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DOI
10.3847/1538-4365/ab2fe1

Publication date
2019

Document Version
Final published version

Published in

Citation for published version (APA):

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A Uniform Search for Thermonuclear Burst Oscillations in the RXTE Legacy Data Set

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Received 2018 December 31; revised 2019 June 4; accepted 2019 June 4; published 2019 November 15

Abstract

We describe a blind uniform search for thermonuclear burst oscillations (TBOs) in the majority of Type I bursts observed by the Rossi X-ray Timing Explorer (RXTE) (2118 bursts from 57 neutron stars). We examined 2–2002 Hz power spectra from the Fourier transform in sliding 0.5–2 s windows, using fine-binned light curves in the 2–60 keV energy range. The significance of the oscillation candidates was assessed by simulations which took into account light-curve variations, dead time, and the sliding time windows. Some of our sources exhibited multi-frequency variability at ≤ 15 Hz that cannot be readily removed with light-curve modeling and may have an astrophysical (non-TBO) nature. Overall, we found that the number and strength of potential candidates depends strongly on the parameters of the search. We found candidates from all previously known RXTE TBO sources, with pulsations that had been detected at similar frequencies in multiple independent time windows, and discovered TBOs from SAX J1810.8–2658. We could not confirm most previously reported tentative TBO detections or identify any obvious candidates just below the detection threshold at similar frequencies in multiple bursts. We computed fractional amplitudes of all TBO candidates and placed upper limits on non-detections. Finally, for a few sources we noted a small excess of candidates with powers comparable to fainter TBOs, but appearing in single independent time windows at random frequencies. At least some of these candidates may be noise spikes that appear interesting due to selection effects. The potential presence of such candidates calls for extra caution if claiming single-window TBO detections.

Key words: X-rays: bursts

Supporting material: machine-readable tables

1. Introduction

Thermonuclear burst oscillations (TBOs) are fast (typically with a frequency of a few hundred Hz), relatively faint (fractional amplitude (FA) of a few percent) oscillations of photon count rate, detected in about 20% of known Type I X-ray bursts. The phenomenon of TBOs is attributed to the development of bright patches during thermonuclear explosions on the surface of accreting neutron stars. Several theories of patch formation have been proposed: flame spreading from the ignition point of the bursts (e.g., Strohmayer et al. 1997b), cooling wakes (Mahmoodifar & Strohmayer 2016), convective patterns (Garcia et al. 2019), or large-scale (magneto)hydrodynamical oscillations in the burning material, induced by the spreading flame (e.g., Heyl 2004). However, none of these can explain all of the observed TBO properties, motivating the development of better physical models for the ignition and progression of thermonuclear reactions on the neutron star surface (see the review by Watts 2012).

From the observational side, it is important to establish as complete a picture of TBOs as possible. Finding TBOs and constraining their properties is not always straightforward; although oscillations are highly coherent, their frequencies can drift (or jump) by a few Hz during the typical few-second duration of the TBO, with oscillations sometimes disappearing and reappearing throughout the burst (Muno et al. 2002a, 2002b). The standard TBO search method relies on a Fourier transform (or calculation of $Z^2$-statistics) in a series of closely overlapping windows covering the burst duration (e.g., Strohmayer et al. 1998). Blind searches assume a constant frequency within a single time window, since searching for frequency derivatives adds an extra dimension to parameter space and is thus computationally expensive.

Estimates of signal significance are traditionally done analytically, based on simple photon-counting statistics (Groth 1975; van der Klis 1989). At the same time, it has been recognized that the distribution of noise powers in real spectra is more complicated, being influenced by the burst envelope and dead time of the detector (van der Klis 1989; Zhang et al. 1995). Using overlapping time windows and custom data filters complicates calculations of the number of independent trials, and thus estimates of TBO candidate significance. Some previous studies addressed these issues by discarding low frequencies affected by variation of the photon count rate due to the burst envelope (e.g., Ootes et al. 2017), directly measuring the dead-time-affected average noise power (e.g., Thompson et al. 2005), using a conservative number of trials (e.g., Bhattacharyya 2007), or estimating candidate significance with the simulation of data for a small number of bursts (e.g., Kaaret et al. 2007).

Searching for TBOs requires a sensitive instrument, operating in hard (1–30 keV) X-rays and capable of providing μs time resolution. So far, the majority of TBO studies have been performed using the large set of observations from the Rossi X-ray Timing Explorer (RXTE; Jahoda et al. 2006), although other telescopes such as Swift (Strohmayer et al. 2008) and AstroSat (Verdhan Chauhan et al. 2017) have also been used to search for TBOs. The relatively quiet period that followed the termination of RXTE’s mission in 2011 December ended with the recent launch of NICER (Arzoumanian et al. 2014) in 2017, and ongoing studies for the next generation of instruments,

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1 http://www.sron.nl/~jeanz/bursterlist.html; see also Galloway et al. (2008) and Watts (2012), and references therein.
Burst oscillations are very coherent pulsations which typically last for several seconds. During this time the oscillation frequency may jump or drift by several Hz. The search for TBOs is therefore usually conducted in separate, but often heavily overlapping, time windows of about 0.25–5 s. Within each window, the photon arrival times are binned into sub-ms bins, then the fast Fourier transform (FFT) is taken from the number of photons versus time and the obtained power spectrum (PS) is examined for outliers. An example of such a spectrum is shown in Figure 1. An alternative to an FFT PS is to use $Z^2$ statistics (Buccheri et al. 1983), which do not require binning of photon arrival times, and can be computed on a finer grid of frequencies (including variable frequency). $Z^2$ statistics are more computationally expensive than FFTs, so they are usually used to search for TBOs from sources with known oscillations in a narrow range of frequencies (e.g., Watts et al. 2005).

2. Significance Estimate of the Power Spectrum for Idealized Light Curves

Once the PS has been computed, potential oscillation candidates are identified as harmonics exceeding a certain threshold. Two questions immediately emerge: (a) for a given candidate, what is the probability of obtaining this power purely due to noise fluctuations, and (b) given the recorded power, what is the distribution of true signal power? The answers to both questions were given in the work of Groth (1975). Below, we repeat the author’s derivations in a somewhat modified form, using a different (nowadays, standard) normalization for the power spectrum.

In Groth (1975) the data time series is assumed to be composed of signal and noise:

$$N_m(t) = N_s(t) + N_n(t),$$

where $N$ is the number of photons in a given time bin and the subscripts correspond to measurement (m), signal (s), and noise (n). The coefficients of the Fourier transform of $N(t)$, $R$ for real and $I$ for imaginary, are the sum of the corresponding coefficients for signal and noise:

$$R_n(\nu) = R_s(\nu) + R_n(\nu),$$

$$I_n(\nu) = I_s(\nu) + I_n(\nu).$$

If $N_n$ has a Poisson distribution, then both $R_n$ and $I_n$ have normal distributions. For the so-called Leahy-normalized $P_n$ (Leahy et al. 1983):

$$P_n = \frac{2}{N_n} (R_n^2 + I_n^2),$$

normal distributions are standard, with mean of 0 and variance of 1. In this case $P_n$ will have a $\chi^2$ distribution with two degrees of freedom.

Assuming that the signal is deterministic, Groth derived an analytical expression for the joint probability distribution of the measured power $P_m$ and the signal of power $P_s$:

$$P_k(P_m, P_s) = \frac{1}{2} \left( \frac{P_m}{P_s} \right)^{(k-1)/2} \exp \left[ -\frac{P_m + P_s}{2} \right]$$

$$\times I_{k-1}(\sqrt{P_m P_s}),$$

where in this equation $I$ is a modified Bessel function of the first kind and $k$ is the number of PS samples summed. Here,
both $P_m$ and $P_s$ are Leahy-normalized and the whole derivation is valid if the total number of noise photons in the time window, $\sum N_n$, is larger than approximately 10.

Equation (4) can be used to estimate the probability distribution of $P_s$ as a function of the measured power $P_m$, $p_k(P_m|P_s)$, or alternatively the probability distribution of measured power $P_m$ as a function of the signal power $P_s$, $p_k(P_s|P_m)$. Figure 2 shows an example of the 2D probability density $p_k(P_m, P_s)$ for $k = 1$ and $k = 4$, together with the median and [0.159, 0.841] percentiles for $p_k(P_m|P_s)$ and $p_k(P_s|P_m)$.

Table 1 gives expressions for the median, mean and standard deviation of 1D distributions $p_k(P_m|P_m)$ and $p_k(P_m|P_s)$. The mean and standard deviation of $p_k(P_m|P_m)$ were given in Groth (1975) and are exact. The rest of the moments are useful approximations, obtained using numerically computed values for $1 \leq k \leq 20$ and both $P_m$ and $P_s$ smaller than 200. For $p_k(P_s|P_s)$, the approximations are valid when $P_m \geq 2(k + \sqrt{k})$. For these $P_m$ the absolute values of discrepancies between the approximation and the numerically computed moments are $\lesssim 0.2k$, $\lesssim 0.02k$, and $\lesssim 0.03k$, for the median, mean, and standard deviation, respectively. For $p_k(P_m|P_s)$, the median value deviates from $P_s + 2k - 1$ by $\lesssim 0.1k$ for $P_s > k$.

For $P_s = 0$, Equation (4) expresses the probability of obtaining $P_m$ without any signal, due to noise alone. This is used to estimate the significance of a potential signal detection. For $k = 1$, Equation (4) reduces to

$$p_1(P_m, 0) = \frac{1}{2} \exp \left[ -\frac{P_m}{2} \right],$$

which is the probability density function (pdf) for the $\chi^2$ distribution with two degrees of freedom. It can be also shown that for $k \geq 1$ the pdf is the $\chi^2$ distribution with $2k$ degrees of freedom.

<table>
<thead>
<tr>
<th>$P_m$ given $P_s$</th>
<th>$P_s$ given $P_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_s + 2k - 1$</td>
<td>$P_m - 2k + 3$</td>
</tr>
<tr>
<td>$P_s + 2k$</td>
<td>$P_m - 2k + 4$</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>$2\sqrt{n} + k$</td>
</tr>
<tr>
<td></td>
<td>$2\sqrt{n} - k + 2$</td>
</tr>
</tbody>
</table>

Note. The moments for $p_k(P_s|P_m)$ and median for $p_k(P_m|P_s)$ are approximations that are not valid for $P_n \lesssim 2k + 3\sqrt{n}$.

### 2.2. Fractional Amplitudes

Besides oscillation frequency, power spectra contain information about the amplitude of pulsations. For example, for a Leahy-normalized PS, the rms FA is defined as:

$$A = \left( \frac{P_s}{\sum N_n} \right)^{1/2}. \quad (6)$$

Let us show that for the simplest case of a purely sinusoidal wave on a constant-rate background, described by a measured photon count of $N_m = \text{Poisson}(C) + B \sin(2\pi n t)$, the FA calculated from Equation (6) is, on average, equal to $B/(C\sqrt{2})$. In this specific case the noise count rate is described by a Poisson process with a mean rate of $C$, and the signal is $N_s = B \sin(2\pi n t)$. The Leahy-normalized power spectrum of the signal is, by definition,

$$P_s = \frac{2}{\sum N_n} (R^2 + I^2). \quad (7)$$

Here, the average total number of noise photons is equal to its average rate times the number of time bins: $\sum N_n = CN_n$. Since $\sum N_n \approx 0$, $\sum N_n \approx \sum N_n = CN_n$. For a sine wave with amplitude $B$, scipy DFT\(^3\) yields a PS harmonic with an

---

\(^3\) https://docs.scipy.org/doc/numpy-1.13.0/reference/routines.fft.html
amplitude of $R^2 + I^2 = B^2 N_{\text{bin}}^2 / 4$. Thus, the Leahey-normalized $P_s = B^2 N_{\text{bin}}^2 / (4C)$ and $A = B / (C \sqrt{2})$.

In the limit of very small noise, $A$ approaches $A = 1 / \sqrt{2} \approx 70\%$. However, formal calculation of FAs may result in arbitrarily large $A$. If there is no signal present, $B = 0$, $P_s = 0$, and $P_m$ is distributed as $\chi^2$ with $2n$ degrees of freedom. The formally estimated $P_s$, given observed $P_m$, regardless of its actual probability, yields a median value of $P_s = P_m - 2k + 3$ (Table 1). For sufficiently large $P_m$, $P_s$ can be such that $A > 1$.

The rms FA is not a uniformly accepted way of describing oscillation amplitude. Some authors quote a full FA ($2B/C$) or a half FA ($B/C$).

For the actual burst observations, the noise level has a contribution from background unrelated to the observed low-mass X-ray binary (both astrophysical and instrumental), and the persistent emission from the source itself. The FAs are usually calculated for photons in the burst only:

$$A = \left( \frac{P}{N_m} \right)^{1/2} \frac{N_m}{N_m - N_{\text{bkg}}}$$

with $N_{\text{bkg}}$ being an estimate of the number of background photons collected during the burst interval.

While analyzing FAs one should bear in mind that there may be additional complications biasing the obtained values: the persistent emission may increase during the burst (Worpel et al. 2013, 2015) and there may be pulsed background, unrelated to TBOs, such as accretion-powered pulsations (APPs) or a pulsed reflection component from the accretion disk.

2.3. Complications and Caveats

The standard approach described above provides a simple and relatively fast method for searching for TBOs. However, there exist some complications and caveats.

(a) The burst count rate may vary significantly within the typical time window (e.g., during the burst rise). This results in excess power at low frequencies, and biases estimates of $P_s$ and its significance.

(b) Because of dead time (time during which the detector is busy processing the current event and cannot record the next one), noise statistics deviate from $\chi^2$. The influence of dead time is larger at higher count rates.

(c) Searching for TBOs in overlapping windows complicates the assessment of the number of independent trials, and thus the significance of $P_s$.

(d) Abrupt variations of the burst count rate cause covariance between harmonics in the PS spectra. This may create the illusion of rapid drift or splitting of the TBO frequency.

In the following sections we will address caveats (a)-(c), complementing the traditional approach with more realistic noise modeling. The influence of rapid count variation on the recorded TBO frequency will be explored in a subsequent work (A. V. Bilous & A. L. Watts 2019, in preparation).

