DISCOVERY OF KILOHERTZ QUASI-PERIODIC OSCILLATIONS IN 4U 1735–44

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Received 1997 December 1; accepted 1997 December 31; published 1998 January 28

ABSTRACT

We discovered a single kilohertz (kHz) quasi-periodic oscillation (QPO) near 1150 Hz in the *Rossi X-Ray Timing Explorer* X-ray light curve of the low-mass X-ray binary and atoll source 4U 1735–44. The rms amplitude of this peak was 2%–3%, and the FWHM was 6–40 Hz. There are indications that the kHz QPO frequency decreased from 1160 to 1145 Hz when the count rate increased, which would be quite different from what is observed in other atoll sources for which kHz QPOs have been discovered. In the X-ray color-color diagram and hardness-intensity diagram, the source traced out the curved branch (the so-called banana branch) that has been found by previous instruments. The kHz QPO was detected only when the source was at the lowest count rates during our observations, i.e., on the lower part of the banana branch. When 4U 1735–44 was at higher count rates, i.e., on the upper part of the banana branch and at a higher inferred mass accretion rate with respect to that on the lower part of the banana branch, the QPO was not detected.

Besides the kHz QPO, we discovered a low-frequency QPO with a frequency near 67 Hz, together with a complex, broad-peaked noise component below 30 Hz. This 67 Hz QPO may be related to the magnetospheric beat-frequency QPO, which is observed on the horizontal branch of Z sources. This idea is supported by the (peaked) noise found in both 4U 1735–44 and Z sources at frequencies just below the QPO frequency.

Subject headings: accretion, accretion disks — stars: individual (4U 1735–44) — stars: neutron — X-rays: stars

1. INTRODUCTION

The low-mass X-ray binaries (LMXBs) can be divided into two subclasses, the atoll sources and the Z sources, after the track they trace out in the X-ray color-color diagram (CD) (Hasinger & van der Klis 1989). Atoll sources trace out an atoll-like shape in the CD (see, e.g., Fig. 6.9 of van der Klis 1995), with a curved branch called the banana branch (divided in the upper part and lower part of the banana branch according to the position in the CD), and one or more patches corresponding to the island state, in which the colors do not change much on timescales of a day. The exact morphology of the island state track, if any, is unknown since it apparently takes a long time to trace it out. Atoll sources have lower mass accretion rates ($\dot{M}$) than Z sources (e.g., Hasinger & van der Klis 1989). In atoll sources, $\dot{M}$ varies considerably between sources, and even within a single source. It is thought that $\dot{M}$ is lowest when the sources are in the island state, increases on the banana branch, and is highest on the upper part of the banana branch. The properties of the rapid X-ray variations that are observed in these sources are correlated with their position on the atoll. When the sources are in the island state,

strong band-limited noise is detected (called high-frequency noise or HFN, with cutoff frequencies between 10 and 30 Hz). This noise is much weaker when atoll sources are on the lower part of the banana branch, and it is undetectable when they are on the upper part of the banana branch.

Quasi-periodic oscillations (QPOs) at kilohertz (kHz) frequencies have been observed in a large number of LMXBs (see van der Klis 1997 for a recent review). The kHz QPOs in atoll sources are usually found when the sources are in the island state and, rarely, when they are on the lower part of the banana branch. When they are on the upper part of the banana branch, so far no kHz QPOs have been detected, with stringent upper limits (Wijnands et al. 1997b; Smale, Zhang, & White 1997). Usually, two simultaneous kHz QPOs are detected, whose frequencies increase with $\dot{M}$. Sometimes, a single kHz QPO is detected (4U 1636–53: Zhang et al. 1996; Wijnands et al. 1997b; Aql X-1: Zhang et al. 1998). In this Letter, we report the discovery of a single kHz QPO near 1150 Hz in the atoll source 4U 1735–44. A preliminary announcement of this discovery was made by Wijnands et al. (1996).

2. OBSERVATIONS AND ANALYSIS

We observed 4U 1735–44 on 1996 August 1, September 1, 4, and 28, and November 29 using the proportional counter array (PCA) on board the *Rossi X-Ray Timing Explorer* (RXTE; Bradt, Rothschild, & Swank 1993) and obtained a total of 27 ks of data. During part of the September 28 observation, only four of the five PCA detectors were on. During all observations, data were collected in 129 photon energy channels (effective energy range: 2–60 keV) with a time resolution of 16 s. Simultaneously, data were collected during the August 1, September 28, and November 29 observations in one broad energy channel (effective range: 2–18.2 keV) with a time resolution of 122 μ s. During the September 1 and 4 observations, data were collected in three broad energy bands with a time resolution of 122 μ s (total effective energy band: 2–17.8 keV).

