DISCOVERY OF TWIN KILOHERTZ QUASI-PERIODIC OSCILLATIONS IN THE HIGH GALACTIC LATITUDE X-RAY TRANSIENT XTE J2123–058

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ABSTRACT

We report the discovery of twin kilohertz quasi-periodic oscillations (QPOs) in the persistent X-ray flux of the new X-ray transient XTE J2123–058. We detected the QPOs in data taken with the proportional counter array (PCA) on board the Rossi X-Ray Timing Explorer (RXTE; Bradt, Rothschild, & Swank 1993) on 1998 June 27 (Levine, Swank, & Smith 1998). Subsequent observations with the proportional counter array (PCA, also on board RXTE; Jahoda et al. 1996) showed two weak X-ray bursts (Takeshima & Strohmayer 1998), probably of type I (i.e., thermonuclear origin), indicating that the compact object is a neutron star. Observations of the optical counterpart (Tomsick et al. 1998a) revealed an orbital period of 5.9567 ± 0.0033 hr (Tomsick et al. 1998b; Ilovaisky & Chevalier 1998). The source has a high galactic latitude of 36°, which is unusual for an X-ray transient.

Quasi-periodic oscillations (QPOs) with frequencies between 200 and 1200 Hz, the so-called kilohertz QPOs, have been found in the persistent emission of numerous low-mass X-ray binaries (LMXBs). They are often found in pairs, with a frequency difference ranging from 250 to 350 Hz. The strength of the oscillations depends on the type (Hasinger & van der Klis 1989) of LMXB; they are usually stronger in atoll sources than in Z-source X-ray bursts. A few sources have shown oscillations during type I X-ray bursts (e.g., Strohmayer et al. 1996, 1998), whose frequencies are believed to be close to the neutron star spin frequency and which are near the kHz QPO frequency difference. On this basis, it has been suggested (Strohmayer et al. 1996; see also Miller, Lamb, & Psaltis 1998) that the frequency difference is equal to the neutron star spin frequency, but this idea has been seriously challenged by results by van der Klis et al. (1997), Méndez et al. (1998a), and Méndez, van der Klis, & van Paradijs (1998).

In this Letter, we present the discovery of kHz QPOs in XTE J2123–058. Preliminary results of this work were already presented by Homan et al. (1998).

1. INTRODUCTION

The X-ray transient XTE J2123–058 was discovered with the all-sky monitor (ASM; Levine et al. 1996) on board the Rossi X-Ray Timing Explorer on 1998 July 14, when the source count rate was at about 50% of its outburst peak level. The frequencies of the QPOs were 853 ± 4 and 1129 ± 8 Hz. The peaks had widths of 32±11 and 50±13 Hz, and the amplitudes were 6.1±0.7% and 6.5±0.9%, respectively. The QPO frequencies increased marginally with count rate, and the amplitudes showed a small increase with photon energy. On the basis of the appearance in the color-color and hardness-intensity diagrams, the low-frequency power spectrum, and the strength of the kHz QPOs, the system can be classified as an atoll source. The source showed five type I X-ray bursts. The distance to the source is estimated to be about 10 (5–15) kpc, which combined with the high Galactic latitude of 36°2 indicates that the source is a located in the Galactic halo.

Subject headings: stars: individual (XTE J2123–058) — stars: neutron — X-rays: stars

2. OBSERVATION AND ANALYSIS

For our analysis, we used data obtained with the PCA. Data were taken on five occasions (see Table 1) for a total of ~43 ks. PCA detectors 4 and 5 were inactive during observation 1, detector 5 was inactive during the last ~1000 s of observation 3, and detector 4 was inactive for ~13,000 s during observation 4. Observation 2 consisted of two scans over the region to determine a better source position (Takeshima & Strohmayer 1998); data from that observation were not included in the color diagrams, and only ~100 s were used for timing analysis. Apart from the standard 1 (0.125 s time resolution in one energy channel) and standard 2 modes (16 s time resolution in 129 energy bands), which were always active, data were obtained in an event mode with a 2±13 s time resolution and 64 energy bands (observations 2 and 3) and in a good xenon mode with a 2±20 s time resolution and 256 energy bands (observations 4 and 5). All modes covered the 2–60 keV energy band. Observation 1 did not yield data with the time resolution required to search for kHz QPOs.

