MILLIHertz OSCILLATION FREQUENCY DRIFT PREDICTS THE OCCURRENCE OF TYPE I X-RAY BURSTS

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ABSTRACT

The millihertz quasi-periodic oscillations (mHz QPOs) discovered in three neutron star low-mass X-ray binaries have been suggested to be a mode of marginally stable nuclear burning on the neutron star surface. We show that, close to the transition between the island and the banana state, 4U 1636–53 exhibits mHz QPOs whose frequencies systematically decrease with time, until the oscillations disappear and a type I X-ray burst occurs. There is a strong correlation between the QPO frequency $\nu$ and the occurrence of X-ray bursts: when $\nu \approx 9$ mHz, no bursts occur, whereas $\nu \approx 9$ mHz does allow the occurrence of bursts. The mHz QPO frequency constitutes the first identified observable that can be used to predict the occurrence of X-ray bursts. If a systematic frequency drift occurs, then a burst happens within a few kiloseconds after $\nu$ drops below 9 mHz. This observational result confirms that the mHz QPO phenomenon is intimately related to the processes that lead to a thermonuclear burst.

Subject headings: X-rays: bursts — X-rays: individual (Aquila X-1, 4U 1608–52, 4U 1636–53)

1. INTRODUCTION

Revnivtsev et al. (2001) discovered a new class of low-frequency quasi-periodic oscillations (QPOs) in three neutron star X-ray binary sources (Aql X-1, 4U 1608–52, and 4U 1636–53). These new QPOs have frequencies between 7 and 9 × 10^{-3} Hz (i.e., they are in the millihertz [mHz] range), and their other properties also differ from those of the other QPOs found in the neutron star systems (e.g., they differ in energy dependence; see van der Klis 2006). Although Revnivtsev et al. (2001) could not discard an interpretation related to disk instabilities, they concluded that the mHz QPOs are likely due to a special mode of nuclear burning on the neutron star surface. This interpretation was strengthened by the results of Yu & van der Klis (2002), who showed that the kilohertz (kHz) QPO frequency is anticorrelated with the luminosity variations during the mHz oscillation, suggesting that the inner edge of the disk moves slightly outward as the luminosity increases during each mHz cycle because of stresses generated by radiation coming from the neutron star surface. This is contrary to the correlation observed between X-ray luminosity ($L_X$) and kHz QPO frequency, where the inner disk edge is thought to move in as the accretion rate, and hence $L_X$, increases (van der Klis 2006 and references therein).

The properties of the mHz QPOs as observed up to now can be summarized as follows:

1. The fractional rms amplitude strongly decreases with energy, from $\approx 2\%$ at 2.5 keV down to an almost undetectable $<0.2\%$ at $\approx 5$ keV.
2. The mHz QPOs occur only in a particular range of X-ray luminosity: $L_{2-20\text{keV}} = (5-11) \times 10^{36}$ ergs s^{-1}.
3. The frequency of the mHz QPOs is between 7 and 9 mHz.
4. The mHz QPOs disappear with the occurrence of a type I X-ray burst.
5. As noted above, the kHz QPO frequency is approximately anticorrelated with the 2–5 keV count rate variations that constitute the mHz oscillation.

Revnivtsev et al. (2001) found the mHz QPOs are transient atoll sources (Aql X-1 and 4U 1608–52); the third one, 4U 1636–53, is a persistent atoll source (Hasinger & van der Klis 1989). The object of our current study, 4U 1636–53, has an orbital period of $\approx 3.8$ hr (van Paradijs et al. 1990) and a companion star with a mass of $\approx 0.4 M_\odot$ (assuming a neutron star of $1.4 M_\odot$; Giles et al. 2002). 4U 1636–53 is an X-ray burst source (Hoffman et al. 1977) showing asymptotic burst oscillation frequencies of $\approx 581$ Hz (Zhang et al. 1997; Strohmayer & Markwardt 2002). The aperiodic timing behavior of 4U 1636–53 has been studied with the EXOSAT Medium Energy instrument (Prins & van der Klis 1997) and with the Rossi X-Ray Timing Explorer (RXTE; e.g., Wijnands et al. 1997; Di Salvo et al. 2003; Altamirano et al. 2007).

