RossiXTE monitoring of 4U 1636–53: I. Long-term evolution and kHz Quasi-Periodic Oscillations

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ABSTRACT
We have monitored the atoll-type neutron star low-mass X-ray binary 4U 1636–53 with the Rossi X-Ray Timing Explorer (RXTE) for more than 1.5 years. Our campaign consisted of short (∼2 ks) pointings separated by two days, regularly monitoring the spectral and timing properties of the source. During the campaign we observed a clear long-term oscillation with a period of ∼30-40 days, already seen in the light curves from the RXTE All-Sky Monitor, which corresponded to regular transitions between the hard (island) and soft (banana) states. We detected kHz QPOs in about a third of the observations, most of which were in the soft (banana) state. The distribution of the frequencies of the peak identified as the lower kHz QPO is found to be different from that previously observed in an independent data set. This suggests that the kHz QPOs in the system shows no intrinsically preferred frequency.

Key words: X-rays: binaries – accretion: accretion discs – stars: neutron

1 INTRODUCTION

High-frequency quasi-periodic oscillations (QPO) in neutron-star X-ray binaries often appear in pairs, with frequencies ranging from a few hundred Hz to more than 1 kHz (see van der Klis 2006 for a review). These so-called kHz QPOs, which were discovered with the Rossi X-Ray Timing explorer (RXTE), provide a probe into the accretion flow very close to the compact objects and can possibly serve as a tool to observe effects of general relativity. Their frequencies are strongly correlated with other timing and spectral features (see Ford & van der Klis 1998; Psaltis, Belloni & van der Klis 1999; Belloni, Psaltis & van der Klis 2002; van Straaten et al. 2005). In particular, the frequencies of the lower ($\nu_{\text{low}}$) and upper ($\nu_{\text{high}}$) kHz QPO are strongly correlated with each other (see Belloni, Méndez & Homan 2005, hereafter BMH05). The correlation is roughly linear (but see Zhang et al. 2006) and similar for all sources (Belloni, Méndez & Homan 2007).

A number of theoretical models have been proposed for the interpretation of these oscillations, based on the identification of their frequencies with various characteristic frequencies in the inner accretion flow (Stella & Vietri 1999; Osherovich & Titarchuk 1999; Zhang 2004; Lamb & Miller 2003). However, there is still no consensus as to the origin of the QPOs.

In an attempt to determine the possible presence of preferred frequencies, as predicted by certain resonance models (see e.g. Abramowicz et al. 2003), BMH05 investigated the distribution of the kHz QPO frequencies for separate sources. They analyzed large samples of RXTE data of five systems and found indications for preferred frequencies in each of the sources. However, it is known that the time evolution of kHz QPO frequencies is similar to a random walk, i.e. the current frequency cannot jump arbitrarily away from the one from a few dozen seconds before (see van der Klis 2006). BMH05 showed that a random walk in frequency, if not sampled for a long time compared to the random walk time scale, also produces apparent preferred frequencies.

To obtain a data set with an improved sampling of the kHz QPO frequency evolution and to determine an unbiased frequency distribution we started a monitoring campaign of one of the five sources studied by BMH05, 4U 1636–53. This source is a member of the atoll class (see Hasinger & van der Klis 1989). It contains a neutron star accreting matter from a companion star of mass $\sim 0.4 \ M_\odot$. 

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with an orbital period of 3.8 hr (see, e.g., van Paradijs et al. 1990). Type-I X-ray bursts were observed several times from 4U 1636–53, sometimes with unusual shapes (e.g., Turner & Breedon 1984; van Paradijs et al. 1986), or unusually long durations (e.g., Wijnands 2001). New results on the X-ray bursts have recently been presented by Bhattacharyya & Strohmayer (2005, 2006). A long-term quasi-periodic variability has been reported from All-Sky Monitor (ASM) data (Shih et al. 2005).

