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Quasiperiodic Oscillation Signatures of Disk Restoration after Type-I X-Ray Bursts from 4U 1636–536

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Abstract

Type-I thermonuclear bursts (TNBs) from neutron star low-mass X-ray binaries (NS LMXBs) originate on the neutron star's surface from the unstable burning of the accreted material. On the other hand, kHz quasiperiodic oscillations (QPOs) are thought to originate in the innermost regions of the inspiralling accretion disk. Type-I TNBs are expected to impact the inner accretion flow, and consequently the kHz QPOs, due to the intense radiation pressure. In this work, we systematically study the evolution of the upper and the lower kHz QPOs immediately before and after a type-I TNB on 4U 1636–536 using *AstroSat* observations in the 3–20 keV band. The analysis of the power density spectra shows the presence of kHz QPOs within 200 s before the onset of the type-I burst. However, we have not detected any prominent signature of the same within 100–200 s after the burst. The kHz QPOs then reemerge after 200 s. The fractional rms variation in the 3–20 keV band drops by 5%–6%, supporting the nonexistence of kHz QPOs in the 200 s postburst zone. The timescale of 200 s coincides with the viscous timescale, highlighting a scenario where the inner disk is temporarily disrupted by the intense radiation from the type-I TNB. The kHz QPO then reestablishes as the inner disk is restored.

Unified Astronomy Thesaurus concepts: Low-mass x-ray binary stars (939); X-ray binary stars (1811); Accretion (14); Stellar accretion disks (1579)

1. Introduction

A low-mass X-ray binary (LMXB) consists of a compact object, either a neutron star (NS) or stellar-mass black hole, that accretes matter from a less evolved companion star (which typically has a mass of $\lesssim 1M_{\odot}$). Accretion occurs via Roche-lobe overflow (J. Frank et al. 1985; T. M. Tauris & E. P. J. van den Heuvel 2006). These systems provide a unique laboratory to study accretion physics in strong gravity because they evolve on humanly observable timescales, as opposed to millions of years in active galactic nuclei (weeks, months to years; P. Martini 2004; P. F. Hopkins et al. 2005; S. Corbel et al. 2013; B. E. Tetarenko et al. 2016).

In particular, NS LMXBs show some extraordinary phenomena, including type-I thermonuclear X-ray bursts (TNBs), which appear as a sudden and dramatic increase in the X-ray brightness of accreting NSs, often reaching intensities many times greater than their persistent emission levels. In typical TNBs, the rising phase of X-ray flux ranges within 1–10 s before showing an exponential decay that spans tens to hundreds of seconds (e.g., W. H. G. Lewin et al. 1993; T. Strohmayer & L. Bildsten 2003; D. K. Galloway et al. 2008; D. K. Galloway & L. Keek 2021). TNBs result from the unstable nuclear burning of accreted hydrogen and/or helium on the surface of the NS (W. H. G. Lewin et al. 1993; T. Strohmayer & L. Bildsten 2003; D. K. Galloway et al. 2008). Another kind of TNB can be observed in NS LMXBs

called type-II TNB, where the duration can vary in a wide range from a few milliseconds to a few hours. Type-II TNBs are thought to arise due to accretion instabilities because the average power in type-II TNBs is almost less by a factor of 10^2 in comparison to the type-I burst (T. Bagnoli et al. 2015). Various studies have shown evidence of interactions between the inner disk region and the burst emission (e.g., W. Yu et al. 1999; J. J. M. in't Zand et al. 2011; L. Keek et al. 2016; Z. Yan et al. 2024). Around a decade ago, P. Peille et al. (2014) discussed a possible interaction between kHz quasiperiodic oscillations (QPOs) and type-I TNBs in 4U 1636–536 and 4U 1608–52. The centroid frequency of the QPOs in NS LMXBs ranges from low frequency (5–60 Hz) to very high frequency (1300 Hz), showcasing a wide range of variability. The QPOs with low frequency (5–60 Hz) and quality factor (Q) > 2 are called low-frequency QPOs (LF QPOs), and the QPOs with frequencies ranging mostly from 400 to 1300 Hz are classified as high-frequency QPOs or kHz QPOs (M. van der Klis 1989; M. V. D. Klis 1997; P. Peille et al. 2015; J. Wang et al. 2016). These kHz oscillations often appear in pairs, with the higher centroid frequencies referred to as the upper kHz QPOs and the lower ones as the lower kHz QPOs. The timescale of these high-frequency variabilities is comparable to the dynamical timescale of the inner disk region. In their work, P. Peille et al. (2014) suggest that kHz QPOs may be affected by type-I bursts on timescales ranging from a few tens to a few hundreds of seconds.

AstroSat, with a high temporal resolution of $10 \mu\text{s}$ and a large effective area of 6000 cm^2 (P. C. Agrawal et al. 2017), has detected kHz QPOs in several persistent atoll NS LMXBs, like 4U 1728–34, and 4U 1702–429, as reported in multiple



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studies (J. V. Chauhan et al. 2017; K. Anand et al. 2024; S. Chattopadhyay et al. 2024).

4U 1636–536 is also a persistent atoll source, first reported by A. P. Willmore et al. (1974), with an orbital period of 3.79 hr, determined from optical light-curve photometry (A. B. Giles et al. 2002). Based on radius expansion, bursts reach the Eddington limit for hydrogen-rich (solar H fraction $X \approx 0.7$) and helium-rich ($X = 0$) material. D. K. Galloway et al. (2006) estimated a distance to the source of (6.0 ± 0.5) kpc for a $1.4 M_{\odot}$ NS, increasing to 7.1 kpc for $2 M_{\odot}$. The system has a reported mass function of $f(M) = 0.76 \pm 0.47 M_{\odot}$ and a donor mass ratio of $M_2/M_{\text{NS}} = 0.21 \pm 0.34$, with an inclination angle of 36° – 74° (J. Casares et al. 2006). 4U 1636–536 frequently exhibits burst oscillation in the type-I TNBs, revealing a spin frequency of 290 Hz and a first overtone near 580 Hz (M. C. Miller 1999). AstroSat observations have also confirmed burst oscillations at 581 Hz (P. Roy et al. 2021). Further, twin kHz QPOs have been detected in its power density spectrum (PDS) using the Rossi X-ray Timing Explorer (RXTE), with lower kHz QPOs between 644 and 769 Hz and upper kHz QPOs between 900 and 1050 Hz (W. Zhang et al. 1996; P. G. Jonker et al. 2002; D. Barret et al. 2005; T. Belloni et al. 2007; Y.-F. Lin et al. 2011).

In this work, we analyzed AstroSat data of 4U1636–536, with an emphasis on studying the presence of kHz QPO before and after a TNB. The paper is organized as follows: Section 2 presents the observation details and basic data reduction procedures. Section 3 discusses the light-curve analysis and the evolution of the source along the hardness–intensity diagram (HID). In Section 4, we explore the results of the advanced temporal analysis. Finally, Section 5 concludes our findings and presents future implementations.

