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Chapter 3

Discovery of a 57–69 Hz quasi-periodic oscillation in GX 13+1

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Abstract

We report the discovery of a quasi-periodic oscillation (QPO) at 61.0±1.7 Hz with the Rossi X-Ray Timing Explorer in the low-mass X-ray binary and persistently bright atoll source GX 13+1 (4U 1811–17). The QPO had an rms amplitude of 1.7±0.2% (2–13.0 keV) and a FWHM of 15.9±4.2 Hz. Its frequency increased with count rate and its amplitude increased with photon energy. In addition a peaked noise component was found with a cut-off frequency around 2 Hz, a power law index of around −4, and an rms amplitude of ~1.8%, probably the well known atoll source high frequency noise. It was only found when the QPO was detected. Very low frequency noise was present with a power law index of ~1, and an rms amplitude of ~4%. A second observation showed similar variability components. In the X-ray color-color diagram the source did not trace out the usual banana branch, but showed a two branched structure.

This is the first detection of a QPO in one of the four persistently bright atoll sources in the galactic bulge. We argue that the QPO properties indicate that it is the same phenomenon as the horizontal branch oscillations (HBO) in Z sources. That HBO might turn up in the persistently bright atoll sources was previously suggested on the basis of the magnetospheric beat frequency model for HBO. We discuss the properties of the new phenomenon within the framework of this model.
CHAPTER 3

3.1 Introduction

Based on their correlated X-ray timing and spectral behavior the brightest low-mass X-ray binaries (LMXBs) can be divided into two groups; the atoll sources and Z sources (Hasinger & van der Klis 1989, hereafter haval989; van der Klis 1995). Atoll sources show two states: the island and the banana state, after the tracks they produce in an X-ray color-color diagram (CD). Z sources on the other hand trace out a Z-like shape in a CD, with usually three branches: the horizontal, the normal, and the flaring branch.

The power spectra of atoll sources can be described by two noise components plus, sometimes, a Lorentzian component to describe quasi-periodic oscillations (QPOs). The first noise component, the very low frequency noise (VLFN) has a power law shape \( P \propto v^{-\alpha} \), with \( 1 \leq \alpha \leq 1.5 \). The other, the high frequency noise (HFN), can be described by a power law with an exponential cut-off \( P \propto v^{-\alpha} e^{-v/v_{\text{cut}}} \), usually with \( 0 \leq \alpha \leq 0.8 \) and \( 0.3 \leq v_{\text{cut}} \leq 25 \) Hz. The HFN sometimes has a local maximum ("peaked noise") around 10-20 Hz (see van der Klis 1995). Yoshida et al. (1993) found peaked noise around 2 Hz. Several broad QPO(-like) peaks were found with the Rossi X-ray Timing Explorer (RXTE) around 20 Hz (Strohmayer et al. 1996; Ford et al. 1997; Yu et al. 1997; Wijnands & van der Klis 1997), and one at 67 Hz (simultaneously with one at 20 Hz, see Wijnands et al. 1998a). In addition to QPOs below 100 Hz, QPOs between 300 and 1200 Hz, the so-called kHz QPOs, have been found.

The power spectra of Z sources show three broad noise components: VLFN with \( 1.5 \leq \alpha \leq 2 \), HFN with \( \alpha \sim 0 \) and \( 30 \leq v_{\text{cut}} \leq 100 \) Hz, and low frequency noise (LFN), which has the same functional shape as the HFN with \( \alpha \sim 0 \) and \( 2 \leq v_{\text{cut}} \leq 20 \) Hz. Note that despite having the same name, HFN in Z sources is not the same phenomenon as HFN in atoll sources. Z sources show three types of QPOs: the normal/flaring branch QPO (N/FBO) with centroid frequencies from 6 to 20 Hz, the horizontal branch QPO (HBO) from 15 to 60 Hz, and the kHz QPOs in the same range as observed in atoll sources. (For an extensive review on the power spectra of atoll and Z sources we refer to van der Klis 1995. For kHz QPOs we refer to van der Klis 1998.)