3. RXTE Data Set

The observations were performed in 1996–2011 with the proportional counter array (PCA; Jahoda et al. 1996) on board the RXTE telescope. The PCA consists of five identical co-aligned proportional counter units (PCUs), each with a $r = 1^\circ$ circular field of view. The number of active PCUs varied between observing sessions and over the course of RXTE’s mission two PCUs went out of order permanently. The PCA is sensitive to photons in the energy range between 2 and 60 keV. Photon counts are processed independently by up to six event analyzers (EAs). Two EAs record data in the standard modes, namely Standard-1 ($t_{\text{res}} = 0.125$ s, one energy channel) and Standard-2 ($t_{\text{res}} = 16$ s, 128 energy channels). The rest of the EAs can be configured in a variety of modes, representing the trade-off between time and spectral resolution due to finite data transfer capacities while streaming the data from the satellite to Earth.

Incoming photons can be recorded in two data modes: either with all photon arrival times recorded separately (“Science Event” mode) or with arrival times binned in small time bins (“Science Array” mode). Typically, Science Event files have good spectral resolution, but suffer from data losses at high count rates. Those Science Array files that have a bin size suitable for oscillation analysis usually have little information about photon energies, but are less prone to data losses. Often, the data were recorded in both Scientific Event and Scientific Array modes and sometimes different time resolutions and energy cuts were available for a single observation.

Burst selection was based on the information available in the 2015 pre-release version of the MINBAR database, which contains the times of arrival, source associations, and other properties of Type I bursts observed with different satellites. We selected all bursts observed with RXTE, excluding bursts which (a) did not have high-$t_{\text{res}}$ ($t_{\text{res}} < 1$ ms) data during the burst and either immediately before or after the burst, (b) did not pass the extended good time interval (GTI) criterion, (c) were missing spacecraft housekeeping data, or (d) had variable bin size in Scientific Array mode. The final sample contained 2118 bursts from 57 sources. In this work we use the MINBAR catalogue burst entry number as a unique burst identifier.

For this paper we did not include burst catcher data, which can be also used for TBO searches (Zhang et al. 1998; Kaaret et al. 2002). This omission was not crucial as there were no bursts that were missing high-time-resolution data on the burst rise, or throughout the burst, that would have been covered by the relevant burst catcher mode (the one with time resolution of 500 $\mu$s or less). Nevertheless, several bursts with severe data gaps may benefit from the use of burst catcher data (e.g., burst #2266 from Aql X-1, see also Zhang et al. 1998).

For each of the 2118 bursts, we downloaded the data for the observations covering the MINBAR burst arrival time. We made a reference LC, using the Standard-1 data re-binned to 0.5 s and searched for a LC peak within ±1 minute of the MINBAR burst arrival time. The peak time $t_{\text{peak}}$ served as the absolute reference point within each burst. LCs were visually inspected and the baseline window was selected manually for each burst. For most of the bursts the baseline window lay within ($t_{\text{peak}} - 30$, $t_{\text{peak}} + 30$), but often it was placed in the burst tail (if no pre-burst data were available) or was shorter because of observation duration constraints or the presence of other bursts nearby. The on-burst window, ($t_{\text{peak}} - d_{\text{rise}}$, $t_{\text{peak}} + d_{\text{decay}}$), was confined to the region where photon count exceeded the baseline mean plus two of its standard deviations. The on-burst window was manually adjusted for bursts with

6. We omitted two known RXTE superbursts (in’t Zand 2017).
7. legacy.gsfc.nasa.gov
peculiar shapes and faint bursts. Figure 3 shows an example of LCs, the baseline, and on-burst windows for two bursts from 4U 1728−34, recorded in different data modes. 

In the event that more than one high-resolution data mode was available for a single burst, we selected files with the largest number of photons per on-burst window, fewer gaps, or with finer time resolution. We did not discard any photons based on their energy, and merged together data files that covered parts of the energy band (e.g., SB_125us_18_23_1s and SB_250_us_14_35_2s). Sometimes files recorded in different data modes contained completely the same information; in this case the data mode was chosen arbitrarily. For uniformity, we converted Scientific Array files to the pseudo-Scientific Event format by recording the counts in each time bin as individual photons with time of arrival (TOA) equal to the bin start time.

Photon arrival times were converted from the mission elapsed time (MET) seconds to the UTC time system with the TIMEZERO value. This leads to timing accuracy\(^8\) of 100 μs, which is sufficient for searching for burst oscillations in small windows (up to 4 s) if one is not trying to phase-connect oscillations between different bursts. Since the noise modeling relies on the housekeeping data that provide information at regularly sampled time intervals in the MET, in this work we chose not to barycenter the data.

Figures 4–5 provide more detailed information about the burst sample. Two overview figures show burst times of arrival, source-by-source (Figure 4) and Standard-1 LCs (Figure 5). Table 2, available in its entirety in machine-readable form, lists entry # and burst arrival time from MINBAR, \(t_{peak}\) in MET, rise, half-peak and decay times, signal-to-noise ratio (S/N) of the burst peak, data mode, and notes for each burst. Notes indicate manual windows for faint bursts and bursts with peculiar shapes, presence of data gaps, partial GTI coverage, or incomplete burst coverage.

4. Noise Simulation and Data Analysis

In order to estimate the significance of oscillation candidates, for each burst we created a number of artificial oscillation-free bursts, which followed the properties of real data as closely as possible. The same search analysis was then conducted on real and simulated data.

Originally, we simulated the bursts by scrambling the intervals between photon arrival times in \(\sim0.1\) s windows. The size of the window was chosen to be much larger than the presumed TBO period, but smaller than the timescales of most large-scale LC variations. A similar technique was used by Fox et al. (2001); however the authors scrambled the LC bins, not the time intervals between individual photons.

Such scrambling preserves deviations from the \(\chi^2\) noise distribution, but destroys any oscillation signal. However, it appeared that this method failed to produce enough statistically independent realizations of noise for some of the count rates.

\(^8\) https://heasarc.gsfc.nasa.gov/docs/xte/abc/time.html
Table 2

Data and FA\textsubscript{up} for One of the Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Entry</th>
<th>MINBAR</th>
<th>TOA</th>
<th>(T_{\text{peak}}) (MET)</th>
<th>Rise (s)</th>
<th>Half-max (s)</th>
<th>Tail (s)</th>
<th>Peak S/N</th>
<th>Data Mode</th>
<th>Notes</th>
<th>Max (P_m)</th>
<th>(\nu)</th>
<th>(T_{\text{win}})</th>
<th>(0.5) (s)</th>
<th>(1.0) (s)</th>
<th>(2.0) (s)</th>
<th>(4.0) (s)</th>
<th>(\text{min FA}_{\text{up}}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HETE J1900.1-2455</td>
<td>3301</td>
<td>2005 Jul 21</td>
<td>23:00:32</td>
<td>364604449.9</td>
<td>14.5</td>
<td>30.5</td>
<td>413.5</td>
<td>1607.7</td>
<td>E\textsubscript{125us_64M_0_1s}</td>
<td>gaps, bad LC, freq cov</td>
<td>34.8</td>
<td>383.50</td>
<td>4.0</td>
<td>4.6</td>
<td>4.5</td>
<td>3.3</td>
<td>2.4</td>
<td>\text{--}</td>
</tr>
<tr>
<td></td>
<td>3362</td>
<td>2006 Mar 20</td>
<td>11:34:06</td>
<td>385472056.4</td>
<td>7.5</td>
<td>9.5</td>
<td>118.0</td>
<td>510.1</td>
<td>SB\textsubscript{125us_8_249_1s}</td>
<td></td>
<td>29.2</td>
<td>228.00</td>
<td>4.0</td>
<td>4.6</td>
<td>3.3</td>
<td>2.4</td>
<td>1.7</td>
<td>\text{--}</td>
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<tr>
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<td>2008 Feb 10</td>
<td>20:32:51</td>
<td>445293182.9</td>
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<td>0.5</td>
<td>7.2</td>
<td>5.2</td>
<td>3.8</td>
<td>2.7</td>
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<tr>
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<td>3818</td>
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<td>08:57:54</td>
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<td>5.5</td>
<td>76.0</td>
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<td>376.25</td>
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<td>2.5</td>
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<tr>
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<td>21:04:32</td>
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<td>E\textsubscript{125us_64M_0_1s}</td>
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<td>674.50</td>
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<td>3.8</td>
<td>2.7</td>
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<tr>
<td></td>
<td>3960</td>
<td>2010 Sep 20</td>
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<tr>
<td></td>
<td>8257</td>
<td>2011 Sep 29</td>
<td>23:43:46</td>
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<td>7.5</td>
<td>5.0</td>
<td>74.5</td>
<td>554.3</td>
<td>E\textsubscript{125us_64M_0_1s}</td>
<td></td>
<td>30.3</td>
<td>776.00</td>
<td>4.0</td>
<td>7.0</td>
<td>5.1</td>
<td>3.7</td>
<td>2.8</td>
<td>\text{--}</td>
</tr>
</tbody>
</table>

Note. Table 2 columns: (1) source name; (2) burst entry \# in MINBAR database; (3) burst TOA in MINBAR database (yyyy-mm-dd hh:mm:ss); (4) time of the best peak; (5) \(dt_{\text{rise}}\), the start of the rise window; (6) \(dt_{\text{halfpeak}}\), the time span between peak and peak on the trailing side; (7) \(dt_{\text{decay}}\), time span between the peak and burst decay; (8) peak S/N; (9) observing modes used for TBO search; (10) notes, including: manual on-burst windows, faint bursts, or bursts with peculiar shapes, presence of data gaps, partial GTI coverage, missing data for at the edges of on-burst window, covariance between Fourier harmonics, and local failures in LC modeling; (11) maximum measured power \(P_m\), low-frequency noise excluded; (12) frequency of maximum \(P_m\); (13) \(T_{\text{win}}\) of the maximum \(P_m\); (14) best upper limit on FA in four window sizes (14a–d). (This table is available in its entirety in machine-readable form.)
Figure 4. Times of arrival of 2118 bursts from the MINBAR catalogue, for which high-\( t_{\text{peak}} \) data were available. The sources are ordered by their coordinates (R.A. first). The dotted vertical line marks the end of the time cut for the sample of Galloway et al. (2008); however, not all of the sources before that date have been examined by Galloway et al. Some of the bursts are so close to each other that the markers overlap completely.
Statistical independence was assessed in the following way: we generated a sequence of 100 photons with constant rate and random arrival times, then reshuffled the time differences between them 1000 times, and computed the power spectra. For each harmonic, a Kolmogorov–Smirnov test was performed to test whether the 1000 realizations were consistent with being drawn from a $\chi^2$ distribution. For about 45% of cases the $p$-value was smaller than 0.05, indicating large deviations from $\chi^2$. Acceptable $p$-values were obtained only for a number of photons larger than about 10,000.

Thus, the scrambling method was abandoned. Instead, we performed random generation of photon TOAs using the approximated LC, with subsequent pruning according to known dead time.

### 4.1. LC Modeling and Simulation of Photon TOA

RXTE records four types of events: “Good Xenon” (GX) events (events that pass all of the discriminators and anticoincidence vetoes, the desired astrophysical signal) and three types considered to be mostly due to instrumental background: “Coincidence” events, “Very Large” (VL) events, or “Propane” events (Jahoda et al. 2006). GX events are recorded per PCU; for the rest the sum over all active PCUs is saved. All four types of events were simulated, since all of them cause dead time, influencing the number of recorded GX events.

In order to simulate the arrival times we used the information from the Standard-1 files, which contain events from the whole energy band, binned in 0.125 s bins. Sometimes, this binning is not sufficient for characterizing the burst rise properly. We
therefore re-normalized the Standard-1 LC\textsuperscript{9} with the weights obtained from the higher-$t_{\text{res}}$ data, binned to one eighth of the Standard-1 resolution (15.625 ms), keeping the total number of Standard-1 events in 0.125 s bins unchanged. If the higher-$t_{\text{res}}$ data were unavailable due to data gaps, uniform weights were applied (Figure 6, top). LC count rates were adjusted for the dead time (see more details in Section 4.2).

We followed two different procedures for simulating GX events and the instrumental background. For the GX events we used a method which was more expensive computationally, but which resulted in better reproduction of the stochastic variation of the count rate.

The method was as follows. First, the dead-time-corrected LC was smoothed with a median filter with a typical length of 0.5 s and a linear spline fit was performed to obtain the estimate of the count rate $LC(t)$ in any arbitrary moment of time (Figure 6, top). The tolerance of spline fit and the size of the median filter window were adjusted on a per-source basis, so that the fit was maximally smooth, yet preserved, by eye, the short-timescale variations in the LC shape. However, for frequencies below $\sim$5 Hz it becomes complicated to distinguish between potential TBOs and non-TBO LC variation, so in this region spurious candidates may be present or the significance of TBO candidates may be underestimated (see the discussion in Section 5). Light curves for each individual PCU were obtained by multiplying the spline fit by the total number of Standard-1 photons recorded by a given PCU, divided by the sum from all PCUs.

Then, the arrival times of the GX events were simulated for each PCU separately using the acceptance–rejection method (von Neumann 1951). We used the standard Python random number generator based on the Mersene Twister algorithm (Matsumoto & Nishimura 1998) to generate $LC_{\text{max}} \times N_{\text{bins}}$ pairs of random variables $(L, T)$. Here, $LC_{\text{max}}$ is the maximum value of $LC(t)$ and $N_{\text{bins}}$ is the number of 0.125 s time bins in the on-burst window (Figure 6, middle). Both $L$ and $T$ were uniformly distributed within $[0, LC_{\text{max}}]$ and the on-burst window, respectively. Then, the pairs with $L < LC(T)$ were discarded. This way, a Poisson distribution of photon TOAs was created, with the instantaneous rate closely matching $LC(t)$, but devoid of any oscillations with periods smaller than the characteristic timescale of the features of the modeled burst envelopes.

For the Propane, Coincidence, and VL events we used a simpler procedure. The LC counts were divided by the number of PCUs, and for each time bin with local count rate $C$ we generated the following number of uniformly distributed TOAs:

$$ N = \text{floor}(C) + \text{Binom}[N = 1, p = \frac{\text{frac}(C)}{100}] $$

(9)

where floor denotes the floor function and Binom is a binomial random variable with number of trials $N$ and success probability $p$. This way the number of simulated photons is very close to the real data value and thus the simulation does not emulate the Poisson noise that is present in the data.

\textsuperscript{9} Namely, GX and Propane + Coincidence LCs. The VL event LC was not renormalized because its count rate is usually low and does not change much during the burst.