2. Data Reduction

To date, AstroSat has observed 4U 1636–536 on 11 occasions since 2016. Notably, type-I TNBs have been detected in the light curves of the 10 observations of 4U 1636–536. For this study, we selected four data sets where kHz QPOs were detected in addition to at least one type-I TNB (S. Chattopadhyay et al. 2025). Finally, we select three of these four data sets (observation IDs G05_195T01_9000000530, hereafter observation 1; G05_195T01_9000000598 (observation 2); and G05_002T01_9000000616 (observation 3)) for further analysis according to the criteria presented in Section 3. These three observations had an LAXPC exposure time of 39, 38, and 33 ks, respectively. The analysis of the LAXPC data was performed using LAXPC-software22Aug15, which is publicly available on the ASSC website.⁶ All orbit files were merged to generate a single level-2 event file. From this file, scientific products, including light curves, energy spectra, and PDS, were derived by applying good time intervals following the standard procedures outlined on the ASSC webpage.⁷ It is important to note that all LAXPC proportional counter units (PCU; PCU 10, PCU 20, and PCU 30) data were utilized for detailed temporal analysis.

3. Light Curve and Hardness–Intensity Diagram

In Figure 1, we show the source evolution through its HID, constructed using the background-subtracted PCU 20 light

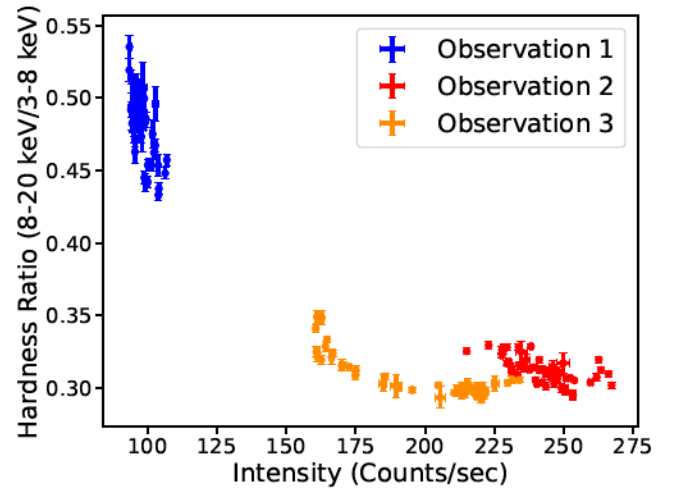


Figure 1. Hardness vs. intensity diagram using LAXPC PCU 20 to see the evolution of the source. The bin time is 1024 s.

curve with a bin size of 1024 s. The hardness ratio is defined as the count rate ratio between the 8–20 and 3–8 keV energy bands, while the intensity represents the total counts in the full 3–20 keV energy band. The source is primarily located in the softer region of the diagram, except during observation 1. As expected, the source count rate increases during the softer state.

As highlighted in Figure 2, the light curves of the three studied observations show the presence of type-I TNBs across the three AstroSat energy bands. In observation 1 and observation 3, three type-I TNBs are identified, while observation 2 shows only a single type-I TNB. To analyze the evolution of kHz QPOs before, during, and after the TNBs, a sufficient amount of data (>200 s) is required to support any conclusions. Based on this criterion, two TNBs from observation 3 and two TNBs from observation 1 are excluded from further analysis due to insufficient data either preceding or following the TNB (see Figure 2), with a single burst meeting our criteria in each of observations 1, 2, and 3, labeled B1, B2, and B3, respectively, in Figure 2. Throughout this work, the periods before and after a TNB are referred to as the preburst zone and postburst zone, respectively. For reference, in subsequent discussions from here on, we will call the B1 in observation 1 as TNB-1, B2 in observation 2 as TNB-2, and B3 in observation 3 as TNB-3 (see Figure 2). The corresponding burst durations ~ 120 s have been excluded from the light curves for further analysis. We further separately analyzed the preburst and postburst zones of each TNB.

4. Temporal Analysis and Results

The LAXPC instrument onboard AstroSat provides an excellent opportunity to study the temporal behavior of the source (H. M. Antia et al. 2017, 2021). We utilized the standard routine `laxpc_find_freqflag` to generate the PDS analyzed in this article (J. S. Yadav et al. 2016). This routine includes several configurable flags that allow users to tailor the PDS creation to their requirements. Among these, the `-h` flag controls the maximum frequency of the PDS (Nyquist frequency), while the `-l` flag specifies the minimum frequency or frequency resolution. For this study, we set the minimum frequency resolution to 31 Hz and the Nyquist frequency to 2000 Hz. All the PDS have been generated in the 3–20 keV

⁶ <http://astrosat-ssc.iucaa.in/laxpcData>

⁷ http://astrosat-ssc.iucaa.in/uploads/threadsPageNew_SXT.html

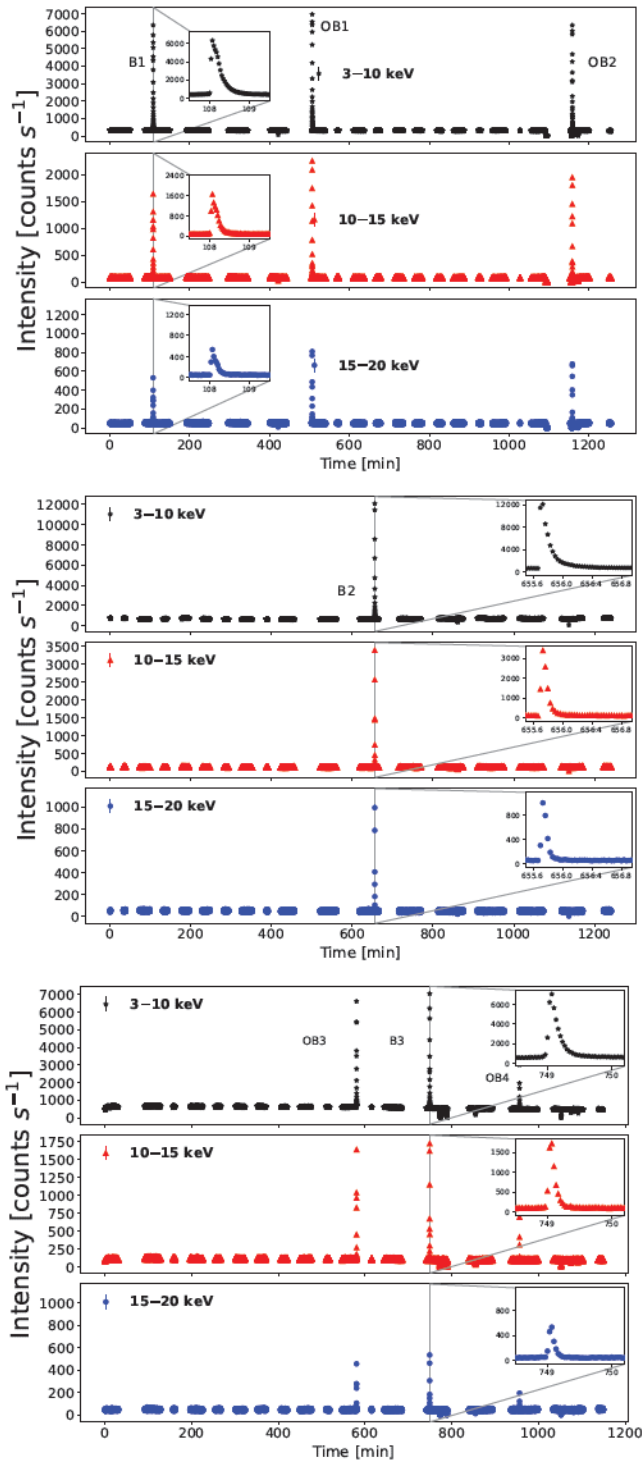


Figure 2. Light curves of observations 1, 2, and 3 in the 3–10, 10–15, and 15–20 keV energy ranges. The abbreviation OB stands for the omitted burst, representing burst emissions that have not been considered for further analysis. B1 (TNB-1), B2 (TNB-2), and B3 (TNB-3) represent bursts considered for further analysis.

