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A Millisecond Oscillation in the Bursting X-Ray Flux of SAX J1810.8–2609

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Abstract

SAX J1810.8−2609 is a faint X-ray transient, mostly known for its low quiescent thermal luminosity, which disagrees with slow cooling in the core. It is also one of a small sample of stars with a mass and radius that has been estimated using spectral modeling of one of its thermonuclear bursts. Here we report the discovery of millisecond oscillation in a type I thermonuclear X-ray burst from SAX J1810.8−2609 observed by *Rossi X-Ray Timing Explorer* (*RXTE*) during the 2007 outburst. A strong signal (probability of false detection corresponding to 5.75σ of the normal distribution) was present at 531.8 Hz during the decay of one out of six bursts observed. An oscillation was detected for about 6 s, during which its frequency increased from 531.4 to 531.9 Hz in a manner similar to other burst oscillation sources. The millisecond oscillation establishes the spin frequency of the neutron star (NS), which is important for the spectral modeling, associated mass–radius inference, and the evolutionary status and cooling behavior of the star. The source goes into outburst semi-regularly (most recently in 2018 April), providing an opportunity to acquire new material for the burst oscillation searches.

Key words: stars: individual (SAX J1810.8-2609) – stars: oscillations (including pulsations) – X-rays: binaries

1. Introduction

Millisecond oscillations in type I X-ray bursts are caused by the development of asymmetric bright patches during thermonuclear explosions on the surface of accreting neutron stars in low-mass X-ray binaries. Burst oscillations are rare phenomena, having only been observed in 18 out of about 110 sources.[5] Oscillation amplitudes can take a range of values (typically, 5%–20% for the fractional rms amplitudes), with higher amplitudes being more prevalent in certain accretion states, and the majority of the non-detections can be attributed to the lack of observations in the appropriate state (Ootes et al. 2017). However, what causes this spread of amplitudes remains a mystery.

Burst oscillations can occur in any part of the burst and usually last for several seconds. They are highly coherent, with frequencies typically (but not always) drifting smoothly upward by 1–3 Hz toward the asymptotic maximum, nearly constant for each source. Oscillation frequencies range from 245 to 620 Hz (Watts 2012), but oscillations at frequencies as low as 11 Hz (e.g., Cavecchi et al. 2011) have also been detected. The similarity between the oscillation and spin frequencies of several accretion-powered pulsars (e.g., SAX J1808.4−3658 (Chakrabarty et al. 2003), XTE J1814−338 (Strohmayer et al. 2003), and others) revealed the tight connection between the oscillation frequency and the spin frequency of the neutron star (NS), enabling the determination of spin frequencies for several neutron stars that do not manifest themselves as pulsars.

Burst oscillations are unique tools for exploring the nuclear burning in the strong gravity and $\sim 10^8$ G magnetic fields on the NS surface. Also, folded waveforms of burst oscillations bear the imprints of the gravitational field at the NS surface, allowing for simultaneous measurements of the star's mass and radius and thus constraining the equation of state of matter at supra-nuclear densities (see Watts et al. 2016, for an overview).

SAX J1810.8−2609 is a low-mass X-ray binary discovered with the Wide Field Camera on board the *BeppoSAX* satellite (Ubertini et al. 1998). The source spends most of its time in a quiescent state, with four outbursts observed so far: in 1998, 2007, 2012, and 2018 (for the most recent one, see Negoro et al. 2018). Both quiescent and outburst luminosities of SAX J1810.8−2609 are considered to be relatively low (Natalucci et al. 2000; Jonker et al. 2004; Fiocchi et al. 2009); however, see the discussion in Degenaar & Wijnands (2013) and Wijnands et al. (2017).

SAX J1810.8−2609's thermal luminosity during quiescence is in disagreement with slow cooling in the NS core, suggesting an order of magnitude smaller accretion rate than is inferred from its outburst activity (Jonker et al. 2004; Allen et al. 2018). Thermal emission from one of the Type I bursts from the 2007 outburst has been used by Suleimanov et al. (2017) to constrain the mass and radius of this NS using the direct cooling tail method (for a more general discussion of these methods, see the discussion in Miller 2013 and Watts et al. 2016). Their analysis yielded $R = 11.5$–13.0 km for the 99% confidence region at an assumed mass of $M = 1.3$–$1.8\,M_\odot$. However, the 68% confidence upper limit that they found on the mass is $\sim 1.5\,M_\odot$.

