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Millihertz quasi-periodic oscillations in 4U 1636−53 associated with bursts with positive convexity only

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ABSTRACT

We investigated the convexity of all type I X-ray bursts with millihertz quasi-periodic oscillations (mHz QPOs) in 4U 1636–53 using archival observations with the Rossi X-ray Timing Explorer. We found that, at a 3.5σ confidence level, in all 39 cases in which the mHz QPOs disappeared at the time of an X-ray burst, the convexity of the burst is positive. The convexity measures the shape of the rising part of the burst light curve and, according to recent models, it is related to the ignition site of bursts on the neutron-star surface. This finding suggests that in 4U 1636−53 these 39 bursts and the marginally-stable nuclear burning process responsible for the mHz QPOs take place at the neutron-star equator. This scenario could explain the inconsistency between the high accretion rate required for triggering mHz QPOs in theoretical models and the relatively low accretion rate derived from observations.

Key words: X-rays: binaries; stars: neutron; accretion, accretion discs; X-rays: bursts; X-rays: individual: 4U 1636−53

1 INTRODUCTION

Nearly half of the accreting neutron stars in low-mass X-ray binaries show Type I X-ray bursts (e.g., in't Zand et al. 2004; Liu et al. 2007; Galloway et al. 2008). These bursts are

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due to unstable thermonuclear burning of accumulated hydrogen and helium on the surface of the neutron star (e.g., Fujimoto et al. 1981). In the last decade another observational phenomenon connected to nuclear burning on the neutron-star surface has been discovered. Revnivtsev et al. (2001) reported the first detection of quasi-periodic oscillations (QPOs) in the millihertz (mHz) range in three neutron-star low-mass X-ray binaries (NS LMXBs): 4U 1608–52, 4U 1636–53, and Aql X-1. Besides the low frequency range between 7 and 9 mHz, the mHz QPOs show some unique properties compared to other types of QPOs in NS LMXBs: The mHz QPOs happen only within a particular luminosity range, $L_{2-20\,\mathrm{keV}} \simeq (5-11) \times 10^{36}$ ergs s^{-1}, and are stronger at low photon energies ($E < 5$ keV) (Revnivtsev et al. 2001; Altamirano et al. 2008).

Altamirano et al. (2008) found that the frequency of the mHz QPO in 4U 1636–53 decreased systematically with time until the QPO became undetectable at the time of a type I X-ray burst when the source was in the transition between hard and soft state usually seen in these systems. Linares et al. (2010) found mHz QPOs in the neutron-star transient IGR J17480–2446 in the globular cluster Terzan 5. These mHz QPOs showed some different properties with respect to the ones in other sources: The QPO frequency was relatively low, always below 4.5 mHz, and the persistent source luminosity at the time the QPOs appeared was high, $L_{2-50\,\mathrm{keV}} \sim 10^{38}$ erg s^{-1}. Furthermore, Linares et al. (2012) found a smooth evolution between X-ray bursts and mHz QPOs in IGR J17480–2446 as the luminosity of the source changed during the outburst, which has never been observed in other mHz QPO sources.

The above observational findings suggest a different origin of the mHz QPOs from other kinds of QPOs (e.g., van Straaten et al. 2002, 2005; van der Klis 2006; Altamirano et al. 2008) in NS LMXBs. Revnivtsev et al. (2001) speculated that a special mode of nuclear burning on the neutron-star surface may be responsible for the mHz QPOs. Heger et al. (2007) proposed that the mHz QPOs could be a consequence of marginally stable nuclear burning of Helium on the neutron-star surface. The model of Heger et al. (2007) is able to explain the characteristic time scale of ~ 2 minutes of the mHz QPOs, and predicts that the QPOs should occur only in a very narrow range of X-ray luminosity. However, the accretion rate at which the mHz QPOs are predicted in the model is close to the Eddington rate, up to one order of magnitude higher than the one implied by the X-ray luminosity at which mHz QPOs were observed. To bring the models and observations into agreement, Heger et al. (2007) proposed that the local accretion rate in the burning layer where the QPOs happen can be higher than the global accretion rate. Keek et al. (2009) found that turbulent chemical mixing of the fuel, together with a higher heat flux from the crust, can explain the observed accretion rate at which mHz QPOs are seen. Furthermore, Altamirano et al. (2008) and Keek et al. (2009) suggested that the cooling process of the layer where the mHz QPOs happen may be responsible for the frequency drift of the QPOs before X-ray bursts. Keek et al. (2014) explored the influence of the fuel composition and nuclear reaction rates on the mHz QPOs, and concluded that no allowed variation in the composition and the reaction rate is able to trigger the mHz QPOs at the observed accretion rates.

