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Search for thermonuclear burst oscillations in the Swift/BAT data set

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This study comprehensively analyzes type I X-ray bursts observed by Swift/BAT from 2005 to April 2024 to search for X-ray burst oscillations (XBOs) in neutron star low-mass X-ray binaries. XBOs, periodic signals detected within type I X-ray bursts, typically range from 11 to 620 Hz and are often observed in the soft X-ray data of these bursts. Using the high-sensitivity and precise timing capabilities of the Swift/BAT, we found 50 type I X-ray bursts from 37 neutron star low-mass X-ray binaries. We conducted a detailed timing analysis of these bursts. For sources with known burst oscillation frequencies, our findings largely corroborate previous studies. However, many sources displayed low confidence levels in the oscillation signals, with Z_1^2 values between 10 and 20. For sources without known oscillation/spin frequencies, we utilized FFT analysis to search for signals across a broad frequency range. This approach revealed potential oscillation signals, with several bursts showing significance levels exceeding 3σ, including those from MAXI J1421−613, XTE J1701−407, XMM J174457−2850.3, Swift J1734.5−3027, IGR J17473−2721, Swift J174805.3−244637, Swift J181723.1−164300, and X 1832−330.

KEYWORDS

neutron star binaries, neutron star (NS), x-ray burst, burst oscillation, x-ray timing

1 Introduction

The X-ray emissions from low-mass X-ray binaries (LMXBs) arise from the accretion processes surrounding compact objects such as neutron stars (NS) or black holes. In the case of NS, the accreted hydrogen, helium, or mixture of them can be consumed via unstable nuclear burning on the stellar surface, leading to the observed type I X-ray bursts (Galloway et al., 2008).

X-ray burst oscillations (XBOs), identified through timing analysis, are periodic signals observed during bursts originating from the NS rotation (Strohmayer et al., 1996; Galloway and Keek, 2021). A type I X-ray burst can form a hot spot on the NS surface, leading to an uneven temperature distribution. The star's rotation modulates this uneven distribution, producing periodic signals in the soft X-ray band (Strohmayer et al., 1997b; Goodwin et al., 2021). The standard methods for XBO detection include a fast Fourier transform (FFT) or Z_n^2 statistics (see Watts, 2012, and references therein). During a burst, the oscillation frequency of XBOs evolves (Muno et al., 2002). To effectively search for and track XBO signals, the dynamic power density spectrum method is commonly used to analyze type I X-ray bursts (e.g., Strohmayer et al., 2008).

However, the mechanisms behind the formation and evolution of these hot spots remain incompletely understood. Proposed surface modes, such as the Rossby model, suggest that type I X-ray bursts can excite oscillations in the NS ocean (Chambers and Watts, 2020). A temperature gradient forms at different heights on the star's surface, and the star's rotation modulates this gradient to produce XBOs (Cumming and Bildsten, 2000; Watts, 2012; Mahmoodifar and Strohmayer, 2016). Nonetheless, these models only partially explain the observed XBO phenomena, necessitating further study into their physical processes and model interpretations.

Detecting XBO signals requires high-energy X-ray telescopes with high timing resolution, large effective areas for substantial photon accumulation, and minimal dead-time effects. Previous searches for XBO signals have utilized data from *RXTE* (Strohmayer, 1999; 2001; Bilous and Watts, 2019) and NICER (Mahmoodifar et al., 2018; Li et al., 2022). Observations have shown that oscillation signals in most bursts exhibit an upward frequency drift and generally occur during the burst's tail. In some burst samples, oscillation signals have such high amplitudes that the accretion pulsar's oscillating frequency diverges from the pulsar's rotation frequency by a few hertz (e.g., Chakrabarty et al., 2003).

Up until now, 349 galactic NS LMXBs have been found and the number is increasing (Avakyan et al., 2023). However, less than 10% of these sources have had their spin frequency and burst oscillation measured. Detecting burst oscillations from sources with unknown spin frequencies, or from newly discovered sources, will expand the sample of accreting pulsars (Patruno et al., 2017). This will allow for a more credible study of the spin frequency distribution, and for searching coherent X-ray pulsation during outbursts. Additionally, among these unknown sources, there may be neutron stars spinning faster than 716 Hz, which would impose stronger constraints on the equation of state of compact stellar objects.

In't Zand et al. (2019) carried out a comprehensive searching and spectral analysis of type I X-ray bursts from Galactic NSs observed by Swift BAT/XRT. They identified 28 X-ray bursts for which BAT event data were available. In this paper, we search the Swift/BAT archives for triggered events of LMXBs from 2005 to April 2024 and perform timing analysis to search burst oscillation. We introduce the observations and data analysis methods in Sect. 2. We provide the results of the type I X-ray burst oscillation in Sect. 3. In Sect. 4, we discuss and summarize the results.