4U 1636–53 is a reference source for studying nuclear burning on the surface of a neutron star, because it shows the full range of burst behavior: single and multipeaked type I X-ray bursts, superbursts, burst oscillations, photospheric radius expansion, regular and irregular burst sequences (e.g., Galloway et al. 2006), and mHz QPOs. As such, it is an ideal source to understand the relation between these different observational manifestations of nuclear burning.

Recently, Shih et al. (2005) reported that 4U 1636–53 has shown a significant decrease in its persistent $L_X$ during the years 2000 and 2001. Altamirano et al. (2007) show that during the low $L_X$ period, 4U 1636–53 is observed in its (hard) island states.

Heger et al. (2007) suggested that the mHz QPOs could be explained as being the consequence of marginally stable nuclear burning on the neutron star surface. They found an oscillatory mode of burning, with a period $P_{\text{ooc}}$ close to the geometric mean of the thermal and accretion timescales of the burning layer. For typical parameters, $P_{\text{ooc}} \approx (t_{\text{thermal}}/t_{\text{accretion}})^{1/2} \approx 2$ minutes, in accordance with the characteristic frequency of the mHz QPOs. The burning is oscillatory only close to the boundary between stable burning and unstable burning (in type I X-ray bursts), which explains the observation that the mHz QPOs were seen within a narrow range of luminosities.

Two of the three sources in which Revnivtsev et al. (2001) found the mHz QPOs are transient atoll sources (Aql X-1 and 4U 1608–52); the third one, 4U 1636–53, is a persistent atoll source (Hasinger & van der Klis 1989). The object of our current study, 4U 1636–53, has an orbital period of $\approx 3.8$ hr (van Paradijs et al. 1990) and a companion star with a mass of $\approx 0.4 M_\odot$ (assuming a neutron star of $1.4 M_\odot$; Giles et al. 2002). 4U 1636–53 is an X-ray burst source (Hoffman et al. 1977) showing asymptotic burst oscillation frequencies of $\approx 581$ Hz (Zhang et al. 1997; Strohmayer & Markwardt 2002). The aperiodic timing behavior of 4U 1636–53 has been studied with the EXOSAT Medium Energy instrument (Prins & van der Klis 1997) and with the Rossi X-Ray Timing Explorer (RXTE; e.g., Wijnands et al. 1997; Di Salvo et al. 2003; Altamirano et al. 2007).

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1 The thermal timescale is defined as $t_{\text{thermal}} = c_p T/e$, where $c_p$, $T$, and $e$ are the heat capacity at constant pressure, the temperature, and the generation rate of nuclear energy, respectively.
2 The accretion timescale is defined as $t_{\text{accretion}} = m/n$, where $y$ and $m$ are the column depth of the burning layer and the local accretion rate, respectively.

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This provides us with an opportunity to study the mHz QPOs in harder and lower luminosity states than was possible up to now.

2. DATA ANALYSIS AND RESULTS

We used data from the RXTE Proportional Counter Array and the High-Energy X-Ray Timing Experiment (PCA and HEXTE, respectively; for instrument information, see Jahoda et al. 2006 and Gruber et al. 1996). Up until June 2006, there were 338 public pointed observations. An observation covers one to five consecutive 90 minute satellite orbits. Usually, an orbit contains between 1 and 5 ks of useful data separated by 1–4 ks data gaps; on rare occasions, the visibility windows were such that RXTE continuously observed the source for up to 27 ks. In total, there were 649 gap-free data segments of length 0.3–27 ks.