Lyu et al. (2015) investigated the relation between the frequency of the mHz QPOs and the temperature of the neutron-star surface in 4U 1636–53 using XMM-Newton and simultaneous RXTE observations, and they found that there was no significant correlation, which is different from theoretical predictions. Besides, Lyu et al. (2015) found that all seven X-ray bursts associated with mHz QPOs in this source were bright, energetic and short, indicating a potential connection between the mHz QPOs and He-rich X-ray bursts.

Cooper & Narayan (2007) found that the latitude at which type I X-ray bursts ignite on the neutron star surface depends on the accretion rate. Later, Maurer & Watts (2008) simulated the influence of ignition latitude, accretion rate and neutron-star rotation on the shape of the rising phase of type I X-ray bursts. They found that bursts that ignite at the equator always have positive convexity, whereas bursts that ignite at high latitude have both positive and negative convexity. The convexity measures the shape of the rising part of the burst light curve, and it is defined as the integrated area of the burst light curve above (positive convexity) or below (negative convexity) a straight line drawn from the start to the peak of the burst. Recently, Mahmoodifar & Strohmayer (2015) further confirmed that the rising part of the light curve of bursts is more concave when ignition starts near the pole compared to when it starts near the equator. Thus, the convexity of an X-ray burst provides information about the ignition site of unstable nuclear burning on the neutron-star surface. The fact that mHz QPOs are closely related to type I X-ray bursts opens up the possibility to study the origin and physics of marginally stable nuclear burning on the neutron-star surface, by investigating mHz QPOs and type I X-ray bursts together. In this paper we focus on the possible connection between mHz QPOs and the convexity of type I X-ray bursts to explore the site on the neutron-star surface at which the marginally stable nuclear burning ignites.

2 OBSERVATIONS AND DATA REDUCTION

We analysed all available data of 4U 1636–53 from the Proportional Counter Array (PCA; Jahoda et al. 2006) on board of the Rossi X-ray Timing Explorer (RXTE) using the Heasoft 6.16. An RXTE observation typically covers 1 to 5 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. This means that our datasets consist of continuous data segments of lengths between 0.3 and 27 ks.

We used 1-s resolution event mode PCA light curves in the $\sim 2-5$ keV range (where the mHz QPOs are the strongest, see Altamirano et al. 2008) and searched for periodicities in each of the gap-free segments separately using Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Press et al. 2002). In those cases where more than one Type I X-ray burst was detected, we searched for mHz QPOs before, after and in-between bursts. We only report those detections that are at least 3σ significant as estimated using the method outlined in Press et al. (2002). When undetected, It is difficult to estimate a general and/or meaningful upper limit on the fractional rms amplitude of the mHz QPOs before an X-ray burst. The reasons could be many: data-gaps just before the burst, or the segment before the burst is too short to detect the QPO significantly, or there is a reduced number of PCUs during that observation. In the few cases without the above problems, we estimated 3σ upper limits as low as 0.4% rms in the 2-5 keV range.

We investigated all X-ray bursts of 4U 1636–53 detected by the PCA/RXTE. For this we produced 0.25-s light curve from the Standard-1/Event data and searched for X-ray bursts in these light curves following the procedure described in Zhang et al. (2011). In order to study the shape and time-scale of the bursts rise, we extracted the bursts light curves from the PCA data with 0.125-s time resolution. To describe the shape of the burst rising phase quantitatively, we used the convexity, $\mathcal{C}$, parameter in our analysis (Maurer & Watts 2008). The convexity describes the curvature of the light-curve rise, and it quantifies whether the curve is convex ($\mathcal{C} > 0$) or concave ($\mathcal{C} < 0$). We used the same method as in Maurer & Watts (2008) to calculate the convexity in the burst light curve of the full PCA energy band; Since different bursts have different durations and peak intensities, we normalised the light curves and time axes so that, from the start to the peak, each burst rises from 0 to 10 normalised intensity units within 0 to 10 normalised time units, and we calculated the convexity in the time interval in which the light curve of the burst rises from 1 to 9 normalised intensity units, for more details of the calculation please refer to Zhang et al. (2016). We also calculated the rising time of each burst, defined as the time interval at the beginning of a burst during which the flux in the light curve is between 10% and 90% of the flux at the peak of the burst.