![Figure 6. Top: LCs of the high-$t_{\text{res}}$ data, binned with 15.625 ms time bins (white), together with the Standard-1 LC, scaled according to the fraction of dead time, and re-normalized to mimic the time resolution of the high-$t_{\text{res}}$ LC outside the data gaps. The orange line shows a spline fit to the scaled and renormalized Standard-1 LC, smoothed with a 0.5 s median filter. Middle: simulation of photon arrival time with the “acceptance–rejection” method. Only 1% of all simulated photons are plotted. Bottom: LC from the simulated photons before and after pruning by dead time and data gaps (green and purple, respectively).]

4.2. Dead Time Pruning

Simulated events were subsequently pruned to account for the detector’s dead time. Dead time calculation for \textit{RXTE} is rather complex and thus deserves a detailed examination. According to Jahoda et al. (2006), \textit{RXTE} PCUs process events independently and the dead time is caused by all events recorded by the PCU. Any event recorded belongs to one and
only to one of the four classes: GX, Coincidence, VL, or Propane events.

In general, there exist two types of dead time: paralyzable (cumulative), where events entering the detector during dead time themselves cause further dead time (even though they are not recorded), and non-paralyzable, where events entering detector during dead time are completely ignored. For RXTE, the actual dead time is a mixture of both types, depending also on event class and assigned energy. However, for most cases $t_d$ can be approximated as $10 \mu s$ non-paralyzable dead time (set by the analog-to-digital converter, ADC) for all classes except VL events. For these, the dead time can vary between 70 and $500 \mu s$ and depends on the instrumental setting, most of the time being approximately $170 \mu s$ (Jahoda et al. 2006).

Zhang et al. (1995) developed an analytic formula for the Leahy-normalized noise PS in the presence of dead time. The mean value $\langle P_s \rangle$ is always less than 2 by some amount which depends on event rate, the type of dead time and its value, the LC bin size, $t_b$, and the FFT frequency. The analytic formula for paralyzable dead time has a much simpler form than that for non-paralyzable dead time.

Jahoda et al. (2006) gives an example showing how to calculate the dead time modifications to pure noise for a count rate below $10^4$ cts PCU$^{-1}$ s$^{-1}$, applying the correction for the paralyzable dead time. Disregarding larger $t_d$ for the VL events:

$$\langle P_s \rangle = 2 - 4r_0t_d \left(1 - \frac{t_d}{2t_b}\right) - 2r_0t_d \frac{N - 1}{N} \left(\frac{t_d}{t_b}\right) \cos \left(\frac{\pi \nu}{\nu_{Nyq}}\right).$$

Here $n$ indicates noise (as in Section 2), $r_0$ is the output rate of all events (all four types combined), $t_d$ is the dead time, $t_b$ is the bin size, $\nu$ is the FFT frequency, $N$ is the number of frequencies in the PS, and $\nu_{Nyq}$ is the Nyquist frequency. The authors also give an ad hoc correction for the larger $t_d$ of VL events, which is much smaller than that introduced by Equation (10) for our $t_d$ and $t_b$ and VL event rates.

Although technically RXTE dead time is a complex mixture of both paralyzable and non-paralyzable dead times, with the non-paralyzable dead time of the ADC contributing the most at energies below $\approx 20$ keV, for the typical RXTE rates and $t_d$ size used in this work, the formulas for paralyzable and non-paralyzable dead times yield essentially the same corrections. Thus, the more simple Equation (10) can be used to estimate the dead time influence on the average noise power.

For our simulations, we treated dead time as purely non-paralyzable. Note that we do not model the absence of dead time caused by events which triggered only VX or alpha chains. According to Jahoda et al. (2006), not doing this leads to a small overestimation of dead time fraction by $\delta t_d/t_b \approx 0.0014$, an amount nearly constant throughout the mission.

Figure 7 shows the average signal power in burst #2980 from Aql X-1 (in which no TBOs were detected). Photons from only one PCU were selected, and a bin size of 1/8192 s $\approx 122 \mu s$ was used, together with an FFT window of 1 s. For this choice of binning and the rates of GX and other events the noise power has only a minuscule dependence on FFT frequency. We have summed all harmonics above 10 Hz (below 10 Hz the PS may be affected by red noise) and compared the noise power to the mean obtained from 1000 simulations, which appeared to match the data well (Figure 7).

Attempting to apply Equation (10) yielded interesting results: if the rate was taken to be the rate of all events (since all of them cause dead time) as stated in Jahoda et al. (2006), the dead time correction was considerably and consistently larger than that required to match both data and simulations. However the correction did match observations well if only the GX events were taken into account. It appears that, for the given range of event rates and the bin/dead time windows, the operations of dead time pruning and selection of GX events are commutative, meaning that GX photons have the same noise power distribution as if they were not affected by the dead time from all other event types. As simulations have shown, this does not hold true for larger count rates (Figure 8); however, such large count rates do not occur in our burst sample.

To summarize, dead time was accounted for in the following way: initially LCs for all four event types were renormalized using the fraction of dead time calculated with the observed rates. Then the TOAs of the four types of events were simulated separately and combined to form a “mixed-bag” event sequence which mimicked the real data. Then events which arrived within $10 \mu s$ after the previous non-VL event and variable $t_d$ after the VL event were removed. Those events were assumed not to cause dead time themselves, so the dead time was by definition non-paralyzable. This procedure was

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10 http://heasarc.nasa.gov/docs/xte/recipes/pca_deadtime.html

11 The RXTE Cook Book states that “the VL event rate is not affected by dead time”; this was not reproduced in the simulations.
The analytic formula is Equation (10) for the total event rate (solid line) and the GX event rate (dashed line). Top: only half of the simulated events were considered to be GX events; the rest were deleted before computing the PS. Bottom: all simulated events were considered to be GX events.

Figure 8. Simulation of Leaky-normalized $P_{\text{fl}}$ for the 1 s Poisson event sequence with $t_{\text{j}} = 10 \, \mu s$, $t_{\text{f}} = 122 \, \mu s$, and various event rates. $P_{\text{fl}}$ is averaged for 50 simulations and 4094 FFT harmonics (omitting the two lowest harmonics). Diamonds and circles show paralyzable and non-paralyzable dead time, respectively. The analytic formula is Equation (10) for the total event rate (solid line) and the GX event rate (dashed line). Top: only half of the simulated events were considered to be GX events; the rest were deleted before computing the PS. Bottom: all simulated events were considered to be GX events.

DFigure 8. Simulation of Leaky-normalized $P_{\text{fl}}$ for the 1 s Poisson event sequence with $t_{\text{j}} = 10 \, \mu s$, $t_{\text{f}} = 122 \, \mu s$, and various event rates. $P_{\text{fl}}$ is averaged for 50 simulations and 4094 FFT harmonics (omitting the two lowest harmonics). Diamonds and circles show paralyzable and non-paralyzable dead time, respectively. The analytic formula is Equation (10) for the total event rate (solid line) and the GX event rate (dashed line). Top: only half of the simulated events were considered to be GX events; the rest were deleted before computing the PS. Bottom: all simulated events were considered to be GX events.

4.3. Accounting for Data Gaps and Occasional Limited Energy Range

Data gaps are losses of data due to saturated telemetry occurring for bursts with high count rate. They typically last from a fraction of a second to several seconds and are not reflected in the GTI table of the data files. To search for data gaps, we selected all time intervals with gaps between two successive photons being larger than 0.02 s. In order to exclude “natural” gaps in bursts with intrinsically low count rate, we calculated the estimated number of photons inside the potential gap and selected only those gaps where this number was larger than two. The number of photons inside the gap was estimated from the mean photon count rate of Standard-1 data and adjusted for the overall difference in the energy band (multiplied by a sum of all Standard-1 counts divided by the sum of all high-$t_{\text{res}}$ counts for the time bins where the latter was larger than 0). All simulated photons inside the data gaps were deleted.

Finally, the photon sequences were adjusted for the difference in energy band between high-$t_{\text{res}}$ data and the Standard-1 data (e.g., Figure 3). For each 0.125 s bin, the ratio between Standard-1 LC and the high-$t_{\text{res}}$ data LC was estimated and the simulated data were pruned by deleting the appropriate fraction of photons at random (Figure 6, bottom).

Both real and simulated photon sequences were binned with sub-ms time bins. For observations in GX data mode, the bin size was $t_{\text{j}} = 2^{-14} \approx 61 \, \mu s$, yielding about eight phase bins in pulse profile at the highest frequency searched. For all other modes, the bin size was two times larger, corresponding to typical $t_{\text{res}} = 122 \, \mu s$. Although 24 bursts had larger $t_{\text{res}}$, they were still binned with the smaller bin size. Among those bursts, five had $t_{\text{res}} = 2^{-11} \approx 488 \, \mu s$, all of them from GRS 1747–312. For these bursts any candidates at frequencies above the Nyquist frequency of 1024 Hz were discarded.

4.4. Fourier Transform

Fourier transforms were taken for the binned sequences in series of 0.5, 1, 2, and 4 s sliding windows, each window starting 0.5 s later than the previous one. The FFT coefficients $R$ and $I$ were recorded for harmonics between 2 and 2002 Hz. The lower limit was set by the smallest non-zero harmonic for the PS in 0.5 s windows. The upper limit reflects the largest possible NS spin frequency allowed by current reasonable models of the neutron star equation of state (Haensel et al. 2009).

In what follows, we will operate with FFT coefficients in a $(\nu, t, T_{\text{win}})$ cell, with $\nu$ being the FFT frequency, $t$ referring to the center of the time window, and $T_{\text{win}}$ being the given window size. The 500 simulation runs were used to make distributions of $R_{\text{fl}}$ and $I_{\text{fl}}$ in each cell. The $I_{\text{fl}}$ and $R_{\text{fl}}$ had, most of the time, Gaussian distributions with the mean influenced by the baseline variation and the standard deviation influenced by the dead time (Figure 9). We used the mean and unbiased estimate of standard deviation of the first $N_{\text{smp}} = 400$ simulation runs to normalize $R_{\text{fl}}$ and $I_{\text{fl}}$ of the real data. Power spectra from the remaining 100 runs, normalized as the same way as the real data, were used to estimate detection significance.

The mean and standard deviation $R_{\text{fl}}$ and $I_{\text{fl}}$ used for re-normalizing are inevitably influenced by the limited number of simulation runs. For pure Poisson noise, the means are random variables with normal distribution, having $\mu = 0$ and $\sigma^2 = 1/N_{\text{smp}} = 0.05$. Since $N_{\text{smp}} \gg 1$, the standard deviation is also distributed normally, with $\mu = 1$ and $\sigma^2 = 2/(N_{\text{smp}} - 1)$. Since the dead time influence has negligible dependence on Fourier frequency, for the normalization we averaged the standard deviation by $800 \times T_{\text{win}}$ harmonics in order to reduce the stochastic error caused by the limited number of simulations. Simulation of $10^5$ pairs of standard normal random variables showed that re-normalizing them by the mean and standard deviation drawn from the appropriate Gaussian distributions causes about 10% of detections above the threshold set by $p_{\chi^2} = 2 \times 10^{-7}$ (adopted as the detection criterion, see Section 4.5) to be false positives. Another 10% of un-normalized candidates had power below the threshold after normalization. It is hard to estimate the rate of false negatives or false positives for the real-data candidates, since it depends on the intrinsic distribution of TBO powers. However, we checked the normalization values for all candidates that were deemed interesting, for example occurring in an unusual place in the burst or being detected from a burst without previously reported TBOs.

In rare cases of a gap occupying most of the FFT window, $I_{\text{fl}}$ and $R_{\text{fl}}$ become covariant at the lowest Fourier frequencies. In such cases the subsequent analysis is not applicable, so we discarded candidates from those cells. The covariance threshold was estimated as follows: we simulated 500 independent normal random variables and the distribution of covariance was calculated. The threshold was set as five times the standard deviation of the covariances.

We also checked for the covariance along the frequency axis.

Such covariance stems from abrupt changes in photon count...
within the window, caused by data gaps or even on the burst rise if the latter is sharp. For each time window and simulation we calculated the autocorrelation function (ACF) from the renormalized simulated $P_n(\nu)$. ACFs from all 500 simulations were added together and the 50% half-width of the peak was measured, with the baseline levels subtracted from the peak. We discarded the PS in the given time window (regardless of frequency) if the 50% half-width of the ACF peak was larger than five harmonics. Such bursts were marked with the "freq cov" comment in the notes to Table 2.

Finally, we removed the cells covering regions where the simulated LC deviated substantially from the real data due to narrow gaps or spikes. Substantial deviation was defined as being larger than 10 standard deviations of the simulated photon count in given 0.125 s or 15.625 ms time bins. Such bursts were marked with the "bad LC" comment in the notes to Table 2.

4.5. Filtering Potential Oscillation Candidates and Computing FAs

In order to filter potential TBO candidates, we selected all cells with renormalized $P_m > P_{up}$, where $P_{up}$ corresponded to a $\chi^2$ probability of getting $2 \times 10^{-4}$ chance candidates per single spectrum:

$$p_{\chi^2}(P_{up}) = \frac{2 \times 10^{-4}}{2000 \times T_{win}}. \quad (11)$$

The choice of $p_{\chi^2}(P_{up})$ was arbitrary and motivated by the requirement to have a manageable number of candidates for the given data sample. For 0.5, 1, 2, and 4 s FFT windows $P_{up}$ was 30.85, 32.24, 33.62, and 35.01, respectively. $P_{up}$ was adopted as the upper limit in the event that no candidate detections were found.

Since the power values in adjacent cells are covariant both in time and (to a smaller extent) in frequency, the number of trials is not equal to the number of cells, $N_{cell}$, and the simple significance formula $p_{\chi^2}(P_{up}) \times N_{cell}$ is not readily applicable. To assess the significance of detections, we performed the same candidate search for the simulated data and compared the number of oscillation candidates from the real data with the distribution of the same values from the simulated data.

For each potential candidate we computed the FA using Equation (8) and the median value of $P_sP_m$ from Table 1, $P_s = P_m + 1$. The uncertainties in FAs were calculated by linear error propagation of the independent parameters in Equation (8) (Ootes et al. 2017). For the uncertainty on $P_s$, we took $[0.159, 0.841]$ percentiles of the $P_sP_m$ distribution. The uncertainty on the number of photons in the FFT window was taken to be Poissonian and the uncertainty in the background level was taken to be the standard deviation of count rates in the baseline window, computed in the overlapping windows of the length equal to the current FFT window.