energy range (see Figures 3, 4, and 5). To analyze the PDS, we have segregated the preburst zone and postburst zone and performed the search for the kHz QPO within 400–1200 Hz as the maximum value of the upper kHz QPO reported for this source is 1176 Hz (R. A. D. Wijnands et al. 1997). The preburst zone is defined as the 100–200 s interval before the burst onset, while the postburst zone corresponds to the same

duration after the burst, ensuring that the average count rates in both regions match (see Table 1 and Figures 3, 4, and 5). Further, the postburst zone has been divided into several small segments to see the evolution of the kHz QPO after the type-I TNB in this system. We have fitted all the PDS using either a single Lorentzian with a single constant or multiple Lorentzians with a constant. The Lorentzians are defined as

$$f(\nu) = \frac{A}{\pi} \left(\frac{\sigma}{(\nu - \nu_0)^2 + \sigma^2} \right), \quad (1)$$

where A is the normalization of the Lorentzian, σ is the width, and ν_0 is the centroid frequency. The best-fitted parameter values are tabulated in Table 1 for further reference.

The results clearly show the presence of kHz QPOs in the preburst zone across all scenarios. However, in the first 100–200 s after the TNB, the PDS reveals no kHz QPOs. These QPOs reappear after approximately 200 s. As illustrated in Table 1 and Figures 3, 4, and 5, the kHz QPO frequency initially drops below the preburst frequency, then increases, approaching the preburst value 800–1000 s after the burst. Additionally, the upper kHz QPO frequency differs significantly between the preburst and postburst zones. In the B2 zone, there is no clear evidence of the lower kHz QPO within 200–500 s postburst, and due to the lack of continuous data, it is unclear if it eventually surpasses the preburst frequency (see Figures 3, 4, and 5).

The rms amplitude of a kHz QPO quantifies the strength of the oscillation and is proportional to the $\sqrt{\text{normalization}}$ of the Lorentzian (T. Belloni et al. 2002; M. van der Klis 2006). The rms is often expressed as a percentage. We have computed the rms in the 3–20 keV energy band, which is given in Table 1. To assess the significance of the detected frequencies, we conducted a statistical test by computing the signal-to-noise ratio (SNR) for each QPO using the method outlined in M. van der Klis (2004) and D. Barret et al. (2008). Using this, we now obtain upper limits on the QPO rms amplitudes when the $\text{SNR} < 3$. Since this SNR does not account for the number of frequency bins that have been searched, we additionally estimated the null hypothesis probability for each QPO using the approach of D. Barret et al. (2008), where we also performed a simulation study to confirm the results. Details have been added in the Appendix. The results indicate that for $\text{SNR} \geq 3$, the null hypothesis probability when one considers the number of frequency bins that are being searched, is still greater than a 95% confidence level. Since the PDS in the postburst zone during the initial 200 s does not show a definitive QPO signature, we used the preburst zone parameters to compare the shift in the 3–20 keV rms between the pre- and postburst zones.

Table 1 illustrates the evolution of the 3–20 keV rms amplitudes for the lower and upper kHz QPOs in the pre- and postburst zones corresponding to TNB-3 and TNB-1. In both cases, the lower kHz QPOs exhibit a notable drop of approximately 5%–6% in rms amplitude between the preburst phase and the initial 200 s postburst. Beyond this 200 s mark, the rms increases and eventually approaches the preburst level. For the upper kHz QPOs, no detection was made in the preburst zone, preventing direct comparison between the pre- and postburst phases in TNB-3. However, for TNB-1, a similar pattern emerges: the rms decreases during the first 200 s postburst, followed by an increase of about 5%–6%. It is to be noted that for observation 3, the third burst (OB4; see Figure 2) has been omitted from the analysis. However, it meets the