3 RESULTS

We detected 207 cases of mHz QPOs and 371 X-ray bursts in the whole RXTE archive. We excluded, and did not analyse further, those bursts that showed at least one of the following characteristics: (i) The burst light curve was incomplete, (ii) the burst light curve had multiple peaks, or (iii) the burst was very weak and hence the light curve was very noisy. We further excluded the superburst in this source (Wijnands 2001; Strohmayer & Markwardt 2002). We were then left with 305 burst with a complete and smooth profile. We considered that a mHz QPO and an X-ray burst are associated if, in an observation, there is a mHz QPO that ends at the same time that an X-ray burst happens. In the rest of the paper we only considered those cases in which the mHz QPOs are associated to an X-ray burst. We detected both mHz QPOs and an associated type I X-ray bursts in 39 observations; the QPOs in these observations always disappeared at the time when the associated X-ray burst appeared. In Figure 1 we show the distribution of the convexity of all type I X-ray bursts and the distribution of the convexity of those bursts that are associated with mHz QPOs in 4U 1636–53. The distribution of the convexity of all bursts is symmetric, with 252 and 53 of them having, respectively, positive and negative convexity. The distribution can be well fitted with a Gaussian function (R-square=0.976) with a mean convexity of 12.3 ± 1.2 (95% confidence level) and a standard deviation of 12.6 ± 1.2. For the 39 bursts associated with mHz QPOs, the convexities are always positive. We list the convexities of these 39 bursts in the Table 1. We found no case in our sample of a mHz QPO that is associated with a burst with negative convexity. In a few observations there is a second burst a few thousand seconds after the burst that is directly associated with the mHz QPO; in these cases we found that the convexity of the second burst can be either positive or negative. Furthermore, we found that the observed continuum flux ranges from 1.9×10^{-9} ergs cm^{-2} s^{-1} to 5×10^{-9} ergs cm^{-2} s^{-1} for bursts with mHz QPOs, and from 1.2×10^{-9} ergs cm^{-2} s^{-1} to 8.2×10^{-9} ergs cm^{-2} s^{-1} for bursts without mHz QPOs. The K-S test probability that the

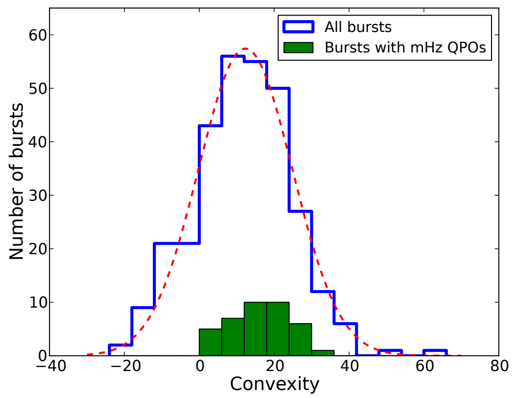

Figure 1. Distribution of the convexities of all X-ray bursts (blue line) and the bursts with mHz QPOs (filled green bars) in 4U 1636–53. The red dashed line in the plot corresponds to the best-fitting Gaussian curve to the the convexity distribution of all bursts.

above two samples come from the same parent population is $P_{K-S} = 0.0083$, which indicates that the distribution of the persistent flux of the two samples is marginally different.

The results shown in Figure 1 suggest that there is a relation between the presence of the mHz QPOs and the convexity of the associated burst. In order to quantify this, we calculated the probability, P_{39}, of selecting 39 random bursts from the distribution of the convexity of all bursts in 4U 1636–53 (see Figure 1), and getting only bursts with positive convexity. Since the convexity can either be positive or negative, we can estimate this probability from the binomial distribution, where the probability of success (where success means $\mathcal{C} > 0$) is $P = 252/305 = 0.826$. The probability is then $P_{39} = 0.826^{39} = 5.8\times10^{-4}$.

We also used the distribution in Figure 1 to simulate 10^6 sets of 39 convexities, and counted the number of trials, N_+, in which all 39 convexities were positive. We found that $N_+ = 594$, corresponding to a probability of 5.9×10^{-4}, consistent with the calculation above.

