spectra based on the unshifted frequency of the lower kilohertz QPO in three frequency bands: a lower kilohertz QPO frequency at 700–800, 800–850 and above 850 Hz. Interestingly, the average power spectrum in the lower kilohertz QPO frequency interval 800–850 Hz showed evidence for two sidebands located symmetrically around the lower kilohertz QPO peak (see Fig. 2). The results of fits to these averaged power spectra are given in Table 1.

Adding more data with respect to the analysis performed by Jonker et al. (2000), we now find a QPO at low frequencies ($\sim 43$ Hz, see Fig. 3). In order to compare the properties of this low-frequency QPO with that of the kilohertz QPOs and the kilohertz QPO separation frequencies, we fitted the average unshifted power spectrum in the frequency range from 1/16 to 256 Hz in the three lower kilohertz QPO frequency intervals as shown in Table 1. In the frequency range 850 Hz and above, the low-frequency QPO was undetectable (see Table 1).

3 DISCUSSION

Following the discovery by Jonker et al. (2000) of a new, third, kilohertz QPO in the power spectra of the three atoll-type LMXBs 4U 1608–52, 1728–34 and 1636–53, we obtained additional data of 4U 1636–53 with the RXTE satellite with the goal of studying in detail the properties of this third kilohertz QPO, also known as the sideband to the lower kilohertz QPO. We selected 4U 1636–53 since in that source there is evidence for the presence of two sidebands located symmetrically around the lower kilohertz QPO peak frequency.

We confirm the presence of a sideband at a frequency 55.5 ± 1.7 Hz higher than that of the lower kilohertz QPO frequency in 4U 1636−53 at a 6σ significance level. Furthermore, the addition of the extra data allowed us to investigate the sideband(s) as a function of the lower kilohertz QPO frequency. We found that when the lower kilohertz QPO has a frequency in the range 800–850 Hz there is significant evidence (3.5σ, single trial) for the presence of a sideband on the lower-frequency side of the lower kilohertz QPO. Selecting lower kilohertz QPO frequencies >850 Hz and combining all the data, the rms amplitude of the lower sideband is significantly less than that of the upper sideband. For the frequency range 700–800 Hz, the upper limit is consistent with the rms amplitude of the upper sideband.

In the framework of the sonic-point and spin-resonance model of Lamb & Miller (2003), the sideband is unlikely to be caused by Lense–Thirring precession at the radius where the spin resonance occurs (near the orbital radius with Kepler frequency $\nu_{\text{spin}}/2$), since, for neutron-star spin frequencies such as those considered here, the Lense–Thirring precession frequency at that radius is $\approx 2$ Hz; this is much too low. It is possible, though, that the radiation pattern

Table 1. Properties of the lower and upper kilohertz QPO ($\nu_1$ and $\nu_2$, respectively), the sidebands to the lower kilohertz QPO, and the low-frequency QPO. The properties displayed in the last three lines have been determined without using the shift-and-add technique. The FWHM of the lower sideband has in all cases been fixed to that of the upper sideband.

<table>
<thead>
<tr>
<th></th>
<th>All frequencies</th>
<th>700–800 Hz</th>
<th>800–850 Hz</th>
<th>850–920 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of data (ks)</td>
<td>244</td>
<td>64</td>
<td>80</td>
<td>99</td>
</tr>
<tr>
<td>Mean $\nu_1$ ± s.d. (Hz)</td>
<td>830 ± 50</td>
<td>763 ± 25</td>
<td>828 ± 15</td>
<td>877 ± 17</td>
</tr>
<tr>
<td>$\Delta \nu_1$ (Hz)</td>
<td>283 ± 5</td>
<td>325 ± 6</td>
<td>286 ± 9</td>
<td>249 ± 4</td>
</tr>
<tr>
<td>$\Delta \nu_{\text{SB, lower}}$ (Hz)</td>
<td>55.5 ± 1.7</td>
<td>47.7 ± 3.5</td>
<td>57.0 ± 2.1</td>
<td>56 ± 2</td>
</tr>
<tr>
<td>rms amplitude $\nu_1$ (per cent)</td>
<td>7.54 ± 0.01</td>
<td>7.94 ± 0.04</td>
<td>7.86 ± 0.02</td>
<td>7.12 ± 0.03</td>
</tr>
<tr>
<td>FWHM $\nu_1$</td>
<td>4.86 ± 0.04</td>
<td>5.4 ± 0.1</td>
<td>4.45 ± 0.06</td>
<td>4.90 ± 0.06</td>
</tr>
<tr>
<td>rms amplitude $\nu_2$ (per cent)</td>
<td>4.03 ± 0.11</td>
<td>4.5 ± 0.3</td>
<td>4.0 ± 0.2</td>
<td>3.4 ± 0.2</td>
</tr>
<tr>
<td>FWHM $\nu_2$</td>
<td>130 ± 11</td>
<td>104 ± 15</td>
<td>120 ± 18</td>
<td>87 ± 13</td>
</tr>
<tr>
<td>rms amplitude $\nu_{\text{SB, lower}}$ (per cent)</td>
<td>&lt;0.9a</td>
<td>&lt;1.5a</td>
<td>1.2 ± 0.2</td>
<td>&lt;0.8a</td>
</tr>
<tr>
<td>rms amplitude $\nu_{\text{SB, upper}}$ (per cent)</td>
<td>1.3 ± 0.1</td>
<td>1.7 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>FWHM $\nu_{\text{SB, upper}}$</td>
<td>12.7 ± 2.7</td>
<td>14 ± 5</td>
<td>12 ± 4</td>
<td>10 ± 4</td>
</tr>
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Without using shift-and-add technique