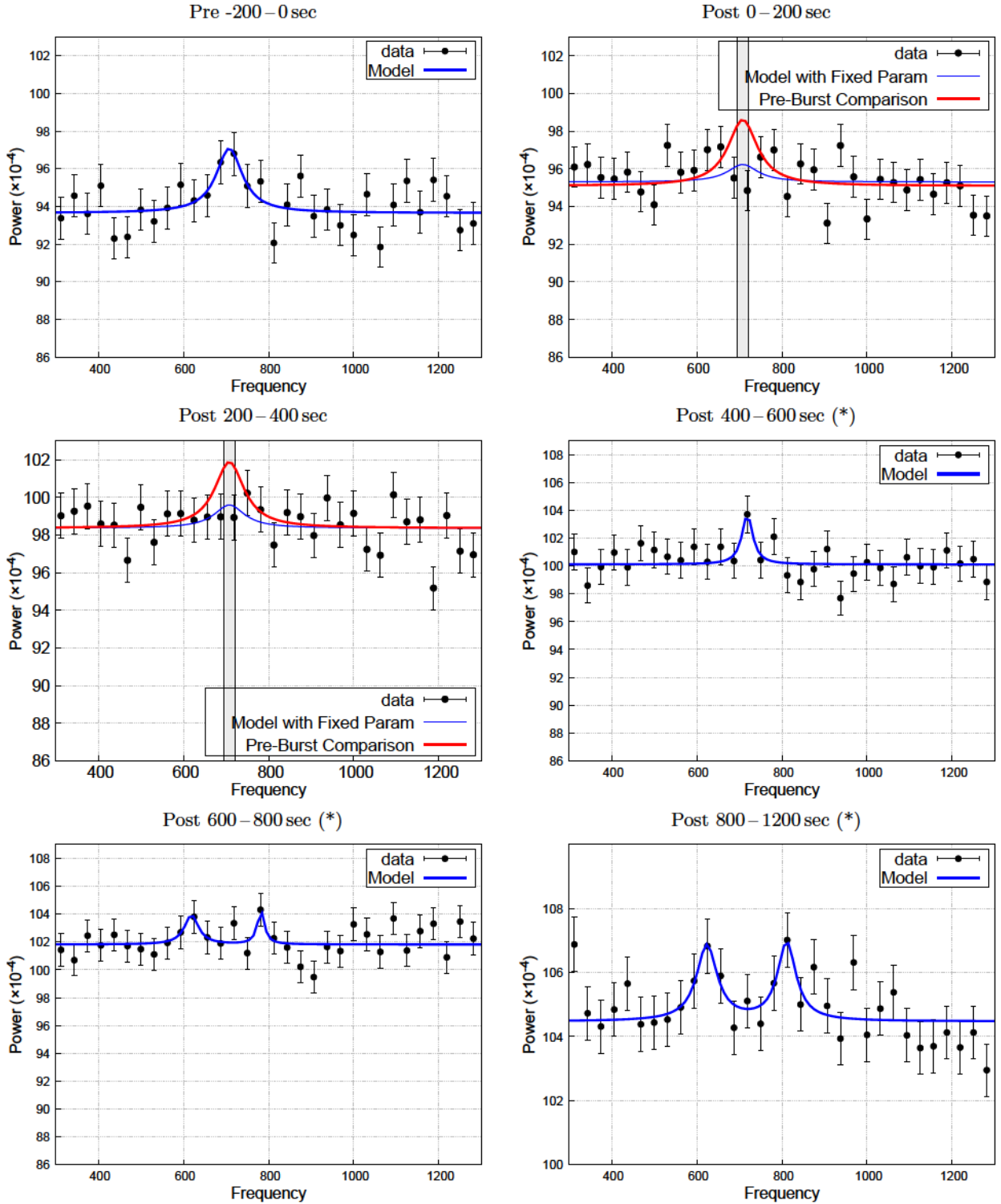


Figure 3. The evolution of the kHz QPO in the preburst and the postburst zone of the type-I TNB of observation 1. While the kHz QPO is present in preburst data, the same QPO is not present in the postburst within 0–400 s data (we overplot the preburst QPO with the blue line, highlighting the lack of signal). In some scenarios (400–600, 600–800, and 800–1200 s), we have changed the y-axis limit to show the prominent presence of the QPO, which has been marked with the *. The frequency is measured in Hz, and the power is normalized by rms.

necessary conditions for the analysis, as we cannot detect any QPO in the preburst and postburst zones.

5. Discussion and Conclusion

For over two decades, it has been hypothesized that type-I TNBs can influence, and in some cases entirely disrupt, the

inner accretion flow in NS LMXBs (e.g., J. J. M. in’t Zand et al. 2011; L. Keek et al. 2016; Z. Yan et al. 2024). Since the work of P. Peille et al. (2014), there has been a lack of systematic observational studies addressing the full extent of this impact. In this study, we investigate the evolution of kHz QPOs before and after TNBs using X-ray observations in the

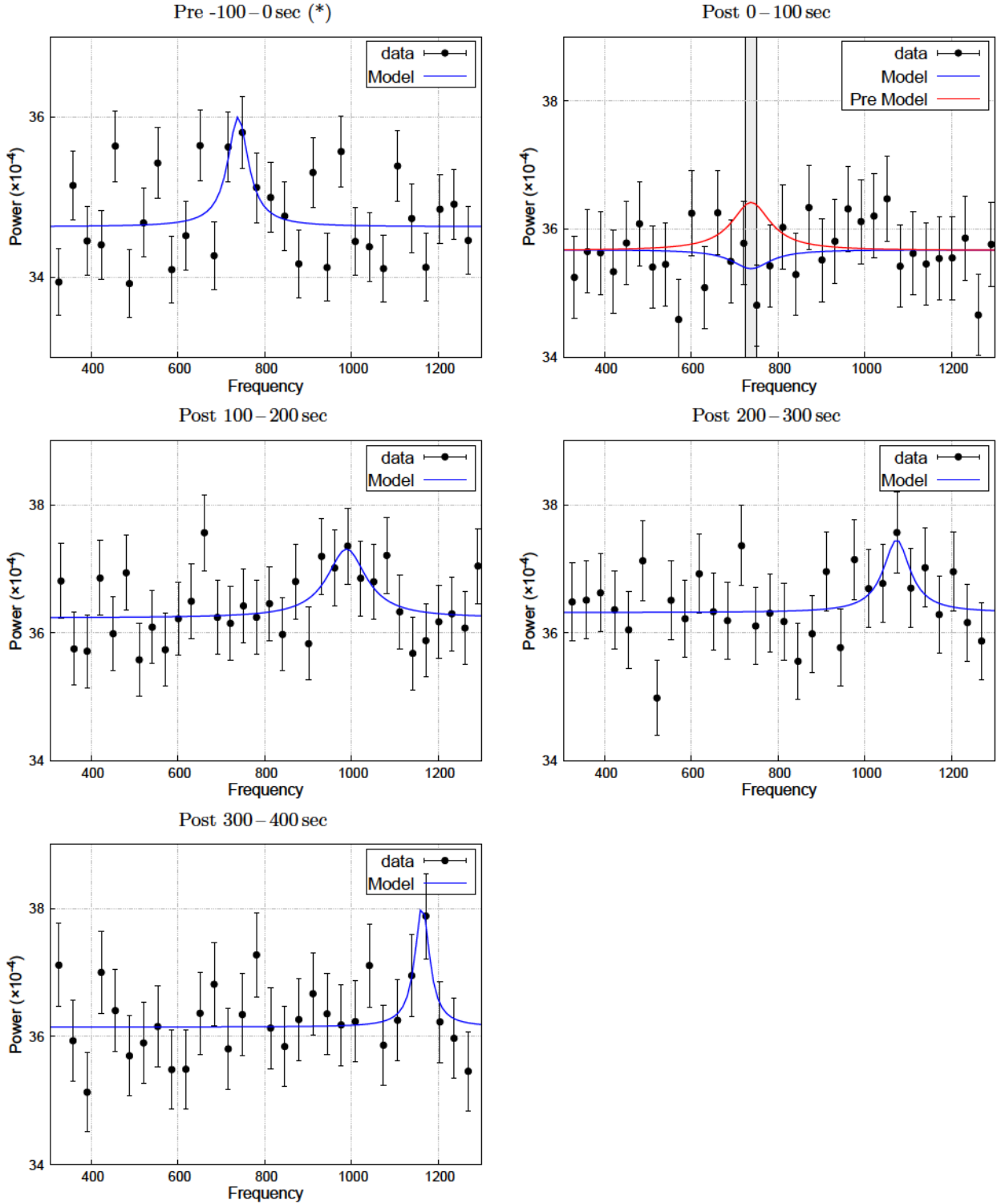


Figure 4. The evolution of the kHz QPO in the preburst and the postburst zone of the type-I TNB of observation 2. While the kHz QPO is present in preburst data, the same QPO is not present in the postburst within 0–100 s data (we overplot the preburst QPO with the blue line, highlighting the lack of signal). In some scenarios (–100–0 s), we have changed the y-axis limit to show the prominent presence of the QPO, which has been marked with the *. The frequency is measured in Hz, and the power is rms normalized.

