THE DISCOVERY OF A 7–14 HZ QUASI-PERIODIC OSCILLATION IN THE X-RAY TRANSIENT XTE J1806–246

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ABSTRACT

We have studied the correlated X-ray spectral and X-ray timing behavior of the X-ray transient XTE J1806–246 using data obtained with the proportional counter array onboard the Rossi X-ray Timing Explorer. In the X-ray color-color diagram two distinct patterns are traced out. The first pattern is a curved branch, which is observed during the rise and the decay of the outburst. This pattern resembles the so-called banana branch of those low-luminosity neutron star low-mass X-ray binaries (LMXBs) which are referred to as atoll sources. The power spectrum of XTE J1806–246 on this curved branch consisted of a power law and a cutoff power law component. The presence of these components and their dependence on position of the source on the branch is also identical to the behavior of atoll sources on the banana branch. Near the end of its outburst, XTE J1806–246 formed patches in the color-color diagram, the spectrum was harder, and the power spectrum showed strong band limited noise, characteristic of the atoll sources in the island state. A second pattern was traced out during the only observation at the peak of the outburst. It consists of a structure which we interpret as formed by two distinct branches. This pattern resembles the normal-flaring branches of the high-luminosity neutron star LMXBs (the Z sources). The discovery of a 7–14 Hz QPO during this observation strengthens this similarity. We conclude that if XTE J1806–246 is a neutron star, it is most likely an atoll source that only at the peak of its outburst reached a luminosity level sufficiently high to show the type of QPO that Z sources show on their normal and flaring branches.

Subject headings: accretion, accretion disks — stars: individual (XTE J1806–246) — stars: neutron — X-rays: stars

1. INTRODUCTION

The new X-ray transient XTE J1806–246 was first detected (Marshall & Strohmayer 1998) with the Rossi X-ray Timing Explorer (RXTE) and later most likely identified in the radio (Hjellming, Mioduszewski, & Rupen 1998) and optical (Hynes, Roche, & Haswell 1998) bands. The source is positionally coincident with the known X-ray transient 2S 1803–245 (Jernigan et al. 1978) and with the X-ray burster SAX J1806.8–2435 (Muller et al. 1998). If the latter identification is correct then this would imply that XTE J1806–246 is a low-mass X-ray binary (LMXB) harboring a low magnetic field strength neutron star and not a black hole. The neutron star LMXBs have been classified into the so-called Z sources and the atoll sources on the basis of their correlated X-ray spectral and X-ray timing behavior (Hasinger & van der Klis 1989). The Z sources trace out a Z shape like track in the X-ray color-color diagram (CD) with the branches called, from top to bottom, the horizontal branch (HB), the normal branch (NB), and the flaring branch (FB). The power spectra of the Z sources show on the HB strong bandlimited noise (called low frequency noise or LFN) with a cutoff frequency of several Hertz, and, simultaneous with this, QPOs between 15 and 60 Hz, which are called horizontal branch QPOs or HBOs. On the NB QPOs appear between 5 and 7 Hz which are called normal branch QPOs or
NBOs. HBOs and NBOs often occur simultaneously. In several Z sources, the NBOs smoothly merge with 7–20 Hz QPOs seen on the FB, the flaring branch QPOs or FBOs. On all branches two additional noise components are found, one at very low frequencies (the very low frequency noise or VLFN), following a power law, and one at frequencies above 10 Hz (the high frequency noise or HFN), which cuts off between 50 and 100 Hz.

The atoll sources trace out a curved branch in the CD, which can be divided in two parts: the island state and the banana branch. When the source is in the island state motion in the CD is not very fast and can take several weeks. The power spectrum is dominated by very strong (sometimes more than 20% rms amplitude) band-limited noise. The band-limited noise is also called HFN but it is at much lower frequencies than the HFN observed in the Z sources and most likely they are not related. Instead, it has been proposed that Z source LFN and atoll source HFN are similar phenomena (van der Klis 1994). On the banana branch the source moves much faster through the CD (on time scales of hours to days) and in the power spectrum only a weak (several percent rms amplitude) power law noise component at low frequencies is observed (the VLFN). The part of the banana branch closest to the island state is called the lower banana branch, the part away the upper banana branch. From the island state via the lower to the upper banana branch the VLFN tends to get stronger and steeper while the HFN becomes much weaker.