Two simultaneous kHz QPOs have been observed in 4U 1636–53, with rms amplitudes increasing with photon energy (Zhang et al. 1996; Wijnands et al. 1997). The frequency of the lower kHz QPO increases, and its amplitude decreases, with inferred $\dot{M}$ (Di Salvo, Méndez & van der Klis 2003; their data are the same as those used by BMH05), and at high $\dot{M}$ the frequency difference between the two QPOs is in the range 240–280 Hz, significantly lower than half the frequency of the oscillations detected during type-I bursts (Méndez et al. 1998). It has been shown that at low inferred mass accretion rate the kHz QPO peak separation in 4U 1636–53 is $\sim 323$ Hz, which exceeds half the neutron star spin frequency as inferred from burst oscillations (Jonker et al. 2002). Third, and possibly fourth, weaker kHz QPOs have been discovered simultaneously with the previously known kHz QPO pair (Jonker et al. 2000); the new kHz QPOs are at frequencies of $\sim 58$ Hz above and below the frequency of the lower kHz QPO respectively, suggesting that these are sidebands to the lower kHz QPO. Barret et al. (2005) reported the results of a systematic archival study of the Proportional Counter Array (PCA) observations of 4U 1636–53 concentrating on the drop in coherence of the lower kHz QPO at high frequencies, as previously found by Di Salvo et al. (2003). After extension of their analysis to a large sample of sources, Barret et al. (2006) interpreted this as evidence for the presence of the innermost stable orbit around the neutron star. This conclusion is under discussion (see Méndez 2006 and Barret et al. 2007).

4U 1636–53, together with 4U 1608–52 and Aql X-1, also shows QPOs at mHz frequencies (Revnivtsev et al. 2001). This feature seems to occur only in a rather narrow range of mass accretion rates, corresponding to X-ray luminosities of $\sim (0.5 - 1.5) \times 10^{37}$ ergs/s, and they disappear after X-ray bursts. Contrary to the general behavior of QPOs, the rms amplitude of the mHz QPOs strongly decreases with energy. These oscillations are thought to be related to nuclear burning on the surface of the neutron star (see Revnivtsev et al. 2001).

In this paper we present the results of the first 1.5 years of our ongoing monitoring campaign of 4U 1636–53. This paper is devoted to the frequency distribution of the kHz QPOs, while following articles will present the results on the X-ray bursts and on a more detailed analysis of the overall evolution.

2 THE CAMPAIGN

In March 2005, we started to observe 4U 1636–53 with RXTE for about 2 ks every two days. Here we include all observations from 1 March 2005 to 14 September 2006, a total of 305 pointings. During the period 2006 March 3 through April 10, daily observations were performed. For each dataset, we extracted a background-subtracted average count rate in the full PCA channel band (corresponding to $\sim$2–60 keV) using standard FTOOLS. We only used data form Proportional Counter Unit #2 (PCU2) as it was the only one consistently operational during all observations. The resulting long-term light curve is shown in the top panel of Fig. 1.
tion with a period of 30-40 days (see Shih et al. 2005) is evident. A total of 49 X-ray bursts was detected (marked with crosses in Fig. 1). On two occasions, 2005 April 20 and 2005 July 31, two X-ray bursts within the same observation were detected. A study of the X-ray bursts will be presented in a forthcoming paper.

3 LONG-TERM EVOLUTION

In order to follow the X-ray color evolution of the source along the count rate oscillation (see top panel of Fig. 1) we extracted background-subtracted count rates from the Standard2 channel bands A=3–10 and B=20–40 (numbering from 1 to 129), nominally 2.5–5.7 keV and 7.8–16.4 keV respectively. We then constructed a hardness ratio \( HR = B/A \). The time evolution of the hardness ratio can be seen in the bottom panel of Fig. 1. The count-rate oscillations correspond to strong spectral changes, which appear to be out of phase with changes in hardness. In order to study this behaviour in more detail, we constructed the Hardness-Intensity Diagram (HID), shown in Fig. 2, using the count rate and hardness ratio from Fig. 1. The source followed a very repetitive path in this diagram, corresponding to the long-period oscillation visible in Fig. 1. Two main regions can be identified in the HID: the hardest points are all at low count rate and correspond to the island state of atoll sources. The soft points span a rather large range of count rate while keeping a nearly constant hardness: they correspond to the banana branch. In between, transitional points are observed. In Fig. 2 we connected consecutive observations with a line: a dotted line if the source moved from hard to soft (leftward) and a solid line if the source moved from soft to hard (rightward). It is clear that 4U 1636–53 traveled the diagram describing a counter-clockwise rotation (although the vertical soft branch in the HID is not actually followed monotonically from top to bottom). Also, the density of transitional points indicate that the transition from hard to soft is faster than the reverse transition. The 47 observations with X-ray bursts are marked with crosses in Fig. 2. Bursts are observed all over the diagram, although there are none corresponding to the hardest points of the island state \( HR > 1.25 \) and around HR=0.8.