3–20 keV band. Our results extend the findings of P. Peille et al. (2014), revealing significant changes in QPO frequency and strength, strong indicators of inner disk disruption and subsequent reformation.

kHz QPOs provide a sensitive probe of the inner accretion flow. Several models have been proposed to explain their origin, including the relativistic precession model (RPM;

L. Stella & M. Vietri 1998, 1999), tidal disruption model (A. Čadež et al. 2008; C. Germanà et al. 2009), and disk oscillation models (S. Kato 2007). Although no consensus has been reached, Y.-F. Lin et al. (2011) showed that the tidal disruption model provides a better fit than the RPM for 4U,1636–536, with lower $\chi^2/\text{degrees of freedom}$ (dof) and improved parameter constraints. However, it fails

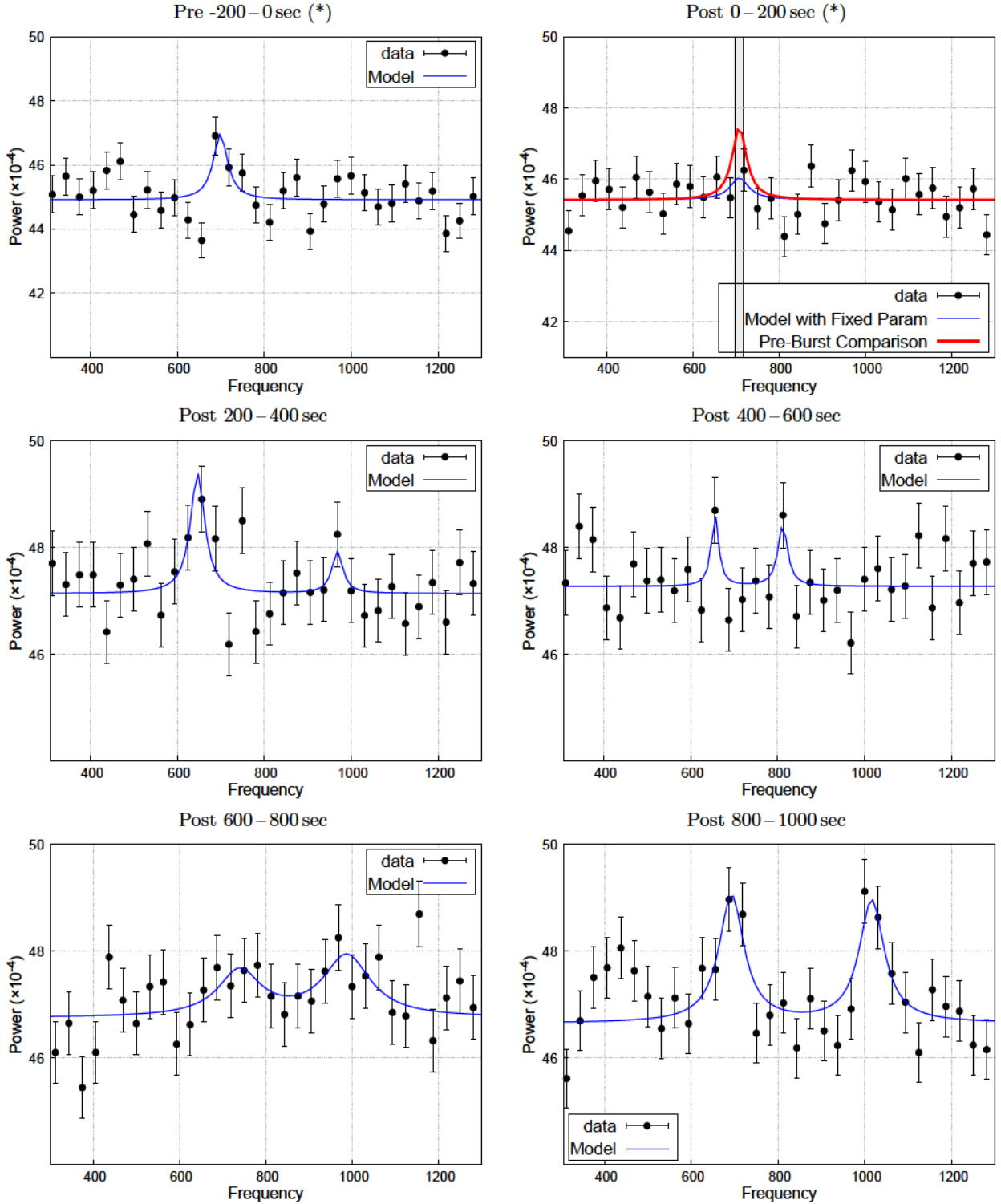


Figure 5. The evolution of the kHz QPO in the preburst and the postburst zone of the type-I TNB of observation 3. While the kHz QPO is present in preburst data, the same QPO is not present in the postburst within 0–200 s data (we overplot the preburst QPO with the blue line, highlighting the lack of signal). In some scenarios (–200–0 and 0–200 s), we have changed the y-axis limit to show the prominent presence of the QPO, which has been marked with the *. The frequency is measured in Hz, and the power is rms normalized.

to explain the expected drop in lower kHz QPOs at high frequencies. In contrast, recent work by S. Chattopadhyay et al. (2025) suggests that the RPM better fits the same data set, yielding a mass of $2.37 M_{\odot}$ and an angular momentum of $1.40 I_{45}/M_{\odot}$. Additional studies considering radiative mechanisms (H. C. Lee et al. 2001; N. Kumar & R. Misra 2014, 2016; C. Bellavita et al. 2022; S. Chattopadhyay et al.

2024) place the origin of kHz QPOs within 12–15 km of the NS, linking them closely to the innermost regions of the accretion disk.

Since TNBs originate from the NS surface (W. H. G. Lewin et al. 1993; T. Strohmayer & L. Bildsten 2003; D. K. Galloway et al. 2008; D. K. Galloway & L. Keek 2021), the intense radiation during a burst is expected to irradiate and potentially

Table 1
The Best-fitted Parameters Obtained from the Fitting of the PDS Using Lorentzian Functions