The physical parameter governing the state changes in a given source is nearly certainly the mass accretion rate (see van der Klis 1995 for a summary of the evidence). Some of the differences between the Z and the atoll sources are also due to the differences in the average accretion rate, but it has been proposed that differences in the neutron star magnetic field strength also play a role (e.g., Hasinger & van der Klis 1989; Psaltis, Lamb, & Miller 1995).

With the launch of RXTE at the end of 1995, in both the Z sources and the atoll sources two other types of QPOs were discovered at much higher frequencies, between 200 and 1200 Hz (the kHz QPOs; see van der Klis 1999 for a recent review). In the Z sources, these kHz QPOs are detected on the HB and the upper part of the NB. In the Z source Sco X-1, the kHz QPOs are detected all the way up to the lower part of the FB. In atoll sources, the kHz QPOs are strong in the island state, weaker on the lower part of the banana branch, and absent on the upper part of the banana branch. The similar properties of the kHz QPOs in the Z sources and the atoll sources suggest that these QPOs are most likely due to the same physical mechanism in both types of sources.

Using data obtained with RXTE not only kHz QPOs were discovered in the atoll sources, but also QPOs with frequencies around 60 to 80 Hz (Strohmayer et al. 1996; Wijnands & van der Klis 1997; Ford et al. 1997; Homan et al. 1998; Wijnands et al. 1998) and in one atoll source a QPO was observed near 7 Hz (Wijnands, van der Klis, & Rijkhorst 1999). The properties of the 60–80 Hz QPOs suggest that they could be due to the same physical mechanism as the HBOs in Z sources (e.g., Homan et al. 1998; Psaltis, Belonli, van der Klis 1999). Wijnands et al. (1999) tentatively suggest that the 7 Hz QPO can be identified with the NBOs in the Z sources. These recent RXTE results show that whatever causes the phenomenological differences between the Z and the atoll sources, it does not prevent similar QPO phenomena from occurring (albeit with differences in incidence and perhaps strength) in both source types.

Here we report on the correlated X-ray spectral and X-ray timing behavior of XTE J1806–246 during the rise, the peak, and the decay of its 1998 outburst. We report the discovery of a 7–14 Hz QPO during the peak of the outburst. A preliminary announcement of this discovery was already made by Wijnands & van der Klis (1998). The correlated X-ray spectral and X-ray timing behavior during the rise and the decay is consistent with that of an atoll source. The outburst peak properties are more reminiscent to Z source normal/flaring branch behavior, which suggests that the lack of phenomena characteristic of the normal/flaring branch in most atoll sources is due to a difference in accretion rate only.

When this paper was essentially completed we became aware of a paper by Revnivtsev, Borozdin, & Emelyanov (1999) which uses the same data. They concentrated on the analysis of the 9 Hz QPO and with respect to that feature obtained results consistent with ours.

2. OBSERVATIONS AND ANALYSIS

XTE J1806–246 was observed by the proportional counter array (PCA) onboard RXTE as
part of public target of opportunity observations for a total of \(\sim 32\) ksec (see Table 1 for a log of the observations). During all observations, data were obtained in 129 photon energy bands covering the energy range 2–60 keV. Simultaneous data were obtained at different epochs with time resolutions of 122 \(\mu\)s or 16 \(\mu\)s in 67 (April 27) or 18 (the other data) photon energy bands covering the range 2–60 keV. During all observations except the April 27 one, data were also obtained with 8 ms time resolution in 16 bands covering the range 2–13 keV.

We calculated FFTs using 16-s data segments of the 122 \(\mu\)s and 16 \(\mu\)s data in order to study the \(> 100\) Hz variability. We also made 128 s FFTs using the 8 ms and 16 \(\mu\)s data in different photon energy bands in order to study the energy dependence of the QPO and the noise components. Finally, we made 128 s cross-spectra between different energy bands from the same data in order to study the time lags of the QPO. To determine the properties of the 7–14 Hz QPO, we fitted the power density spectra of May 3 with a function containing a constant (representing the dead-time modified Poisson level), a power law (representing the underlying continuum), and a Lorentzian (representing the QPO). To determine the properties of the peaked noise component, we fitted the power density spectra of the other data, after subtracting the dead-time modified Poisson level, with a power law and an exponentially cut-off power law (representing the peaked noise). The uncertainties in the fit parameters were determined using \(\Delta \chi^2 = 1\). Upper limits correspond to a 95% confidence level.