2 Observations and data analysis

The Swift/BAT triggering system is designed to identify gamma-ray bursts (GRBs) and other fast transients in high energy from various sources, including black holes, NSs, and magnetars. In this study, we found 50 non-GRB events from the GCN Notice Archive. These events are from 37 distinct sources, with 22 triggers related to NS LMXBs exhibiting X-ray burst oscillations or coherent pulsations, and the remaining samples involving NS LMXBs without known spin frequency. The absolute timing accuracy, 0.1 m of the recorded event files allows us to perform timing analysys. The Swift/BAT data were processed using the batgrbproduct command, and 1-s binned light curves were extracted in the 13–20 keV energy band. Subsequently, the batbinevt command was employed to transform the event data for each X-ray burst into a mask-weighted (background-subtracted) light curve in the 13–20 keV band. The burst peak flux and duration were determined by analyzing these light curves, with the duration, t_{90}, defined as the time interval during which the cumulative photon count increases from 5% to 95% of the total count (Kouveliotou et al., 1993). The light curves of all 50 bursts are displayed in Figure1.

Type I X-ray burst sources were categorized based on the presence or absence of previously detected XBOs or coherent pulsations. For the sources without known spin frequency, our analysis of bursts is explained as follows.

Initially, we applied FFT to the event files from each burst, segmenting the analysis into 4-s intervals with a step size of 0.5 s. For each window, statistically independent FFT was recorded between 10 and 2000 Hz with a step of 0.25 Hz. The light curve of duration T is evenly divided into N channels, where $N = 2^m$, and m is an integer. The time series, x_k, represents the number of photons in the kth channel, where k ranges from 0 to $N-1$. Following Leahy et al. (1983), we computed the Leahy-normalized power spectrum P_j for each segment,

$$P_j = \frac{2}{N_{\rm tot}}\left[\left(\sum_{k=1}^{N} x_k \cos 2\pi\nu_j t_k\right)^2 + \left(\sum_{k=1}^{N} x_k \sin 2\pi\nu_j t_k\right)^2\right], \quad (1)$$

where $N_{\rm tot}$ is the total number of photons. We then obtain the frequency of the oscillation signal according to the power spectrum.

Oscillation signal confirmation is applied using Z_n^2 statistic. We employ the Z_n^2 statistic on the 13–20 keV event data to confirm the presence of oscillation signals. This method is more computationally intensive than FFT but offers higher frequency precision. The Z_n^2 statistic is defined as follows (Buccheri et al., 1983):

$$Z_n^2 = \frac{2}{N_{tot}}\sum_{k=1}^{n}\left[\left(\sum_{j=1}^{N_{\rm tot}} \cos k\phi_j\right)^2 + \left(\sum_{j=1}^{N_{\rm tot}} \sin k\phi_j\right)^2\right], \quad (2)$$

where n is the harmonic number. Since the first harmonic provides the strongest signal strength and contains most of the dynamic information, we adopt $n = 1$. And ϕ_j is the photon phase defined as

$$\phi_j = 2\pi\int_{t_0}^{t_j} \nu(t)\,dt, \quad (3)$$

where t_0 is the reference time, t_j is the arrival time of the photon relative to t_0, and $\nu(t)$ represents a constant frequency model. When $\nu(t)$ does not change with time, $\phi_j = 2\pi\nu t_j$. The maximum value of Z_1^2 on the dynamic power spectrum and its corresponding frequency were identified.

For sources with previously identified XBOs or coherent pulsations, a dynamic power spectrum was generated by applying the Z_1^2 statistic around the known oscillation frequency (±2 Hz), with analysis intervals set to 4 s and a 0.125-s step size.

We evaluated the confidence level for all burst oscillation signals. The total number of trials is $N = N_t \times N_\nu$, with N_t representing the number of time bins and N_ν representing the number of frequency bins. According to Roy et al. (2021), the single-trial chance probability is given by the survival function $e^{-Z_{\rm n}^2/2}$, where $Z_{\rm n}^2$ is the maximized Z_1^2 or P_m. The confidence level is determined as$X\sigma$ $(X = \sqrt{2}erf^{-1}(1-x))$. For the Z_1^2 statistics, we assessed the