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<tbody>
<tr>
<td>rms amplitude $\nu_\text{low}$ (per cent)</td>
<td>–</td>
<td>2.7 ± 0.2</td>
<td>2.3 ± 0.1</td>
<td>&lt;1.6a</td>
</tr>
<tr>
<td>FWHM $\nu_\text{low}$ (Hz)</td>
<td>–</td>
<td>17 ± 3</td>
<td>20 ± 4</td>
<td>–</td>
</tr>
<tr>
<td>Frequency $\nu_\text{low}$ (Hz)</td>
<td>–</td>
<td>42.1 ± 0.8</td>
<td>43.5 ± 1.6</td>
<td>–</td>
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</table>

*a95 per cent upper limits (determined using $\Delta \chi^2 = 2.71$).
responsible for the upper kilohertz QPO is modulated by the Lense–Thirring precession at the sonic-point radius; this modulation would then in turn modulate the formation of the lower kilohertz QPO. In such a scenario, the upper kilohertz QPO should also display sidebands. The fact that these have not yet been detected can be explained by the large FWHM of the upper kilohertz QPO, which precludes the detection of such sidebands. The skewed shape of the upper kilohertz QPO in the average power spectrum (see e.g. Fig. 1) can be explained by the fact that the upper kilohertz QPO rms amplitude and $\Delta f$ change as a function of kilohertz QPO frequency (e.g. Méndez et al. 1998a; Table 1).

If Lense–Thirring precession is responsible for the production of the sideband, and if the sideband separation frequency $\Delta f_{SB}$ reflects the Lense–Thirring precession frequency, $\Delta f_{SB}$ would be expected to change as the Keplerian frequency squared ($\Delta f_{SB} \propto f^2_k$). In Fig. 4 we plot $\Delta f_{SB}$ as a function of the lower (left-hand panel) and upper kilohertz QPO (right-hand panel), respectively. The sideband separation frequency $\Delta f_{SB}$ is consistent with being constant when the lower (upper) kilohertz QPO frequency changes by $\sim 100$ Hz ($\sim 38$ Hz), respectively. In the left (right) panel of Fig. 4, we also show the best-fitting quadratic relation assuming that the lower (upper) kilohertz QPO reflects the Keplerian motion at a preferred radius in the disc and that $\Delta f_{SB}$ is the Lense–Thirring precession frequency at that preferred radius. The normalization of the quadratic curve is given by

$$v_{LT} = \frac{8\pi^2 I \nu_s^2}{c^2 M_{NS}},$$

where $v_{LT}$ is the Lense–Thirring precession frequency, $I$ is the moment of inertia of the neutron star, $\nu_s$ is the spin frequency of the star [which is $\sim 581$ Hz in the case of 4U 1636–53 from Strohmayer et al. (1997)], $c$ is the speed of light, and $M_{NS}$ is the mass of the neutron star. The curve in the left-hand panel requires $I_{45}/m$ to be $3.05 \pm 0.07$, and that in the right-hand panel $0.17 \pm 0.01$, where $I_{45}$ and $m$ are in units of $10^{45}$ g cm$^2$ and $M_\odot$, respectively; the expected range of this quantity is between 0.5 and 2 (Stella & Vietri 1998).

Recently, a model explaining the kilohertz QPOs has been proposed that invokes the existence of a non-linear resonance between the vertical and radial epicyclic frequencies in an accretion disc around a neutron star (Abramowicz et al. 2003). Some versions of this model also include a resonance of these frequencies with the spin frequency of the neutron star (Kluźniak et al. 2004; Lee, Abramowicz & Kluźniak 2004). The resonance model has been introduced as a way to explain the existence of preferred values in the distribution of QPO frequency ratios (Abramowicz et al. 2003; but see Belloni, Méndez & Homan 2004) as well as the commensurability of the neutron-star spin and the kilohertz QPO frequency separation. So far it has not been explored whether a resonance mechanism could also explain the sidebands to the kilohertz QPOs. For instance, it may be possible that the Lense–Thirring precession...
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