We produced energy spectra for each observation using standard data modes and fitted them in the 2–25 and 20–150 keV bands for PCA and HEXTE, respectively. The interstellar absorption $N_{\text{H}}$ was fixed at $3.75 \times 10^{21}$ cm$^{-2}$ (see Schulz 1999; Fiocchi et al. 2006). We used 1 s resolution event mode PCA light curves in the $\approx 2–5$ keV range (where the mHz QPOs are strongest) and searched for periodicities in each of the 649 segments separately, using Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Press et al. 1992). Segments in which one or more type I X-ray bursts were detected were searched for periodicities before, in between, and after the bursts. We find that the oscillations in the $\approx 2–5$ keV range are evident from the light curves (see, e.g., Fig. 1 in Revnivtsev et al. 2001). The significance, as estimated from our Lomb-Scargle periodograms, confirms that the oscillations are all above the 3 $\sigma$ level. We estimated the uncertainties in the measured frequencies by fitting a sinusoid to 1000 s data segments, to minimize frequency-drift effects. The typical errors on the frequency are of the order of $(2–6) \times 10^{-5}$ Hz [or $(2–6) \times 10^{-2}$ mHz].

We detected mHz QPOs in 124 of the 649 segments. Most occur in segments with less than 4 ks of useful data, and some-times the QPOs cover only part of a segment. Revnivtsev et al. (2001) reported the characteristics of the mHz QPOs between 1996 March and 1999 February. Using the X-ray colors averaged per observation as reported by Altamirano et al. (2007), we find that their data sample the region at hard colors $\approx 0.7$ and soft colors $\approx 1$ (see Fig. 1), which represent the so-called banana state (van der Klis 2006). Some of the later observations also sample the banana state. We reanalyzed all the data in this region of the color-color diagram and found results that are consistent with those reported by Revnivtsev et al. (2001): the frequency of the QPOs varies randomly between 6 and 9 mHz.

In the harder state, close to the transition between the island and the banana state and marked with the ellipse drawn in Figure 1, we found 22 segments with significant mHz QPOs; in these observations, the $(2–150$ keV) luminosity was $(6–10) \times 10^{35}[d/(6 \text{ kpc})]^2$ ergs s$^{-1}$, whereas for the other observations, corresponding to the banana state, it was higher, $(10–35) \times 10^{36}[d/(6 \text{ kpc})]^2$ ergs s$^{-1}$.

Among the 22 segments, we distinguish two groups on the basis of segment length: the first consisted of four segments, each with more than 14 ks of uninterrupted data, and the second consisted of 18 segments, each corresponding to one orbit with less than $\approx 4$ ks of useful data. For all four segments in the first group, we measure a systematic decrease of frequency from between 10.7 and 12.5 mHz down to less than 9 mHz over a time interval of 8–12 ks, after which an X-ray burst occurs and the QPOs disappear (the QPOs become much less than 3 $\sigma$ significant). Figure 2 shows a representative dynamical power spectrum corresponding to one of these segments (interval B in Fig. 3). The QPO is present $\approx 12$ ks

Fig. 1.—Color-color diagram (Altamirano et al. 2007). Each data point represents the average of an observation ($\approx 20$ to $\approx 30$ ks). The ellipse marks the region in which mHz QPOs with decreasing frequency were found. The labels A, B, and C correspond to those in Fig. 3.

Fig. 2.—Dynamical power spectrum, smoothed with a 750 s sliding window with steps of 200 s, showing the mHz QPOs during the last 12 ks before the X-ray burst occurs. This sequence corresponds to interval B in Figs. 1 and 3; i.e., observation 60032-05-02-00). The three black vertical lines correspond to the times of occurrence of the X-ray bursts. For clarity, we plot only powers above 10 that correspond to $\approx 3$ $\sigma$ (single trial per 750 s window but normalized to the number of possible frequencies in the range 0.05–0.5 Hz).
before the burst, and its frequency systematically decreases with time from $\approx 10.7$ mHz down to $\approx 7.6$ mHz. Then the X-ray burst occurs, and the QPO disappears. In the second group, 16 of the 18 segments of $\approx 4$ ks show a decrease in the mHz QPO frequency, either within a segment or between two or three consecutive orbits (with $2-4$ ks data gaps in between), at rates consistent with those seen in the four long segments. The two remaining segments are too short and isolated to constrain the frequency drift very well.

To illustrate the interplay between this very systematic behavior of the mHz QPOs and our data structure, in Figure 3 we show a representative light curve. A, B, and C mark three intervals in which the mHz QPOs were detected and in which each terminate with an X-ray burst. As can be seen, we have data in which mHz QPOs are detected and followed through consecutive segments (interval A), and data in which the oscillations are detected and disappear within one segment (intervals B and C). Furthermore, we have data in which the oscillations are present from the start of the observation (interval B) as well as data in which the mHz QPOs appear during an observation (intervals A and C).