A few potential uncertainties are not included in the given FA errors. First, we do not include the variation of background
within the burst from Worpel et al. (2015), since it is not available for all bursts in our sample. We also do not correct for the possibility of the TBO frequency falling between FFT harmonics. Simulation showed that with our choice of FFT windows and oversampling in time, the FA can be underestimated by as much as a factor of 0.68. However only in 9% of cases (assuming no prior knowledge of TBO frequency) is suppression of FAs stronger than 0.85.

Finally, we did not account for bias caused by the limited number of trials. Simulated distribution of \( P_\text{rem} \) for the normalized data had a mean and median consistent with the ones from Table 1. The standard deviation of \( P_\text{rem} \) for the normalized data was larger by a small value of \( \lesssim 0.4\% \).

4.6. Organizing the Results

Table 2 gives a general picture of the maximum power recorded for each individual burst, as well as the smallest FA of potential detection (defined by the threshold detection probability, Equation (11)). Besides renormalized power \( P_\text{rem} \), it lists its frequency and \( T_\text{win} \), as well as the smallest FA up for all four \( T_\text{win} \).

Table 3 contains basic properties for each source (number of bursts, total duration, median S/N of the burst peak, minimum and median upper limits on FAs in 1 s window at the burst peak), providing an overview of the amount and quality of observational material for each source as well as the extent of FA range that can be probed by our analysis. The properties of oscillation candidates are given per frequency group, with a group being defined as the candidates with \( |\Delta f| \leq 2 \text{ Hz} \) (matching the lowest frequency resolution). For each frequency group we list the number of bursts with TBO candidates in this frequency range and the number of bursts with candidates in one of three non-overlapping regions: “R,” defined as the region between rise and peak of the burst, “B” starting at the peak and spanning three times half-peak width (more or less corresponding to the traditional on-burst windows), and “T” covering the rest of the burst tail. For each frequency group we list also the average \( P_\text{m} \) of the candidates in each of the four Fourier windows. The remaining three columns give a handle on the number of spurious candidates in both real and simulated data, listing the total number of real-data non-TBO candidates (counting the ones from overlapping windows as independent and omitting low-frequency ones), the average number of candidates in the simulated data (averaged over 100 simulation runs), and the percentile of the real-data number with respect to a 100-run simulation sample, \( p \).

Table 4 gives more detailed information about each group of candidates (except for the low-frequency ones) for each individual burst, listing MINBAR burst entry, MINBAR TOA, frequency range, location of candidates within the burst (R, B, or T), number of independent time windows, and the maximum FA for each size of Fourier window.

Finally, for each group of candidates we provide reference plots, aggregating information about frequency, TOA, power, and FA of candidates, as well as upper limits on FAs. Figure 10 gives an example of such a plot, with separate panels for the burst LC and the frequency, FA, and power of the candidates. To conserve space, the rest of the reference plots are made more condensed, without legends and with individual panels merged together.

5. Results

5.1. Low-frequency Noise

The mean values of simulated Fourier coefficients, \( \langle R_n \rangle \) and \( \langle I_n \rangle \), give us a handle on how much the power spectrum is affected by the change of photon count rate during Fourier window. Figure 11 shows an example of the frequency-dependent distribution of the absolute values of Fourier coefficients for all \( \nu, t, T_\text{win} = 1 \text{ s} \) cells in the bursts from 4U 1702–429, omitting the cells with large frequency covariance or large discrepancy between the simulated and real LCs (see Section 4.4). At higher Fourier frequencies the spread of \( \langle R_n \rangle \) and \( \langle I_n \rangle \) is mostly determined by the finite number of simulation runs, whereas at the lower frequencies we record an excess of large coefficient values. For the majority of the sources this excess continues to at least 100 Hz. In rare cases frequencies as high as 1000 Hz can be still affected.

Renormalization of Fourier coefficients allowed us to remove most of the described power excess. However, we still record a relatively large number of strong candidates at frequencies below \( \sim 15 \text{ Hz} \). Some of these candidates can be associated with obvious flaws in LC modeling, where our spline failed to reproduce short peaks or drops in the LC (Figure 12, left, hereafter “type I” low-frequency candidates). Other low-frequency candidates cannot be immediately connected to the imperfect LC modeling (hereafter “type II” low-frequency candidates). Several sources (e.g., Cyg X-2, EXO 0748–76, EXO 1745–248) exhibited such unexplained bursts of low-frequency candidates spanning multiple harmonics and sometimes showing at distinctly separate frequencies (Figure 12, right). The origin of this type II low-frequency noise remains unclear: it could well be astrophysical, associated with either the bursting surface or the accretion disk (see for example van der Klis 2006).

Although mostly recorded from fast-spinning neutron stars, TBOs can occur at frequencies as low as 11 Hz (IGR J17480–2446, Cavecchi et al. 2011). So far, only one such slow TBO source is known and finding another one (or one spinning at even lower frequency) would be very interesting. In general, however, we found that PSs at the lowest frequencies of few Hz are difficult to interpret, since it is hard to distinguish between LC variation and oscillations here. An example of such a problematic spectrum is shown in Figure 13. Oscillations with a frequency of about 3 Hz are clearly visible in the LC. With the given choice of smoothing and spline-fitting parameters, LC modeling removes some of the count rate variation and changes the shape of the peak in the PS. More stringent LC models can reproduce the observed LC variations, removing the peak completely.

We have inspected visually all diagnostic plots featuring type II low-frequency candidates looking for signals resembling the 11 Hz TBOs from IGR J17480–2446: with detections in multiple independent time windows and multiple bursts, at frequencies larger than the lowest recorded frequency of 2 Hz and without candidates of comparable strength at the nearby, but distinctly separate frequencies. No such candidates were found.

5.2. Dead Time

In Section 4.2 we reviewed the methods of estimating the influence of the instrument’s dead time on the observed noise
**Table 3**

Overview of Bursts and TBO Candidates

<p>| Source       | N&lt;sub&gt;best&lt;/sub&gt; Total | Total Duration (s) | Median SN&lt;sub&gt;peak&lt;/sub&gt; | 6a 1 s FA&lt;sub&gt;up&lt;/sub&gt; | # of Noise Candidates | χ&lt;sup&gt;2&lt;/sup&gt; | Mean Simul | Mean Real Data | p | ν (Hz) | Any | R | B | T | 0.5 s | 1.0 s | 2.0 s | 4.0 s |
|--------------|------------------------|--------------------|--------------------------|------------------------|------------------------|-----------|------------|----------------|---|--------|------|---|---|---|------|------|------|------|------|
| 4U 0513-40   | 18                     | 896.5              | 135.3                    | 8 13                   | 1.43                   | 1.10      | 2           | 0.28           | 2.00–3.25 | 1738.75 | 1 0 0 | 1 | 1 | 1 | 39.3 | 52.0 | 56.6 | 51.9 |
| 4U 0614+09   | 1                      | 34.5               | 1406.4                   | 2 2                    | 0.06                   | 0.02      | 0           | 1.00           |            | 86.00 | 1 0 0 0 1 | 31.2 |
| EXO 0748-676 | 159                    | 15560.0            | 100.7                    | 5 14                   | 24.90                  | 22.05     | 39          | 0.01           | 2.00–14.50 | 133.75 | 1 0 0 | 1 | 1 | 1 | 36.1 | 36.7 | 38.5 | 42.9 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 333.75 | 1 0 0 0 1 | 36.7 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 339.00 | 1 0 0 0 1 | 36.7 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 361.00 | 1 0 0 0 1 | 38.5 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 390.00 | 1 0 0 0 1 | 35.3 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 399.50 | 1 0 0 0 1 | 34.4 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 414.00 | 1 0 0 0 1 | 37.1 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 470.00 | 1 0 0 0 0 | 31.8 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 539.00 | 1 0 0 0 1 | 40.6 |
| 551.50–552.50| 2 2                   | 0 0 0 0 0           |                          |                        |                        | 34.5      | 45.5        | 46.8           |            | 34.50 | 0 0 0 0 1 | 40.4 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 401.00 | 1 0 0 0 1 | 35.3 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 831.50 | 1 0 0 0 1 | 35.6 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 867.00 | 1 0 0 0 1 | 35.7 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 873.00–874.00 | 0 0 1 1 1 | 32.7 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 948.00 | 1 0 0 0 1 | 32.4 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 1005.00 | 1 0 0 0 0 | 35.6 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 1027.25 | 1 0 0 0 1 | 35.3 |
|              |                        |                    |                          |                        |                        |           |             |                |            | 1108.00 | 1 0 0 0 0 | 35.6 |
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| 2S 0918-549  | 4                      | 514.0              | 82.9                     | 4 10                   | 0.82                   | 0.72      | 1           | 0.51           | 2.00–7.00 | 1200.00 | 1 0 0 0 1 | 37.0 |
| 4U 1254-69   | 7                      | 116.5              | 47.9                     | 15 16                  | 0.19                   | 0.17      | 0           | 1.00           | 2.00–3.25 | 1450.00 | 1 0 0 0 1 | 35.9 |
| 4U 1323-62   | 40                     | 2814.5             | 53.5                     | 12 21                  | 4.50                   | 4.11      | 5           | 0.38           | 2.00–3.25 | 656.00 | 1 0 0 0 1 | 32.2 |</p>
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Note. Table 3 columns: (1) source name; (2) number of bursts suitable for TBO search; (3) total burst duration; (4) median S/N of the burst peak on the sample of all bursts from the given source; (5) upper limits on FA in 1 s Fourier windows on a burst peak, (a) minimum (b) median; (6) number of noise candidates above selected detection threshold (excluding low-frequency candidates and candidates in the known TBO frequency range), (6a) predicted by Equation (4), treating all time windows as independent, (6b) mean number per simulation run, averaged over 100 simulation runs, (6c) number of noise candidates from the real data; (7) percentile of the real-data number of noise candidates with respect to a 100-run simulation sample; (8) boundaries of the frequency groups (groups of candidates with frequency separation \( |\nu| \leq 2 \) Hz), with known TBO frequencies in bold and low-frequency groups in italic; (9) number of bursts with candidates in a given frequency group, in any region (9a) and in the Rise, Burst, or Tail regions (9b–9d); (10) average \( P_m \) of the candidates in each of the four Fourier windows sizes (10a–10d).
In order to investigate the dead time influence, we recorded the mean un-normalized simulated power at frequencies above 1 kHz. At these frequencies the bias caused by LC variation is small for all of our sources (Section 5.1). We found that the simulated noise power did not have any discernible dependence on the number of PCUs that were on, and varied between 1.5 and 2, depending on the total photon count rate recorded by the PCUs (obtained from Standard-1 data files). This count rate is always equal to or larger than the count rate derived from the high-\textit{f}_{\text{req}} data.

Figure 14 (left) provides the reference for average simulated noise power versus count rate per PCU in high-\textit{f}_{\text{req}} and Standard-1 files. For count rates larger than \(8 \times 10^3 \text{ cts s}^{-1} \text{PCU}^{-1}\), \(P_n\) is smaller than about 1.7, differing dramatically from the value of 2 prescribed by the ideal \(\chi^2\) noise model. Thus, neglecting dead time influence for bright bursts can lead to an underestimation of the potential signal significance by orders of magnitude. The average power is considerably smaller than 1.7 at the peaks of at least one burst from 4U 0614+09, 4U 1608−552, Aql X-1, HETE J1900.1−2455, and SAX J1808.4−3658.
Comparison of noise powers between real and simulated data is not straightforward because of the large intrinsic noise variance: for $P_n$ obeying $\chi^2$ distribution with two degrees of freedom, the standard deviation of noise powers is 2, the same as the mean value. Averaging all harmonics above 1 kHz reduces the standard deviation to $\approx 0.045$ for $T_{\text{win}} = 1$ s and allows us to pinpoint the influence of dead time. For simulated data, additional averaging by 100 simulation runs further reduces the standard deviation by a factor of 10. Figure 14 (right) shows the 2D distribution of such average noise powers in real and simulated data. For most values of simulated power, the noise powers for the real data appeared to be statistically slightly larger than the corresponding simulated power, most probably stemming from the simplifications we made during dead time pruning. The discrepancy can reach as much as 0.15 for $\langle P_n \rangle \approx 1.6$, but is not larger than 0.02 for the more common
\( \langle P_m \rangle \gtrsim 1.8 \). This leads to an overestimation of the real data candidate significance by a factor that can be as large as a few (for the largest count rates), but more commonly of about a few percent.

It is worth mentioning that dead time also biases the measured FAs of TBO candidates, since the fraction of dead time is different during the crests and troughs of the oscillation trains. Using non-normalized \( P_m \) in Equation (8) may bias FAs by as much as a factor of \( (1.5/2)^{0.5} \approx 0.87 \).

### 5.3. Overall Simulation Quality and Glimmer Candidates

In order to assess whether our simulations are adequately reproducing the data, we compared the distributions of normalized powers \( P_m \) for the real and simulated data sets. For each source and \( T_{\text{win}} \) we combined powers in two frequency regions: between 15 and 1000 Hz (thus excluding any low-frequency noise), and between 1000 and 2000 Hz (see Figure 15, left, for an example). The distributions for real data and the mean distribution of 100 simulation runs match reasonably well. Moreover the distribution of normalized \( P_m \) is well described by \( \chi^2 \) statistics, assuming a conservative number of trials (i.e., treating all time windows as independent, Figure 15, right). The same is true for the candidates from all four \( T_{\text{win}} \) combined—the estimates of the average number of candidates using Equation (5) and assuming all windows and harmonics to be independent are not dramatically different from the average number of candidates from the simulation runs (see also Table 3).

However, for some of the sources the match is not perfect. After normalizing the raw-data distribution by the corresponding mean and standard deviation of 100 simulated data distributions, one can see that there is a systematic discrepancy between the two for \( P_m \lesssim 20 \). The amount of discrepancy is usually larger for frequencies below 1000 Hz and varies considerably from source to source. It may stem from imperfect dead time or LC modeling, or any weak broadband astrophysical signal.

For some of the sources, we found a small excess of higher-power candidates (e.g., with \( P_m > 35 \) on Figure 15). This excess can be present in either of the two frequency groups and is equivalent to 5–10 standard deviations in a given power bin. The examination of the cumulative versions of the normalized power distributions for all \( T_{\text{win}} \) combined showed that for several sources, e.g., 4U 1608–522, EXO 0748–676, Cyg X-2, and others, the number of candidates above the detection threshold on the real data (excluding frequency ranges of known TBO) is larger than the corresponding number in \( \geq 99% \) of the simulation runs \( (p \leq 0.01, \text{see Table 3}) \). On the other hand, the prolific TBO source 4U 1636–536 yielded fewer real-data noise candidates than any of 100 simulations. The origin of this discrepancy is unclear.