In Figure 2 we show the distribution of the rising time of all X-ray bursts in 4U 1636–53. The rising time ranges from 0.4 s to 23 s and follows a bimodal distribution with peaks at ∼1 s and ∼3 s, respectively. In Figure 3 we show the rising time vs. convexity of all bursts (blue snow symbols) and those bursts with mHz QPOs (red stars). The vertical line in this Figure is at a convexity of zero, while the horizontal line is at a rising time equal to 2 s; the latter is approximately the value at which the distribution of rising times in Figure 2 shows a local minimum. It is apparent that all bursts with mHz QPOs are located on the lower right corner of this Figure: All bursts with mHz QPO have positive convexity and, except for one case, they all have rising times shorter than 2 s. From this Figure it is also apparent that not all bursts in that part of the diagram show mHz QPOs.

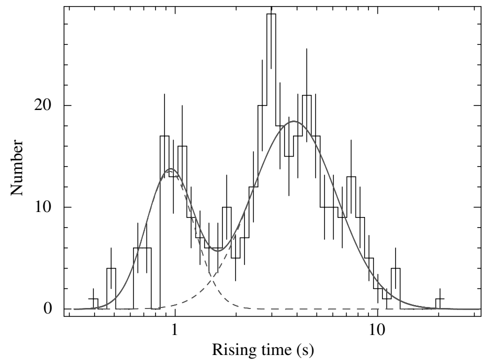

Figure 2. Distribution of the rising time of X-ray bursts in 4U 1636–53. We used the dashed-lines to show the two best-fitted gaussians to the histogram, and the sum of the two Gauss components is shown as the black curve in the plot.

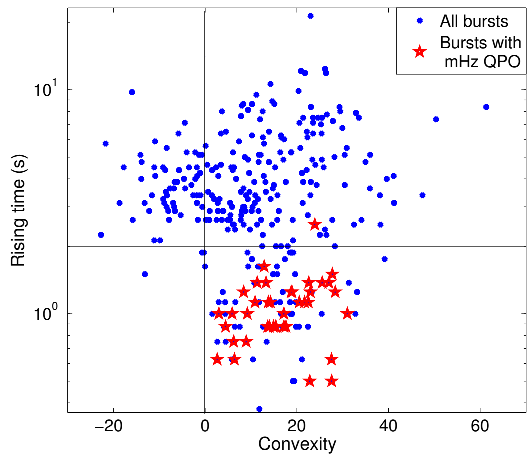

Figure 3. Rising time vs. convexity of X-ray bursts (blue snow symbols) and the bursts with mHz QPOs (red stars) in 4U 1636–53. The vertical and horizontal line in the plot corresponds to a convexity equal to 0 and a rising time equal to 2 s.

4 DISCUSSION

Using data from the full RXTE archive we found that all type I X-ray bursts associated with the mHz QPOs (39 in total) in 4U 1636–53 have positive convexity. We did not find a single case in our sample of an X-ray burst with negative convexity associated to a mHz QPO. The probability that this happens only by chance is less than $6{\times}10^{-4}$, corresponding to a significance level of $\sim 3.5\ \sigma$.

Using numerical simulations of the propagation of a burning front on the neutron-star surface, Maurer & Watts (2008) found that bursts that ignite at the equator always have positive convexity, whereas bursts that ignite at high latitude have both positive and negative convexity. Mahmoodifar & Strohmayer (2015) confirmed this result in their simulations, and also found that the rising time of bursts that ignite at the equator is short, whereas the rising time is both short or long for bursts that ignite at high latitudes (see also Maurer & Watts 2008). In Table 2 we summarise the results of Maurer & Watts (2008) and Mahmoodifar &

Table 1. List of the convexities of the 39 bursts associated with mHz QPOs in 4U 1636–53. The continuum flux is from 2 to 50 keV in unit of 10^{-9} ergs cm^{-2} s^{-1}. The convexity error here is at 1-σ significance level.