The standard 2 data of detectors 1–3 were background corrected and used to create light curves, color-color diagrams (CDs), and hardness-intensity diagrams (HIDs). Figure 1 shows the ASM and PCA light curves. For observation 2, only the maximum count rate reached during the two scans is plotted (open circle). Figure 2 shows the CD and HID of observations 1 and 3–5 combined. Data during X-ray bursts were excluded from Figures 1 and 2.

Using all available high time resolution data, we made Fourier transforms of 16 s data segments to create power spectra ranging from 1/16 to 2048 Hz to search for kHz QPOs. To study the low-frequency power spectrum, we also created 1/128 to 512 Hz power spectra using 128 s data segments. Power spectra were selected on time, count rate, and position in the CD and HID and were averaged before further analysis. The properties of the kHz QPOs were measured by fitting the resulting average power spectra from 300 to 2048 Hz with a
TABLE 1

LOG OF THE PCA OBSERVATIONS OF XTE J2123–058

| Observation | Date  | Begin (UTC) | End (UTC) |
|-------------|-------|-------------|-----------|
| 1           | Jun 27 | 23:29       | 23:42     |
| 2           | Jun 29 | 00:33       | 01:09     |
| 3           | Jun 29 | 16:01       | 17:20     |
| 4           | Jul 14 | 09:41       | 19:42     |
| 5           | Jul 22 | 04:54       | 17:49     |

fit function composed of a constant, representing the Poisson level, and a Lorentzian for each QPO. The low-frequency power spectra were fitted with a power law plus a power law with an exponential cutoff. The values for the rms amplitudes are background corrected. Errors on the fit parameters were determined using \( \Delta \chi^2 = 1 \). All of the upper limits quoted are 95% confidence limits. In case of the kHz QPOs, upper limits were determined by fixing the FWHM to 25 Hz.

3. RESULTS

We found two simultaneous kHz QPOs in the data of observation 4 (see Fig. 3). This observation consisted of six \( \sim 3300 \) s intervals of contiguous data, hereafter “orbits,” separated by \( \sim 2400 \) s intervals during which no data were obtained. The QPOs were strongest during the first two orbits, when the count rate was lowest. In these orbits, the QPOs had frequencies of \( 853 \pm 4 \) and \( 1129 \pm 8 \) Hz, widths of \( 32^{+18}_{-8} \) and \( 50^{+18}_{-11} \) Hz, and rms amplitudes of \( 6.1^{+0.6}_{-0.7} \% \) and \( 6.5^{+0.8}_{-0.9} \% \) (unless otherwise stated, all fit parameters are those measured in the 2–11.2 keV band). The mean 2–60 keV background-corrected count rate during the first two orbits was 485 counts s\(^{-1}\).

There are indications for an increase of QPO strength with photon energy. In the 2–5.7 keV band, only upper limits could be determined of 6.2% and 5.2% rms for the lower and higher frequency QPO, respectively. In the 5.7–11.2 keV band, the frequencies and widths are consistent with the values obtained in the 2–11.2 keV band; the amplitudes are \( 8.8^{+1.1}_{-1.0} \% \) and \( 9.0^{+1.5}_{-1.3} \% \) rms. Only upper limits could be determined in the 11.2–16.7 keV band of 18.5% and 24.2% rms.

A more detailed analysis showed a difference between the data of the first and second orbit. The power spectra of the first orbit clearly showed the low-frequency QPO at 849 \( \pm 2 \) Hz with a width of \( 20^{+3}_{-2} \) Hz and an amplitude of \( 6.7^{+0.7}_{-0.4} \% \) rms, whereas the other QPO was only marginally detectable at 1110 \( \pm 10 \) Hz with an amplitude of \( 4.8^{+0.9}_{-0.7} \% \) rms and its width fixed at 35 Hz. In the power spectra of the second orbit, the lower QPO is very narrow and its width was fixed at 6 Hz; it had a frequency of 871 \( \pm 2 \) Hz and an amplitude of \( 3.4^{+1.2}_{-1.0} \% \) rms. The high-frequency QPO was found at 1141 \(^{+4}_{-3} \) Hz with a width of \( 32^{+15}_{-11} \) Hz and an amplitude of \( 7.1^{+1.0}_{-0.7} \% \).
rms. The mean (2–60 keV) background-corrected count rates of the first and second orbits were, respectively, 478 and 497 counts s\(^{-1}\), with standard deviations (for 16 s time bins) of 22 and 16 counts s\(^{-1}\). So, the QPO frequency increased with count rate, while the frequency difference was consistent with being constant at \(\sim 265\) Hz.