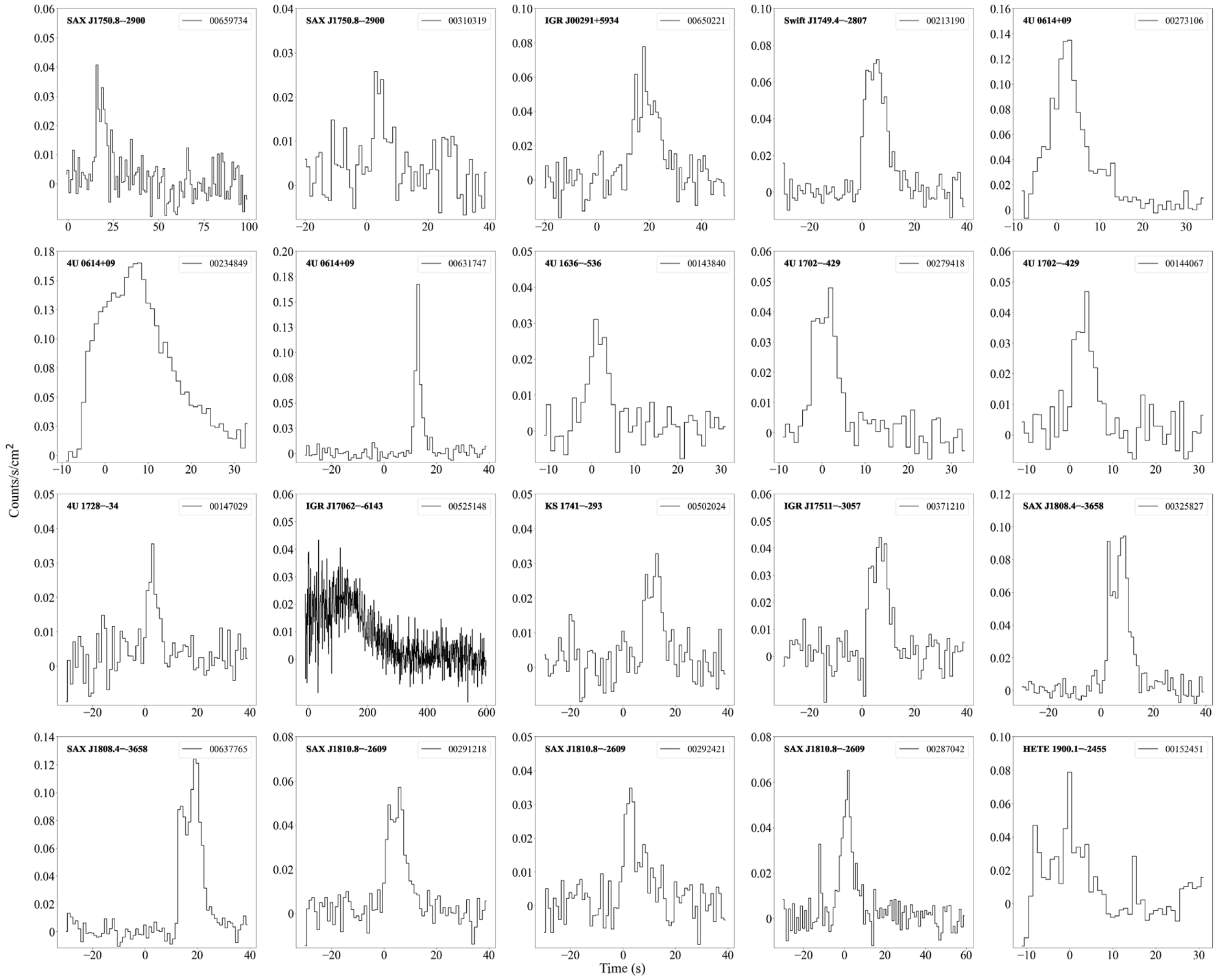

FIGURE 1
(Continued).

probability *Prob* that the signal measured in *N* trials was solely produced by noise (Ootes et al., 2017).

In addition to the oscillation frequency, the power spectrum contains information about the pulse amplitude. For the Leahy-normalized power spectrum, the root mean square (RMS) amplitude is defined as follows,

$$A_{\mathrm{rms}} = \sqrt{\frac{Z_n^2}{N_\gamma}\left(\frac{N_\gamma}{N_\gamma - B}\right)}, \tag{4}$$

where N_γ and B represent the total and the background photon counts, respectively.

3 Results

Based on Equations 1–4, we carried out the XBO searching. The results of the two categories of burst sources are summarized in Tables 1, 2. Definitions of burst parameters follow those provided by in't Zand et al. (2019).

3.1 Individual sources with detected XBO or coherent pulsation

For sources with previously detected XBOs or coherent pulsations, we analyzed the bursts to determine the maximum Z_1^2 values and their confidence levels. Most bursts did not exhibit significant signals near the known frequencies, with confidence levels below 3σ. Here, we only provide the details for several LMXBs.