For the analysis of the X-ray spectral variations, we used

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FIG. 1.—(a) CD and (b) HID of 4U 1735–44. The soft color is the count rate ratio between 3.9–6.0 and 2.0–3.9 keV; the hard color is the count rate ratio between 8.6–18.9 and 6.0–8.6 keV; the intensity is the four-detector count rate in the photon energy range of 2.0–18.9 keV. The count rates are background-subtracted, but not dead-time-corrected (typically 1% correction). All points are 16 s averages. In the HID, the three boxes are shown that were used to select power spectra to study the timing properties. Typical error bars on the colors and intensity are plotted in the lower right-hand corner of the diagrams.

the 16 s data of the four detectors that were always on. In constructing the CD, we used for the soft color the count rate ratio between 3.9–6.0 and 2.0–3.9 keV, and for the hard color the ratio between 8.6–18.9 and 6.0–8.6 keV. For the hardness-intensity diagram (HID), we used as intensity the count rates in the energy band 2.0–18.9 keV, and for the hardness, we used the same as that used for the hard color in the CD. For the analysis of the rapid time variability, we made power density spectra of all the available 2–18.2 and 2–17.8 keV data and combined these. For determining the properties of the kHz QPOs, we fitted the 128–2048 Hz power spectra with a function consisting of a constant and one or two Lorentzian peaks. For measuring the high-frequency noise and the low-frequency QPO, we fitted the 0.1–512 Hz power spectra with a constant, an exponentially cutoff power law, and one or two Lorentzian peaks. The errors on the fit parameters were determined using $\Delta\chi^2 = 1.0$; the upper limits were determined using $\Delta\chi^2 = 2.71$, corresponding to a 95% confidence level. Upper limits on the kHz QPOs were determined using a fixed FWHM of 50 Hz.

3. RESULTS

3.1. Atoll Source State

The CD and HID for all data combined are shown in Figure 1. The source traced out a clear banana branch in both

diagrams. There is more scatter on the upper part of the banana branch in the HID than in the CD, which is due to the fact that during the September 1 and 4 observations, when the source was on the upper part of the banana branch, the count rate was slightly higher than during the other observations. From the CD and the strength of the HFN (see § 3.3), it is clear that 4U 1735–44 was never in the island state during our observations.

3.2. Kilohertz QPO

We selected power spectra according to the position of the source on the banana branch in the HID (thus effectively by the count rate level in the HID). In the combined data of regions 1, 2, and 3 (see Fig. 1b), we detected a kHz QPO at 1149 ± 4 Hz at an amplitude that differed from zero by 5.6 times the 1σ uncertainty (Table 1), quite significant when taking into account the ~ 30 trials implicit in our procedure to search the power spectrum out to 1200 Hz. The QPO was not detected in the rest of the data. In order to determine the behavior of the kHz QPO with changing position of the source in the HID, we divided the region in which the kHz QPO was found into three parts (see Fig. 1b and Table 1). In the data corresponding to regions 1 and 2, we detected the kHz QPO at 1161 ± 1 Hz (3.3σ) and 1144 ± 4 Hz (4.8σ), respectively. In the data of region 3, the kHz QPO was not detected.

We also made power spectrum selections based on continuous time intervals (mainly different *RXTE* data segments). In the first 8000 s (5040 s of data; 1996 August 1 14:17–16:15 UTC) of the observation on August 1, we detected a kHz QPO at 1149 ± 3 Hz (4.5σ). We divided this data segment in the intervals 0–2000 s (1296 s of data) and 2000–8000 s (3744 s of data) and detected the 1160 Hz QPO in the first interval (4.0σ ; 1567 ± 25 counts s^{-1} for 2–18.9 keV) and the 1145 Hz QPO in the second interval (4.8σ ; 1623 ± 49 counts s^{-1} for 2–18.9 keV; see Fig. 2a). The 1145 Hz QPO was also detected in the time interval 1996 September 28 12:50–13:49 UT (3.8σ ; 3520 s of data).

In both cases, the kHz QPO near 1160 Hz was the narrowest and least significant. Applying an *F*-test to the χ^2 of the fits with and without this QPO, we obtain probabilities of $3.0 \times$

TABLE 1
kHz QPO PROPERTIES^a

Selection ^b	Count Rate ^c (counts s^{-1})	rms ^d (%)	FWHM (Hz)	Frequency (Hz)
1 + 2 + 3	1660 ± 72	3.1 ± 0.3 (5.6 σ)	42 ± 13	1149 ± 4
1	1570 ± 18	2.2 ± 0.3 (3.3 σ)	7 ± 5	1161 ± 1
2	1652 ± 30	3.3 ± 0.4 (4.8 σ)	34 ± 12	1144 ± 4
3	1758 ± 24	<3.1	...	...
Rest	2065 ± 157	<1.7	...	...