For the last four orbits of observation 4 and for the other observations, only upper limits on the presence of kHz QPOs could be determined. They were, in the 2–11.2 keV band, 16%, 4.4%, 4.3%, and 4.5% rms for, respectively, observations 2, 3, 4 (last four orbits), and 5.

Selections of all the observation 4 data based on the position in the CD and HID showed that the QPOs are only found at the lowest soft colors and count rates. No other significant dependence of QPO properties on color or intensity could be distinguished based on these selections.

We performed time lag measurements between the 3.5–9.3 and 9.3–14.9 keV energy bands. In both QPOs, the lags were consistent with being zero, but also with what has been found by Vaughan et al. (1997, 1998) for other sources with kHz QPOs. The lags are \(-8 \pm 4 \times 10^{-2}\) ms for the lower and \(-5 \pm 4 \times 10^{-2}\) ms for the higher frequency QPO, where the minus sign indicates a soft lag.

Observations 3, 4, and 5 were combined to study the low-frequency power spectrum (see Fig. 4). The average power spectrum (2–11.2 keV) was fitted with a power law plus a power law with an exponential cutoff. The rms amplitude of the power-law component was 2.61% \(\pm\) 0.05% (integrated over 0.01–1 Hz), and its power-law index was \(-1.10 \pm 0.04\). The second component had an rms amplitude of 4.5% \(\pm\) 0.3% (1–100 Hz), a power-law index of 1.3 \(\pm\) 0.5, and a cutoff frequency of 17 \(\pm\) 5 Hz. Selections were made on soft color. For soft colors higher than 2.6, the average power spectrum is well described by a single power law with an rms amplitude of 2.40% \(\pm\) 0.15% and a power-law index of \(-1.23 \pm 0.15\). For a possible power-law component with an exponential cutoff, an upper limit of 2% was determined. The average power spectrum for soft colors lower than 2.6 was fitted with a power law (2.47% \(\pm\) 0.05% rms and power-law index of \(-1.07 \pm 0.04\)) plus an exponentially cutoff power law (5.1% \(\pm\) 0.3% rms, power law index of 1.2 \(\pm\) 0.4, and a cutoff frequency of 20 \(\pm\) 6 Hz). In the power spectra of the last four orbits of observation 4, an equally good fit could be obtained by replacing the cutoff power law by a Lorentzian at 39 \(\pm\) 2 Hz, with an rms amplitude of 5.0% \(\pm\) 0.6% and an FWHM of 20 \(\pm\) 7 Hz.

We have analyzed five X-ray bursts which, based on the spectral softening during their decay, are most probably of type I. We searched for burst oscillations in 1 s power spectra (1–1024 Hz). This was done in the 2–60 keV and 3.5–15 keV energy bands, during the rise and decay of each burst. Data of the five bursts were also added to increase sensitivity. No oscillations were found, with upper limits on their amplitudes of 20% rms. Two very strong bursts were observed during observation 5. When corrected for the persistent emission obtained from the 100 s just before the bursts, their peak count rates (2–11.2 keV) are \(2550 \pm 60\) and \(2540 \pm 60\) counts s\(^{-1}\). These peak count rates are very close to each other and also much higher than those of the other three bursts (which had peak count rates of \(\sim 500, \sim 1200,\) and \(\sim 330\) counts s\(^{-1}\)). It is possible that the peak count rates are so similar because they are related to the Eddington luminosity reached in photospheric radius expansion bursts. Indeed, both bursts show a splitting of their main peak at higher photon energies, which usually is an indication for radius expansion (Lewin, van Paradijs, & Taam 1993). Fitting the burst spectra with a blackbody model did not conclusively show that radius expansion had occurred. However, an anticorrelation was found between the temperature and the radius of the blackbody, a feature that is typical for radius expansion bursts (Lewin et al. 1993). If the bursts are indeed radius expansion bursts, the distance to the source can be estimated (see Lewin et al. 1993). Assuming cosmic abundances, a 1.4 \(M_\odot\) neutron star mass, 10 km radius, and isotropic emission, the upper limit to the distance is \(\sim 14\) kpc. Using the observational relation between \(M_\gamma\), \(P_{\text{orb}}\), and \(L_\gamma/L_{\text{edd}}\) found by van Paradijs & McClintock (1994), we can estimate the distance in another way. Taking \(m_\gamma = 16.8\) (Tom sick et al. 1998b), \(A_\gamma = 0.36\) (Schlegel, Finkbeiner, & Davis, 1998), \(F_\gamma \approx 2.5 \times 10^{-9}\) ergs s\(^{-1}\) (from observation 3, which was closest to the optical observation), and the orbital period found by Tom sick et al. (1998b) and Ilovaisky & Chevalier (1998), we find a distance to the source between 10 and 15 kpc. Finally, a distance estimate can be made on the basis of the average burst duration (\(\tau\) and/or the observed ratio of persistent X-ray flux to the average flux emitted in X-ray bursts (\(\alpha\)), both of which show a strong correlation with \(\gamma = L_\gamma/L_{\text{edd}}\) (Lewin et al. 1993). For observation 5 (\(\tau \approx 12\) s, \(\alpha \approx 120\), and \(F_\gamma \approx 1 \times 10^{-9}\) ergs s\(^{-1}\)), this gives a distance range of 5–11 kpc. Combining the three methods gives a distance that is probably about 10 (5–15) kpc, which, using the galactic latitude of \(-36^\circ 2\), gives a distance from the Galactic plane of 6 (3–9) kpc.