HETE 1900.1−2455. HETE 1900.1−2455 is an X-ray source discovered by the High Energy Transient Detector-2 (HETE-2 Vanderspek et al., 2005). Kaaret et al. (2006) reported an orbital period of 83.3 min for this system, with the companion star likely being a Roche lobe-filling brown dwarf. Additionally, the distance to the source estimated from X-ray bursts is between 4.3 and 4.7 kpc (Suzuki et al., 2007; Galloway et al., 2008). Watts et al. (2009) identified an oscillation signal at a frequency of 377 Hz from HETE J1900.1−2455 using *RXTE* and *Swift* data. We extended this study to include two bursts observed by *Swift*/BAT, focusing on the

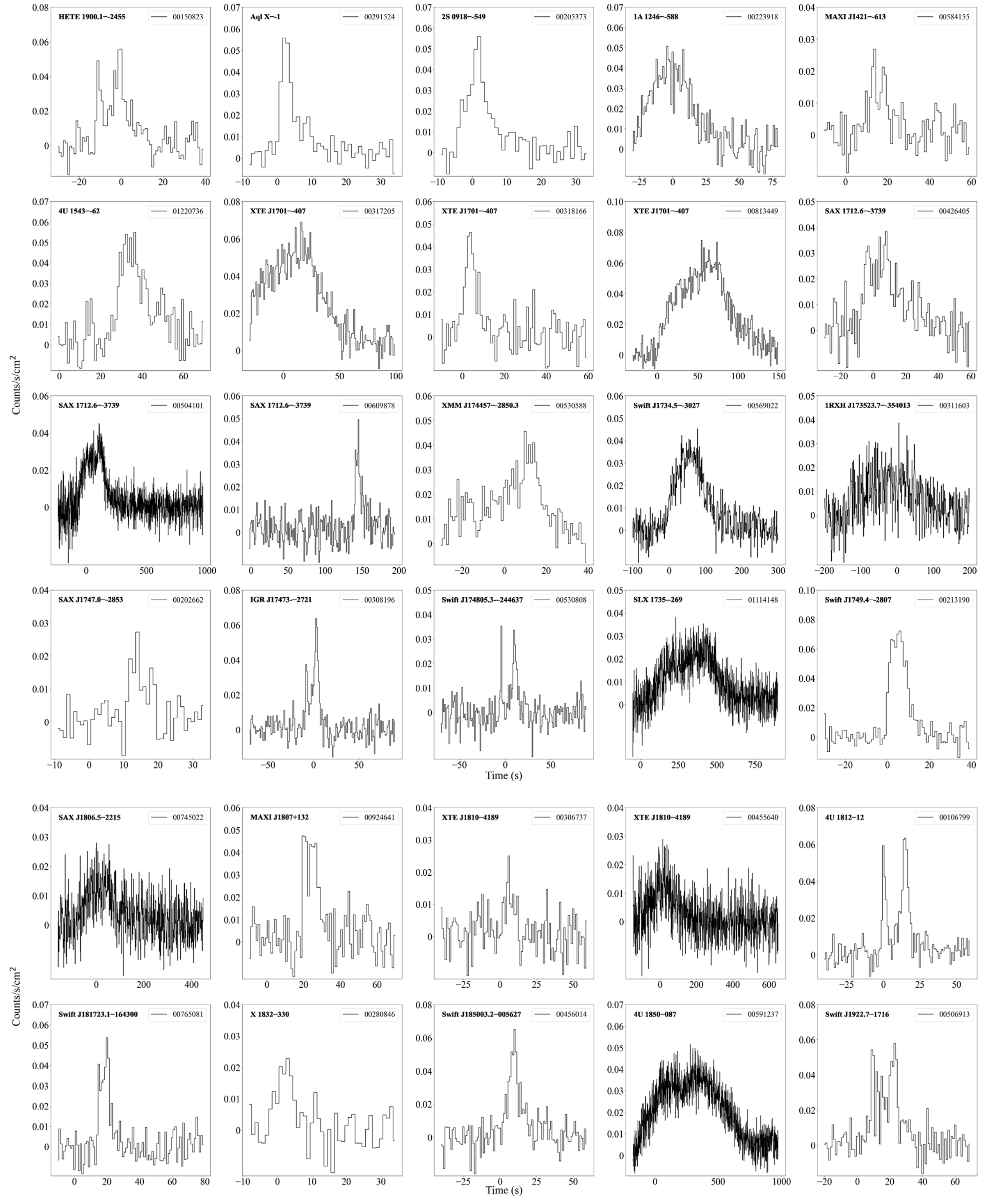

FIGURE 1
(Continued). BAT light curves of all 50 X-ray bursts. In each panel, the start time is the trigger of the X-ray burst from in't Zand et al. (2019) and https://gcn.gsfc.nasa.gov/swift_grbs.html. The source name and the trigger number are shown in each panel.,

frequency range of 375–379 Hz. The maximum Z_1^2 values recorded were 14.02 and 21.51 near 376.5 Hz. The oscillation signal from the burst on 17 August 2005, was significant at the 1.6σ level.