Obs.	Comp.	Param.	Preburst	Postburst	Postburst	Postburst	Postburst	Postburst	Postburst
			−200–0/−100–0	0–200/0–100	200–400/100–200	400–600/200–300	600–800/300–400	800–1200	1200–1400
1	Lorentzian 1	ν_1	708 13	708 [†]	708 [†]	719 15	619 19	623 13	
		σ_1	42 20	42 [†]	42 [†]	<61	<25	30 14	
		rms (%)	20 3	<8.36	<13	17 4	<14	15 3	
		SNR	6.7	1.1	2.6	3.6	3.90	4.0	
	Lorentzian 2	ν_2					785 33	811 13	1130 21
		σ_2					<25	26 12	<54
		rms (%)					<15	14.8 3	15 4.4
		SNR					4.45	4.3	3.0
		Source CR (C_s)	321 25	313 22	307 22	303 22	300 22	295 21	287 20
		χ^2/dof	0.93/28	1.11/30	0.88/30	0.65/28	0.73/25	1.1/25	0.78/28
2	Lorentzian 1	ν_1	738 14	738 [†]					
		σ_1	<54	54 [†]					
		rms (%)	11 4	<4.0					
		SNR	3.33	0.5					
	Lorentzian 2	ν_2			989 21	1073 20	1163 10		
		σ_2			55 35	37 26	<30		
		rms (%)			13 3.5	10 4	11 4		
		SNR			4.41	3.1	4.3		
		Source CR (C_s)	699 31	687 27	674 27	671 27	677 34		
		χ^2/dof	1.26/28	1.21/30	0.72/28	0.74/28	0.73/28		
3	Lorentzian 1	ν_1	698 6	698 [†]	648 10	655 55	739 44	695 10	
		σ_1	<13	13 [†]	<15	<19	<90	<35	
		rms (%)	11 3	<5.0	10.8 3	7 1	<12	14 2	
		SNR	7.5	1.54	6.58	3.0	3.25	7.13	
	Lorentzian 2	ν_2			968 54	812 40	988 27	1015 8	
		σ_2			<37	<20	<66	<35	
		rms (%)			<11	<5	<12	<12	
		SNR			4.2	1.74	3.8	5.3	
		Source CR (C_s)	562 28	558 15	540 24	538 24	542 26	543 24	
		χ^2/dof	1.3/28	0.83/30	0.81/25	0.82/25	1.09/25	1.2/25	

Note. “Lorentzian 1” and “Lorentzian 2” represent two Lorentzian components. ν is the centroid frequency and σ is the FWHM. SNR is calculated using: $0.5 \times (\text{rms})^2 \times C_t \times \sqrt{T/2\sigma}$ (M. van der Klis 2004; D. Barret et al. 2008), where C_t is the total count rate, T is the segment exposure, and rms is backscaled: $\text{rms}_{\text{backscaled}} = (C_t/C_b) \times \text{rms}$, with $C_t = C_s + C_b$. C_b is the count rate of the background, which remains more or less constant across the different segments of the different observations. For observation 1, this is around 152 counts s^{−1}. For observation 2 and observation 3, these are 156 and 145 counts s^{−1}, respectively.

disturb the nearby inner accretion flow (e.g., J. J. M. in’t Zand et al. 2011; L. Keek et al. 2016; Z. Yan et al. 2024). This interaction can lead to observable changes in kHz QPO properties. W. Yu et al. (1999) and P. Peille et al. (2014) provided early evidence of such interactions, including cases where QPOs disappear following intense bursts.

P. Peille et al. (2014) reported two types of TNB-related QPO behavior in 4U 1636–536. In long bursts, with peak count rates reaching 10^4 counts s^{−1} (6–50 keV), QPOs vanished and reappeared after delays of up to several hundred seconds. In other bursts, QPOs were largely unaffected. Their analysis, limited to −200 to +400 s around the burst, found no QPOs for 80–248 s postburst in some cases.

Our study (see Section 4) expands the temporal coverage beyond 400 s and detects persistent lower kHz QPOs in all preburst phases (TNB-1, TNB-2, and TNB-3), with frequencies ranging from 683–768 Hz. The upper kHz QPO is not detected preburst. Postburst, both QPOs vanish for the first 100–200 s—consistent with the upper limits set by P. Peille et al. (2014)—indicating either a disruption of the inner disk or the dominance of burst emission suppressing QPO visibility. This is supported by:

1. Nondetection of QPOs in 10–20 keV, where burst intensity is lower, ruling out energy band dependence.
2. Uniform 100–200 s QPO reappearance delay across all three TNBs, regardless of burst peak intensity or spectral state.

After 200 s, kHz QPOs reappear. In TNB-3, the lower kHz QPO fractional rms gradually increases between 200 and 800 s, exceeding the preburst amplitude by 800–1000 s. A similar trend is seen in TNB-2, although the lower QPO is undetected between 200 and 600 s. Interestingly, the upper kHz QPO reemerges 200 s postburst even if it was absent before, hinting at a potentially earlier recovery of high-frequency modes.

To explain this, one may interpret burst-induced disruptions as temporarily removing an inner flow, and as the disk recovers postburst, the inner accretion flow re-forms, possibly explaining the gradual reappearance of higher-frequency QPOs. The inner regions of the accretion flow are generally associated with the kHz QPO, as, for example, in the model where they are attributed to the Keplerian and the epicyclic frequency of a characteristic radius close to the NS in the RPM model (L. Stella & M. Vietri 1998, 1999). The low frequency

QPO could then arise from the Lense–Thirring precession of the inner flow (A. Ingram et al. 2009; A. Ingram & C. Done 2010). The disappearance and reappearance of the kHz QPOs would be expected from models where they arise from an inner accretion flow that gets disrupted during a TNB.

The reappearance timescale of QPOs likely reflects the viscous timescale (t_{visc}) governing disk refilling after burst-induced disruption (H. C. Spruit 1995). Viscous timescale is estimated as $t_{\text{visc}} \sim \frac{R^2}{\nu}$, where R is the radial distance and ν the kinematic viscosity (J. Frank et al. 1985; A. Ingram 2012). During a burst, the radiation pressure at near-Eddington luminosities ($L_{\text{Edd}} \sim 3 \times 10^{38} \text{ erg s}^{-1}$ for a $2.4 M_{\odot}$ NS) can exceed gravity, pushing the disk outward (P. C. Fragile et al. 2020). Afterwards, the inner disk gradually refills over t_{visc} , depending on ν . Assuming an inner disk radius of $R_{\text{in}} = 4 \times 10^6 \text{ cm}$ (S. Chattopadhyay et al. 2025) and a kinematic viscosity in the range of $\nu = 10^{10} - 10^{13} \text{ cm}^2 \text{ s}^{-1}$ (J. Frank et al. 1985), we estimate:

For $\nu = 10^{10} \text{ cm}^2 \text{ s}^{-1}$:

$$t_{\text{visc}} = \frac{(4 \times 10^6)^2}{10^{10}} = \frac{1.6 \times 10^{13}}{10^{10}} = 1600 \text{ s.} \quad (2)$$

For $\nu = 10^{11} \text{ cm}^2 \text{ s}^{-1}$:

$$t_{\text{visc}} = \frac{(4 \times 10^6)^2}{10^{11}} = \frac{1.6 \times 10^{13}}{10^{11}} = 160 \text{ s.} \quad (3)$$

For $\nu = 10^{13} \text{ cm}^2 \text{ s}^{-1}$:

$$t_{\text{visc}} = \frac{(4 \times 10^6)^2}{10^{13}} = \frac{1.6 \times 10^{13}}{10^{13}} = 1.6 \text{ s.} \quad (4)$$

The 160–200 s delay we observe corresponds well with $\nu = 10^{11} \text{ cm}^2 \text{ s}^{-1}$, supporting the interpretation that viscous timescales govern QPO recovery after burst-induced disk disruption.

In summary, our results provide compelling evidence for temporary inner disk disruption caused by type-I TNBs, followed by viscous refilling. The systematic disappearance and reappearance of kHz QPOs—along with changes in their strength—support a strong causal link between bursts and inner accretion flow dynamics.