GX 13+1 has been classified as an atoll source, although of all atoll sources it shows properties which are closest to that seen in the Z sources (haval989). Moreover, Schulz et al. (1989) put GX 13+1 among the luminous sources that have been classified as Z sources. Together with GX 3+1, GX 9+1, and GX 9+9, GX 13+1 forms the subclass of the persistently bright atoll sources. In the CD they have only been seen to trace out banana branches and their power spectra can be described by relatively strong (~3.5% rms) VLFN and weak (~2.5% rms) HFN, as compared to other atoll sources. No QPOs have been found before in these sources, neither at frequencies below 100 Hz nor at kHz frequencies (Wijnands et al. 1998b; Strohmayer 1998).

For GX 13+1, so far no HFN has been observed. Its banana branch resembled a more or less straight strip in the CD, whereas the other three sources showed more curved banana branches (haval1989). Stella et al. (1985) have reported bimodal behavior of GX 13+1 in the hardness-intensity diagram (HID). In one state the spectral hardness was correlated with count rate, while in the other it was anticorrelated. The transition between the two states occurred
Figure 3.1: The 5-detector light curves of the October 28 and November 10 observations. The intensity is the count rate in the 2–19.7 keV band. Time resolution is 16 s. $T = 0$ on October 28 corresponds to 02:16:49 UTC and on November 10 to 09:19:29 UTC. Typical error bars are shown in the upper left of the figures.

within one hour.

The main difference between atoll and Z sources is the mass accretion rate, $\dot{M}$. Atoll sources accrete at $\dot{M} \lesssim 0.5\dot{M}_{Edd}$, whereas Z sources accrete at near Eddington rates. It was proposed by hava1989 that a second difference lies in the strength of the magnetic field strength $B$ of the accreting neutron star. Recent spectral modeling by Psaltis & Lamb (1998) suggests that indeed atoll sources have $B < 10^9$ Gauss and Z sources $B \sim 10^9–10^{10}$ Gauss. The bright atoll sources are found to have a higher inferred $B$ than the low luminosity atoll sources, making them the best candidates to show Z source HBO.

In this Letter we report the discovery of a 57–69 Hz QPO and of a two branched structure in the CD and HID of GX 13+1. We suggest that the QPO is the same phenomenon as Z source HBO.

### 3.2 Observations and analysis

We observed GX 13+1 with the proportional counter array (PCA) onboard RXTE, on October 28 1996 02:15–05:15 UTC and on November 10 1996 09:19–12:13 UTC. Except for a ~300 s interval during the October 28 observation, when proportional counter unit (PCU) four was inactive, data (a total of $\sim 1.2 \times 10^4$ s) were collected with all five PCUs in three simultaneous data modes: 16 s time resolution in 129 photon energy bands (covering the energy range 2–60 keV); $2^{-12}$ s time resolution in 3 bands (2–4.9 keV, 4.9–8.6 keV, and 8.6–13.0 keV); $2^{-16}$ s
Figure 3.2: The color-color diagram (a) and hardness-intensity diagram (b) of GX 13+1. Filled circles depict October 28 data, open circles November 10 data. For energy bands, see text. Each point is the average of a 16 s interval. Typical error bars are shown in the upper left of the figures.

time resolution in 64 bands (covering the range 13.0–60 keV).

The 16 s data were used to construct light curves (Fig. 3.1) and CDs and HIDs (Fig. 3.2). Only data with all five PCUs on were used. The data were background corrected, but no dead-time corrections (~1%) were applied. The data gaps in Figure 3.1 are due to Earth occultations of the source, or to passages of the satellite through the South Atlantic Anomaly. The average 2–19.7 keV count rate during the first part of the October 28 observation is ~3800 cts/s, during the second and third part ~4700 cts/s, and during the November 10 observation ~4400 cts/s. For the soft color we used the count rate ratio between 3.9–6.4 keV and 2–3.9 keV; for the hard color the ratio between 8.6–19.7 keV and 6.4–8.6 keV. For the intensity we used the count rate in the 2–19.7 keV energy range.

Power density spectra were made of all the 2^{-12} s data using 16 s data segments. For measuring the (low frequency) QPO we fitted the 0.1–256 Hz power spectra with a constant representing the Poisson level, a power law representing the VLFN, a power law with an exponential cut-off representing the HFN, and a Lorentzian representing the QPO. Errors on the fit parameters were determined using $\Delta \chi^2 = 1$, upper limits with $\Delta \chi^2 = 2.71$, corresponding to a 95% confidence level. Upper limits on (sub-)harmonics of the QPO were determined by setting the frequency to half or twice the QPO frequency and by fixing the FWHM to half or twice the FWHM of the QPO. Upper limits for kHz QPOs were determined by fitting the 200–2048 Hz power spectra with a constant and a Lorentzian with a conservatively assumed FWHM of 150 Hz. This was done in the 2–13.0 keV, 13.0–60 keV, and 2–60 keV energy ranges.
3.3 Results