4U 1702−429. The X-ray burster 4U 1702−429 (also known as Ara X−1) was discovered in 1976 by the Eighth Orbiting Solar Observatory (OSO-8) and later classified as an atoll

TABLE 1 The source of XBO has been detected.

Object	Trigger number	Observation date (UTC)	Peak count rate (c $s^{-1}cm^{-2}$)	t_{90}(s)	ν(Hz)	Max of Z_1^2	1 − prob (%)	σ	Reference[b]
SAX J1750.8−2900	00,659,734	2015-10-16 01:25:59	0.04	28.0	600	14.84			Galloway et al. (2008)
	00,310,319	2008-04-27 18:35:45	0.03	29.3		11.37			
IGR J00291 + 5934	00,650,221	2015-07-25 02:12:05	0.08	15.5	598.89	20.98		0.8	Sanna et al. (2017)
Swift J1749.4−2807	00,213,190	2006-06-02 23:54:34	0.07	13.0	518	14.28			
4U 0614 + 09	00,273,106	2007-03-30 08:53:21	0.13	19.3	415	13.80			Strohmayer et al. (2008)
	00,234,849	2006-10-21 09:02:00	0.16	26.0		40.37	99.99	4.4	
	00,631,747	2015-02-19 16:42:24	0.17	5.0		10.81			
4U 1636−536	00,143,840	2005-07-02 09:01:17	0.03	9.0	581	11.94			Strohmayer et al. (1998)
4U 1702−429	00,279,418	2007-05-16 21:00:25	0.05	10.0	329	15.23			Strohmayer and Markwardt (2002)
	00,144,067	2005-07-03 20:29:23	0.05	11.3		23.56	92.6	1.7	
4U 1728−34	00,147,029	2005-07-21 11:14:30	0.04	23.8	363	11.54			Markwardt et al. (1999)
IGR J17062−6143	00,525,148	2012-06-25 22:42:32	0.04	299	163	21.28		< 1	Bult et al. (2021)
KS 1741−293	00,502,024	2011-09-01 12:07:22	0.03	14.0	589	11.55			Strohmayer et al. (1997a)
IGR J17511−3057	00,371,210	2009-09-30 18:31:57	0.04	9.3	245	11.37			Altamirano et al. (2010)
SAX J1808.4−3658	00,325,827	2008-09-24 20:14:24	0.09	11.0	401	17.92			Chakrabarty et al. (2003)
	00,637,765	2015-04-11 19:36:25	0.12	12.5		14.36			
SAX J1810.8−2609	00,291,218	2007-09-16 15:54:17	0.06	12.0	532	13.15			Bilous et al. (2018)
	00,292,421	2007-09-27 15:09:44	0.03	12.0		13.69			
	00,287,042	2007-08-05 11:27:26	0.07	20.5		16.13			
HETE 1900.1−2455	00,152,451	2005-08-28 15:09:37	0.08	2.0	376.25	14.03			Watts et al. (2009)

(Continued on the following page)

TABLE 1 (*Continued*) The source of XBO has been detected.

Object	Trigger number	Observation date (UTC)	Peak count rate (c $s^{-1}cm^{-2}$)	t_{90}(s)	ν(Hz)	Max of Z_1^2	1 – prob (%)	σ	Reference[b]
	00,150,823	2005-08-17 12:19:58	0.06	19.3		21.51	90.59	1.6	
Aql X−1	00,291,524	2007-09-19 07:56:35	0.06	14.3	549	10.10			Zhang et al. (1998)

Note—Observation Date is the start time of trigger.

source using EXOSAT data. Galloway et al. (2008) estimated the distance to be 5.46 ± 0.19 kpc using photospheric radius expansion bursts. The NS has a radius of 12.4 ± 0.4 km and a mass of $1.4 - 1.5M_{\odot}$ (Varun et al., 2024). Markwardt et al. (1999) identified the burst oscillation signal at 329 Hz from *RXTE* data. Our analysis of two bursts from 4U 1702–429 observed by *Swift*/BAT focused on the 327–331 Hz frequency range. We determined the maximum Z_1^2 values around 328.75–329.25 Hz to be 15.23 and 23.56, with the burst in July 2005 exhibiting a significance level of 1.7σ.