ObsId	Star time of burst	End time of burst	Convexity	Rising time (s)	Absorbed continuum flux
10088-01-08-030	50448.73395	50448.73699	11.3 ± 1.1	1.4	4.8
30053-02-02-02	51044.48934	51044.48976	13.3 ± 1.2	1.4	3.9
40028-01-02-00	51236.36632	51236.36671	17.2 ± 1.6	1.0	4.1
40028-01-04-00	51297.07198	51297.07243	4.5 ± 1.5	0.9	4.6
40028-01-08-00	51347.98825	51347.98866	25.5 ± 1.5	1.4	5.0
40031-01-01-06	51350.79575	51350.79613	12.9 ± 1.2	1.6	3.8
40028-01-15-00	51710.21233	51710.21290	6.4 ± 2.1	0.6	4.3
40028-01-19-00	51768.98081	51768.98125	14.2 ± 1.6	1.1	3.8
40028-01-20-00	51820.98111	51820.98157	5.9 ± 1.3	1.0	3.7
50030-02-05-00	51942.10024	51942.10065	3.0 ±1.4	1.0	4.1
50030-02-09-000	52004.71326	52004.71366	8.4 ± 1.3	1.3	4.1
50030-02-10-00	52029.22818	52029.22864	10.9 ± 1.3	1.1	3.1
60032-01-02-00G	52075.13477	52075.13512	27.6 ± 2.8	0.5	2.3
60032-01-12-000	52182.61618	52182.61667	13.6 ± 1.5	0.9	2.7
60032-01-14-01	52214.31827	52214.31882	18.9 ± 1.4	1.3	3.2
60032-01-18-00G	52273.69081	52273.69130	15.4 ± 1.2	0.9	2.0
60032-01-20-000	52283.01851	52283.01896	23.0 ± 2.0	1.3	2.3
60032-01-20-01	52283.53362	52283.53417	27.7 ± 1.2	1.5	2.4
60032-05-01-00	52286.05404	52286.05451	2.6 ± 2.4	0.6	1.9
60032-05-02-00	52286.55466	52286.55519	17.6 ± 1.7	0.9	2.0
60032-05-04-00	52287.52190	52287.52233	9.2 ± 1.7	1.0	2.0
60032-05-06-00	52288.51431	52288.51476	27.0 ± 1.5	1.4	2.1
60032-05-07-00	52288.97438	52288.97489	6.2 ± 2.0	0.8	1.9
60032-05-07-01	52289.29282	52289.29320	15.4 ± 2.6	0.9	1.9
60032-05-09-00	52289.97694	52289.97737	17.2 ± 2.8	0.9	2.1
60032-05-18-00	52390.21340	52390.21392	23.9 ±1.2	2.5	3.0
60032-05-23-000	52646.77066	52646.77097	14.0 ± 0.8	0.9	2.4
91024-01-30-10	53688.95191	53688.95234	14.9 ±1.8	0.9	4.3
91152-05-02-00	53919.07399	53919.07437	18.8 ± 1.5	1.3	4.0
92023-01-29-10	54050.90204	54050.90238	22.8 ±3.5	0.5	2.9
92023-01-31-10	54054.24902	54054.24948	20.5 ±1.5	1.1	2.9
70036-01-02-010	54271.04381	54271.04432	13.8 ±0.8	1.1	3.1
70036-01-02-00	54272.09180	54272.09229	27.6 ± 2.9	0.6	3.2
93091-01-01-000	54371.71897	54371.71937	28.4 ±1.8	1.3	2.0
93087-01-24-10	54522.68638	54522.68680	21.7 ±1.7	1.1	2.5
93091-01-02-00	54523.57841	54523.57893	8.9 ± 2.2	0.8	2.8
93087-01-04-20	54678.26783	54678.26838	22.6 ±2.0	1.4	2.5
94310-01-01-00	54904.83290	54904.83362	22.5 ± 1.6	1.1	2.6
94310-01-03-000	55079.21966	55079.22008	31.0 ±1.7	1.0	2.4

Strohmayer (2015), statements ***1a*** and ***1b***, together with our own findings, statements ***2a*** and ***2b***. The last row in that Table shows the statements, ***3***, that follow logically from either the *a* or the *b* statements.

Bursts with short rising time are likely fuelled by Helium (Fujimoto et al. 1981). The apparent connection between mHz QPO and bursts with short rising time (Figure 3) suggests the possibility that mHz QPOs are due to marginally-stable nuclear burning of Helium on the neutron-star surface (Heger et al. 2007). However, there are as many bursts with a short rising time without mHz QPO as with mHz QPO (lower right corner of Figure 3), which indicates that marginally-stable Helium burning can not be the only reason for the presence of mHz QPOs.

Table 2. Properties of X-ray bursts.