During the October 28 observation the source did not trace out a banana branch in the CD. Instead two distinct branches could be identified (see Fig. 3.2a): a lower branch and an upper branch, separated by a gap in the CD around a hard color of ~0.6, corresponding to the first gap in the light curve (Fig. 3.1). The other gaps in the light curve did not appear as gaps in the CD and HID. The source started at the right end of the lower branch, then moved up to the top of the upper branch along the curve and ended halfway down the upper branch. Just before the first gap in the light curve the source was in the upward curved part of the lower branch. Hence the points at the left part of the lower branch above hard colors of ~0.5 are in all likelihood evidence of motion towards the upper branch that continued during the gap. A slightly curved branch was traced out in the CD during the November 10 observation, close to the upper branch of the October 28 observation. The source started in the lower part of the branch, moved to the top and ended in the lower part.

In all the October 28 data combined we discovered a QPO at 61.0±1.7 Hz, with a FWHM of 15.9±4.2 Hz, an rms amplitude of 1.7±0.2%, and a significance of 4.8σ (2–13.0 keV). The power spectrum is shown in Figure 3.3. In the lower branch the QPO could not be detected significantly (2.2σ) at 61.0 Hz, with an upper limit on the rms amplitude of 1.7%. In the upper branch the QPO was detected (4.7σ) at 59.7±1.9 Hz with an rms amplitude of 2.1±0.3% and a FWHM of 21.4±5.8 Hz. A count rate selection showed that the QPO frequency on the upper branch increased with count rate; from 57.0±1.4 Hz between ~4050 and ~4700 cts/s to 64.5±2.1 Hz between ~4700 and ~5600 cts/s. The FWHM and rms amplitude did
not change significantly; from $11.6\pm4.4$ Hz to $14.1\pm7.8$ Hz and from $1.8^{+0.3}_{-0.2}$ to $2.0^{+0.4}_{-0.3}$% respectively. Upper limits on a sub-harmonic or second harmonic were respectively 1.0% rms and 0.8% rms. The VLFN had an rms amplitude of $\sim4.3$% and a slope of $\sim1.3$. Its properties did not vary significantly between the two branches. In addition to the VLFN a peaked noise component was detected (7.4σ) with a cut-off frequency of $2.1\pm0.6$ Hz, a power law index of $-3.6\pm1.2$, and an rms amplitude of $1.9^{+0.2}_{-0.1}$%. This noise feature is probably atoll source HFN. In the upper branch it had an rms amplitude of $2.3\pm0.2$%, in the lower branch it was undetectable with an upper limit of 1.5% rms. No kHz QPOs were found between 200 and 2048 Hz, with upper limits on the rms of $2.1$% (2–13.0 keV), $21.0$% (13.0–60 keV), and $2.3$% (2–60 keV).

The strength of the QPO increased with photon energy (Fig. 3.4). The energy spectrum of the HFN was both consistent with that seen for the QPO and with being constant. The VLFN strength increased up to $\sim11$ keV and decreased thereafter.

In the November 10 data we may have detected (2.5σ) a similar QPO at $71.0\pm2.5$ Hz with a FWHM of $12.4^{+11.3}_{-5.9}$ Hz and an rms amplitude of $1.2^{+0.8}_{-0.4}$%. At high count rates, $\sim4500$ cts/s, the QPO was found to be a bit more significant (3.1σ) at $68.8\pm2.0$ Hz, with an rms amplitude.
of 1.4$^{+0.3}_{-0.2}$% and a FWHM of 10.4±4.9 Hz. At lower count rates, ∼4100 cts/s, an upper limit for the rms amplitude was obtained of 1.2%. The VLFN had the same slope as in the first observation, and an rms amplitude of ∼3.7%. Again HFN was detected (6.4σ) with an rms amplitude of 1.7±0.2%, a power law index of $-4.5 \pm 1.5$, and a cut-off frequency of 2.1 ± 0.9 Hz. Again no kHz QPOs were detected, with upper limits on the rms of 2.3% (2–13.0 keV), 19.9% (13.0–60 keV), and 2.2% (2–60 keV).