4. DISCUSSION

We have found two simultaneous kHz QPOs in the X-ray flux of XTE J2123–058. The frequencies of the QPOs, \(-850–870\) Hz for the lower and \(-1110–1140\) Hz for the upper peak, are within the range observed for other sources. Their widths and rms amplitudes are also comparable to what is found in other LMXBs (van der Klis 1998). The QPOs are only found when the count rate and soft color are lowest. When the QPO
frequencies changed ~20–30 Hz, the frequency difference remained consistent with being constant at ~265 Hz.

From the other sources showing kHz QPOs, it was already evident that the QPO frequencies, although strongly dependent in a given source on the difference between the instantaneous luminosity and the average luminosity, do not depend on the average luminosity itself. XTE J2123–058 complicates this puzzle. A transient with a time-averaged luminosity a factor of ~10–2000 (averaging the total outburst luminosity over 3 yr) lower than in the persistent sources, it again shows exactly the same kHz QPO frequencies.

Several properties (Hasinger & van der Klis 1989) suggest that XTE J2123–058 is an atoll source:

1. The appearance in the CD and HID is reminiscent of the shapes traced out by atoll sources; the pattern traced out by XTE J2123–058 is then probably related to the lower and upper banana.

2. The low-frequency power spectra can be fitted with a power-law component (which we identify with very low-frequency noise) plus an exponentially cutoff power law (which we identify with high-frequency noise). In asotoll sources, the high-frequency noise is much weaker when the source is in the upper banana than when it is in the lower banana. Also, the strength of these noise components is comparable to that found in atoll sources on the banana branch (van der Klis 1995).

3. The strength of the kHz QPOs is relatively high (~9%), a common value for atoll sources.

On this basis, we classify this source as an atoll source. The bursting properties strengthen this classification. Although there are two Z-sources (Cyg X-2 and GX 17+2) that occasionally show X-ray bursts, the high burst frequency (five in ~43 ks) is usually regarded as a property of atoll sources. From the two strong bursts, we can derive a value for the persistent luminosity that is smaller than ~0.35L_{Edd}, which is typical for atoll sources. The kHz QPOs are only seen in the lower banana, i.e., at low accretion rates, which is also seen in other atoll sources (Wijnands et al. 1997, 1998; Méndez et al. 1999, 1998).

The estimated distance from the Galactic plane of 6 (3–9) kpc is unusually high when compared to other LMXBs and suggests that the source is located in the Galactic halo. For 18 neutron star LMXBs, van Paradijs & White (1995) found an rms value for the distance from the Galactic plane of 1.0 kpc. An important factor determining the height distribution of LMXBs is the magnitude of any kick received during the formation of the neutron star (van Paradijs & White 1995; Ramachandran & Bhattacharya 1997). These kicks can result in high system velocities. We calculated the system velocity needed to reach a height of 6 kpc by integrating orbits in the gravitational potential of Kuijken & Gilmore (1989). We found system velocities between 150 and 400 km s^{-1}, depending on the pre-kick location in the Galactic plane. These are relatively high velocities, and the kicks needed to obtain them can easily disrupt a binary. Since the distance of XTE J2123–058 from the Galactic plane is comparable to that of globular clusters, another scenario might be that the source was ejected from a globular cluster. In this case, a much smaller system velocity (typically 40 km s^{-1}) is required, which can easily be obtained from binary–single star or binary-binary interactions in a globular cluster (Phinney & Sigurdsson 1991; Sigurdsson & Phinney 1995).

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