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Detection of a 1258-Hz high-amplitude kilohertz quasi-periodic oscillation in the ultracompact X-ray binary 1A 1246–588

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ABSTRACT

We have observed the ultracompact low-mass X-ray binary (LMXB) 1A 1246−588 with the *Rossi X-ray Timing Explorer* (*RXTE*). In this paper we report the discovery of a kilohertz quasi-periodic oscillation (QPO) in 1A 1246−588. The kilohertz QPO was only detected when the source was in a soft high-flux state reminiscent of the lower banana branch in atoll sources. Only one kilohertz QPO peak is detected at a relatively high frequency of 1258 ± 2 Hz and at a single trial significance of more than 7σ. Kilohertz QPOs with a higher frequency have only been found on two occasions in 4U 0614+09. Furthermore, the frequency is higher than that found for the lower kilohertz QPO in any source, strongly suggesting that the QPO is the upper of the kilohertz QPO pair often found in LMXBs. The full width at half-maximum is 25 ± 4 Hz, making the coherence the highest found for an upper kilohertz QPO. From a distance estimate of ≈6 kpc from a radius expansion burst we derive that 1A 1246−588 is at a persistent flux of ≈0.2–0.3 per cent of the Eddington flux, hence 1A 1246−588 is one of the weakest LMXBs for which a kilohertz QPO has been detected. The rms amplitude in the 5–60 keV band is 27 ± 3 per cent; this is the highest for any kilohertz QPO source so far, in line with the general anticorrelation between source luminosity and rms amplitude of the kilohertz QPO peak identified before. Using the X-ray spectral information we produce a colour–colour diagram. The source behaviour in this diagram provides further evidence for the atoll nature of the source.

Key words: accretion, accretion discs – binaries: close – stars: individual: 1A 1246−588 – stars: neutron – X-rays: binaries.

1 INTRODUCTION

Ultracompact X-ray binaries (UCXBs) are low-mass X-ray binaries (LMXBs) that have an orbital period shorter than $P_{\mathrm{orb}} \approx 1$ h, implying such a small Roche lobe that the donor in an UCXB will have lost (most of) its hydrogen (Nelson, Rappaport & Joss 1986; Savonije, de Kool & van den Heuvel 1986). For 12 LMXBs P_{orb} has been measured to be in the ultracompact regime (Nelemans & Jonker 2006).

In the power spectra of ∼20 accreting neutron star LMXBs kilohertz quasi-periodic oscillations (QPOs) have been discovered (see van der Klis 2006b, for a review). Kilohertz QPOs are thought to be caused by motion of matter a few kilometres above the surface of accreting neutron stars. Even though there is as yet no agreement about the exact physical mechanism causing the X-ray light curves to be modulated at kilohertz frequencies, 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. Hence, the kilohertz QPOs potentially allow one to detect effects of the strong gravitational fields and to constrain the neutron star mass–radius relation (e.g. Miller, Lamb & Psaltis 1998).

Often two kilohertz QPO peaks separated by $\Delta\nu = 200$–360 Hz are found (again see van der Klis 2006b, for a review). The highest frequencies have been observed in the UCXB 4U 0614+09 (1329 ± 4 Hz, van Straaten et al. 2000 and 1273.6 ± 9.5 Hz, van Straaten et al. 2002). At high ($\gtrsim$400 Hz) neutron star spin frequencies $\Delta\nu$ has been found to be equal to half the spin frequency (e.g. in SAX J1808.4−3658; Wijnands et al. 2003), whereas in sources where the neutron star spin is $\lesssim$350 Hz $\Delta\nu$ is found to be close to the spin frequency (see Strohmayer & Bildsten 2006; van der Klis 2006a,b, for reviews).