5.1. Caveats and Limitations

While our study presents compelling evidence for the disruption and reformation of the inner accretion disk by type-I TNBs in 4U 1636–536, several caveats must be considered when interpreting the results.

First, our analysis is based on a small sample of bursts (TNB-1, TNB-2, and TNB-3). Although these provide valuable insights, the limited number restricts the statistical robustness and generalizability of our conclusions. Previous studies have shown that burst–QPO interactions can vary significantly from burst to burst (e.g., W. Yu et al. 1999; P. Peille et al. 2014), highlighting the need for a broader sample to assess systematic trends.

Second, the nondetection of kHz QPOs in the immediate postburst phase may result not only from physical disruption but also from instrumental limitations. High photon flux during bursts can increase background noise and mask subtle oscillatory features, especially in the PDS (J. J. M. in’t Zand

et al. 2011; L. Keek et al. 2016). Therefore, the absence of QPOs might partially reflect observational constraints rather than true disappearance.

Third, the viscous timescale estimates we adopt are based on simplified α -disk models (J. Frank et al. 1985; H. C. Spruit 1995; A. Ingram 2012). In reality, the accretion disk viscosity, structure, and response to bursts may be influenced by additional effects such as magnetic fields, burst-driven turbulence, or changes in disk ionization (P. C. Fragile et al. 2020). Hence, while our estimated recovery time aligns with the observed QPO reappearance (~ 200 s), this should be regarded as an order-of-magnitude consistency rather than a precise measurement.

Fourth, the theoretical interpretation of kHz QPOs remains model-dependent. While our findings support the relativistic precession model (L. Stella & M. Vietri 1998, 1999), alternative models such as the tidal disruption (Y.-F. Lin et al. 2011) or disk oscillation frameworks (S. Kato 2007) may also reproduce certain aspects of the observed QPO behavior. As no single model currently explains all QPO characteristics across different sources, caution is warranted in drawing firm physical conclusions based solely on QPO properties.

Lastly, our study does not consider the role of the X-ray corona or jet in modulating or responding to burst events (T. D. Russell et al. 2024). These components are dynamically coupled with the disk and could potentially affect the QPO detectability and energy-dependent characteristics (H. Stiele et al. 2013; C. Bellavita et al. 2022). Future multiwavelength and higher-resolution studies may help disentangle these contributions.

Acknowledgments and Data Availability

We thank the referee for the valuable comments. We want to thank Dr. Thomas D. Russell for his insightful suggestions and discussions that helped us improve the results presented here. In this study, we utilized LAXPC and SXT data from AstroSat, provided by the Indian Space Science Data Centre (ISSDC). The research leading to these results has been funded by the Department of Space, Government of India, ISRO under grant No. DS_2B-13013(2)/10/2020-Sec.2. Further, J.C. and R.S. acknowledge support from the Leverhulme Trust grant RPG-2023-240. We extend our gratitude to the AstroSat Science Support Cell (ASSC) for their assistance. We also appreciate the efforts of the LAXPC and SXT Payload Operation Centers (POC) at TIFR, Mumbai. S.C. is thankful to IUCAA (Inter-University Centre for Astronomy and Astrophysics) for providing periodic visits to carry out the research. Additionally, software from HEASARC was employed in this analysis. The LAXPC and SXT archival data that have been used in this article can be found at AstroSat ISSDC website (https://astrobrowse.issdc.gov.in/astro_archive/archive).

Appendix

Estimation of Null Hypothesis Probability for a kHz QPO Detection

We provide a formalism to estimate the null hypothesis probability for a kHz QPO detection by taking into account the number of frequency bins (i.e., the range of frequencies) that have been searched. This formalism is based on the results shown in D. A. Leahy et al. (1983) and R. Misra & K. Shanthi (2004).

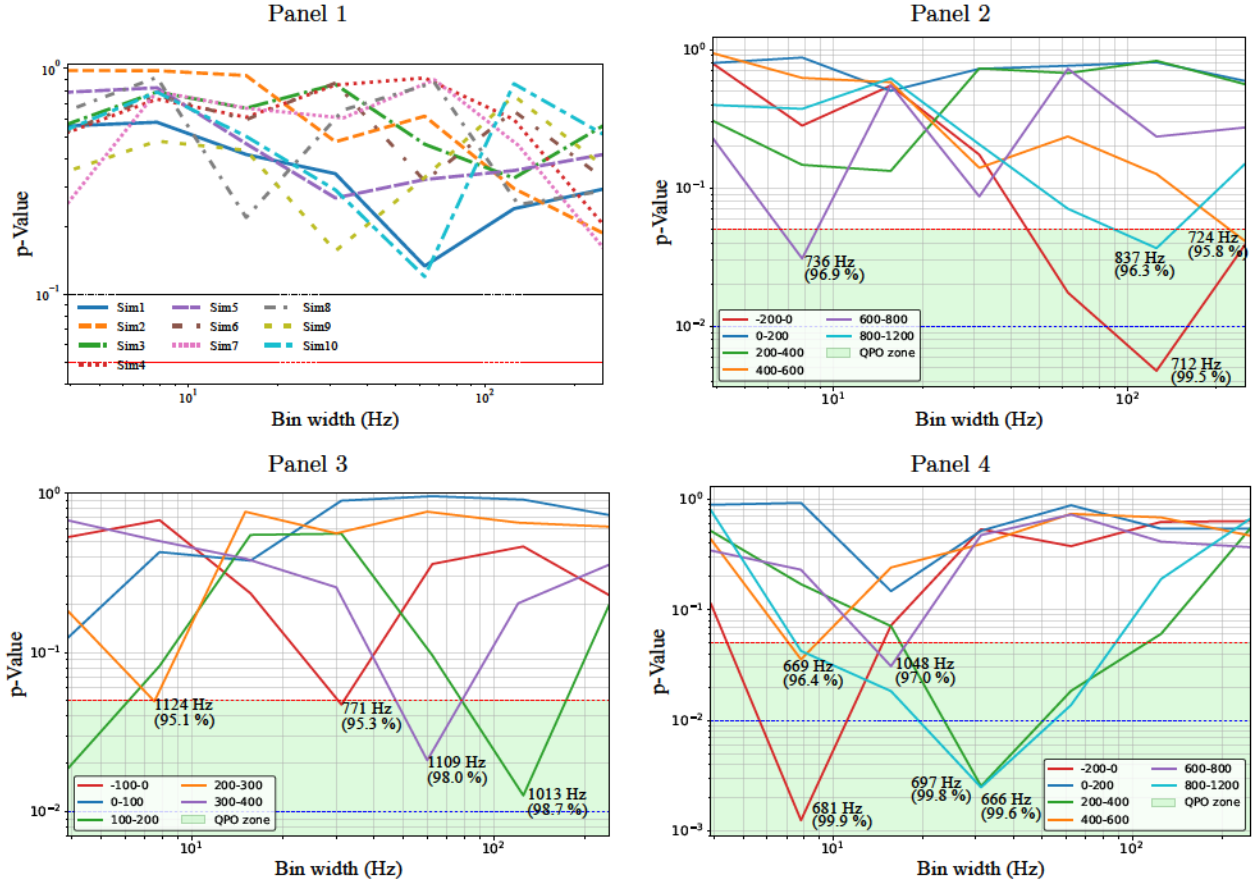


Figure 6. Plot of probability (p -value) vs. bin frequency. Black, red, and blue horizontal lines mark the p -value thresholds of 0.1, 0.05, and 0.01. Each curve from panel (2) to panel (4) (left to right) corresponds to a segment from observation 1 (panel (2)), observation 2 (panel (3)), and observation 3 (panel (4)) around bursts 1, 2, and 3, respectively. Panel (1) shows the simulated PDS in the absence of intrinsic variability, which is created using simulated event files that take the same spectra and count rate as the data. In such cases, $p_N(<P_{\max})$ is always less than 0.1.