The PCA light curve, the CDs, and the hardness-intensity diagrams (HIDs) were created using 64 s averages of the 16 s data. In the CDs, the soft color is defined as the logarithm of the 3.5–6.4 keV/2.0–3.5 keV count rate ratio and the hard color as the logarithm of the 9.7–16.0 keV/6.4–9.7 keV count rate ratio. The definition of the colors in the HIDs are the same as in the CDs. The count rates in the HIDs are for the photon energy range 2.0–16.0 keV. All count rates quoted in this paper are for 5 detectors. The count rates used in the diagrams are background-subtracted but not dead-time corrected. The dead-time correction is 3%–5%.

3. RESULTS

The outburst light curve is presented in Figure 1. During 1998 April the source was rising from \(\sim 5000\) to \(\sim 7200\) counts s\(^{-1}\) (2.0–16.0 keV). It reached a maximum of between 7000–8000 counts s\(^{-1}\) in the 1998 May 3 observation. After May 3 the count rate decreased; the source became almost undetectable (\(\sim 10–20\) counts s\(^{-1}\)) by July (see Table 1).

The CD of all data before 1998 July 1 is presented in Figure 2a. The data taken on July 1 and 17 are not plotted because of the very low statistics of the data. In Figure 2b, different tracks are traced out at different moments in the outburst. A blow up of the data obtained between April 27 and May 22 is shown in Figure 2c. During the rise (the April data) and the decay (the May 17–22 data) the source traced out a curved branch in the CD (Fig. 2c). In Figure 2a the CD is compared to the hard HID (Fig. 3b; the hard color versus the count rate) and the soft HID (Fig. 3c; the soft color versus the count rate, note the axes are interchanged). Clearly visible from these figures is that although the count rate can be different by about 2000 counts s\(^{-1}\), the hard and the soft color can have the same values (this is best visible by comparing the April data which each other). By comparing the April 27 and the May 17 observation, it is also clear that the soft color can have different values at the same count rates. From Figure 2 it can also be seen on which dates the source was at a certain position in the CD. During the June observations, the source was in two distinct places in the CD and HIDs which are separate from the rest of the data (see Fig. 2a). During the peak of the outburst the source traced out, in a different part of the CD compared to the rise and decay data, a pattern which we interpret as a two-branched structure (Fig. 2d). When examining the CD at higher (16 seconds) time resolution, it is clear that at the beginning of the May 3 observation the source was located on the lower part of the right branch in the CD. The source then gradually moved via the lower part of the left branch to the upper left part. At the same time the count rate increased from about 7100 to about 7400 counts s\(^{-1}\) (2.0–16.0 keV). After a data gap of about 2000 seconds, due to an Earth occultation of the source, the count rate had increased to about 7500–7600 counts s\(^{-1}\) (2.0–16.0 keV) and the source was on the upper part of the right branch in the CD (compare also Fig. 3a and b). It is impossible to say whether the source
jumped to this place in the CD or moved gradually to it. In the latter case it is also not possible to say if this gradual motion of the source followed the same track or followed a different route. The CD is compared to the HID in Figure 4. By comparing $a$ and $c$ it can be seen what the count rate was at a certain position in the CD.

The source not only traced out different tracks in the CD during the rise and the decay with respect to the peak of the outburst, but also the power spectra were remarkably different. During the rise and the decay two noise components can be distinguished in the power spectrum (Fig. 3 left): a noise component following a power law at low frequency (the VLFN) and a broad noise component which can be represented by a power law with an exponential cutoff between 5 and 20 Hz (the HFN). The strengths of these noise components and their other properties during the different observations are displayed in Table 1. During the last observation in the decay for which noise could be detected (1998 June 14; see Fig. 4 right) the strength of the HFN had increased to about 14%. The VLFN could not be detected down to 0.01 Hz (note that Revnivtsev et al. 1999 reported the presence of the VLFN below 0.01 Hz). During the last two observations (1998 July 1 and 17) no noise could be detected, however, the upper limits of typically 30% rms amplitude on any noise component are not very stringent. During the peak of the outburst the power spectrum is quite different. The VLFN is still present but the HFN component is replaced by a very significant (44σ) QPO (Fig. 3 middle) with a frequency of 9.03±0.05 Hz, a FWHM of 5.6±0.2 Hz, and an rms amplitude of 5.30±0.06%.