1A 1246−588 was discovered with the Ariel–V observatory in the mid-1970s at a level of roughly (1–2) × 10^{-10} erg cm^{-2} s^{-1}

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(2–10 keV) by Seward et al. (1976), but it had also been detected by UHURU a few years earlier (Forman et al. 1978). The Ariel-V data exhibited a flare with a peak five times above the lowest level (Carpenter et al. 1977). On 1985 February 16, the first pointed observation of 1A 1246−588 was taken with EXOSAT. From the HEASARC standard products we found that the light curve is featureless and the 2–10 keV flux is 9.5×10^{-11} erg cm^{-2} s^{-1}. In 1997, the first X-ray burst was detected with the BeppoSAX Wide Field Cameras (WFCs; Piro et al. 1997) from a position consistent with that of 1A 1246−588 (Boller et al. 1997). The increased localization accuracy provided by the WFCs enabled an identification with a *ROSAT* source and thus the position is known with an accuracy of 9 arcsec (Boller et al. 1997). This enabled Bassa et al. (2006) to identify the optical counterpart and determine an UCXB nature through the ratio of the X-ray to optical flux. In 2006 August a type I X-ray burst was detected with the *Swift* Burst Alert Telescope (Kong 2006; Romano et al. 2006) and the satellite autonomously slewed to the target within 193 s. The burst was still detectable with the *Swift* X-ray telescope and the total duration could be accurately determined to be 28 min. Such a duration is similar to the long bursts from other UCXBs (see in 't Zand, Jonker & Markwardt 2007).

Here, we report our analysis of *Rossi X-ray Timing Explorer* (*RXTE*) observations of 1A 1246−588.

2 OBSERVATIONS, ANALYSIS AND RESULTS

We have used proportional counter array (PCA) data from 55 short *RXTE* observations of 1A 1246-588. All data obtained between MJD 53720 and 54108 (UTC; 2005 December 16–2007 January 15) amounting to a total of $\approx$45 ks were taken from programme P90042. In the top panel of Fig. 1 we have plotted the light curve obtained with the *RXTE* All Sky Monitor (ASM). Besides ASM count rate we show the source flux in erg cm^{-2} s^{-1}; for this we used the fact that the 1A 1246−588 PCA X-ray spectrum in the low-flux state resembles that of the Crab. The source is persistently detected. It remained at a level of roughly 0.37 ASM counts s^{-1} which is 5 mCrab (2–12 keV), except for a long period between 1998 October (MJD 51100) and 2001 October (MJD 52200) when it exhibited much more variability and the flux went up to 2.4 ASM counts s^{-1} (32 mCrab) and similarly after mid-2004. There are flare-like features visible with peak fluxes that are $\approx$3 times higher than normal, last a couple of weeks and have a recurrence time between $\approx$20 and 100 d. In the bottom panel of Fig. 1 we show the absorbed 2–10 keV flux as derived from fitting an absorbed power law plus blackbody model to the X-ray spectra extracted from the *RXTE*/PCA Standard 2 data (using FTOOLS 6.0.4 and XSPEC 12.2.1; Arnaud 1996).

Using 16-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 the full energy band of 2–60 keV. We first combined all the power spectra from all data. The high-frequency (256–4096 Hz) part of the average power spectrum was searched for the presence of kilohertz QPOs. We did not detect a kilohertz QPO. However, we next selected the data for which the total PCA count rate was above $\sim$150 counts s^{-1}. A strong kilohertz QPO was discovered. Subsequent subselections showed that the kilohertz QPO was significantly present only in the flare data before MJD 53800 (see Fig. 1).