1. Results from simulations:			
a. Low-latitude ignition	$\Longrightarrow$	$\mathcal{C} > 0$	(1,2)
High-latitude ignition	$\Longrightarrow$	$\mathcal{C} > 0$ or $\mathcal{C} < 0$	
	...		
b. Low-latitude ignition	$\Longrightarrow$	Short rising time	(1,2)
High-latitude ignition	$\Longrightarrow$	Long/Short rising time	
2. Results from observations:			
a. mHz QPOs	$\Longrightarrow$	$\mathcal{C} > 0$	(3)
no mHz QPOs	$\Longrightarrow$	$\mathcal{C} > 0$ or $\mathcal{C} < 0$	
	...		
b. mHz QPOs	$\Longrightarrow$	Short rising time	(3)
no mHz QPOs	$\Longrightarrow$	Long/Short rising time	
3. The statements *a* or *b* are logically equivalent to:			
mHz QPOs	$\Longrightarrow$	Low-latitude ignition	
no mHz QPOs	$\Longrightarrow$	Low-/High-latitude ignition	

References: (1) Maurer & Watts (2008); (2) Mahmoodifar & Strohmayer (2015); (3) This paper.

From Table 2 we can conclude that all the 39 bursts with positive convexity and short rising time that are associated with mHz QPOs ignited at the neutron-star equator. For, if bursts associated with mHz QPOs ignited anywhere on the neutron-star surface (therefore these 39 bursts would correspond to cases of positive convexity and either low- or high-latitude ignition in the analysis of Maurer & Watts (2008)), we would have expected to see also cases of mHz QPOs associated with bursts with negative convexity in our sample. While in this scenario bursts with positive convexity but no associated mHz QPO would have in principle ignited at high latitudes, some of them may also have ignited at the equator if, for instance, those bursts happened at an accretion rate in which marginally stable nuclear burning would not be at work (e.g., Heger et al. 2007). Also, in some cases a QPO might be present just before an X-ray burst, but we are unable to detect it either because we do not have enough data before a burst (e.g., if the data segment before the burst was too short), or because the data are not of sufficient quality to detect the QPO significantly (e.g., if some PCU detectors were not operating during that observation).

The simplest scenario that follows from this is that the marginally-stable burning (that produces the QPO) and the unstable burning (that produces the burst) take place at the same physical location. There should still be enough fuel at the equator to trigger a burst after the mHz QPOs if, similar to the case of unstable burning at high luminosity (e.g., van Paradijs et al. 1988; Muno et al. 2000; Cornelisse et al. 2003; Heger et al. 2007), marginally-stable burning consumes only a fraction of the fuel on the surface of the neutron star. We cannot discard, however, more complex scenarios in which the sites of marginally-stable and unstable burning are physically disconnected, mHz QPOs and bursts with positive convexity happen at any latitude, but some other mechanism ensure that mHz QPOs and bursts with positive convexity are causally connected.

Fujimoto et al. (1981) proposed that the thermal stability and burst ignition of a neutron star actually depends on the accretion rate per unit area, $\dot{m}$, instead of the global accretion rate. The quantity $\dot{m}$ needs not to be the same everywhere on the neutron-star surface (e.g., Fujimoto et al. 1981; Bildsten 1998). During accretion, the infalling matter first reaches the equator and then spreads over the whole surface of the neutron star, therefore $\dot{m}$ will be higher at the equator than at high latitudes. If the mHz QPOs happen at the equator, the local accretion rate per unit area, $\dot{m}$, would also be the key parameter that determines whether marginally stable nuclear burning on the neutron-star surface takes place: when nuclear burning occurs around the equator, $\dot{m}$ is high enough to trigger the mHz QPOs, while there are no mHz QPOs when the nuclear burning happens at high latitudes where $\dot{m}$ is below the threshold value to trigger the marginally-stable nuclear burning process. The fact that the distribution of the persistent flux of observations with and without mHz QPOs is consistent with being the same further enhances the argument that it is the local accretion rate $\dot{m}$ that triggers mHz QPOs. This picture is similar to the one proposed in Heger et al. (2007) in which the accreted fuel that is responsible for the marginally-stable nuclear burning is confined at a certain burning depth, where the local accretion rate could be much higher than the global accretion rate. This scenario is able to bridge the gap between the high accretion rate required for triggering the mHz QPOs in the models and the relatively low accretion rate implied from observations.

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