### 3.1. The QPO

In order to study this QPO in more detail, we made 64 s FFTs of the 1998 May 3 data and fitted the QPO with a Lorentzian in each individual power spectrum. In order to correlate the obtained QPO parameters with the position of the source in the CD, we used the $S_z$ parameterization, which has been developed for the Z sources ($S_z$ is a measure of the curve length along the track in the CD; see Wijnands et al. 1997 and Wijnands 1999 and references therein for detailed descriptions of this procedure). We selected arbitrarily the normal points where $S_z = 1$ and $S_z = 2$ (see Fig. 2d).

The behavior of the QPO parameters, the 2.0–16.0 keV count rate, and the $S_z$ values as a function of time are presented in Figure 5. The QPO parameters versus the QPO frequency, the 2.0–16.0 keV count rate, and $S_z$ are displayed in Figure 7. From these two figures it is clear that the QPO parameters (Figs. 7a, e, and g) do not have a strict correlation with the count rate. This is also apparent when comparing Figure 7a with Figures 3c, d, and e. The QPO rms versus its frequency (Fig. 7a), shows two distinct branches. From Figures 3c and d it can been seen that the transition between these two branches occurred around 1000 seconds after the beginning of the May 3 observation. After the data gap between 2000 and 4500 seconds (due to an Earth occultation of the source), the source has returned to the original branch. From Figure 7c it is clear that these two branches correspond to different places in the CD. The points with the low rms amplitude for the QPO occur below $S_z = 1.5$: the points with the high rms amplitude occur when $S_z > 1.5$. This differences in QPO behavior are also apparent in Figures 7f and h. Below $S_z = 1.5$ the FWHM and frequency behave erratically. Above $S_z = 1.5$ the FWHM and in particular the QPO frequency increase when $S_z$ increases. This means that above $S_z > 1.5$ the QPO frequency is well correlated with the position of the source in the CD. For $S_z < 1.5$ the correlation breaks down.

The energy dependence of the QPO is shown in Figure 8. There is a clear increase of the rms amplitude of the QPO with photon energy below ~12 keV. Above 12 keV, the rms amplitude seems to level off. We tried to measure any time lags in this QPO as a function of energy. The obtained time lags between the energy bands 2.8–5.3 keV and 5.3–13.0 keV were consistent with zero ($-0.06±0.4$ msec).

### 3.2. The noise components during the rise and the decay

When excluding the May 3 observations in the CD, a curved branch is present. We investigated the behavior of the noise components as a function of the position of the source on this branch. We divided the branch is five parts (see Fig. 2c). Note that only in area 3 are data used of the rise and the decay together. In areas 1 and 2, only data of the rise is used and in areas 4 and 5 only data of the decay. During the rise, the source moved first from area 1 via area 2 into area 3 (April 27), and then back via area 2 (April 28)
into area 1 (April 29) (see also Fig. 3). During the first observation in the decay (May 17 00:29–00:54), the source was in area 4. In the subsequent observations, the source moved first to area 5, and then back via area 4 (May 17 12:42–13:56) into area 3 (May 22). The motion can be followed when comparing the CD (Fig. 3a) with the soft HID (Fig. 3c).

The results of the fits in the different areas are summarized in Table 2. The VLFN increases in strength and becomes steeper from the upper left part (area 1) to the upper right part of the curved branch (area 5), while the HFN decreases in strength. The index and the cutoff frequency of the HFN do not have a clear correlation with the position of the source in the CD. In area 5, the HFN is not peaked (as is the case in the other areas) and no cutoff frequency could be determined.

Both noise components have similar relationships with photon energy as the 7–14 Hz QPO: they increase in strength up to an energy of \( \sim 12 \) keV above which they remain approximately constant. Although both the HFN and the QPO peak at roughly the same frequency and have similar energy dependence of their strengths, it is unclear whether the peaked HFN evolved into the QPO or was replaced by it.

### 3.3. Kilohertz QPOs

We intensively searched for QPOs between 200 and 1500 Hz. None were detected with conservative upper limits on the amplitude (2–60 keV; assuming a FWHM of 150 Hz for the kHz QPOs) of 1%–2% rms during the rise of the outburst, 2.0% rms during the peak of the outburst, 2.0–3.0% rms during the decay of the outburst when XTE J1806–246 was on the curved branch, 4.7% rms on June 8, 12.5% on June 14, and around 80% during the July observations.