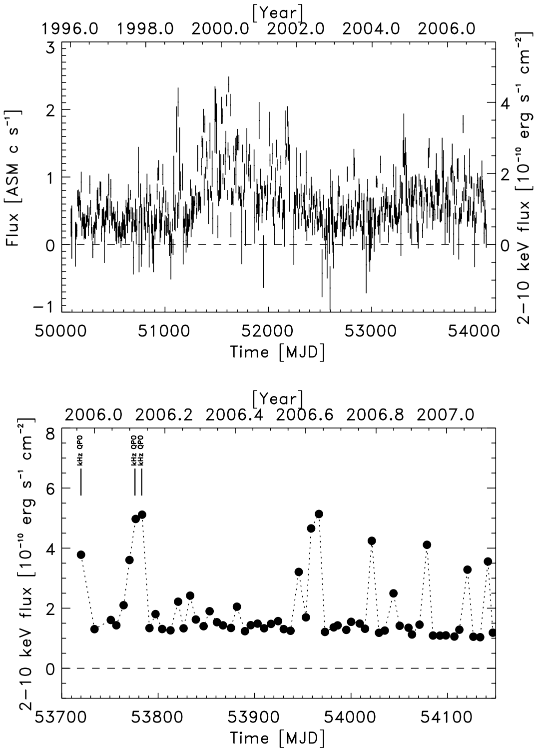

Figure 1. Top panel: The *RXTE* ASM 7-d average light curve of 1A 1246−588. The ordinate on the left-/right-hand side gives the source flux in ASM counts s^{-1}/2–10 keV in erg cm^{-2} s^{-1}. The flare episodes where the count rate increases by a factor of $\approx$3 can be discerned. Bottom panel: The observed (absorbed) 2–10 keV flux derived from the PCA monitoring observations of 1A 1246−588 fitting an absorbed blackbody plus power-law model to the Standard 2 data. We have also indicated the observations during which the kilohertz QPO was significantly detected. Note that the abscissae of the top and bottom panels are different and that the size of the data points is larger than the error on the data points in the bottom panel.

We fitted the 64-2048 Hz part of the average power spectrum of the three observations indicated in Fig. 1 with kHz QPOi combined. A fit function, consisting of the sum of a constant to represent the Poisson noise and a Lorentzian to represent the kilohertz QPO, was used. With a reduced $\chi^2 = 0.86$ for 207 degrees of freedom the fit was good. The kilohertz QPO has a frequency of 1258 ± 2 Hz and a full width at half-maximum (FWHM) of 25 ± 4 Hz, see Fig. 2 (here and below we report 1σ single parameter errors determined using $\Delta\chi^2 = 1.0$). The single trial significance in the full 2–60 keV band is 7.5σ. Even when taking into account the $\lesssim$1000 trials we performed, the significance is still 6.8σ. The rms amplitude expressed as a fraction of the source count rate in the 2–60 keV band is 17.2 ± 1.5 per cent. In order to compare the rms amplitude of the QPO with previous work of, for example, Jonker et al. (2001) we also calculated power spectra in the 5–60 keV energy band. The fractional rms amplitude in that band is 27 ± 3 per cent. The average source count rate in the 2–60 keV band in the three observations containing the kilohertz QPO is 85 ± 1 counts s^{-1} whereas it is 52 ± 1 counts s^{-1} in the 5–60 keV band. As we will argue in Section 3 the detected kilohertz QPO can most likely be associated with the upper of the kilohertz QPO pair found in several LMXBs. In order to put an upper limit on the presence of a lower kilohertz QPO we determine a 95 per cent confidence upper limit on the presence of a kilohertz QPO at a frequency 200–400 Hz less than 1258 Hz for a QPO FWHM of 50, 100 or 150 Hz. The upper limit on the presence of such a QPO is 20 per cent (2–60 keV). For completeness we did the same for a kilohertz QPO at a frequency 200–400 Hz higher than 1258 Hz. The upper limit on the presence of such a QPO is 13 per cent (2–60 keV). We also inspected the low-frequency (0.1–256 Hz) part of the average power spectrum containing the kilohertz QPO. We

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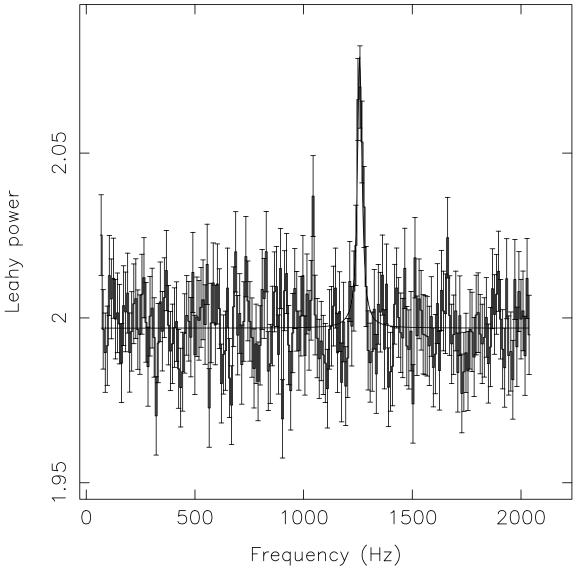