Such marginally significant noise candidates (dubbed “glimmer candidates,” reflecting potential attractiveness) are detected in a single independent time window, at seemingly random, never-repeating frequencies\(^\text{12}\) and throughout all on-burst windows. Some of the candidates occur at lower frequencies in time windows with substantial count rate variation and their significance is very sensitive to LC modeling. Glimmer candidates can be present in the bursts with TBOs, sometimes even in the same time bins as TBOs.\(^\text{12}\) Except for two 1108 Hz candidates from EXO 0748–676; see Table 3.

![Figure 11](image.png)

**Figure 11.** Example of the frequency-dependent distribution of both Fourier coefficients \(|f|\) and \(|R|\). The distribution was computed in 1 s windows using the data from 4U 1702–429. For plotting purposes, the harmonics from 2 to 2000 Hz were grouped in 4 Hz bins. Color marks histogram values in a given 2D (frequency/coefficient value) bin. White corresponds to zero counts in a given bin, black to one or a few. The color becomes progressively lighter as the number of counts increases. The left and right panels highlight different parts of the distribution, below and above 100 Hz, respectively. For both panels, the top subplot shows the average coefficients from the simulated photon sequences. The middle subplot shows the data and the lower subplot shows the normalized data, with the mean value of the simulated coefficients subtracted. Simulations removed most of the low-frequency noise, but some of it is still present at very low frequencies.

Folded glimmer candidates produce sinusoidal profiles and some of them are stronger than weak TBOs (e.g., Figure 16).

It must be noted that whether the source has glimmer candidates depends on the detection threshold. For example SAX J1808.4–3658 has \( p = 0.22 \) at the standard detection threshold; however, the power of some of the noise candidates is much larger than any of the simulated powers. On the other hand, for MXB 1658–298 \( p \) drops from 0.06 to 0.01 if the threshold probability is multiplied by 3.7 (Appendix A.1.4).

One must be very careful in interpreting glimmer candidates. By definition, a source has glimmer candidates if the number of detections outside TBO frequencies and not immediately connected to low-frequency noise is larger than the number of candidates in 99% of simulation runs. This means that, assuming a sufficiently large number of bursts per source, 1% of all sources will have glimmer candidates purely due to chance. At our detection threshold, five sources, or 8.8% had \( p \leq 0.01 \), which is larger than the expected 1%, suggesting that at least some of the glimmer candidates may have an astrophysical origin. Some may for example be connected to type II low-frequency candidates that happen to occur at somewhat higher frequency and more than 2 Hz apart from other candidates, thus being placed in a separate frequency group by our grouping procedure.

### 5.4. TBOs from Known Oscillation Sources

Seventeen TBO sources were known prior to our analysis. These are sources with TBOs detected at similar frequencies, in
several independent time bins, several bursts, or at frequencies close to the frequency of APPs. All of these sources yielded candidates at frequencies close to those reported previously and all but one had more candidates than any of the simulation runs \((p = 0)\) in a purely blind search. We note that the TBO candidates from the accreting millisecond pulsar (MSP) HETE J1900.1−2455 would not have been significant in our blind search which neglected closeness to the known APP frequency for this source, since the TBOs come from one independent time window and have moderate power. For the other sources, sometimes we did not have any candidates (including sub-threshold; see Section 5.8 for our definition of sub-threshold candidates) where they have been reported previously. This may be explained by differences in data processing.

In general, we find that the measured power of TBO candidates depends strongly on the size of the Fourier window and its location. Because we searched in several windows of different length, we were able to give a more complete picture of the FAs, which may be important for bursts with more than one oscillation train, i.e., bursts with photospheric radius expansion (PRE), with a short train of TBOs in the rise and a longer train after the burst peak. We have compiled an extensive data set of FAs (Table 4) as well as upper limits for each of the four window lengths (Table 2), to support future studies of TBO physics (see Section 6).

For many of the TBO sources a considerable fraction of TBO candidates came from data regions with large influence from dead time (Figure 17). Low-frequency noise does not have much of an influence—only in a few cases were the absolute mean values of the simulated Fourier coefficients larger than \(6 \times 0.05\) (see Sections 4.4 and 5.1 and Figure 11). More information about each TBO source is given in Appendix A.1.

5.5. Tentative TBO Detections from the Literature

Eight sources in our sample had tentative TBO detections prior to our analysis (see Table 2 in Watts 2012). Here we summarize the results of our analysis of these sources; more detailed information about each of them is given in Appendix A.2.
No TBO candidates were detected in the only burst from 4U 0614+09, observed by RXTE. Previously, the 415 Hz oscillations were reported from one burst observed with Swift. The FA limits from the RXTE burst are more stringent than the detection reported from the Swift but, as we know from other sources, TBOs are not consistently detectable in all bursts from a given source.

The previously reported 529 Hz TBO candidate from 1A 1744−361 was also detected in our analysis; however, it was too faint to be significant given the number of trials. The presence of sub-threshold candidates tracing out a small frequency drift argues in favor of this candidate being a genuine TBO, but a new detection is needed to confirm this.
TBO candidates from 4U 1254–69 (95 Hz), XTE J1739–285 (1122 Hz), and SAX J1748.9–2021 (410 Hz), discovered in time windows with sizes similar to the range of $T_{\text{win}}$ used in this work, were in our analysis not significant enough to pass the detection threshold. The sources did not have any clusters of sub-threshold candidates close to the reported frequencies. TBOs from another two sources, MXB 1730–35 (306 Hz) and GS 1826–24 (611 Hz), were claimed based on stacked power spectra. None of our candidates for these sources was close to the frequencies reported in the previous papers.

XB 1916–053, with its pair of TBO candidates at frequencies 2 Hz apart, remained controversial in our analysis. In addition to these two, we detect four other strong candidates, all of them potentially due to type II low-frequency noise. None of the simulated data sets had as many candidates as the real data, whether or not one counted the 270 Hz candidates as a TBO. A more precise estimate of the significance of this signal should take into account frequency separation between the candidates; however, this is outside the scope of this work.

### 5.6. New TBO Discoveries

One more TBO source has been discovered, SAX J1810.8–2609, yielding strong ($P_m = 79$) 531 Hz oscillations in one independent time window (see Appendix A.3.4). The candidate power is so strong that it has small $p(\chi^2)$ probability assuming the most conservative number of trials (counting all harmonics and all time bins from the whole 57-source sample as independent). Full details of this discovery are reported in Bilous et al. (2018).

Besides that, we recorded an interesting pair of $\sim$600 Hz candidates from IGR J17473–2721 (see also Appendix A.3.3). These candidates were faint ($p > 0.5$), but came within 3 Hz from each other and framed the burst peak during a burst with PRE, showing typical features of TBOs from established TBO sources (e.g., SAX J1750.8–2900).

### 5.7. Other Sources

Out of the remaining 30 sources in our sample that had no published record of TBOs prior to our study, 23 were unremarkable, with the number of noise candidates reproduced well by simulations. Some of these sources also had low-frequency noise of type I or II. Seven more sources had a marginally significant number of candidates (albeit occurring at random frequencies), or stronger and more broadband low-frequency noise. More details can be found in Appendix A.3.

### 5.8. Sub-threshold Candidates

Even if an individual candidate has moderate power that is below our nominal threshold, a cluster of sub-threshold candidates in a relatively narrow frequency range may indicate the presence of TBOs. We performed a simple search for such a clustering of sub-threshold candidates by summing the powers of all candidates with

$$p_{\text{sh}}(\chi^2) < \frac{10^{-1}}{2000 \times T_{\text{win}}}.$$  

which corresponds to $P_m$ of 17.03, 18.42, 19.81, and 21.19 for $T_{\text{win}}$ of 0.5–2 s. The sums, $S(\nu)$, were additionally added in 2, 4, or 8 Hz frequency bins and normalized by burst duration. The stacks of $S(\nu)$ were then inspected visually for traces of power excess correlated in frequency.

Interestingly, for known TBO sources the bursts without TBO candidates did not necessarily yield sub-threshold candidates, with $S(\nu)$ in the TBO frequency range being similar to $S(\nu)$ at other frequencies (e.g., Figure 18, left). Nevertheless, some of the known TBO sources did have sub-threshold TBO candidates, with the most prominent example being IGR J17480–2445. Only two bursts from this source have candidates at 10–11 Hz in Table 3, but many more bursts have relatively large $S(\nu)$ (Figure 18, middle).

About half of sources in our sample exhibited low-frequency noise on $S(\nu)$ stacks, sometimes extending to $\sim$20 Hz. For Cyg X-2, this frequency region was particularly noisy with multiple sub-threshold candidates at random frequencies (Figure 18, right).

None of the sources showed any obvious clustering of candidates at frequencies different from the frequencies of known TBOs. This was something of a surprise: we had anticipated that there would be sub-threshold candidates emerging from such a large data set. It also must be noted that, similarly to most TBO searches, our analysis does not include the effects of any potential smearing due to intrinsic TBO frequency drift and Doppler shifts due to the motion of the Earth and the binary orbit, all of which would reduce detectability.

### 6. Summary

In this work, we conducted a large-scale blind search for TBOs for the majority of type-I X-ray bursts observed by RXTE. In comparison to previous work, our analysis encompassed more sources, and probed potential signals on a range of timescales and further into burst tails, treating all sources in a uniform fashion.

In order to estimate the significance of selected oscillation candidates, we developed a more realistic noise model by...
simulating photon sequences with variable count rate which mimicked the real light curves and was affected by dead time. Fourier spectra from simulated sequences were used to renormalize the corresponding Fourier spectra from the real data and thus to remove the low-frequency noise due to variable count rate, and to restore the dead-time-affected average power.

Our noise model showed that abrupt LC variations, for example during the burst rise or data gaps, can bias the noise statistics in a frequency-dependent manner at frequencies up to approximately 100 Hz or, in several cases, even up to 1 kHz (thus no longer being confined to low frequencies). LC modeling allowed us to remove most of this bias. However, in some cases we still detect strong candidates below 16 Hz. These low-frequency candidates did not immediately resemble known low-frequency TBOs from IGR J17480–2446: with detections in multiple independent time windows and multiple bursts, at frequencies larger than the lowest recorded frequency of 2 Hz, and without candidates of comparable strength at nearby, but distinctly separate, frequencies. Some of the detected low-frequency candidates are clearly generated by nearby, but distinctly separate, frequencies. Some of the detected low-frequency candidates were clearly generated by nearby, but distinctly separate, frequencies.

Several more sources yielded candidates not immediately connected to flaws in LC modeling (e.g., Cyg X-2, 4U 1729 –34, EXO 0748–676, EXO 1745–248, and others). Such candidates, dubbed “type II” low-frequency candidates, frequently appeared to be grouped in time and/or frequency, sometimes appearing at distinct frequencies simultaneously. It is possible that these type II low-frequency candidates may have an astrophysical origin: perhaps a non-TBO process on the burning surface, or varying emission due to the effect of the burst on the accretion flow (see for example Worpel et al. 2013, 2015). Generally, the signal at the lowest frequencies in our spectra (below approximately 5 Hz) is quite hard to interpret, since its strength depends substantially on how closely the model LC follows the real one.

The instrumental dead time had, somewhat surprisingly, a rather large influence on the power spectra statistics, with the average noise power dropping below 1.7 for the burst peaks of five sources, some of them with TBOs. Neglecting the influence of dead time can lead to underestimation of candidate TBO significance by as much as two orders of magnitude.

Overall, our noise models provide an important insight into the statistics of RXTE power spectra, but they do not give a perfect description of the data, most probably because of the set of assumptions regarding the dead time influence and what constitutes a “real” LC. Also, some bias is caused by the limited number of simulations run to derive the statistical properties of noise. From the computational point of view, it is much easier to estimate the average noise power using harmonics past $\lesssim$1 kHz, renormalize the power spectra, and use $\chi^2$ probability distribution with a conservative number of trials (treating all time windows as independent, regardless of overlap) to estimate the candidate significance. However, this approach would not work at lower Fourier frequencies during the burst rise or during data gaps.

We have also found that abrupt changes in the LC rate (sharp rise or a data gap) can lead to covariance between adjacent Fourier harmonics and can manifest as a fast change of TBO frequency. A quantitative investigation of this phenomenon will be presented in subsequent work. Overall, data gaps obliterate part of the signal and bias the FA evolution: using data with gaps should be avoided if at all possible. Future X-ray telescopes aiming to study this phenomenon should aim for high throughput.

For our study, we selected all candidates with renormalized $\chi^2$ probabilities less than $2 \times 10^{-4}$ per spectrum. This resulted in the power thresholds varying with time window size. Our choice of detection threshold was to some degree arbitrary, but was motivated by a wish to analyze a manageable number of candidates. The significance of these candidate detections was then estimated by comparing the number of candidates in the real data to a pool of an additional 100 of simulated spectra, renormalized in the same way as the real data.

Our candidates included all previously known TBOs. For one of the sources, the accreting MSP HETE J1900.1–2455, the detection in a single time window was not significant because of the large number of trials in our analysis. The study that reported this finding originally searched a narrower frequency range around the known pulsar frequency (Watts et al. 2009). We find that the power of candidates depends dramatically on the specific window sizes and degrees of overlap used.

Overall, we have compiled an extensive data set containing information on the frequency and FAs of all selected candidates, as well as upper limits on FAs derived from the threshold powers. We anticipate that this information will be a valuable resource for future studies of TBO properties, particularly when used in conjunction with the burst property

![Figure 17](https://example.com/figure17.png)
The conditions under which TBOs are excited and detectable are important factors in assessing the viability of physical models for the TBO mechanism (Watts 2012).

Eight sources in our data set had prior claims of TBOs where the claimed detections were either weak and came from one independent time window (or, in the case of XB 1916−053, two close but separated frequencies in a single burst or several stacked bursts. We were unable to confirm TBOs from any of those sources. Some of the previously claimed detections had smaller powers in our analysis (which can be sensitive to the choice of the time windows) and were not significant when compared to noise simulations. For 4U 0614+09 we had different bursts than those with potential TBOs (which came from a different telescope); the burst in the RXTE sample showed no TBO candidates. Other claimed detections were based on analysis of stacked spectra and yielded no candidates in our time windows.