### 4. DISCUSSION

We have analyzed the correlated X-ray spectral and X-ray timing behavior of the new X-ray transient XTE J1806–246 during its 1998 outburst. During the peak of the outburst we discovered a very significant (44\( \sigma \)) QPO near 9 Hz. This QPO was not detected during the rise and the decay of the outburst, however, a broad peaked noise component near 10 Hz was. Also, the behavior in the CD was different between the rise and the decay of the outburst compared with the peak. During the peak of the outburst a pattern was traced out, which we interpret as a two branched structure. The QPO frequency seemed to be correlated with the position of the source in (at least a part of) the CD: the frequency increased when the source moved from lower part of the left branch to the upper part of the right branch. Outside the peak of the outburst, a broad curved branch was traced out when the count rate was above 3500 counts s\(^{-1}\) (2.0–16.0 keV). Below this count rate only distinct patches in the CD were formed during the different observations, which were not connect with each other. This pattern most likely is due to the sparsity of data in the decay of the outburst. The strength of the HFN increased slightly when the source moved from the upper right in the CD to the upper left, while the VLFN strength decreased and it became less steep. The HFN increased to about 14% rms amplitude when the count rate had dropped below 350 counts s\(^{-1}\) (2.0–16.0 keV).

The positional coincidence of XTE J1806–246 with the X-ray burster SAX J1806.8–2435 makes it likely that they are one and the same source. This would suggest that XTE J1806–246 contains a neutron star. Although similar frequency QPOs as the 9 Hz QPO in XTE J1806–246 have also been discovered in black-hole candidates, they are more often detected in the neutron star systems (the Z sources, and on one occasion in an atoll source [Wijnands et al. 1999]). So, this is in accordance with the idea that XTE J1806–246 contains a neutron star and not a black-hole.

#### 4.1. Atoll source versus Z source

The neutron star LMXBs have been classified into Z sources and atoll sources (see § ??). The differences between the Z sources and the atoll sources have been interpreted (e.g., Hasinger & van der Klis 1989) as due to a difference in the accretion rate and in the strength of the magnetic field of the neutron star. From the higher intrinsic luminosity of the Z sources compared to that of the atoll sources, it was suggested that the Z sources accrete near the critical Eddington accretion rate (e.g., Hasinger & van der Klis 1989; Smale 1998; Bradshaw, Fomalont, & Geldzahler 1998) but that most atoll sources accrete at a significantly lower accretion rate. The magnetospheric beat-frequency (MBF) model (Alphar & Shaham 1985; Lamb et al. 1985) for the HBOs in the Z sources in combination with the absence
of similar QPOs in the atoll sources, suggested that the magnetic field strengths of the neutron stars in the Z sources are higher than those in the atoll sources. X-ray spectral modeling (Psaltis et al. 1995) also suggested that the magnetic field strength in the atoll sources is significantly less than that in the Z sources. Because the magnetic field strengths of the atoll sources are thought to be significantly above zero (e.g., Psaltis et al. 1995), the MBF model predicted that similar QPOs might be observable in the atoll sources, but at a lower strength than in the Z sources. With RXTE similar frequency QPOs have indeed been found in the atoll sources, however, it has still to be determined whether the strengths of these QPOs are significantly less than those of the HBOs in the Z sources.

The presence of the 5–20 Hz QPO (the N/FBO) in Z sources at their highest inferred mass accretion rates and the absence of similar QPOs in the atoll sources, had led to models for this QPO in which the accretion rate has to be near the Eddington accretion rate in order for the production mechanism of this QPO to be activated (e.g., Fortner, Lamb, & Miller 1989; Alpar et al. 1992). If these models are correct, then similar QPOs should also be visible in the atoll sources when they reach the Eddington mass accretion rate (if they could). Recently, in the atoll source 4U 1820–30 a 7 Hz QPO was discovered (Wijnands et al. 1999) at times when this source was accreting at its highest observed inferred mass accretion rate. However, this highest observed accretion rate was well below the Eddington mass accretion rate (Wijnands et al. 1999). If this 7 Hz QPO is due to the same physical mechanism as the N/FBOs in the Z sources, then either the production mechanism for this QPO is already activated at accretion rates much lower than the Eddington accretion rate, or the accretion rate estimated from the X-ray flux in 4U 1820–30 is significantly less than the true accretion rate. In the latter situation, a significant part of the energy released near the neutron star must be beamed away from us or has to eventually be emitted not in X-rays but at other wavelengths or in, e.g., ejecta. It remains to be seen to what extent the Fortner et al. (1989) model could accommodate this.