Figure 2. Part of the Leahy et al. (1983) normalized average 2–60 keV power spectrum of the three observations indicated in Fig. 1. The kilohertz QPO is clearly visible. It has a more than 7σ single trial significance. The solid line represents the best-fitting model consisting of a constant plus a Lorentzian.

found a strong (27.4 ± 1.0 per cent; 2–60 keV) band-limited noise component. We characterized the band-limited noise component by fitting a Lorentzian to the averaged low-frequency power spectrum. Its central frequency was 24 ± 1 Hz, whereas the FWHM was 24 ± 2 Hz.

Using the 16-s resolution Standard 2 data we further created colour–colour diagrams (CDs; Fig. 3). A soft colour is plotted versus a hard colour; the soft and hard colours are defined as the ratio between the count rates in the 3.5–6.4 and 2.0–3.5 keV bands and that between the 9.7–16.0 and the 6.4–9.7 keV bands, respectively. The observed count rates have been corrected for dead-time effects and we have subtracted the background for each proportional counter unit (PCU) separately. We further corrected the colours for small changes in the instrumental response (the gain) and for differences in response between the various PCUs, using Crab observations close in time and assuming the Crab colours to be constant (for a full description of the correction see van Straaten et al. 2003). The CD of 1A 1246−588 bears hallmarks of that of the island and lower banana branch of an ‘atoll’ source (Hasinger & van der Klis 1989; see Fig. 3). Clearly present is the island state in the top left-hand part of Fig. 3 where the source, as in other atoll sources, spends much of its time since motions in the CD are generally slower here. Due to the low count rate and the fact that often only one or two PCUs were active, we have plotted the average colour of each observation. Given the short duration of each observation (on average less than 1 ks), the chance that the source moved over a large area in the CD is small. The large dots indicate two of the observations when the kilohertz QPO was present. The elevation above the Earth’s limb for the first PCA observation, when the kilohertz QPO was also present, was too low to create a reliable colour–colour point. The timing properties of that observation are not affected by the close presence of the Earth’s limb.

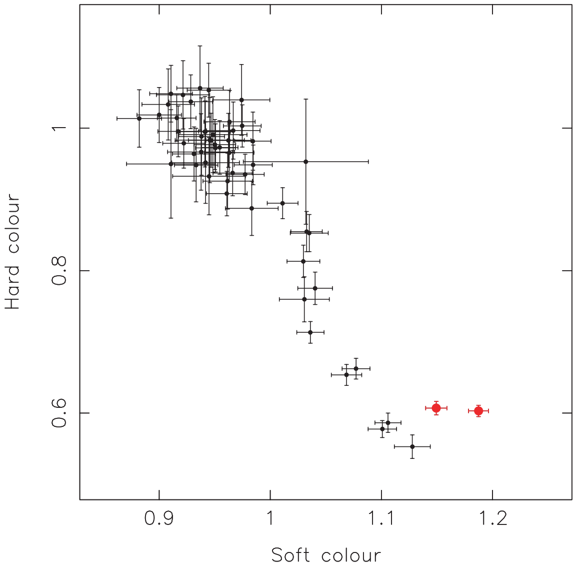

Figure 3. Colour–colour diagram of the Standard 2 PCA data. The small dots are the average colour of the source during one PCA observation. The large dots at a soft colour between 1.1 and 1.2 are the observations when the kilohertz QPO was detected. The soft and hard colours are defined as the ratio between the count rates in the 3.5–6.4 and 2.0–3.5 keV bands and that between the 9.7–16.0 and the 6.4–9.7 keV bands, respectively.