Among our 22 segments, the frequency of the oscillations varies in the range 7–14.3 mHz, with directly observed onset frequencies between 10.7 and 14.3 mHz. Interpolating through gaps, we find that the QPOs last for 7.5–16 ks. Over such intervals, the frequency is always consistently decreasing at an average rate of $0.07-0.15$ mHz ks$^{-1}$, and the frequency is always dropping to $\approx 9$ mHz just before an X-ray burst (as estimated from the last 750 s before the burst). Interestingly, this last result applies to all cases in which we detect the mHz QPOs before an X-ray burst, including the cases that occur in the banana state; it seems that, independent of the spectral state of the source, no X-ray burst will occur if the mHz QPOs are present at a frequency higher than $\approx 9$ mHz (bursts do occur in both states that are not preceded by detectable mHz QPOs).

No relation between the $2-60$ keV count rate and the frequency was found; in two of the four long segments, the count rate decreased about 10% during the time that the mHz QPOs were present, whereas, in the other two long segments, the count rate increased by approximately the same amount. No clear relation was found between frequency range covered and duration of the oscillation; perhaps this is related to the fact that, as shown in Figure 2, the frequency does not decrease smoothly but has short periods in which it is consistent with being constant.

When 4U 1636–53 is observed close to its island state–banana state transition, the mHz QPOs disappear only when an X-ray burst occurs. However, this is not the case for the banana state, because we also found observations in which the oscillations disappear below detectable levels without the occurrence of an X-ray burst. The interval of time required to again detect the oscillations after a burst occurred is variable. The two extreme cases are (1) observation 60032-01-06-000, where no mHz QPOs were detected during the $\approx 15$ ks of uninterrupted data after an X-ray burst, and (2) observation 40028-01-06-00, where mHz QPOs are detected again $\approx 6000$ s after an X-ray burst occurred. We note that, in the first case, the source was close to the transition between island and banana state, whereas, in the second case, the source was in the banana state. Nevertheless, no clear relation between this waiting time and the source state (island or banana state) was found. As bursts may be missed because of gaps in data, a time interval of $\approx 1000$ s between a (missed) X-ray burst and the onset of QPOs cannot in some cases be excluded (e.g., interval A in Fig. 3).

3. DISCUSSION

We have shown that, close to the transition between the island and the banana state, 4U 1636–53 exhibits mHz QPOs whose frequency systematically decreases with time until the oscillations disappear with the occurrence of a type I X-ray burst. The mHz QPO frequency $\nu$ constitutes the first identified observable that can be used to predict the occurrence of X-ray bursts: when $\nu \approx 9$ mHz, no bursts occur; whereas $\nu \approx 9$ mHz does allow the occurrence of bursts. If a systematic frequency drift occurs, then a burst happens within a few kiloseconds after $\nu$ drops below 9 mHz. This observational result confirms that the mHz QPO phenomenon is intimately related to the processes that lead to a thermonuclear burst.

The fact that the observation of a systematic frequency decrease with time implies that a future X-ray burst will occur and strongly suggests that the frequency of the mHz QPOs is related to the burning processes on the neutron star surface. One possibility is that the frequency of the QPO is somehow a measurement of the accumulation of fresh fuel that will be available on the neutron star surface for a future thermonuclear burst.

To our knowledge, there has been only one attempt to theoretically explain the mHz QPO phenomena (Heger et al. 2007). In this model the frequency of the QPO depends on, among other things, the amount of available fresh fuel, on the local accretion rate, and the composition of the material. It is beyond the scope of this Letter to perform numerical simulations like those reported by Heger et al. (2007). In the rest of this discussion, we briefly compare their model predictions with our observations and propose some more complex scenarios.