It is interesting to investigate if XTE J1806–246 fits in in the above described picture, and, if so, how exactly. During the rise and the decay of the outburst a curved branch was traced out, which resembles the banana branch in atoll sources. Also, the behavior of the noise components with the position of the source on this curved branch (HFN becoming stronger and the VLFN weaker and less steep when the source moves from the right to the left in this diagram) is characteristic of the behavior of the noise components observed in atoll sources when they move from the upper banana branch to the lower banana branch. Interestingly, when the count rate drops further in the decay, distinct patches are formed separated from the curved branch. The HFN increases to about 14% rms amplitude with decreasing count rate and the VLFN becomes undetectable down to 0.01 Hz in the June 14 observation (the last observation which has sufficient statistics to detect noise in the power spectrum). The present of such strong noise and distinct patches in the CD are characteristic of atoll source behavior when these sources are in the island state (see, e.g., Hasinger & van der Klis 1989; Méndez 1999). Note, that similar weak VLFN components, as observed in the June 14 observation (Revnivtsev et al. 1999), have been observed in other atoll sources when they were in their island states (Hasinger & van der Klis 1989). So, XTE J1806–246 during the rise and the fall of its outburst displayed all characteristics typical of an atoll source and, if the source is indeed a neutron star, it should be classified as such.

In the original report of the discovery of the QPO in XTE J1806–246 (Wijnands & van der Klis 1998) we suggested, that if the 7–14 Hz QPO in XTE J1806–246 is due to the same physical mechanism as the 7–20 Hz QPOs in the Z sources, XTE J1806–246 might be a Z source. However, the discovery of the 7 Hz QPO in the atoll source 4U 1820–30 (Wijnands et al. 1999) has since shown that QPOs between 7–20 Hz are in neutron star systems not exclusively found in the Z sources. The correlation of the frequency of the QPO with the position of the source in part of the CD is very similar to the behavior of the NBO in XTE J1806–246 (Wijnands & van der Klis 1998). So, XTE J1806–246 during the rise and the fall of its outburst displayed all characteristics typical of an atoll source and, if the source is indeed a neutron star, it should be classified as such.
ample of an atoll source simultaneously exhibiting a NB/FB like pattern in the CD. (A related case may be Cir X-1, which sometimes shows atoll characteristics [Oosterbroek et al. 1995] and at other times what appears to be a Z-track and HBO- and NBO-like QPOs [Shirey et al. 1998, 1999]).

It is possible that XTE J1806–246 during the peak of the outburst reaches near Eddington mass accretion rates, as is required in the Fortner et al. (1989) model for the NBO. The observed absorbed flux between 2 and 30 keV during the peak of the outburst is about $1.9 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$. The source is located in the direction to the galactic bulge ($l \sim 6.1, b \sim -1.9$). Assuming a distance of 8 kpc, the intrinsic luminosity of the source is $1.5 \times 10^{38}$ ergs s$^{-1}$, which is close to the Eddington accretion limit for a 1.4 solar mass neutron star. However, during the rise and the decay the observed X-ray count rate and flux ($\sim 1.8 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$) are very close to those observed during the peak of the outburst, suggesting that also at those epochs XTE J1806–246 was accreting near the Eddington accretion limit. It is unclear why only during the peak of the outburst XTE J1806–246 showed the 7–14 Hz QPO; perhaps this is related to a difference in the accretion flow between persistent and transient sources caused by the large changes in the mass accretion rate in the latter.

4.2. Other types of QPOs?

Both the Z sources and the atoll sources exhibit, at their lowest observed inferred mass accretion rates, kHz QPOs and QPOs between 15–70 Hz. Therefore, we looked in particular at the data obtained during the lowest count rates for XTE J1806–246 to search for similar QPOs. No significant kHz QPOs were detected but with upper limits which are not inconsistent with the derived values of the kHz QPOs in the Z sources and in some atoll sources. Interestingly, when we combine the power spectra obtained for areas 1 and 2 in Figure 2, we detect a $4.8\sigma$ QPO with a frequency of $70.6 \pm 1.6$ Hz, a FWHM of $12.6^{+4.6}_{-3.2}$ Hz, and an rms amplitude of $1.2\% \pm 0.1\%$. This QPO is also marginally visible in Fig. 3 left. However, when we include the Poisson level as an unknown parameter in the fit the significance of this QPO drops to about $3.5\sigma$. Taking into account the number of trials involved in our search method this QPO needs confirmation. However, the presence of such a $\sim 70$ Hz QPO is very similar to similar frequency QPOs observed in atoll sources in their lower banana branch and to the HBOs observed in the Z sources on their HB.