3 DISCUSSION

Using *RXTE* PCA data we have discovered a kilohertz QPO in the X-ray emission of the ultracompact X-ray binary 1A 1246−588. At a frequency of 1258 ± 2 Hz the kilohertz QPO frequency is rather high in comparison with those found in other sources (for an overview see van der Klis 2006b). Furthermore, the fractional rms amplitude of the kilohertz QPO measured in the 5–60 keV band is the highest found in any kilohertz QPO source. From the properties of a photospheric radius expansion burst in ’t Zand et al. (in preparation) derive a distance to the source of ≈6 kpc. This implies a persistent source luminosity of ≈0.2–0.3 per cent of the Eddington luminosity, making 1A 1246−588 one of the weakest LMXBs for which a kilohertz QPO has been detected; the other similarly weak source is 2S 0918−549 (Jonker et al. 2001). The high frequency and high coherence of the kilohertz QPO peak suggest that it can be identified as the upper kilohertz QPO. The lower kilohertz QPO has never been detected at frequencies higher than ≈1000 Hz when both kilohertz QPO peaks were detected simultaneously (van der Klis 2006b) and the coherence of the upper kilohertz QPO is found to increase at frequencies above ≈1100 Hz (Barret, Olive & Miller 2006; Méndez 2006). The spectral properties suggest that 1A 1246−588 belongs to the class of ‘atoll’ sources. The kilohertz QPO was only significantly detected when the source was in the lower banana branch similar to what has been found in other atoll sources (Méndez et al. 1999; van Straaten et al. 2000).

The high frequency yields the exciting possibility to obtain constraints on the neutron star. For instance, if a second simultaneous kilohertz QPO is discovered, the neutron star spin rate can be constrained. In the eight sources where both twin kilohertz QPOs and neutron star spins were directly measured, $\Delta\nu \approx \nu_{\rm spin}$ or $\Delta\nu \approx \nu_{\rm spin}/2$ (see review by van der Klis 2006b). Another constraint involves the neutron star mass and radius. The measured 1258 Hz frequency is high. Only in one object has a higher frequency ever been measured (see Section 1). If one interprets the observed QPO frequency as a Keplerian frequency and requires that the neutron star is smaller than the radius associated with that Keplerian frequency a neutron star mass-dependent limit can be put on the neutron star

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radius. In addition, if one assumes that the innermost stable circular orbit has a radius also smaller than the associated Keplerian radius a limit on the neutron star mass is obtained (Miller et al. 1998). Assuming a non-rotating neutron star this yields the following limits on the mass and radius of the neutron star for the 1258-Hz QPO: $M_{\rm NS} < 1.75\ {\rm M}_{\odot}$ and $R < 15.5$ km.

As mentioned above the fractional rms amplitude of the kilohertz QPO is the highest found to date. Similarly, the fractional rms amplitude of the broad low-frequency noise component is very high at 27 per cent (2–60 keV). This all fits-in with the trend of increasing rms amplitude for a decreasing source luminosity as shown for the upper kilohertz QPO before by Jonker et al. (2001). Using the data from Jonker et al. (2001) and the data on 1A 1246−588 we have fitted the relation between the fractional rms amplitude of the upper kilohertz QPO and source luminosity. A power-law fit gives an index of -0.35 ± 0.01. From fig. 3 in Méndez (2006) it seems as if the increase in the maximum fractional rms amplitude of a source with decreasing source luminosity levels off at 18–20 per cent (measured in the 2–60 keV band). However, the kilohertz QPO that we found in 1A 1246−588 does not seem to be compatible with this trend. Even though the measured amplitude in the 2–60 keV band of 17.2 ± 1.5 per cent is close to this saturation level, this amplitude is measured while the QPO frequency was very high (1258 Hz). In other sources the rms amplitude of the upper kilohertz QPO decreases strongly at upper kilohertz QPO frequencies above 700–800 Hz. Hence, either the relation between kilohertz QPO frequency and fractional rms amplitude is significantly different in 1A 1246−588 from that in other sources or the increase in fractional rms amplitude and source luminosity does not level off at 18–20 per cent but keeps increasing.

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