Analytical and numerical results based on the simplified one-
zone model of Paczyński (1983) in the Heger et al. (2007) marginally stable burning model (see § 1) predict that (1) close to the boundary between stable and unstable burning, the neutron star surface will show temperature fluctuations with constant frequency $\nu$ if the local accretion rate $\dot{m}$ remains constant; (2) this marginally stable burning regime will occur at $\dot{m}$ near the Eddington limit (hence, accretion must be confined to a surface area that is much smaller that the total area of the neutron star); (3) $\nu$ correlates with $\dot{m}$ (see Fig. 4 in Heger et al. 2007); and (4) thermonuclear bursts and mHz QPOs should not be observed at the same luminosity or, presumably, at the same $\dot{m}$.

In this Letter, we show that for constant luminosity, the QPO frequency can systematically decrease in time and that instantaneously measured frequencies can be the same for different luminosities. We also show that mHz QPOs and thermonuclear bursts do in fact occur at the same luminosity and that both phenomena are clearly related. This means that we are dealing with a more complex scenario than that introduced by Heger et al. (2007).

The amount of time between the preceding X-ray burst and the onset of mHz QPOs is variable (>6 ks) and apparently independent of source state. If the system is locally accreting at $\dot{m} \approx \dot{m}_{\text{iso}}$ and if none of the accreting fuel is burnt, only $\approx 1000$ s are required to accrete a fuel layer of column depth $\psi$ capable of undergoing marginally stable burning ($\psi \approx 10^2$ g cm$^{-2}$ and $\dot{m} \approx 8 \times 10^4$ g cm$^{-2}$ s$^{-1}$; see, e.g., Heger et al. 2007). One possible explanation for the observed longer intervals between burst and onset of oscillations is that a large fraction of the accreted fuel is burnt as it is accreted onto the neutron star surface. Of course, the burning fraction could vary in time, and this estimate assumes that all the fuel was burnt during the last X-ray burst, which is not always true (Bildsten 1998). Interestingly, if this interpretation is correct and low partial burning fractions can occur, under certain conditions, the mHz QPOs could appear in much less than 1000 s after an X-ray burst.

The fact that the amount of time between the preceding X-ray burst and the onset of mHz QPOs is variable may also be an indication that not all the accreted fuel is burnt or available for marginally stable burning. For example, accretion onto an equatorial region occupying less than 10% of the surface area of the star could occur (Heger et al. 2007). Another possibility is that part of the fresh fuel burns stably at a rate $B(t)$ per unit area, while the other part leaks away from this region at a rate $\dot{R}(t)$. Although the material accumulated at a rate $\dot{R}(t)$ would serve as fuel for a thermonuclear burst, marginally stable burning of the matter on the equatorial belt is (in principle) still possible. Although such a scenario cannot explain the frequency drifts that we observe, it can explain why mHz QPOs and X-ray bursts do occur at the same $\dot{m}$. If mHz QPOs only occur at a certain local accretion rate $\dot{m} = \dot{m}_{\text{local}}$, a small change in the effective local accretion rate will lead to an absence of mHz QPOs. This might explain why the mHz QPOs are not always present between X-ray bursts.

Another possibility (which is not taken into account in the model by Heger et al. 2007) is that there is a significant heat flux deeper in the star that heats the region that is undergoing marginally stable burning. For example, there might be changes in heat flux that are caused by the conduction of energy inward into deeper layers during an X-ray burst and then slowly outward toward the surface. Such a change in the heat flux could affect the conditions of the burning layer [e.g., the temperature or the burning rate $B(t)$] and therefore could affect the characteristics of the burning processes on the neutron star surface.

Other aspects of the observations offer further challenges to theoretical models that try to explain the burning processes on the neutron star surface as well as to those models that try to explain the states of atoll sources. In particular, why are the systematic frequency drifts observed close to the transition between the island and the banana state, whereas the frequencies are approximately constant in the banana state? This may be another indication that the disk geometry of the system changes during the state transition (see, e.g., Gierliński & Done 2002). Also, why do the oscillations disappear only when an X-ray burst occurs during the transition between the island and the banana state, whereas they can disappear without an X-ray burst in the banana state (see § 2)? Clearly, further theoretical work is needed. More observational work on the interactions between mHz QPOs and X-ray bursts is in progress and will provide further clues for theoretical models.

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