^a All errors correspond to $\Delta\chi^2 = 1$. The upper limits are for 50 Hz FWHM and correspond to the 95% confidence level ($\Delta\chi^2 = 2.71$).

^b The sets used are shown in Fig. 1b.

^c The errors are the standard deviation of the count rate distribution of the selection used. The energy range is 2–18.9 keV.

^d The energy range is 2–18.2 keV.

FIG. 2.—Typical Leahy normalized power spectra in the energy range of 2–18 keV. (a) The kHz QPO; (b) the complex high-frequency noise and the 67 Hz QPO. Both power spectra were selected for the time interval of 1996 August 1 15:12–16:15 UTC.

10^{-5} and 1.3×10^{-5} for the count rate selection data and the time selection data, respectively, for the hypothesis that the 1160 Hz QPO was not present in the data. Since the effective number of trials implicit in our search for a peak near 1149 Hz was about 14, the 1160 Hz QPO was detected at high confidence.

We tested the significance of the frequency change between HID regions 1 and 2, and between the 0–2000 and 2000–8000 s intervals, by fitting simultaneously the two power spectra and by either forcing the frequency to be the same in both fits or leaving both frequencies free. Applying an F -test to the χ^2 values of these fits, we obtain probabilities of 2×10^{-2} and 3×10^{-4} , respectively, for the hypothesis that the frequency of the kHz QPOs did not change in the sense reported. The probability differs considerably between the two selection methods. Although there are no trials in this determination, this frequency shift needs further confirmation.

It is known from other LMXBs that the kHz QPOs are strongest at the high photon energies. However, due to the lack of energy resolution of the high timing data when the kHz QPO was present, we could not check this for 4U 1735–44.

In the power spectrum of the combined regions 1, 2, and 3, we detected simultaneously with the 1149 Hz QPO a second peak at 900 ± 14 Hz (FWHM of 68 ± 29 Hz; amplitude of $2.6\% \pm 0.4\%$ rms; 3.4σ). Applying an F -test to the χ^2 of the fit with and without the 900 Hz QPO, we obtain a probability of 2.2×10^{-4} for the hypothesis that the 900 Hz QPO was not present in the data, indicating that the 900 Hz QPO was detected at a 3.8σ level. Taking into account the number of trials (approximately eight), this QPO is only marginally significant. Shifting the 1160 Hz QPO to 1140 Hz and averaging all QPO data together (cf. Méndez et al. 1997b) did not improve the significance of the second QPO. If this second QPO is really present, the frequency separation would be ~ 250 Hz, not uncommon as a peak difference in LMXBs.

3.3. Low-Frequency Power Spectrum

In the power spectrum below 100 Hz for the time interval 1996 August 1 15:12–16:15 UTC, a 67 Hz QPO and peaked noise below 30 Hz were clearly detected (Fig. 2b). The peaked-noise component had a complex form. We fitted this noise component with an exponentially cutoff power law plus a Lorentzian. Including this Lorentzian in the fits improved the quality of the fits considerably and made the properties of the 67

Hz QPOs much easier to determine. The rms amplitude, power-law index, and cutoff frequency of the cutoff power law were $3.7\% \pm 0.7\%$, -1.1 ± 0.5 , and 8 ± 3 Hz. The rms amplitude, FWHM, and frequencies of the extra Lorentzian and the 67 Hz QPO were $5.1\% \pm 0.7\%$ (3.9σ) and $3.0\% \pm 0.3\%$ (4.9σ), 17 ± 3 and 17 ± 5 Hz, and 28.7 ± 0.9 and 67 ± 2 Hz, respectively. The 67 Hz QPO and the noise component were best detected when 4U 1735–44 was on the lower part of the banana branch, at count rates below $1800 \text{ counts s}^{-1}$ (regions 1, 2, and 3 of Fig. 1b). The behavior of the properties of the 67 Hz QPO with count rate and position of the source on the banana branch could not be determined accurately. However, it was clear that the 67 Hz QPO and the peaked-noise component are weaker at somewhat higher count rates and not detected when the source is on the upper part of the banana branch.

4. DISCUSSION

We detected for the first time a kHz QPO in 4U 1735–44. Its frequency was near 1149 Hz. A second kHz QPO might be present at ~ 900 Hz, but this needs confirmation. The kHz QPO was detected only when the source was at the lowest count rates during our observations (i.e., on the lower part of the banana branch). There is an indication that the kHz QPO frequency decreased with increasing count rate, which would be quite different from what is observed in other LMXBs showing kHz QPOs. Most kHz QPOs increase in frequency with increasing M . Perhaps the small frequency decrease indicates that the inner accretion disk reached the innermost stable orbit during our observations. When the inner disk reaches the innermost stable orbit, it is expected (Kaaret, Ford, & Chen 1997; Miller, Lamb, & Psaltis 1997) that the increase in kHz QPO frequency with M levels off. The frequency of the kHz QPO could then change erratically (Kaaret et al. 1997), and a small frequency decrease could be observed.