4U 0614 + 09. 4U 0614 + 09 is an X-ray burster and persistent low-mass X-ray binary (LMXB) located in the direction of the anti-galactic center at a distance of approximately 3.2 kpc (Kuulkers et al., 2010). Strohmayer et al. (2008) detected an XBO from 4U 0614 + 09 at 414.75 Hz in the tail of one of two bursts. This was the first XBO found using *Swift*/BAT, suggesting a spin frequency of ≈415 Hz. Chen et al. (2022) reported a bright thermonuclear X-ray burst observed by GECAM on 24 January 2021, and found a burst oscillation of 413 Hz consistent with Strohmayer et al. (2008). We searched three bursts from 4U 0614 + 09 observed by Swift/BAT in the 413–417 Hz frequency range. The maximum Z_1^2 values were 13.80, 40.37 (99.99879 % ≈ 4.4 σ), and 10.81. The XBO of the second burst is consistent with earlier findings by Strohmayer et al. (2008).

IGR J17062–6143. IGR J17062–6143 is an accreting millisecond X-ray pulsar with a spin frequency of 163.65 Hz (Strohmayer and Keek, 2017). We found no significant oscillation signal near 163 Hz, with the maximum Z_1^2 value near 163 Hz being 21.28.

3.2 Sources without previously detected XBOs

We perform FFT timing analysis for sources without known spin frequency by selecting photon arrival times within the 13–20 keV energy band to identify potential burst oscillation signals. The FFT powers for 11 LMXBs are shown below.

2S 0918–549. Juett and Chakrabarty (2003) identified 2S 0918–549 as an ultra-compact X-ray binary (UCXB) with an orbital period of 17.4 min. This source exhibited a high neon-to-oxygen abundance ratio, suggesting a CO or ONe white dwarf companion star. in't Zand et al. (2005) proposed the companion to be a helium white dwarf. Zhong and Wang (2011) reported a type I X-ray burst in 2006 with an oscillation signal candidate at a frequency of 774.06 Hz. Applying the Z_1^2 statistic in the 772–776 Hz, we obtained a maximum P_m of 23.64, corresponding to a single-trial chance probability of $7.36 \times 10^{-6} \approx 2.2\sigma$.

MAXI J1421–613. MAXI J1421–613 is a soft transient X-ray burster discovered by the MAXI Nova Alert system on 9 January 2014, (Nobukawa et al., 2023). For the type I X-ray burst observed by Swift in 2014, the frequency of the suspected oscillation signal after FFT processing was 474.39 Hz. The maximum P_m was 31.47, with a single-trial chance probability of $\times$ $1.4710^{-7} \approx 3.5\sigma$. The Z_1^2 statistical test, applied within the 472–476 Hz frequency range, identified a peak value of 29.71.

XTE J1701–407. XTE J1701–407 is a transient X-ray source discovered by *RXTE* on 8 June 2008 (Markwardt et al., 2008). Linares et al. (2009) placed an upper limit on the distance to the source at 6.1 kpc based on the maximum luminosity reached by the burst. Analysis of three bursts observed by *Swift* revealed potential oscillation signal frequencies of 546.57, 838.71, and 645.19 Hz after FFT processing. The corresponding maximum P_m values were 33.36, 24.40, and 30.11, with significance levels of 3.2σ, 2.5σ, and 2.6σ, respectively.

XMM J174457–2850.3. XMM J174457–2850.3 is a transient X-ray source near the Galactic center (Degenaar et al., 2014). For the type I X-ray burst observed by *Swift*/BAT in 2012, the frequency of the potential oscillation signal after FFT processing was 757.70 Hz. The maximum P_m value was 25.51, with a significance level of 3.6σ.

Swift J1734.5–3027. Swift J1734.5–3027 is a hard X-ray transient discovered by *Swift* during its September 2013 outburst (Bozzo et al., 2015). For its burst in 2013, the potential oscillation signal was 264.80 Hz. The maximum P_m value obtained by FFT was 34.00, with a significance level of 3.1σ.

IGR J17473–2721. The X-ray transient source IGR J17473–2721 was discovered in an April 2005 burst by the International Gamma-ray Astrophysics Laboratory (INTEGRAL) in the Galactic Centre region (Altamirano et al., 2008). For the type I X-ray burst observed by *Swift* in 2008, FFT analysis identified a potential oscillation signal at 352.29 Hz. The maximum P_m value obtained was 31.99, with a significance level of 3.2σ. The potential burst oscillation signal was detected during the burst's tail phase.

TABLE 2 Sources without previously detected XBOs.