One of the sources without previously reported TBOs, SAX J1810.8−269, yielded a strong, brief 531 Hz pulsation in one of the bursts. The signal was detected in one independent time window; however, its strength ($P_m > 70$) speaks in favor of it being a TBO (for a more in-depth significance analysis, see Bilous et al. 2018). The other sources did not provide any compelling TBO candidates, despite our removing most of the low-frequency noise and making better significance estimates for bright bursts. In addition, we found no groups of sub-threshold candidates, probing probabilities up to 100 higher than our adopted detection threshold. This was somewhat surprising: we had anticipated finding at least some clusters of sub-threshold candidates in such a large burst sample.

An interesting (albeit not formally significant in our analysis) pair of ~600 Hz TBO candidates was recorded from IGR J17473−2721. The candidates were rather faint, but came close in frequency (within 3 Hz) and framed the burst peak during a burst with PRE. More than half of the simulation runs had as many or more candidates (at arbitrary frequencies) with at least the same significance.

Another source with previously reported potential TBOs with similar characteristics, XB 1916−053 had much more significant candidates, with as few as 2% of the simulations runs having the candidates at least as strong as the strongest one on the real data. Overall, IGR J17473−2721 and XB 1916−053 would be interesting sources for subsequent follow-up.

Our estimate of candidate significance treated all frequencies as independent and did not include important TBO features such as frequency drift coupled with signal disappearance during PRE. In the case of weaker signals, it is currently unclear how small a gap in frequency should be for the signals to be attributed to a single TBO.

We found that some of the sources exhibited a marginally significant number of noise candidates, meaning that 99% or more simulation runs had a smaller number of candidates. These appeared at random frequencies both below and above 1 kHz in single independent time windows and were often stronger than some of the TBO detections in individual bursts, reaching $P_m \gtrsim 40$. We dub them “glimmer” candidates. It is possible that some of the glimmer candidates are of astrophysical origin (especially those at lower frequencies).
7. Conclusions

TBOs are transient phenomena with rapidly changing properties. The measured power of potential TBO candidates depends greatly on the specific choices regarding data selection, such as energy filters, time windows, degree of overlap, summing harmonics, or adjacent time windows and stacking spectra from different bursts. Thus, considering the researcher’s natural desire to find TBOs, one must be very careful in estimating the number of trials resulting from tweaking the search parameters and exploring multiple sources.

While searching for high-power narrowband signals using Fourier transform in overlapping time windows, it is generally reasonable to use a $\chi^2$ model of the distribution of the noise powers with the conservative number of trials, after correcting for dead time influence, LC variation, and making sure that the harmonics in Fourier spectra are not covariant. However, it is strongly advisable to verify that a $\chi^2$ distribution actually describes well the noise powers of a given data set.

Our search for TBOs resulted in several short (each detected in one independent time window) candidates with powers comparable to those of the fainter TBOs ($P_m \sim 30–40$). These candidates, dubbed “glimmer,” are marginally significant, meaning that 99% or more simulation runs had a smaller number of candidates. They produce sinusoidal oscillation profiles and in all aspects resemble fainter TBOs. However, they occur at random frequencies within a single source and sometimes are coincident in time with real TBOs. In part, glimmer candidates may stem from selection bias; however, an astrophysical origin is not excluded. Regardless of their nature, the phenomenon of glimmer candidates may explain the large number of unconfirmed single-window detections, e.g., Kaaret et al. (2002), especially considering the tendency of under-estimating the number of trials.

For the potential detections with the smaller power, the best corroboration of TBO nature is detecting the signal at the same frequency in independent time windows; however, the intrinsic frequency drift and Doppler modulations complicate this. It is therefore important to develop a procedure for estimating significance of signals with drifting or jumping signal. This would help to refine the significance of the frequency jump in MXB 1658–298 (Wijnands et al. 2001), the drifting candidate in 1A 1744–361 (Bhattacharyya et al. 2006), a pair of 270 Hz candidates XB 1916–053 (Galloway et al. 2001), and a potential pair of 600 Hz candidates from IGR 17473–2721 (this work).

Despite our efforts, we did not find TBOs below 200 Hz and during high count rates. Several measures can be undertaken to obtain a better, more complete picture of TBOs. Obtaining new data using better instrumentation with higher throughput leads to better sensitivity and the absence of data gaps allows a better characterization of the frequency evolution. Continuing searching is also an option, since TBOs may appear from the sources without promising candidates, although having some theoretical guidance would be better, something the data could be used for. Further improvement of TBO searches can also be made by selecting only that part of energy spectrum where there are most burst photons, in order to minimize the relative contribution of background. Having ephemerides would also help to correct for the Doppler change in frequency: this would be especially helpful for the ultra-compact binaries such as 4U 1820–303 or the potential ultra-compact binary 2S 0918–549.

A.V.B. and A.L.W. acknowledge support from ERC Starting grant No. 639217 CSINEUTRON- STAR (PI: A.L. Watts). We would like to thank Duncan Galloway and the MINBAR team for sharing a pre-release version of the MINBAR database with us. A.V.B. thanks Hauke Worpe for sharing the data on background variation during type I bursts.

Appendix A

Individual Sources

A.1. Individual Sources with Previously Detected TBO

A.1.1. EXO 0748–676

Galloway et al. (2010) reported on two strong TBO candidates from the rise of two bursts out of 157 bursts searched. The candidates (with powers of 59.68 and 48.26) were detected in one independent time window per burst at the frequencies of 552 and 552.5 Hz. The estimate of the significance of the pair of candidates separated by $<1$ Hz was based on the conservative number of trials and led to 6.3σ significance.

Earlier, Villarreal & Strohmayer (2004) had reported a 5.35σ-equivalent 45 Hz oscillation in the stacked spectra of 38 bursts. This candidate does not show up in the larger burst sample of Galloway et al. (2010), and its origin is unclear.

Our sample consists of 159 bursts, the majority with long tails (∼90 s). We detect candidates at 551.5–552.5 Hz from the same two bursts as Galloway et al. (2010). In both bursts the candidates come from a few time windows, all of them dependent (e.g., Figure 19). The sub-threshold candidates hint at a frequency evolution. The highest powers of candidates in the 551.5–552.5 Hz frequency range are 57.5 and 51.4 (56.8 and 49.2 on non-normalized data, respectively), whereas the maximum $P_m$ outside this frequency region is 43.6. None of the simulations had the same $P_m$ as the strongest candidate; however, we did not make a significance estimate for the pair of candidates close in frequency.

Our analysis procedure does not find TBO candidates in the 552–554 Hz frequency region from the two fainter bursts mentioned in Galloway et al. (2010) (even sub-threshold).

EXO 0748-676 is remarkable as a prolific source of type II low-frequency candidates. Low-frequency candidates come from 2 to 14.5 Hz. Sometimes they are confined to 2–3 Hz, sometimes they chaotically occupy all frequencies up to 13 Hz, and sometimes they occur at distinctly separate frequencies, e.g., 5 or 9 Hz.

The source yielded a few dozen (glimmer) candidates with $p = 0.01$, none of them close to the 45 Hz of Villarreal & Strohmayer (2004). Some of the candidates at widely separated frequencies come from the same burst, sometimes even from the same time windows.

A.1.2. 4U 1608–522

TBOs from 4U 1608–522 have been detected at 619 Hz in multiple bursts in the rise and after the burst peak by Galloway et al. (2008). The authors report large gradual frequency drifts, and FAs of 5%–15%.

Our sample has 52 bursts, some of them very strong, suffering from data gaps and reduced average noise power (going down to 1.6). TBOs were detected at 616–620 Hz in seven bursts (e.g., Figure 20). Two bursts had TBO signals in one independent time window (one of them had more
sub-threshold candidates). The oscillations are mostly detected in the B region; one burst has TBOs starting in the rise. The gradual frequency drift throughout the TBO duration and FAs of 3%–12% is consistent with Galloway et al. (2008) and Ootes et al. (2017).

In addition to TBOs, we record several type I low-frequency and about a dozen glimmer candidates ($p = 0$).

A.1.3. 4U 1636–536

4U 1636–536 is one of the most prolific and best-studied TBO sources. Our sample contains 368 bursts from 4U 1636–536, forming the largest sample among the 57 sources that we have in total. Some of the bursts are quite bright, with average noise power dropping as low as 1.7.

TBOs at 576–582 Hz were detected from 75 bursts, most of them in the RB regions (the only detection in the T region is at its left edge). About 30% of the TBO detections are in one independent time window. FAs on the order of 5%–15%, can reach up to 50% on the rise (Figure 21). The same large FAs on the rise were previously reported by Strohmayer et al. (1999). The FAs that we find broadly coincide with the values reported in Ootes et al. (2017), Galloway et al. (2008), and Miller (2000).

In addition to TBO candidates, we detect a few low-frequency candidates and a large, but insignificant, number of noise candidates ($p = 1$). Miller (1999) reported a significant signal at 290 Hz from the sum of 0.75 s intervals on the rise of five bursts. None of our noise candidates was close to 290 Hz.

A.1.4. MXB 1658–298 (X 1658–298)

TBOs at 567 Hz were discovered by Wijnands et al. (2001), who detected them in six bursts out of 14 observed. The TBOs had small (0.5–1 Hz) frequency drift and FAs on the order of 10%. A larger sample of bursts was later explored by Galloway et al. (2008).

Our sample yielded 26 bursts, four of them with TBO candidates in the 566.75–567.25 Hz frequency range. The candidates are rather weak, with peak powers of 35–45, in one independent time window per burst. Some of them occur on the rise, some a few seconds after the burst peak. Formally, two TBOs are labeled as coming from the tail region, but those bursts had a sharp intensity drop, so that the B region was narrow. FAs on the order of 10% are broadly consistent with the values reported in Wijnands et al. (2001) and Galloway et al. (2008) for all bursts except for burst #2519. There, we have FAs three times smaller (consistent with Wijnands et al. 2001).

Interestingly, there is a discrepancy in burst detections. Galloway et al. (2008) do not confirm one burst with a detection reported in Wijnands et al. (2001), but have one more with a detection from 2001. We do not have any noticeable sub-threshold candidates in three of the bursts with detections reported in these two papers. FAup are similar to or even lower than the reported detections.

The standard threshold does not yield any low-frequency candidates. A small number of noise candidates is not statistically significant.

Wijnands et al. (2001) reported a burst (#2519) with oscillations reappearing at a frequency larger by about 5 Hz (571.5 Hz), with similar signal strength (maximum $P_m = 32$ for 2 s sliding windows with 0.25 s offset using the $Z^2$ statistic). This candidate does not exceed our detection threshold (corresponding to $P_m = 33.62$ for 2 s windows); however, we do detect a bunch of sub-threshold candidates in the same region. The candidate with the smallest probability has $P_m = 30$ in 1 s window at 571 Hz (30.2 on non-normalized data). It is definitely not as strong as the TBOs earlier in the burst (Figure 22). The discrepancy between our values and those of Wijnands et al. (2001) can be readily explained by the different choice of FFT windows and using FFT versus $Z^2$. 
None of the remaining bursts yielded candidates within the 10 Hz region of the TBO frequency range. It is hard to tell whether the 571 Hz candidate is related to TBOs. Two outcomes are possible: (a) it is a TBO, as is stated in Wijnands et al. (2001); (b) it is a glimmer candidate. Wijnands et al. estimate its significance taking into account only trials in the 10 Hz frequency region around the TBOs. However, it is unclear whether this is a correct choice, since this region was chosen after the candidate was found on a broader search from 100 to 1200 Hz. Our analysis with the probability threshold multiplied by a factor of 3.7 yields nine more candidates, eight of them below 1000 Hz and one above. Some of these candidates are stronger than the 571 Hz one. The simulated data do not have, on average, this many candidates: only one simulation run had as many as 10 candidates ($p = 0.01$). Thus, it is possible that MXB 1658–298 has glimmer candidates, and the peak at 571 Hz is one of them. It is also worth noting that this candidate has a softer spectrum than the TBOs earlier in the burst (Wijnands et al. 2001).

The most robust way to prove that a step candidate is a TBO would be to detect it once again at the same frequency, preferably with larger power.

### A.1.5. 4U 1702–429

Oscillations around 329 Hz were discovered by Markwardt et al. (1999) in five out of six bursts observed at the time. The TBO frequency was gradually increasing during all bursts, and the reported FAs ranged from a few % up to 18%.

Our sample contains 50 bursts from this source, some of them with gaps and noise power as low as 1.8. Among these, 32 yielded TBO signals at 326.00–330.5 Hz in the R and B regions.

FAs of approximately 3%–15% broadly match the values reported by Ootes et al. (2017) and Galloway et al. (2008). Some of the bursts have detections in one independent window, with or without multiple sub-threshold detections in independent windows. There are also many sub-threshold detections from bursts with strong TBOs (e.g., Figure 23). We see large gradual frequency rises; however, some of this frequency evolution may be biased by the rapid variation of the count rate during the burst rise or gaps.

In addition to TBOs, our burst sample yielded some type I low-frequency candidates at 2–3 Hz due to the unmodeled spikes on the rise of several bursts, and a statistically insignificant number of noise candidates.

### A.1.6. IGR J17191–2821

TBOs at 294 Hz were discovered by Altamirano et al. (2010a) in three bursts out of five observed (one of them showed significant oscillations only in part of the energy band). Two bursts exhibited a large gradual frequency drift, 2–3 Hz over about 10 s. The authors reported 5%–10% rms amplitude in the 2–17 keV energy range.

Our sample consists of the same bursts as in Altamirano et al. (2010a). We detect TBOs in two bursts at the same frequency in the B region. The burst with the weakest TBOs from Altamirano et al. had sub-threshold candidates in the TBO frequency range. The FAs of the detections are broadly similar to those measured by Altamirano et al., despite the differences in time window sizes and energy cuts. For burst #3513 (Figure 24), we do not record TBOs closer to the burst rise, having only one sub-threshold candidate there.

In addition to TBOs, one type I low-frequency candidate was detected.

### A.1.7. 4U 1728–34

TBOs from 4U 1728–34 were discovered by Strohmayer et al. (1996) at 363–364 Hz. The oscillations are characterized
by a gradual few Hz upward frequency drift and FAs as as large as 10%. A larger sample of bursts was subsequently searched for TBOs by van Straaten et al. (2001), Galloway et al. (2008), and Ootes et al. (2017).

Our sample contains 141 bursts from this source. Some of them have data gaps and average noise power as low as 1.8. Thirty-four bursts yielded TBO candidates in the frequency range 362–364 Hz. All TBO candidates except one were detected in the R and B regions. The only one from the T region is on its left edge. Some of the bursts show detections in multiple independent time windows with gradual frequency drift over the course of the TBO train (Figure 25). Sometimes the frequency evolution is biased by data gaps. Some of the bursts have fainter detections in one independent time window, on the rise or in the B region.