4.3. Conclusion

The behavior observed for XTE J1806–246 during the 1998 outburst is consistent with that of an atoll source which at the peak of the outburst reached a X-ray luminosity level where the NBO mechanism switched on. This makes the source the second atoll source, after 4U 1820–30 (Wijnands et al. 1999), that exhibits QPOs with frequencies near 7–9 Hz. This source can be very useful to study the similarities and the differences between Z sources (including Cir X-1, which is probable a Z source; Shirey et al. 1998; 1999) and atoll sources, allowing us to get a better insight in the processes at work in the inner part of the accretion disk.

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Fig. 1.— The daily averaged *RXTE* All Sky Monitor light curve (1.3–12.1 keV; top) and the *RXTE/PCA* light curve (bottom) of XTE J1806–246. The PCA count rates are in the energy band 2.0–16 keV and are background subtracted but not deadtime corrected. Each point in the PCA light curve represents 64 s averages.
Fig. 2.— Color-color diagrams of XTE J1806–246 created from the data obtained between 1998 Apr 27 and Jun 14 (a). A blow up of the data obtained between 1998 Apr 27 and May 22 is given in b. The rise and the decay data obtained in the same interval as in b are given in c, the data obtained during the peak of the outburst are given in d. The soft color is the logarithm of the count rate ratio between 3.5–6.4 and 2.0–3.5 keV and the hard color is the logarithm the count rate ratio between 9.7–16.0 and 6.4–9.7 keV. The count rates which are used to calculate the colors are corrected for background. In c, the areas used to select the power spectra are given; in d, the spline is given which has been used to calculate the $S_z$ values of the power spectra which were selected on time. All points are 64 s averages.
Fig. 3.— Color-color diagram of XTE J1806–246 created from the data obtained between 1998 Apr 27 and Jun 14 (a), excluding the May 3 data. In b the hard color versus 2.0–16.0 keV count rate is shown (the hard hardness-intensity diagram). In c the soft color versus the 2.0–16.0 keV count rate is shown (the soft hardness-intensity diagram). For the definitions of the colors see Fig. 2. The axes in c are interchanged in order to allow easier comparison with a. All points are 64 s averages.
Fig. 4.— Color-color diagram of XTE J1806–246 created from the data obtained on May 3 (a). In b the hard color versus 2.0–16.0 keV count rate is shown (the hard hardness-intensity diagram). In c the soft color versus the 2.0–1.60 keV count rate is shown (the soft hardness-intensity diagram). For the definitions of the colors see Fig. 2. The axes in c are interchanged in order to allow easier comparison with a. All points are 64 s averages.

Fig. 5.— Typical power spectra during the rise and the decay of the outburst (left; taken on 1998 April 29), showing the VLFN and HFN component, the peak of the outburst (middle; taken on 1998 May 3) showing the QPO, and the last observation in the decay which has sufficient statistics to detect the noise in the power spectrum (right; taken on 1998 June 14). The Poisson level has been subtracted.
Fig. 6.— The count rate (a), $S_2$ (b), the frequency of the QPO (c), the rms amplitude (2–60 keV) of the QPO (d), and the FWHM of the QPO (e) as a function of time from 1998 May 3 21:03:47 UTC. The count rate is in the photon energy band 2.0–16.0 keV and are background subtracted but not deadtime corrected. The gap between about 2000 and 4500 seconds is due to an Earth occultation of the source.
Fig. 7.— The rms amplitude (2–60 keV) of the QPO as a function of its frequency (a), the count rate (b), and $S_z$ (c). The FWHM of the QPO as a function of its frequency (d), the count rate (e), and $S_z$ (f). The frequency of the QPO as a function of count rate (g) and $S_z$ (h). The count rates used in these figures are in the energy range 2.0–16.0 keV and are background subtracted but not deadtime corrected.
Fig. 8.— The fractional rms amplitude of the 7–14 Hz QPO versus the photon energy.
### Table 1