4 TIMING ANALYSIS

For each observation, we divided the light curve from the full PCA energy band in intervals 16 seconds long and produced a Power Density Spectrum (PDS) for each stretch of data. The time resolution used was 256\( \mu \)s, corresponding to a Nyquist frequency of 2048 Hz. We normalized the PDS according to Leahy et al. (1983), obtaining a time-frequency image. We also averaged all PDS corresponding to a single observation in order to increase statistics. The average PDS were then normalized to fractional rms (Belloni & Hasinger 1990). The frequency region 300–1300 Hz was rebinned into 128 bins (frequency resolution \( \sim 8 \) Hz) and the resulting power spectrum was fitted using XSPEC 11.3 with a model consisting of a constant and one or two Lorentzians. In a few cases, an additional zero-centered Lorentzian was added to take into account a broad component.

In this way we detected a significant QPO peak in 95 observations from our sample of 305. In three cases also a second significant QPO was detected. Since kHz QPO frequencies drift on short time scales, we rebinned each time-frequency image by a factor of 4 in time (resolution 64s) and inspected all images for peaks showing changes in their centroid frequency. We found such a variable-frequency peak in 53 cases out of 95, while for the other 42 observations, no significant peak was detected at 64 s resolution. For the observations with a visible variable peak, we fitted each 64s PDS separately with a constant plus Lorentzian model and recovered the frequency evolution versus time. The fits were performed with a Lorentzian with a FWHM fixed at 4 Hz in order to constrain the automatic fits to narrow components. In the following, we refer to these as variable-peak observations.

In the three cases where two peaks were detected, we obviously have a lower and an upper kHz QPO. When only one peak is detected, the identification of the QPO has to be made in a different way. In Fig. 3 for each observation we plot the average QPO centroid frequency as a function of spectral hardness. Two populations of points immediately emerge: above a hardness of 0.75, the QPO frequency is anti-correlated with hardness, while below that threshold there is no correlation. Such a segregation is known (see Méndez & van der Klis 1999, Méndez et al. 1999) and allows us to identify the two types of QPO: lower-kHz QPO at low hardness, upper-kHz QPO at high hardness.

With this classification of peaks, we can examine the distribution of centroid frequencies. The bottom panel of Fig. 4 shows the distribution of variable-peak frequencies, together with the corresponding histogram from BMH05. The new data are distributed in a very different way and over a wider range of frequencies. There are broad peaks visible, but none corresponding to the main peak observed.
by BMH05. A Kolmogorov-Smirnov test, applied over the same frequency range gives a probability of $10^{-26}$ that the two sets were drawn from the same parent population. The dashed lines mark the region corresponding, within errors, to frequencies that would correspond to a 3:2 ratio of upper and lower kHz QPO frequency, calculated with the frequency correlations in BMH05. While no BMH05 detections fell in that region, a few do so in the new sample.

While the data in Fig. 4 represent only the variable-peak frequencies, i.e. lower kHz QPOs which were sufficiently narrow and strong to be followed in time with a 64s resolution, it is interesting to examine the histograms of the remaining frequencies identified with a lower kHz QPO, consisting of one frequency per observation, and of the frequencies identified with the upper kHz QPO. These can be seen in Fig. 5. In the top panel are all frequencies identified with as lower-kHz QPO, one point per observation: in gray the ones which could also be followed on 64s time scale, in black the others. In the bottom panel are all frequencies identified with as upper-kHz QPO, also one point per observation. The upper kHz frequencies are evenly distributed over the full range, while the lower kHz QPOs show a concentration at high frequencies.

The distributions described above derive from a set of positive detections, while a large number of observations did not yield a significant QPO. This raises a problem of completeness that needs to be addressed. We ran simulations to determine the percentage of lower kHz QPO peaks that we could have missed as a function of centroid frequency. For each frequency in our range, we produced 100 PDS corresponding to an observation of 2ks with 3 PCUs on and a source count rate equal to the minimum observed value (see Fig. 1). The rms and $Q$ value for the QPO were derived from the curves reported by Barret et al. (2005). The result is that we are near 100% detection efficiency across the frequency range 400-1000 Hz, with a decrease at the boundaries, reaching 30% at 250 Hz and 1150 Hz. This means that our search is complete within the observed range and the frequency distributions are not biased for missing additional peaks.