On the basis of its luminosity and its burst properties (e.g., van Paradijs et al. 1979, 1988; Lewin et al. 1980), 4U 1735–44 is believed to have a higher M than the lower luminosity atoll sources (e.g., 4U 0614+4192, 4U 1728+28), but a lower M than the more luminous sources (e.g., GX 9+9, GX 9+1). Thus, 4U 1735–44 is believed to have intermediate M for an atoll source. The detection of only a weak kHz QPO, only at low M , supports this. So far, for the atoll sources with the highest M , no kHz QPOs have been found, with upper limits of typically 1%–2% (GX 9+9, GX 9+1; Wijnands, van der

Klis, & van Paradijs 1997a; GX 13+1: Homan et al. 1998; GX 3+1: Strohmayer et al. 1997). For the sources with lower $\dot{M}$, kHz QPOs are often detected with rms amplitudes of 6%–11% in the total PCA energy range (see, e.g., Strohmayer et al. 1996; Zhang et al. 1996; Berger et al. 1996; Méndez et al. 1997a). The weak kHz QPO in 4U 1735–44 detected only at the lowest count rates during our observations (i.e., when the source was on the lower part of the banana branch) fits naturally in this scheme. We expect that if $\dot{M}$ for 4U 1735–44 would drop below our lowest level, the kHz QPOs would become stronger and two peaks would be detected simultaneously.

The kHz QPOs in atoll sources are usually found when the sources are at low inferred $\dot{M}$, i.e., when they are in the island state (Strohmayer et al. 1996; Méndez et al. 1997a; Yu et al. 1997) and on the lower part of the banana branch (Wijnands et al. 1997b; Smale et al. 1997). At the lowest inferred $\dot{M}$ in the island state of 4U 0614+09, no kHz QPOs were detected. So far, no kHz QPOs have been detected when the sources are at higher inferred $\dot{M}$, i.e., when they are on the upper part of the banana branch, with stringent upper limits (Wijnands et al. 1997b; Smale et al. 1997). The kHz QPO in 4U 1735–44 is only detected when the source was at the lowest count rates during our observations (on the lower part of the banana branch) and undetectable at higher count rates (farther up the banana branch, at higher inferred $\dot{M}$). It seems that the kHz QPOs in atoll sources are present at low $\dot{M}$, but possibly not at the lowest $\dot{M}$ (Méndez et al. 1997a), and disappear when $\dot{M}$ increases.

Besides the kHz QPO, we detected a QPO at 67 Hz. Also, peaked noise with a complex form below 30 Hz is detected, obviously the well-known HFN in atoll sources (Hasinger & van der Klis 1989). The HFN was not detected when the source was on the upper part of the banana branch (at the highest count rates during our observations), and the 67 Hz QPO already disappeared when the source was in the middle part of the banana branch. Similar low-frequency QPOs were detected

in several other atoll sources (e.g., Hasinger & van der Klis 1989; Strohmayer et al. 1996; Wijnands & van der Klis 1997; Homan et al. 1998). It is possible that the 67 Hz QPO detected in 4U 1735–44 is similar to the horizontal branch QPOs (HBOs) in Z sources. This is supported by the facts that the frequency of this QPO is similar to the frequencies of the HBOs in Z sources (although a fundamental frequency as high as 67 Hz has never been observed for a HBO in Z sources), and that it is accompanied by a (peaked) noise component similar to what is found in the Z sources (the so-called low-frequency noise [LFN]). Van der Klis (1994) already suggested that the HFN in atoll sources is due to the same physical process as the LFN in Z sources.

Recently, Stella & Vietri (1998) proposed that the low-frequency QPOs observed in atoll sources are due to a precession of the innermost disk region, dominated by the Lense-Thirring effect. If we assume that the 900 Hz QPO is real, then the frequency difference would be 249 Hz. Following their reasoning and assumptions, and assuming that the neutron star spin frequency is this frequency difference, we derive a maximum precession frequency of ~ 28 Hz. The 67 Hz QPO we discovered in 4U 1735–44 can not be explained easily by this model without an I/M (where I is the moment of inertia of the neutron star and M the neutron star mass) that is more than 2 times larger than allowed for any mass and equation of state. However, the complex nature of the HFN, and especially the peak near 29 Hz, could be due to the precession of the inner disk.

This work was supported in part by the Netherlands Foundation for Research in Astronomy (ASTRON) grant 781-76-017 and by NSF grant AST 93-15133. B. V. (NAG 5-3340), F. K. L. (NAG 5-2925), J. v. P. (NAG 5-3269, NAG 5-3271), and W. H. G. L. acknowledge support from US NASA grants. M. M. is a fellow of the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina.

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