Because of relativistic rotational effects, knowing the spin frequency of NS is important for spectral modeling both in quiescence and during outbursts and bursts (Bauböck et al. 2015; Burke et al. 2018). It would also put constraints on the evolutionary history of the system (e.g., how much accretion it has experienced), which could be helpful for explaining the low temperature of the NS (Allen et al. 2018).

In this Letter we report the discovery of a 531.8 Hz burst oscillation in one of the six bursts recorded by *Rossi X-Ray Timing Explorer* (*RXTE*) in the 2007 outburst. This makes SAX J1810.8−2609 the 19th known source with burst

[5] http://www.sron.nl/~jeanz/bursterlist.html, see also Galloway et al. (2008), Watts (2012), and references therein.

Table 1
Summary of Burst Properties: All Quantities Except for Burst Duration are Taken from the MINBAR Catalog; Estimates of Burst Duration Come from A. V. Bilous et al. (2018, in preparation)

Burst#	*RXTE* ObsID	Burst Epoch (MJD UT)	Burst Start Date (yyyy mm dd)	Burst Duration (s)	Peak Count Rate per PCU (10^3 ct s^{-1})	Bolometric Fluence (10^{-6} erg cm^{-2})	Persistent Flux (10^{-9} erg cm^{-2})	Photospheric Radius Expansion?
1	93044-02-04-00	54325.89373	2007 Aug 13	106	6.7(1)	1.37(1)	1.012(5)	yes
2	93044-02-05-00	54326.97236	2007 Aug 14	89	5.6(1)	1.05(5)	1.225(5)	no
3	93044-02-07-00	54332.87613	2007 Aug 20	75	8.8(1)	0.81(1)	1.12(6)	yes
4	93093-01-01-00	54369.80255	2007 Sep 26	91	5.8(1)	0.96(1)	1.21(3)	no
5	93093-01-01-00	54370.05022	2007 Sep 27	70	5.5(1)	0.92(1)	1.21(3)	no
6	93093-01-01-01	54370.33383	2007 Sep 27	66	5.8(1)	0.93(9)	1.16(8)	no

oscillations and places the system among the fast-spinning NSs in low-mass X-ray binaries.

2. Data Analysis

We analyzed the data from the Proportional Counter Array on board *RXTE* (Jahoda et al. 2006) for the six bursts that were observed between 2007 August and September. The observation IDs and the MJDs of arrival (Table 1) were taken from the Multi-INstrument Burst ARchive (MINBAR;[6] D. K. Galloway et al. 2018, in preparation). The duration was defined as the time span where 2–60 keV, 0.5 s count rate from Standard-1 files was larger than mean plus two standard deviations of the count rate in the pre-burst baseline window. For the oscillation searches we used Science Event files (`E_125us_64M_0_1s`), which had time resolution of 122 μ and 64-channel energy resolution in the 2–60 keV range.

In order to search for oscillations, we applied the standard technique of calculating power spectra in sliding windows of $\Delta T = 0.5$, 1, 2, and 4 s; each new window started with a 0.5 s offset with respect to the previous one. For each window, Fourier frequencies between 2 and 2002 Hz were recorded. The upper limit on the oscillation frequency reflects the upper limit on NS spin frequency set by all of the current reasonable models of the NS equation of state (Haensel et al. 2009).

One of the bursts (#3 in Table 1) yielded a strong signal at frequencies of about 532 Hz for all fast Fourier transform (FFT) window lengths. The Leahy-normalized power (Leahy et al. 1983) was largest for 4 s windows, reaching $P_{\rm m} = 71.5$ at 531.75 Hz, well above the $P_{\rm m} = 2$ mean noise level (Figure 1). Assuming the noise power is distributed as χ^2 with two degrees of freedom, the single-trial probability of obtaining such power is 3×10^{-16}. By a conservative estimate, counting all of the time bins and time windows as independent trials, the number of trials for all six bursts in total include 994×4 time windows with 1000–8000 frequency bins per window, summing up to $N_{\rm tr} = 994 \times (1000 + 2000 + 4000 + 8000) \approx 1.5 \times 10^7$. Even with this conservative estimate, the chance probability of obtaining such a strong signal (4.5×10^{-9}) is negligible. The estimated value of the chance probability corresponds to 5.75σ of the normal distribution.