FAs of the TBO candidates are broadly comparable to the values reported in Galloway et al. (2008) and Ootes et al. (2017), but are consistently smaller than those in van Straaten et al. (2001) by a factor of about 1.5 although the FA evolution throughout the burst is similar. This is explained by the differences in data processing: van Straaten et al. added power from several frequency bins in 4 Hz windows around maximum power.

In addition to TBO candidates, our analysis yielded multiple low-frequency candidates, both type I and type II, and a statistically insignificant number of noise candidates.

A.1.8. KS 1731−260

Oscillations at 523.93 Hz were discovered by Smith et al. (1997) in the single burst observed at the time. Later, Galloway et al. (2008) searched for TBOs in 26 more bursts and found them in three. Ootes et al. (2017), using different window sizes, also found oscillations in six bursts out of 27.

Because of the GTI requirement, our sample consisted of 26 bursts. TBOs were detected in three of them, at frequencies of 523.5–524.25 Hz, all of them right after the burst peak (e.g., Figure 26). Two bursts yielded detections in multiple independent time windows, one in a single time window but with more independent sub-threshold candidates on the rise. One more burst had sub-threshold candidates only. FAs of 4%–14% are broadly consistent with the values reported by Galloway et al. (2008) and Ootes et al. (2017).

The source yielded also a small, statistically insignificant number of noise candidates.
A.1.9. GRS 1741.9−2853

Strohmayer et al. (1997a) reported on 589 Hz TBOs in three bursts from GRS 1741.9−2853. The FA of detections were up to 13%, but these were for favorable energy cuts and custom time window intervals. The source was not in outburst again before the end of the RXTE mission. In 2013, Barrière et al. (2015) observed GRS 1741.9−2853 with NuSTAR. Unfortunately, the 2.5 ms dead time of NuSTAR hindered TBO detection. No oscillations were found, with the upper limits from simulations of the injected signals being higher than the detections in Strohmayer et al. (1997a).

Our sample consists of seven bursts. We detected TBO candidates at 589.00−589.75 Hz. For both bursts, the candidates came from the B region, with an FA of about 5%, broadly comparable with the values reported in Galloway et al. (2008).

In one burst, candidates were detected in two independent time windows, but of different length and not at the same frequency (Figure 27). The other burst yielded a detection in one independent window and another independent sub-threshold candidate. The third burst with TBOs from Strohmayer et al. (1997a) was not covered by GTI.

The candidates around 589.5 Hz are not strong, with $P_m < 40$. All three independent-window candidates come from different frequencies, but the spread is smaller than 1 Hz. For the strongest candidate, 5% of simulations yielded the same or a larger number of candidates with equal or larger $P_m$. However, selecting all candidates above threshold yields $p = 0$. The fact that the candidates are grouped in frequency speaks in favor of their TBO nature; however, a strict estimate of the significance of this grouping is beyond the scope of this paper.

In addition to TBO candidates, GRS 1741.9−2853 has some type II low-frequency candidates in the 2−4 Hz range, and one noise candidate ($p = 0.3$) at 1829.25 Hz.

A.1.10. IGR J17480−2446

TBOs from an unusually slowly spinning accreting pulsar IGR J17480−2446 were discovered by Cavecchi et al. (2011). Very strong 11 Hz oscillations were detected in one burst, with FAs of 30% and no frequency drift. The remaining 230 bursts explored by Cavecchi et al. also yielded TBOs in FFT windows from 10 to 300 s, with FAs down to 3%. The search was conducted on barycentered data using the APP ephemeris.

Our sample contained 297 bursts, with median peak S/N of only 6.4. Most of the times for the on-burst windows were set manually and were short, of about 5 s. Our FFT windows are shorter and the upper limits on FA are consequently much larger than in Cavecchi et al. (2011); we find characteristic upper limits on the FA on the order of 70%. Using our analysis procedure, only two bursts had candidates in the range of 10−11 Hz. Similarly to XTE J1814−338 and IGR J17511−3057, the range of TBO frequencies reflects the coarseness of the Fourier grid, with detections at 10 Hz coming from 0.5 s windows.

One of the bursts (#4192) had strong oscillations throughout the entire on-burst window (Figure 28), with a typical FA of 30%, maximum up to 90%. The average FA on 10−20 s timescales would have matched that reported in Cavecchi et al. (2011). Another yielded a relatively faint ($P_m \approx 40$) detection in a single independent 4 s window (more if one considers sub-threshold candidates). For this burst, calculated FAs of ~90% are most probably affected by an overestimated pre-burst background level.

Burst #4192 had several low-frequency (2−3 Hz) candidates of type II. Overall, the burst sample yielded a large but statistically insignificant number of noise candidates.

A.1.11. IGR J17498−2921

IGR J17498−2921 is an accreting MSP with TBOs at 401 Hz, discovered by Linares et al. (2011). Chakraborty & Bhattacharyya (2012) analyzed 12 bursts from IGR
J17498–2921 and detected TBOs from two bursts in averaged 1 s spectra. The PCA field of view contains several other bursters and the 10 bursts without oscillations may be from another source; however, the authors argue that this is unlikely.

The MINBAR catalogue lists only two bursts from IGR J17498–2921. From both bursts we detected TBOs in the B region, without frequency drift. There were also some sub-threshold candidates on the tail. The FAs of 10% were consistent with those of Chakraborty & Bhattacharyya (2012). One burst had two independent-window detections, the other only one independent detection, but with sub-threshold candidates at the same frequency in the tail (FA of 30%, Figure 29). In addition to TBOs, only one low-frequency candidate was detected.

A.1.12. SAX J1750.8–2900

TBOs at 601 Hz were discovered by Kaaret et al. (2002) in one of the four bursts studied. The authors used merged event lists from the event and burst catcher modes, without any energy selection and searched for signal in 4 s windows overlapping by 0.125 s in the frequency range between 200 and 1200 Hz. TBOs were found in both the rise and decay, with a maximum power of 49.3 five seconds after the burst rise. No FAs were reported.

We detected TBOs from the same burst in two independent time windows, with similar maximum power, five seconds after the burst rise. Similarly to Kaaret et al. (2002), we record frequency drift and the disappearance of the TBO signal during the burst peak. TBOs on the rise occur in shorter windows and have larger FAs than TBOs right after the burst peak (Figure 30).

Galloway et al. (2008) found TBOs on the rise of two more bursts. These bursts have only sub-threshold candidates in our analysis, with FAs similar to those measured by Galloway et al.

The first burst has frequency behavior similar to burst #2717, while TBOs from the second one do not have noticeable frequency drift and also appear at burst peak.

In 2008, SAX J1750.8–2900 went into outburst again, adding two more bursts to the MINBAR sample. No TBO candidates were recorded from these bursts, even at the sub-threshold level.

For the strongest candidate, none of the simulations has candidates of similar strength. For both candidate groups, before and after the burst peak the peak power was over 40. The highest $P_m$ outside the frequency region around 600 Hz was smaller than 30. Despite the absence of candidates detected in independent time windows at the same frequency, the power of the candidates, the close proximity of their frequencies, and the presence of sub-threshold candidates in two more bursts speak in favor of these candidates being TBOs.

No low-frequency or noise candidates were detected from this source.

A.1.13. IGR J17511–3057

IGR J17511–3057 is an accreting MSP with TBOs at 245 Hz discovered by Altamirano et al. (2010b). Burst oscillations are seen in all bursts in the sample. For fainter bursts, the oscillations are detected earlier in the burst. For brighter bursts, TBOs often disappear at the burst peak. The authors note a small (0.1 Hz) frequency drift on the rise and report FAs of 5%–12%, with FAs on the tail larger than on the rise and peak.

The MINBAR database lists nine bursts for this source, all of them with TBOs in the same regions as in Altamirano et al. (2010b). One of the bursts has TBOs in one independent time window only. We do not observe any frequency drift on the rise, although our Fourier frequency resolution is rather coarse. Similarly to XTE J1814–338, the frequency range of the detections reflects the coarseness of the Fourier frequency grid.
Like Altamirano et al. (2010b), we note a dip in FAs during burst peaks (Figure 31), although in a smaller number of bursts than they do. Our FAs are also consistent with those of Altamirano et al.

No low-frequency or noise candidates were detected from this source.

A.1.14. SAX J1808.4–3658

SAX J1808.4–3658 is an accreting MSP with APPs and TBOs at 401 Hz (Wijnands & van der Klis 1998; Chakrabarty et al. 2003).

Minbar catalogue lists nine Type I bursts, three of which have not been analyzed for TBO behavior before. We find TBOs in seven bursts. The source is very bright and some observing sessions suffer from data gaps. Typical behavior is as follows: TBOs start at the burst onset and rapidly drift in frequency up or down by a few Hz within a single FFT window of 0.5–1 s (the amount of perceived drift may be biased by frequency covariance). The FAs on the rise are on the order of 10%–40%. Oscillations disappear during the burst peak, even accounting for the dead time, which lowers the noise power to 1.6. Then oscillations reappear at frequencies slightly higher or lower and are fairly stable in frequency with wave-like variations of FAs, which at the same time increase slightly on the tail. The FAs after burst rise are on the order of few %. One burst did not show oscillations on the rise; another had only sub-threshold candidates on the rise. Such TBO properties are consistent with those reported previously (Chakrabarty et al. 2003; Bhattacharyya & Strohmayer 2006, 2007; Galloway et al. 2008).

One of the bursts has type II low-frequency noise, a strong TBO, and a peculiar low-frequency glimmer candidate at 8 Hz, with peak power exceeding 60 (Figure 32). Note that the standard detection threshold yields \( p = 0.22 \); however, the power of the glimmer candidate is much larger than any power in the simulated data sets. The oscillation profile folded with 8 Hz frequency has a sinusoidal shape.

A.1.15. XTE J1814–338

The accreting MSP XTE J1814–338 is one of the best studied TBO sources (Strohmayer et al. 2003; Watts et al. 2005, 2008; Watts & Strohmayer 2006). Our sample consisted of 28 bursts, all of which have been studied before. We detect TBOs with power above the threshold in 26 bursts. The two remaining bursts did not have GTI coverage during the burst rise and peak, but had weak sub-threshold candidates during the tail.

The oscillation frequency (314 Hz) does not change by more than the Fourier frequency resolution during the burst; the apparent frequency range in Table 4 reflects the coarseness of the Fourier frequency grid.

The oscillations do not disappear during the burst peak and are often present in the burst tail. There are also many sub-threshold candidates. FAs tend to be roughly constant throughout the duration of the oscillation, until it disappears under the rising FA up (Figure 33). On top of the constant level, there are evident wave-like variations of FAs. In general, our measurements of FAs of \( \sim 10\% \) are broadly consistent with Galloway et al. (2008) and Watts et al. (2008).

A.1.16. HETE J1900.1–2455

HETE J1900.1–2455 is an accreting MSP with a spin frequency of \( \sim 377 \) Hz (Patruno 2012). TBOs in a single burst were discovered by Watts et al. (2009). The authors detected significant signal in four consecutive independent 2 s windows for \( 2–30 \) keV photons. The reported FAs were 3.5% in the same energy range.

Our sample consisted of eight bursts, one of them with data gaps. The bursts are quite bright and during the peak the mean noise power drops to 1.7. Despite accounting for the influence of dead time, our search did not result in any new TBO detections—relatively faint TBO candidates were detected at 376.25 Hz only in the same burst as in Watts et al. (2009). Only one independent time window yielded \( P_m \) above the detection
threshold (Figure 34), although sub-threshold candidates extend longer both in time and the frequency maps the same frequency evolution as in Watts et al. (2009). The FA was 4.5%, comparable to the value in Watts et al., noting that we have made different choices of windows and energy ranges.

HETE J1900.1−2455 is a good illustration of the advantages of using external information to narrow down the frequency range searched. TBOs at 376.25 Hz would have been deemed insignificant by our broad frequency range analysis—a 3% of our simulation runs had at least one candidate with probability equal to or smaller than the probability of the TBO candidate. The source also has some low-frequency noise and an insignificant number of noise candidates.

A.1.17. Aql X-1

TBOs at 549 Hz were discovered by Zhang et al. (1998) in RXTE burst catcher data. Later, Casella et al. (2008) reported on strong ($P_m = 120$) APPs at 550.27 Hz in a single 150 s time window which was not close to any burst.

Our sample consisted of 73 bursts, about half of them suffering from data gaps (e.g., Figure 35). Noise power at the burst peak often drops to as low as 1.7. TBOs were detected in eight bursts in the R and B regions in the frequency range 547.4–550 Hz.

For several bursts, TBOs were detected in one independent window only. For brighter TBOs, there is a hint of a gradual frequency drift (∼1 Hz over few seconds), although gaps in the data have a large adverse effect on the observed frequencies. FAs of TBOs are on the order of 4%–7%, broadly consistent with the values reported in Zhang et al. (1998), Galloway et al. (2008), and Ootes et al. (2017).

In addition to TBO candidates, we detected multiple low-frequency candidates at 2–6 Hz and an insignificant number of noise candidates.

A.2. Individual Sources with Tentative TBO Detections Reported by Previous Papers

In this section we discuss sources for which TBO detections have been claimed, or tentatively claimed, by previous works and which were classified as tentative in the review article by Watts (2012). There are eight sources in this category: 4U 0614+09, 4U 1254−69 (XB 1254−690), MXB 1730−335 (rapid burster), XTE J1739−285, 1A 1744−361,
A.2.1. 4U 0614+09

Strohmayer et al. (2008) found a 415 Hz signal in a 10 s window in the tail of one of the two bursts in their sample. The bursts were detected in 2006 and 2007 with Swift. The oscillations had FAs of 12.3% and occurred in the 13–20 keV energy range, in one of the 10 s windows. The signal had 4σ significance assuming a conservative number of trials.

The RXTE sample consists of only one burst, different to those observed by Strohmayer et al. (2008). The burst was extremely bright, resulting in the telemetry rate being heavily saturated, which caused large data gaps. The burst started with a very bright sub-second spike, followed by a gap, which is an indication of PRE. This spike was not included in the on-burst window although it was part of the real burst rise. Our LC modeling did not reproduce a short gap at about 4 s from the burst start, thus all candidates from the time windows covering that moment were discarded. We detected no candidates above the specified threshold. Our count rates imply much stronger upper limits on FA, around 2%.