5 DISCUSSION

Using a series of short observations at regular intervals with RXTE, we found that the 30 – 40 day quasi-periodicity seen in the RXTE/ASM light curve of 4U 1636–53 (Shih et al. 2005) is due to regular state transitions between the hard (island) and soft (banana) states. These cyclic state transitions in 4U 1636–53 have been repeating for at least 5 years now, and they follow a hysteresis cycle similar to the one seen in black-hole binaries in outburst. This is the first time ever that this hysteresis pattern has been observed in a persistent neutron star system.

We found that the distribution of frequencies of the lower kHz QPO in 4U 1636–53 changed significantly compared to the distribution in the observations used by BMH05. This is consistent with the proposal by BMH05 that the peaks in the distribution of the kHz QPO frequencies are due to the combination of a random walk of the QPO frequencies and the observational sampling. This definitely shows that in 4U 1636–53 there are no preferred frequen-
5.1 The distribution of QPO frequencies

In Fig. 4 we compare the distribution of lower kHz QPO frequencies in 4U 1636–53 from this campaign to the distribution of lower kHz QPO frequencies for the same source taken from BMH05, which was based on data taken before 1998. This comparison shows that in the new data the peaks in the distribution are less pronounced than they were in the data of BMH05, which was based on data taken before 1998. This means that the BMH05 frequencies are associated to a high stable flux, while the data from our campaign are associated to a much more variable flux level. It is known that the frequency of the kHz QPOs in these systems show a positive correlation with source count rate on short (hours) time scales. On long time scales, this correlation shows shifts in count rate, producing what is known as “parallel lines” (Méndez et al. 1999). A possible explanation for this phenomenon was proposed by van der Klis (2001): the frequency would depend on the current mass accretion rate normalized by its long-term average. This would mean that in the BMH05 data, since the long-term average did not vary much, the frequencies would be observed to vary less than in our more recent data.

The distribution of lower kHz QPO frequencies shown in Fig. 4 gives a different view than what was found by BMH05, but confirms their conclusions. Our new results confirm the absence of one or more preferred frequencies. In particular, there is nothing special in the distribution of frequencies at around 650 Hz, which corresponds to an upper to lower kHz QPO frequency ratio of 1.5.

5.2 Long term evolution

Our data set also provides a unique view of the long term evolution of a persistent neutron star LMXBs. We found that the ~ 30 – 40 day periodicity seen in the RXTE/ASM
light curve of 4U 1636–53 up to December 2004 (Shih et al. 2005) is still present in our observations, up to September 2006. Figs. 1 and 2 show that 4U 1636–53 moves regularly along the HID track, following this ∼30–40 days periodicity. In other words, the periodicity in the light curve is caused by a regular alternation of soft (island) and hard (banana) states. In combination with RXTE/ASM light curves (see Shih et al. 2005), our observations suggest that the state transitions have been repeating regularly for at least 5 years.

The HID of 4U 1636–53 shares some similarities with the corresponding diagrams for neutron star and black-hole transients (Maccarone & Coppi 2003; Belloni et al. 2005; Homan & Belloni 2005). In particular, during outbursts, these systems follow a counter-clockwise path in their HID as they switch between their hard and soft states. For these systems, the outbursts start with a hard peak, which means that the hysteresis can also be interpreted as the soft flux lagging the hard one (see e.g. Yu et al. 2004). The case of 4U 1636–53 is the same. The hard-soft (island-banana) transition always takes place at a higher flux value than the returning transition to the hard (island) state, similar to what is observed in black-hole transients, where the hard-soft transition always takes place at a higher flux than the reverse transition. 4U 1636–53 is the first persistent system for which such a hysteresis cycle has been observed repeatedly. A comparison of the ASM light curve of 4U 1705–44 with the color analysis of Olive, Barret & Gierliński (2003) indicates that this source might behave in a similar way. Shih et al. (2005) show a similar quasi-periodic modulation in the ASM flux of KS 1731–260, but no dense sampling with the PCA is available to check for state transitions. A more detailed analysis of the hysteresis behavior will be presented in a future paper.

6 CONCLUSIONS

We reported the results of a one and a half year campaign to observe 4U 1635–53. The observational strategy of a regular monitoring has the advantage of yielding an unbiased coverage of the evolution of the system along its quasi-regular 30–40 days oscillation. We found by BMH05, based on previous RXTE observations. The conclusion is that there is no preferred frequency or frequency ratio in 4U 1636–53.

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