Consider a system characterized by white (or Poisson) noise, such that the PDS is frequency independent and given by P_0 . For a finite number of segments, M , the sum of the power obtained for each segment will be distributed as a χ^2 distribution with degree $2M$ (D. A. Leahy et al. 1983). This means that the probability distribution for the average computed power, P , at a given frequency bin will be

$$p(P) dP = \frac{2M}{P_0} \chi^2\left(\frac{2MP}{P_0}, 2M\right) dP. \quad (\text{A1})$$

Note that $p(P) dP$ is properly normalized (i.e., its integral over all P is unity), and that the expectation value is given by

$$\langle P \rangle = \int P \times p(P) dP = P_0. \quad (\text{A2})$$

The probability that the computed power P is less than a given value $P_{\max}$ is

$$p(<P_{\max}) = \int_0^{\frac{2MP_{\max}}{P_0}} \chi^2(x, 2M) dx = \Gamma\left(M, \frac{MP_{\max}}{P_0}\right), \quad (\text{A3})$$

where $\Gamma(a, x)$ is the incomplete gamma function. The probability for N frequency bins that all the powers are less

than $P_{\max}$ is then $p(<P_{\max})^N$. This then provides the null hypothesis probability, that in the absence of a signal, the maximum value of the power for N number of frequency bins, $P_{\max}$, has been obtained by chance, is

$$p_N(<P_{\max}) = 1 - \left[\Gamma\left(M, \frac{MP_{\max}}{P_0}\right) \right]^N. \quad (\text{A4})$$

This probability will depend on the range of frequencies that are searched for and also on the frequency width. If there is a real detectable QPO in the light curve, then the probability will decrease to a significant minimum value when the frequency width is roughly equal to the width of the QPO. Thus, the formalism would be to compute $p_N(<P_{\max})$ for different frequency widths, and if it decreases below a significant level, then the technique would have detected a QPO at the frequency at which $P_{\max}$ is achieved with a width roughly corresponding to the frequency width.

Before we apply this methodology to the power spectra reported in this work, we discuss some of its limitations and assumptions. It is assumed that in the absence of a QPO, the system has only Poisson noise. If the power spectra are Leahy normalized, this would mean that $P_0 = 2$. However, the LAXPC detector has dead time ($\tau_d = 42 \mu\text{s}$), which would change the expected Poisson noise level (W. Zhang et al. 1995; J. Yadav et al. 2016). For frequencies less than $1/\tau_d$, the Poisson noise should still be frequency independent with

Table 2
Lowest p -values from Various Segments with Corresponding Frequencies, SNR, and Lorentzian Fit Parameters

Freq. (Hz)	Bin Width (Hz)	p	$(1 - p)\%$	SNR	Fit Freq. (Hz)	Width (Hz)	Obs.	Segment
712	125	0.0047	99.5	6.7	708 13	42 20	1	–200–0
626	7.81	0.51	49	1.1	708 [†]	42 [†]	1	0–200
751	15.62	0.13	87	2.6	708 [†]	42 [†]	1	200–400
724	250	0.0412	95.8	3.6	719 15	<61	1	400–600
736	7.81	0.0308	96.9	4.45	785 33	<25	1	600–800
619	62.5	0.0706	93	4.0	623 13	30 14	1	800–1200
837	125	0.0366	96.3	4.3	811 13	26 12	1	800–1200
771	31.25	0.047	95.3	3.3	738 14	<54	2	–100–0
642	15.62	0.37	63	0.5	738 [†]	54 [†]	2	0–100
1013	125	0.013	98.7	4.41	989 21	55 35	2	100–200
1124	7.81	0.049	95.1	3.1	1073 20	37 26	2	200–300
1109	62.5	0.02	98	4.3	1163 10	<30	2	300–400
681	7.81	0.0012	99.9	7.5	698 6	<13	3	–200–0
666	7.81	0.14	86	1.54	698 [†]	13 [†]	3	0–200
666	31.25	0.0037	99.6	6.58	648 10	<15	3	200–400
669	7.81	0.0356	96.4	3.0	655 55	<19	3	400–600
1048	15.62	0.03	97.0	3.8	988 27	<66	3	600–800
697	31.25	0.0024	99.8	7.13	695 30	<35	3	800–1200
1001	15.62	0.018	98.2	5.3	1015 8	<35	3	800–1200

values less than 2. However, it is important to check the effect of dead time on the probability estimation. We use the LAXPC simulator code⁸ to generate 10 simulated event files for the same spectra and count rate as the data, and then use them to obtain simulated power spectra in the absence of any intrinsic variability. The code incorporates a dead time of 42 microseconds. We estimate P_o using the average of the power in the frequency range under consideration, which is 400–1200 Hz, and then compute $p_N(<P_{\max})$ for the power spectra for different frequency bins. The results are plotted in Figure 6 (top panel), where we see that, as expected, $p_N(<P_{\max})$ is always less than 0.1. The formalism requires estimating the probability for different frequency bins, and this has not been taken into account in the overall probability computation. Since the maximum power for different frequency bins is correlated with each other, the probability estimates are not independent. If the search is undertaken for a relatively small number of frequency bins, the approach will still be reliable. There are also some effects that may lead to an overestimation of the probability, i.e., the results obtained may be conservative ones. Since P_o is being estimated using the average of power at different frequencies, the presence of a QPO will increase P_o above the Poisson level and hence would lead to an increase in $p_N(<P_{\max})$. Also, the formalism does not consider the possibility of more than one QPO in the power spectrum, and for such cases, the significance of the detection should be higher than the one estimated.

For all the power spectra reported in this work, we compute $p_N(<P_{\max})$ in the frequency range 400–1200 Hz for different frequency widths and plot the results in Figure 6. The minimum $p_N(<P_{\max})$ obtained with the corresponding frequency and frequency width are listed in Table 2, including the centroid frequency, width, and SNR obtained from fitting as

described in Table 1. The table shows that for an SNR > 3, the corresponding $p_N(<P_{\max})$ is less than 0.05, when one considers the number of frequency bins that are being searched for. Thus, the SNR would correspond to a detection at >95% confidence level if its value is larger than 3.

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⁸ http://astrosat-ssc.iucaa.in/proposal_preparation

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