Our non-detection does not challenge the TBO claim of Strohmayer et al. (2008), since even sources with strong TBO records have bursts that are apparently devoid of oscillations. However, it remains the case that TBOs were detected essentially only in one independent time window, from one burst. Detecting the oscillations at similar frequencies from more bursts would strengthen the conclusion.

A.2.2. 4U 1254−69 (XB 1254−690)

Bhattacharyya (2007) reported on a tentative 95 Hz candidate from the rising phase of one of the five bursts recorded. The $P_m = 24.3$ TBO candidate was found in the first 1 s interval after the burst start and had an FA of 0.31 ± 0.07. The signal was confined to a 1 s time window and no significant frequency evolution was found, according to the authors. The significance was estimated to be 95%, considering the number of harmonics and windows searched.

We have two more bursts compared to Bhattacharyya (2007). Using our formal detection criterion, our analysis did not yield any candidates in the same data. However we did confirm similar powers ($P_m$ of about 25.5) at the same frequency of 95 Hz. The sub-threshold candidates at this frequency are strongest in 1 s windows; there are fewer significant sub-threshold candidates at other window sizes, but not in independent windows. The FA of the maximum-power signal is similar to that in Bhattacharyya (2007).

Lowering the detection threshold to 25.43 on the 1 s window and correspondingly at other windows (multiplying the threshold probability by a factor of 30), we get five additional noise candidates ($p = 0.3$), both below and above 1000 Hz, all in the bursts analyzed by Bhattacharyya (2007). Bhattacharyya did not find any significant oscillations in other bursts up to 2048 Hz; however, our data suggest otherwise. This may be explained by differences in the choice of windows and oversampling factor.

Some of our sub-threshold candidates also occur in 1 s time windows and are stronger than the power reported by Bhattacharyya. We conclude there is not enough evidence to classify the 95 Hz oscillation candidate as a TBO and not as a noise candidate.

A.2.3. MXB 1730−335 (Rapid Burster)

Fox et al. (2001) described a tentative 306.5 Hz TBO candidate in the sum of spectra from the rising part of 31 bursts, with 1.8% of it being a chance detection according to their simulations. According to the authors, various tweaks to the data selection parameters affected the detection significance in
different ways. The candidate was not detected in single bursts, and was not confirmed in two subsequent outbursts.

Our sample consisted of 57 bursts, some of them with data gaps. We did not detect any candidates at frequencies close to 306.5 Hz. The source yielded some type II low-frequency candidates within 2–6 Hz, and a large, but not significant, number of noise candidates ($p = 0.16$). One of the candidates (at 18.25 Hz) is quite strong, with $P_m = 46.5$ (Figure 16). This candidate has a power of 44.52 on non-normalized data. Only 2% of simulation runs have one or more candidates of the same or larger significance.

A.2.4. XTE J1739–285

A tentative sub-ms oscillation from XTE J1739–285 was found by Kaaret et al. (2007). The authors reported a 1122 Hz candidate in one of the six bursts examined. The authors used a different energy cut for the PCU0 compared to the other PCUs in order to to minimize background, since the PCU0 had recently lost its propane layer. Kaaret et al. used 4 s FFTs with a 0.125 s step. The maximum candidate power was 42. The significance of the candidate (equivalent to 3.97 $\sigma$ of normal distribution) was estimated with simulations based on LC modeling, taking into account dead time. The candidate was not confirmed by Galloway et al. (2008), who used non-overlapping 4 s windows and potentially different energy cuts.

Our sample had the same bursts as in Kaaret et al. (2007) and Galloway et al. (2008). We did not find any candidates from this source, having on average 0.29 candidates from our simulation runs.

The maximum power from the burst in Kaaret et al. (2007) is 29.5 in a 4 s window at the same frequency in a similar place during the burst tail. Increasing the detection threshold probability by a factor of 16.5 to match $P_m = 29.5$ (29.9 on non-normalized data) in 4 s windows yielded five additional candidates ($p = 0.6$), some of which were more significant than the 1122 Hz one. Thus, in our analysis there is not enough evidence to classify the 1122 Hz candidate as a TBO and not a noise candidate.

The tentative detection of Kaaret et al. (2007) presents an interesting case since it is rather strong; its significance was established using simulations but it was not confirmed using different energy cuts and window overlap. It may be possible that the custom energy cuts Kaaret et al. (2007) were using were more sensitive to potential oscillations. However, it also may be the case that their noise model was not entirely correct (no analysis of model applicability was given) or that the detection was not related to TBOs (e.g., a glimmer candidate).

Detection of the 1122 Hz signal in more bursts in the future would serve as the strongest corroboration of its TBO nature. It is also worth re-examining the existing RXTE data, investigating the influence of energy cuts on the 1122 Hz candidate’s power and the distribution of $P_m$ in general.

A.2.5. 1A 1744–361

A burst oscillation candidate was found by Bhattacharyya et al. (2006) in the single burst observed by RXTE. The signal appeared at $\sim$529 Hz in the rise of burst #3298. Splitting the peak into 4 s power spectra, and using a $\Delta f$ spectrum, indicated a small (<0.5 Hz) step in frequency. The highest rms FAs were 10.3% in the >3 keV band and 15% for >8 keV. The candidate was also found by Galloway et al. (2008), who reported an FA of 11.3 ± 1.8%.

Our analysis on a sample of three bursts yielded exactly one candidate, matching that from Bhattacharyya et al. (2006). The candidate was at 529 Hz, with $P_a = 35.4$ (34.24 on non-normalized data) in one 1 s window (Figure 36). There are also sub-threshold candidates with different FFT windows. The sub-threshold detections are somewhat later and higher in frequency, but none of them occurs in an independent time window. The associated FA is similar to that reported previously: 11 ± 2%. Our sample contains two more bursts compared to the previous analysis. The additional bursts are a factor of a few fainter, and the upper limits on FAs are about three times larger than the FA of detection.

For the simulation runs, 10% of them have one or more candidates above the detection threshold. For the higher threshold corresponding to $P = 35$ in 1 s windows, only 1% of simulations had one or more candidate.

Based on the power alone, the 529 Hz candidate is not strong enough to be classified as a TBO in our analysis. However, the presence of sub-threshold candidates hinting at frequency drift makes this candidate interesting. A definitive answer requires the detection of candidates at similar frequencies from future bursts.

A.2.6. SAX J1748.9–2011

Kaaret et al. (2003) reported on a $P_m = 38.7$ TBO candidate at 409.7 Hz in one of the 15 bursts observed. The authors used merged photon TOA lists from event and burst catcher modes and computed FFTs in 3 s successive time windows with 0.25 s steps. The oscillations lasted for about 4 s and did not show any obvious frequency evolution. The significance of the detection was estimated to be equivalent to 4.4 $\sigma$ of the normal distribution; however, the number of time windows searched was not taken into account. Later, Altamirano et al. (2008)
found intermittent APPs at 442.36 Hz in the persistent emission, with Leahy-normalized power as large as 100 with favorable data selection. The authors repeated the analysis of Kaaret et al. (2003), but without window overlap. Taking into account the number of time windows searched, the significance of the 409.7 Hz candidate dropped to $\lesssim 2.5\sigma$.

Our sample consisted of 29 bursts from the 2001 and 2010 outbursts. One low-frequency and two noise candidates were detected, none of them close to 409 or 442 Hz. For the same burst as Kaaret et al. (2003), we detected at 409.75 Hz a maximum power of 33.2 in a 4 s window.

Multiplying the detection probability by a factor of 2.5 to match $P_m = 33.2$ in 4 s windows yielded two more candidates, some of which were more significant than the 409.75 Hz one. About half of the simulation runs had the same or a larger number of candidates.

The weakness of the 409.7 Hz candidate and, more importantly, the detection of a strong pulsation signal at a distinct frequency by Altamirano et al. (2008) lead us to conclude that the candidate reported by Kaaret et al. (2003) was a spurious detection.

A.3. Sources without Previously Detected TBOs

A.3.1. Unremarkable Sources

The following twelve sources yielded no TBO candidates in our analysis: 4U 2129$+_{12}$, Cir X-1, GRS 1747$−_{312}$, KS 1741$−_{293}$, SLX 1735$−_{269}$, SAX J1747.0$−_{2853}$, XB 1832$−_{330}$, XTE J1709$−_{267}$, XTE J1739$−_{285}$, XTE J1810$−_{189}$, GX 3$+_{1}$, and SAX J1806.5$−_{2215}$. All of these sources had $< 30$ bursts with total burst duration of $< 15$ min per source. The median peak S/N of the bursts differed by two orders of magnitude, from 8 to 580, and the median upper limits on FAs in 1 s time windows at the burst peaks (hereafter, characteristic FAup) were anywhere from 5% to 81%. The average number of candidates from simulated bursts ranged from 0.02 to 1.1. Of these sources, GX 3$+_{1}$ and SAX J1806.5$−_{2215}$ each had type I low-frequency candidates in one burst.

2S 0918$−_{549}$, 4U 0513$−_{40}$, IGR J17597$−_{2201}$, and Ser X-1 also had a relatively small number of bursts ($<20$), with parameters comparable to the previous groups and a similar ($\sim 1$) average number of simulated candidates per source. These sources yielded some type I low-frequency candidates and one or two noise candidates. A significant fraction of simulation runs ($p = 0.16−0.5$) had the same or a larger number of candidates. All noise candidates from real data had powers relatively close to the selection thresholds.

The following group of sources yielded type II low-frequency candidates at frequencies of 2$−_{4}$ Hz: 4U 0836$−_{429}$, 4U 1323$−_{62}$, and 4U 1705$−_{44}$. Those sources had longer total observing burst durations (18$−_{70}$ min), moderate median peak S/Ns ($\sim 50$), and characteristic FAup of about 10%. Several noise candidates recorded had a large chance of being due to random noise fluctuations, with $p$ ranging from 0.4 to 0.8.

1A 1742$−_{294}$, XTE J1701$−_{462}$, 4U 1735$−_{444}$, 4U 1746$−_{37}$, and XTE J2123$−_{058}$ each yielded a small number of noise candidates and no low-frequency candidates. The number of bursts, total duration, median peak S/N, and characteristic FA varied by a factor of few within this group; however, for all sources the large fraction of simulated bursts ($p = 0.13−0.83$) had the same or a larger number of noise candidates. A negative result from TBO searches from 4U 1746$−_{37}$ was reported previously in Ootes et al. (2017).

GX 17$+_{1}$ had unusually long bursts (average duration 4.5 min). Six candidates were detected with $p = 0.7$. About two thirds of our sample was previously examined by Kuulkers et al. (2002), who did not find any signal beyond $P_m = 42.8$ in time windows of 0.25 and 2 s. For all bursts in the sample, the maximum power above 10 Hz did not exceed 37.5.
A.3.2. Sources with Somewhat Larger Number of Noise or Low-frequency Candidates

The relatively faint sources XTE J1710−281 and SLX 1744–300 had a marginally significant number of noise candidates per source ($p$ of 0.02 and 0.01, respectively). None of the candidates was particularly strong, and their frequencies were scattered between 20 and 1980 Hz. No low-frequency candidates were recorded.

A stronger source, 4U 1722−30, yielded a rather strong single candidate. This was recorded at 22 Hz at burst peak in a 0.5 s time window covering a small dip in the LC. This dip was well modeled and had no low-frequency type I candidates associated with it. The candidate had a power of 36.49, with an unnormalized power of 33.59. Only one out of 100 simulations yielded one or more candidates with the same or larger power. A similarly strong candidate coming from a 1 s time window right after the burst peak and had $P_m = 39.7$ (34.69 in unnormalized data) and $p = 0.02$. It is worth mentioning that NICER has observed PRE bursts from this source recently, and no oscillations have been detected (Keek et al. 2018). Overall, although these candidates are rather strong, their power depends greatly on proper LC modeling.

Two other faint sources, EXO 1745−248 and Cyg X-2 had remarkably numerous and strong low-frequency candidates (type II). For EXO 1745−248, these candidates were recorded within most of the on-burst windows at multiple frequencies between 2 and 12 Hz. Sometimes the candidates were grouped in time, similarly to IGR J17473−2721. Only one noise candidate ($p = 0.4$) was detected from this source, at 14.5 Hz, with multiple low-frequency candidates from the same time windows at 2–8 Hz.

The low-frequency candidates from Cyg X-2 exhibited various behaviors: during some bursts they were confined to a single frequency; during others they were spread chaotically within 2–12 Hz or occurred at two separate frequencies (e.g., 3 and 9 Hz). Few glimmer candidates were recorded, with $p = 0.01$.

A.3.3. IGR J17473−2721: An Interesting Pair of Candidates

IGR J17473−2721 generated an interesting pair of candidates at 602 and 605 Hz occurring a few seconds apart in the same burst (Figure 38). The first candidate came from a 0.5 s window on the burst rise, had $P_m = 31.3$ (29.3 on non-normalized data), and an FA of 13%. The second candidate came from a 1 s window right after the burst peak and had $P_m$ of 36.8 (33.8 on non-normalized data) and an FA of 4%. The other 43 bursts did not have any candidates at similar frequencies.

The moderate power (more than half of simulations had the same or larger number of candidates of at least the same significance) and the lack of detections in multiple time windows or bursts do not allow us to classify these candidates as TBOs; however, the other properties (candidates framing burst peak for the PRE burst, second candidate being a few Hz higher than the first one) are similar to confirmed TBOs (see, e.g., SAX J1750.8−2900).

IGR J17473−2721 also had many low-frequency candidates at frequencies of 2–6.25 Hz. Sometimes low-frequency candidates were spread uniformly throughout an on-burst window, sometimes they formed distinct groups.

A.3.4. SAX J1810.8−269: New TBO Source

The MINBAR catalogue lists six bursts from SAX J1810.8−269. They are relatively bright and some of them have data gaps. Strong oscillations ($P_m = 78.58$, 74.28 on the non-normalized data) were discovered at ~531 Hz in the B region of one of the bursts (Figure 39). For the adopted detection threshold, the signal is present in one independent 4 s time window. None of the simulations had a signal with similar...
However, the occurrence within the burst (marked as PRE in the MINBAR catalogue) and frequency separation resemble typical TBO behavior.

No low-frequency or noise candidates were detected from SAX J1810.8-269.

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Figure 38. Interesting pair of oscillation candidates from IGR J17473–2721. The candidates are rather faint and not significant based on their power alone. However, the occurrence within the burst (marked as PRE in the MINBAR catalogue) and frequency separation resemble typical TBO behavior.

Figure 39. TBOs from a new oscillation source SAX J1810.8–269. 