Up to now, there have been known 18 sources with burst oscillations. Nine more sources have tentative detections (Watts 2012). Normally, the detection of coherent oscillations at similar frequencies in multiple bursts or in multiple independent time bins serves as a firm corroboration of burst oscillations. Although the oscillation from SAX J1810.8−2609 appeared in two independent time bins (see below), it was detected in one burst only, motivating more searches for burst oscillations in the future.

For burst #3, oscillation with $P_{\rm m} > 24$ (corresponding to $p < 6 \times 10^{-6}$ for χ^2 noise distribution) was detected in two independent consecutive 4 s time bins. The probability of such a detection being due to chance is $p^2 \times 994 \times 8000 \approx 3 \times 10^{-4}$, where we make the most conservative estimate for the number of trials, $N_{\rm tr} = 994 \times 2000 \times \Delta T$. Overall, the $P_{\rm m} = 71.5$, 5.75σ single-bin single burst oscillation detection for SAX J1810.8−2609 is more significant than detections from other sources deemed "tentative" in Watts (2012; up to 4.9σ). It is also more significant than at least some of the discovery detections of subsequently confirmed burst oscillations (e.g., SAX J1750.8−2900, 5.0σ, Kaaret et al. 2002).

In order to explore the possible frequency drift, we computed a dynamic power spectrum using Z^2 statistics (Buccheri et al. 1983). Unlike Fourier transforms that use binned data, Z^2 statistics use the time of arrival of each individual photon and can be computed at arbitrarily close frequencies (although the frequency resolution is still determined by the choice of ΔT). We used 4 s time bins overlapping by 3.875 s and frequency bins starting from 531 Hz and increasing in 0.125 Hz steps. The dynamic power spectrum is shown on Figure 2. The oscillation signal is present at 6–12 s counting from the burst start and the frequency drifts from 531.4 to about 531.9 Hz. The largest value of the Z^2 statistic was 81.

The Leahy-normalized power spectra were used to compute the fractional amplitude of oscillation (Watts et al. 2005):

$$A = \left(\frac{P_{\rm s}}{N_{\rm m}}\right)^{1/2} \frac{N_{\rm m}}{N_{\rm m} - N_{\rm bkg}}. \qquad (1)$$

Here $P_{\rm s}$ is the Leahy-normalized power of signal in the absence of noise, $N_{\rm m}$ is the number of photons in the given time bin, and $N_{\rm bkg}$ is the estimated number of background photons in the same time bin. We used the median value of $P_{\rm s} = P_{\rm m} + 1$ from the distribution of $P_{\rm s}$ given $P_{\rm m}$ derived by Groth (1975), but with Leahy normalization (see discussion in Watts 2012). The uncertainty on $P_{\rm s}$ was taken from [0.159, 0.841] percentiles of the same distribution. The uncertainty on the number of photons in a time bin, $N_{\rm m}$, was taken to be Poissonian, and the uncertainty in the background level was taken to be the standard deviation of count rates in the 4 s overlapping time bins within 120 s window prior to the burst onset. Fractional amplitude errors were calculated as linear error propagation of the independent parameters (Ootes et al. 2017). For the strongest signal, the fractional rms amplitude was $4.7 \pm 0.6\%$. We did not detect any signal at the first harmonic frequency: between 1063 and 1064 Hz the maximum $P_{\rm m}$ was 2.6. In order to place the upper limit on the oscillation amplitude at the first harmonic, we used distribution of $P_{\rm s}$ given $P_{\rm m} = 2.6$ from Groth (1975), but with Leahy normalization. Adopting the 0.841 percentile of $P_{\rm s}$, $P_{\rm s} \approx 8.1$, as an upper limit on signal power, we find the fractional rms amplitude to be less than 1.5%.