LOG OF THE OBSERVATIONS AND THE FIT PARAMETERS OF THE NOISE COMPONENTS DURING THOSE OBSERVATIONS

| Obs. ID | Date (n 1998) | Start – End (UT) | On source time (ksec) | Count rate range | Fit parameters VLFN | Fit parameters HFN |
|---------|--------------|-----------------|----------------------|-----------------|---------------------|--------------------|
|         |              |                 |                      |                 | Rms (%)            | Index (%)          | Rms (%)            | Index (%) | Cutoff freq. (Hz) |
| 30412-01-01-00 | Apr 27 | 19:31–21:44 | 5.2 | 5000–5630 (5290) | 1.3±0.2, 0.8±0.1 | 3.7±0.1, 1.2±0.2 | 7.2±0.7 |
| 30412-01-02-00 | Apr 28 | 18:59–20:30 | 2.6 | 5895–6405 (6150) | 1.3±0.1, 1.0±0.1 | 3.3±0.1, 1.8±0.3 | 6.0±0.8 |
| 30412-01-03-00 | Apr 29 | 20:42–21:38 | 3.3 | 6700–7195 (6950) | 1.2±0.06, 0.77±0.06 | 3.3±0.2, 1.8±0.4 | 9.1±1.5 |
| 30412-01-04-00 | May 03 | 21:01–22:32 | 2.9 | 6810–8045 (7315) | 0.9±0.06, 0.77±0.06 | –, –, – | – |
| 30412-01-05-00 | May 17 | 21:01–22:32 | 3.3 | 6810–8045 (7315) | 1.3±0.1, 0.99±0.09 | 3.1±0.2, 1.9±0.6 | 5.5±1.3 |
| 30412-01-05-01 | May 17 | 00:29–00:54 | 1.5 | 4855–5585 (5215) | 3.0±0.4, 1.29±0.10 | 1.4±0.2, 2.0±1.4 | 3.5±1.3 |
| 30412-01-06-00 | May 22 | 11:06–12:07 | 3.5 | 3495–4310 (3930) | 4.2±0.3, 1.42±0.05 | 3.4±0.9, 2.6±0.4 | 4.0±0.6 |
| 30412-01-07-00 | Jun 08 | 07:59–09:30 | 2.9 | 1075–1285 (1190) | 3.8±0.3, 1.38±0.06 | 3.4±0.9, 2.6±0.4 | 4.0±0.6 |
| 30412-01-08-00 | Jun 14 | 20:54–22:02 | 3.6 | 3495–4310 (3930) | 3.8±0.3, 1.38±0.06 | 3.4±0.9, 2.6±0.4 | 4.0±0.6 |
| 30412-01-09-00 | Jul 01 | 19:45–20:23 | 0.9 | 271–313 (290) | 7.8±2.7, 2.0±0.2 | 5.7±0.4, 1.3±0.4 | 12.6±2.8 |
| 30412-01-10-00 | Jul 17 | 19:50–20:24 | 1.7 | 15–29 (22) | <5.3, 3 | 14.3±0.7, 0.2±0.1 | 19.6±3.2 |

a In the photon energy range 2.0–16.0 keV. The values between brackets are the averaged count rates.
b Integrated over 0.001–1.0 Hz; 2–60 keV.
c Integrated over 1.0–100.0 Hz; 2–60 keV.
d Parameter fixed.

### Table 2

NOISE PARAMETERS VERSUS POSITION IN THE CD

| CD areaa | Rmsb (%) | Index | Rmsc (%) | Index | Cutoff freq. (Hz) |
|----------|----------|-------|----------|-------|------------------|
| 1        | 1.27±0.05 | 0.77±0.06 | 3.4±0.1 | −1.3±0.2 | 8.6±1.1 |
| 2        | 1.6±0.1  | 1.09±0.08 | 3.77±0.08 | −1.1±0.2 | 7.9±0.7 |
| 3        | 3.1±0.3  | 1.32±0.06 | 3.44±0.08 | −1.8±0.3 | 5.0±0.6 |
| 4        | 2.9±0.2  | 1.29±0.07 | 2.8±0.1  | −1.6±0.4 | 6.2±1.2 |
| 5        | 5.2±0.7  | 1.56±0.09 | 1.9±0.2  | 0.6±0.1  | ∞d |

a For the selections see Fig. 2c.
b Integrated over 0.001–1.0 Hz; 2–60 keV.
c Integrated over 1.0–100.0 Hz; 2–60 keV.
d Parameter fixed.