### 3.4 Discussion

We have discovered a QPO in GX 13+1 between 57 and 65 Hz and around 69 Hz. It is the first time a QPO has been found in a persistently bright atoll source. The rms amplitude of the QPO increased with photon energy. Together with the QPO, a peaked noise component was found, probably atoll source HFN, with a cut-off frequency of ∼2 Hz. The HFN was only detected when the QPO was present. In the October data the QPO was only found in the upper branch, i.e. at high count rates. On the upper branch the QPO frequency increased with count rate from ∼57 Hz to ∼65 Hz. In the November data the QPO could only be detected at high count rates. Assuming that $\dot{M}$ and count rate were positively correlated, the QPO frequency increased with $\dot{M}$, at least on the upper branch in the October observation. However, during the November observation we found the QPO at ∼69 Hz; the mean count rate was then lower than during the October observation of the ∼65 Hz QPO.

The pattern traced out by GX 13+1 in the CD and HID in our observations does not resemble the patterns traced out by other atoll sources. Atoll sources trace out islands and/or a banana branch. During EXOSAT observations GX 13+1 traced out a banana branch (hava1989) which is quite different from what we observed with RXTE. We also do not find evidence for the bimodal behavior found by Stella et al. (1985) in the sense that both our branches in the HID show a positive correlation between hard color and count rate. The relatively sharp turn in the CD and HID may be related to one of the vertices in the patterns traced out by Z sources.

Comparison with EXOSAT observations, using our RXTE energy spectra folded with the EXOSAT response matrix, shows that the source was ∼30% brighter during the RXTE observations. (Note that in the RXTE ASM light curve the source shows intrinsic variations of ∼50%; during our observations the ASM count rate was near average.) This might explain why the two branched structure has not been seen before in GX 13+1. In any case EXOSAT was not sensitive enough to have detected the QPO reported in this Letter.

Recently Stella & Vietri (1998) proposed that at least some of the < 100 Hz QPOs observed in atoll sources are due to Lense-Thirring precession of the inner part of the accretion disk. In order to test this model one needs the frequencies of the simultaneously observed kHz QPOs. Since no kHz QPOs have been observed in GX 13+1 it is not possible to test this model. The upper limits on kHz QPOs are comparable with those found in the other members of the subclass (Wijnands et al. 1998b; Strohmayer 1998).

The QPO properties (frequency, dependence on $\dot{M}$, energy spectrum, and the simultaneous
presence of a band limited noise component (the HFN) are all similar to those found for HBO in Z sources. On the basis of the above described similarities we suggest that the QPO we found is the same phenomenon as the HBO, and that the HFN component is related to the QPO in a similar way as Z source LFN to HBO. The identification of atoll source HFN with Z source LFN was previously proposed by van der Klis (1994).

The HBO in Z sources can be explained by the magnetospheric beat frequency model (Alpar & Shaham 1985; Lamb et al. 1985), according to which the observed QPO frequency is the difference between the neutron star spin frequency and the frequency at which blobs of matter orbit the neutron star at the magnetospheric radius. In this model the frequency increases with $\dot{M}$ and decreases with neutron star spin frequency and $B$. The HBO is observed at frequencies between 15 and 60 Hz. LFN is found with a cut-off frequency between 2 and 20 Hz; it usually appears and disappears together with the HBO. In quantitative models the LFN is naturally produced as an extra component to the HBO, with a total power that is comparable to that in the HBO (Shibazaki & Lamb 1987). Both components get stronger with photon energy.

According to hava1989 the properties of atoll and Z sources are determined by $\dot{M}$ and $B$. Spectral modeling based on this picture shows that of all atoll sources, the persistently bright subclass, especially GX 13+1, have $\dot{M}$ and $B$ closest to those of the Z sources (Psaltis & Lamb 1998). On the basis of the magnetospheric beat frequency model one might therefore expect to see HBO-like phenomena in these sources. The detection of a HBO-like phenomenon in GX 13+1 seems to confirm these expectations. The fact that the QPO frequency in GX 13+1 is at the high end of the HBO frequency range in Z sources can be explained by a slower spinning neutron star or/and by a $B$ that is lower than in the Z sources, but still high enough to produce HBO. A higher $\dot{M}$ than Z sources is unlikely in view of the luminosity.

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Bibliography

Stella, L., White, N. E., & Taylor, B. G. 1985, in Recent Results on Cataclysmic Variables, 125