No signal was found in any of the other five bursts, although their peak count rates are comparable (Table 1). Bolometric fluences and the levels of persistent flux at burst times are also similar between all six bursts, although burst #3 has the largest peak count rate and the smallest bolometric fluence. Interestingly though, burst #3 is one of the two bursts out of six from this source with photospheric radius expansion in the MINBAR catalog.

3. Discussion

The oscillation from SAX J1810.8−2609 has properties that are typical for the burst oscillations from other sources: frequency around 500 Hz, duration of few seconds, the small upward frequency drift toward an asymptotic frequency, and moderate fractional amplitudes. However, the rapid frequency drift happens relatively late after the peak of the burst, which seems to be difficult to reconcile with a spreading hotspot

[6] https://burst.sci.monash.edu/minbar/

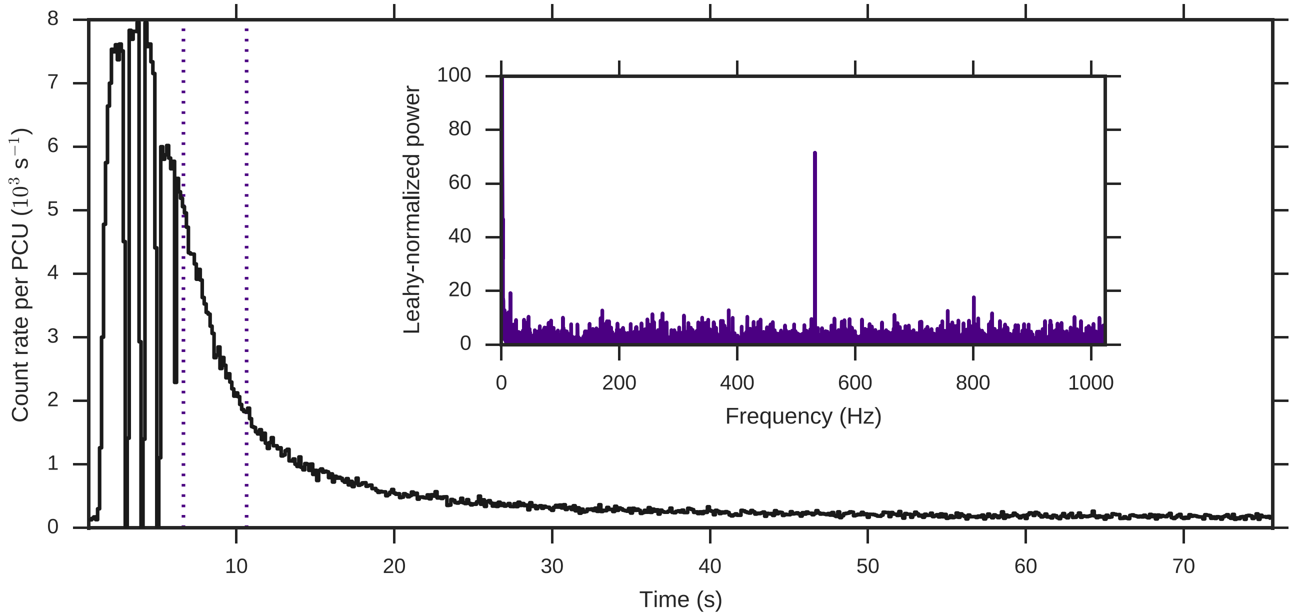

Figure 1. Burst #3 from Table 1. The main panel shows count rate of Science Event data, with time counted from the burst start. Small data gaps due to telemetry limitations are present at higher count rates. The inset shows the Leahy-normalized power spectrum from the 4 s time interval marked with dashed lines on the main panel. In this time interval the oscillation signal was the strongest, with the power of over 70 at 531.75 Hz.