Object	Trigger number	Observation date (UTC)	Peak count rate (c $s^{-1}cm^{-2}$)	t_{90}(s)	ν(Hz)	Max of P_m	Chance probability	σ
2S 0918−549	00,205,373	2006-04-15 03:38:09	0.06	15.0	774.06	23.64	7.36×10^{-6}	2.2
1A 1246−588	00,223,918	2006-08-11 02:59:56	0.05	54.8	607.60	30.05	2.98×10^{-7}	2.8
MAXI J1421−613	00,584,155	2014-01-18 08:39:20	0.03	14.8	474.39	31.47	1.47×10^{-7}	3.5
4U 1543−62	01,220,736	2024-04-08 15:13:54	0.05	27.0	611.88	18.05	7.49×10^{-5}	< 1
XTE J1701−407	00,317,205	2008-07-17 13:30:00	0.07	72.3	546.57	33.36	5.70×10^{-8}	3.2
	00,318,166	2008-07-27 22:31:20	0.05	12.8	838.71	24.40	5.03×10^{-6}	2.5
	00,813,449	2018-03-09 18:20:35	0.07	102.5	645.19	30.11	2.90×10^{-7}	2.6
SAX 1712.6−3739	00,426,405	2010-07-01 14:55:41	0.04	34.8	491.67	26.53	1.73×10^{-6}	2.4
	00,504,101	2011-09-26 20:11:29	0.05	234	863.40	28.81	5.55×10^{-7}	2.0
	00,609,878	2014-08-18 17:10:04	0.05	29.8	727.93	27.39	1.13×10^{-6}	2.6
XMM J174457−2850.3	00,530,588	2012-08-11 04:43:54	0.05	4.3	757.70	25.21	3.60×10^{-6}	3.6
Swift J1734.5−3027	00,569,022	2013-09-01 09:13:17	0.05	137.3	264.80	34.00	4.14×10^{-8}	3.1
1RXH J173523.7−354013	00,311,603	2008-05-14 10:32:37	0.04	217.8	905.90	30.26	2.69×10^{-7}	2.4
SAX J1747.0−2853	00,202,662	2006-03-25 00:53:03	0.03	14.8	334.78	23.84	2.27×10^{-6}	2.3
IGR J17473−2721	00,308,196	2008-03-31 09:03:33	0.06	14.8	352.29	31.99	1.13×10^{-7}	3.5
Swift J174805.3−−244637	00,530,808	2012-08-13 09:13:34	0.04	20.8	163.54	32.38	9.31×10^{-8}	3.5
SLX 1735-269	01,114,148	2022-07-02 01:53:06	0.04	407.5	177.26	31.41	1.51×10^{-7}	2.3
Swift J1749.4−2807	00,213,190	2006-06-02 23:54:34	0.07	13.0	651.03	25.05	3.63×10^{-6}	2.6
SAX J1806.5−2215	00,745,022	2017-04-01 19:00:53	0.03	197.5	384.98	27.85	8.96×10^{-7}	1.9
MAXI J1807+132	00,924,641	2019-09-10 07:02:29	0.05	17.5	226.26	26.28	1.97×10^{-6}	2.6

(Continued on the following page)

TABLE 2 (*Continued*) Sources without previously detected XBOs.

Object	Trigger number	Observation date (UTC)	Peak count rate (c $s^{-1}cm^{-2}$)	t_{90}(s)	ν(Hz)	Max of P_m	Chance probability	σ
XTE J1810−4189	00,306,737	2008-03-18 22:32:52	0.02	9.0	332.07	21.34	2.32×10^{-5}	2.1
	00,455,640	2011-06-19 00:59:37	0.03	183.3	511.99	32.35	9.45×10^{-8}	2.8
4U 1812−12	00,106,799	2005-02-24 12:40:45	0.06	27.8	241.77	25.08	3.58×10^{-6}	2.2
Swift J181723.1−164300	00,765,081	2017-07-28 16:57:58	0.05	9.75	946.60	34.01	4.12×10^{-8}	4.0
X 1832−330	00,280,846	2007-05-30 07:44:15	0.02	8.8	44.75	30.36	2.56×10^{-7}	3.5
Swift J185003.2−005627	00,456,014	2011-06-25 00:06:08	0.07	16.0	204.58	24.56	4.64×10^{-6}	2.4
4U 1850−087	00,591,237	2014-03-10 21:05:00	0.05	616	382.11	26.03	2.23×10^{-6}	< 1
Swift J1922.7−1716	00,506,913	2011-11-03 14:12:13	0.06	22.0	204.58	24.56	4.63×10^{-6}	2.2

Note—Observation Date is the start time of trigger.

Swift J174805.3−−244637. Swift J174805.3−244637, a transient LMXB located within the Terzan 5 globular cluster, exhibited a type I X-ray burst in 2012. FFT analysis revealed an oscillation signal at 163.52 Hz. The Z_1^2 statistical test, applied within the 161–165 Hz range, produced a maximum P_m value of 32.38, corresponding to a significance level of 3.5σ.