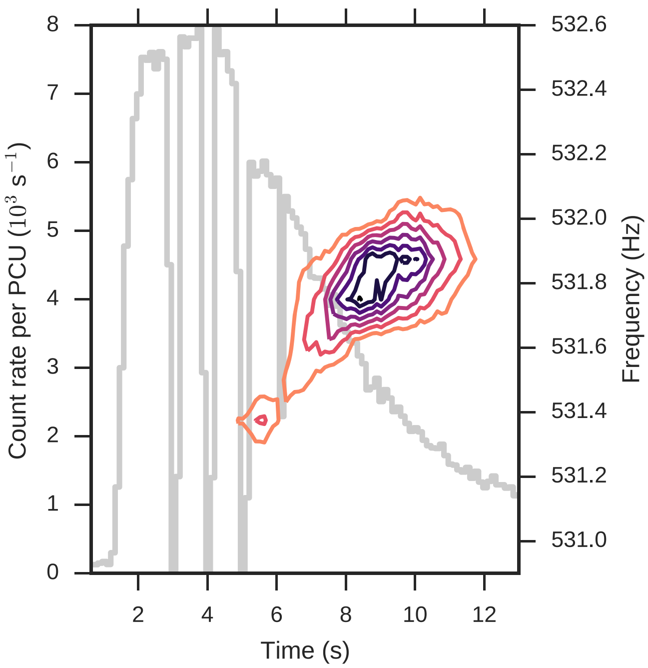

Figure 2. Z^2 power spectrum of burst #3. The Z^2 values were computed in 4 s intervals overlapping by 3.875 s, at frequencies oversampled by a factor of 2. The power is plotted at the midpoint of each interval. Contour levels mark Z^2 from 20 to 80 with the step of 10. The peak power was 81.

model. Some possible explanations involve surface modes or vortices forming in the tail of the burst (e.g., Spitkovsky et al. 2002; Heyl 2004).

The oscillation has been observed in the burst with the strongest photospheric radius expansion (PRE; out of two such bursts in the sample). Another burst with PRE, #1 from Table 1, has been used to constrain mass and radius of this NS using the direct cooling tail method, which uses atmospheric models to convert the spectral evolution during burst tail to the stellar angular size (Suleimanov et al. 2017). As shown by Bauböck et al. (2015), rapid rotation can have a significant effect on the radius using this method: failure to include rotational effects leads to the radius or mass being underestimated. Neither Nättilä et al. (2016) nor Suleimanov et al. (2017) included rotation in their models, as it complicates the computations by introducing two more free parameters (spin period and inclination). Establishing the spin frequency of SAX J1810.8−2609 allows us to make corrections to the model and obtain better constraints on mass and radius of this NS. A spin rate of 532 Hz could result in a radius up to ∼5% larger (Bauböck et al. 2015).

Knowing the spin of NS is important for modeling the spectrum of persistent outburst emission. Burke et al. (2018) analyzed a sample of sources where the spin is known and found that Comptonization strength is larger for more rapidly spinning stars. The observations are thus in agreement with the theoretical scenario, in which for more rapidly spinning neutron stars less energy is liberated during the deceleration of accreted material in a boundary layer, resulting in a lower seed photon luminosity and less Compton cooling in the corona. SAX J1810.8−2609 has a relatively large spin frequency, which might naturally explain the fact that the accretion spectrum does not have a clear cutoff below 200 keV (Natalucci et al. 2000).

Finally, the high spin frequency of SAX J1810.8−2609 may corroborate or eliminate some mechanisms suggested to explain its very low quiescent luminosity. According to Allen et al. (2018), some of the possible explanations for the unusually low temperature of this NS include some enhanced cooling processes (e.g., direct Urca), a hybrid crust, or overestimation of the time-averaged outburst accretion rate. If the system is young or had extremely low accretion rates, it could not accrete enough material to replace the NS crust during its lifetime, forming so-called hybrid crust. Deep crustal heating is suppressed in a hybrid crust (Wijnands et al. 2013). The high spin frequency of SAX J1810.8−2609, if due to accretion-induced spin-up, may be at odds with the system being either young or having low accretion rate.

Enhanced cooling via the direct Urca process requires more massive NS (1.6–1.8 $M_{\odot}$). Currently this mass is outside the 68% probability region of Suleimanov et al. (2017), however it needs to be revisited with spin corrections included. As was shown by Bauböck et al. (2015), for a known radius, neglecting rotation underestimates the mass.

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