SLX 1735−269. SLX 1735−269, identified as an ultra-compact X-ray binary candidate (Moutard et al., 2024), was discovered in 1985 during the Spacelab 2 mission as a persistent X-ray source in the energy range 3–30 keV (Skinner et al., 1987). FFT analysis of Swift/BAT data from 2022 revealed an oscillation signal at 177.26 Hz, with a maximum P_m value of 31.41.

MAXI J1807 + 132. MAXI J1807 + 132 is an X-ray transient discovered by the nova-search system of MAXI on 13 March 2017 (Negoro et al., 2017). Swift observed a type I X-ray burst from this source in 2015. FFT processing indicated a suspected oscillation signal at 226.26 Hz, with a maximum P_m value of 26.28 and a significance level of 2.6σ.

Swift J181723.1−164300. Barthelmy et al. (2017) reported that at 16:57:57 UT on 28 July 2017, Swift/BAT triggered and located the source Swift J181723.1−164300. Moreover, Swift/BAT detected a burst and certified the source as a new bursting NS low-mass X-ray binary. FFT analysis of the 2017 burst revealed an oscillation frequency of 946.60 Hz, with a peak P_m value of 34.01 and a significance level of 4.2 σ. A subsequent Z_1^2 test near the oscillation frequency found a maximum Z_1^2 value of 37.33.

X 1832−330. The source was discovered by the High Energy Astronomy Observatory-1 (HEAO-1) (Hertz and Wood, 1985), and is one of the brightest LMXBs in galactic globular clusters. Engel et al. (2012) proposed a candidate orbital period of 2.15 h for X 1832−330 based on a 6.5-h observation of the optical counterpart with the Gemini South telescope. Analysis of type I X-ray bursts recorded by Swift in 2007 revealed an oscillation signal at 775.76 Hz through FFT processing. The peak P_m value observed was 30.36, corresponding to a significance level of 3.5σ.

4 Discussion

This study provides an extensive analysis of Swift/BAT observations of NS LMXBs over nearly two decades, from 2005 to April 2024. Our dataset comprised 50 type I X-ray bursts, with 21 previously analyzed for burst oscillation signals and 29 newly found. The analysis focused on both sources with previously detected XBOs or coherent pulsations and sources without prior detections, applying FFT and Z_1^2 statistical techniques to identify potential oscillation signals.

For the bursts with known oscillation signals, our analysis confirmed previously reported results, such as the case of 4U 0614 + 09 in 2007 exhibited a significant oscillation signal (Strohmayer et al., 2008). However, most of the bursts showed Z_1^2 values between 10 and

20, indicating low confidence levels for the detected oscillation signals.

For sources without known spin frequencies, we employed FFT analysis to search for burst oscillation signals. The detected oscillation candidates spanned a wide frequency range from 40 to 950 Hz, with maximum P_m values varying between 28 and 34. Most of these signals had significance levels below 3σ. Exceptions included MAXI J1421–613, XTE J1701–407, XMM J174457–2850.3, Swift J1734.5–3027, IGR J17473–2721, Swift J174805.3–244637, Swift J181723.1–164300, and X 1832–330, all of which showed significance levels greater than 3σ. Of particular interest is the burst from Swift J181723.1–164300 observed in 2007, which exhibited a significance level exceeding 4σ at a frequency of 946 Hz. The oscillation signal in this burst was prominently observed during its initial rise and subsequent decay phases. If the burst oscillation frequency is confirmed in the future, this source hosts the highest spinning NS.

While theoretical models exist to explain X-ray burst oscillations (XBOs), they do not fully account for all observed phenomena. This highlights the necessity for continued observational efforts, enhanced theoretical models, and comprehensive analyses. Recent advancements in observational technology and analytical methodologies have considerably improved our capability to detect and analyze XBOs.

Future research will benefit from combining data from multiple observatories and utilizing advanced statistical methods to enhance the sensitivity and reliability of burst oscillation detection. Considering the low occurrence rate of burst oscillations, observing more bursts will help increase the number of burst oscillation detection. The anticipated contributions from next-generation telescopes, such as eXTP, THESEUS, ATHENA (Zhang et al., 2019; Amati et al., 2018; Barret et al., 2018), are expected to significantly enhance our observational capabilities. These telescopes, equipped with instruments featuring large effective collecting areas, wide fields of view, and high timing accuracy in the soft X-ray band, will allow for more precise measurements of neutron star properties. These advantages will enable more precise measurements of NS properties, thereby providing tighter constraints on the equation of state of dense matter. Such efforts are providing unprecedented opportunities to study XBOs with greater precision and are essential for refining theoretical models of XBOs and advancing our understanding of these complex phenomena.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Q-XL: Writing–original draft, Writing–review and editing. ZL: Writing–original draft, Writing–review and editing. Y-YP: Writing–original draft, Writing–review and editing. MF: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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