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DISCOVERY OF A 552 HZ BURST OSCILLATION IN THE LOW-MASS X-RAY BINARY EXO 0748−676

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ABSTRACT

We report the detection of pulsations at 552 Hz in the rising phase of two type-I (thermonuclear) X-ray bursts observed from the accreting neutron star EXO 0748−676 in 2007 January and December, by the *Rossi X-ray Timing Explorer*. The fractional amplitude was 15% (rms). The dynamic power density spectrum for each burst revealed an increase in frequency of ≈ 1–2 Hz while the oscillation was present. The frequency drift, the high significance of the detections and the almost identical signal frequencies measured in two bursts separated by 11 months, confirms this signal as a burst oscillation similar to those found in 13 other sources to date. We thus conclude that the spin frequency in EXO 0748−676 is within a few Hz of 552 Hz, rather than 45 Hz as was suggested from an earlier signal detection by Villarreal & Strohmayer (2004). Consequently, Doppler broadening must significantly affect spectral features arising from the neutron star surface, so that the narrow absorption features previously reported from an *XMM-Newton* spectrum could not have arisen there. The origin of both the previously reported 45 Hz oscillation and the X-ray absorption lines is now uncertain.

Subject headings: stars: neutron — X-rays: binaries — X-rays: bursts — X-rays: individual(EXO 0748-676)

1. INTRODUCTION

Neutron stars in low-mass X-ray binaries (LMXBs) provide observational evidence for their rapid spins reluctantly, and via increasingly diverse phenomena. Highly coherent burst oscillations, occuring only around the peak of thermonuclear (type-I) bursts, were the first such phenomenon to be discovered, and since have been detected in ≈ 14 sources (e.g. Watts et al. 2008). Continuous pulsations in the persistent emission occur even more infrequently, and occur at just above the burst oscillation frequency in those sources which exhibit both (Chakrabarty et al. 2003). This result supports the hypothesis that the burst oscillation frequency traces the neutron star spin. Most recently, intermittent persistent pulsations have been detected in several sources, including one previously known burst oscillation source (e.g. Galloway et al. 2007; Altamirano et al. 2008; Casella et al. 2008).

It is uncertain why some sources show pulsations or burst oscillations and others do not. Additionally, sources which exhibit burst oscillations do not do so in every burst. In fact, the presence of oscillations can be as rare as 1 burst in 14 (for 4U 1916−053; see Galloway et al. 2008). The mechanism by which the burst oscillations are produced is yet another uncertainty. Although oscillations are observed at high (fractional) amplitudes early in some bursts, consistent with a spreading "hot spot" model (e.g. Strohmayer et al. 1997), the oscillations in the burst tail, when the burning must have spread to the entire stellar surface, are harder to explain. The oscillations may instead (or also) arise from anisotropies in the surface brightness originating from hydrodynamic instabilities (Spitkovsky et al. 2002) or modes excited in the neutron star ocean (e.g. Cumming & Bildsten 2000; see also Heyl 2004; Piro & Bildsten 2005).

The low-mass X-ray binary EXO 0748−676 is particularly well-studied. This transient was discovered during *EXOSAT* observations in 1985 (Parmar et al. 1986), which also revealed the first thermonuclear bursts from the source as well as X-ray dipping activity. Synchronous X-ray and optical eclipses (Crampton et al. 1986) are observed once every 3.82 hr orbit. A variety of low- and high-frequency variability has been characterised (e.g. Homan et al. 1999; Homan & van der Klis 2000), notably including a 695 Hz quasi-periodic oscillation. More recently, absorption features in the summed X-ray spectra of bursts observed by *XMM-Newton* were identified as redshifted lines from near the neutron star surface ($z = 0.35$; Cottam et al. 2002). The narrowness of these features requires that the neutron star is rotating slowly, as rotation speeds $\gtrsim 100$ Hz will broaden the line profiles to the point where they are undetectable (Özel & Psaltis 2003; Chang et al. 2006; Bhattacharyya et al. 2006). Subsequently, Villarreal & Strohmayer (2004) detected a 45 Hz peak in the summed power spectrum of 38 thermonuclear bursts, which they interpreted as a spin frequency sufficiently slow to give negligible broadening. However, subsequent followup studies have failed to con-

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firm the spectral line detection (e.g. Cottam et al. 2008).

Here we present analysis of recently observed bursts from EXO 0748−676 which suggest that the neutron star spin is not 45 Hz, but 552 Hz.

2. OBSERVATIONS

We analysed observations of EXO 0748−676 made with the Proportional Counter Array (PCA; Jahoda et al. 1996) onboard the *Rossi X-ray Timing Explorer* (*RXTE*). The PCA consists of five identical, co-aligned proportional counter units (PCUs), sensitive to photons in the energy range 2–60 keV. A passive collimator restricts incoming photons to a circular field-of-view with radius $\approx 1^\circ$. Photon counts from the PCA are processed independently by up to 6 Event Analyzers (EAs) in a variety of configurations, permitting time resolution down to $1\mu s$ and up to 256 spectral channels.

In an earlier paper we presented a detailed study of the properties of all thermonuclear bursts in public *RXTE* data through 2007 June (Galloway et al. 2008, hereafter G08). Additional observations are continually being made public, and we are periodically analysing these newly available data[4] to extend the G08 sample. EXO 0748−676 was observed intensively throughout 2006–7 to monitor low- and high-frequency quasi-periodic oscillations. We analysed 223 additional observations to the G08 sample, and detected 67 additional thermonuclear bursts. Our burst detection and analysis procedures are identical to those of G08.

One component of the analyses is a search for burst oscillations from sources that have not previously exhibited them. For each burst, we extract a lightcurve over the full PCA energy range and binned on $122\mu s$. We then search for oscillations while the burst flux is at least 10% of the peak value for that burst. For EXO 0748−676, the search duration in all the bursts was typically in the range 12–90 s, or 40 s in the mean. The search is carried out by computing Fast Fourier Transforms (FFTs) of overlapping windows of data of length 1, 2, and 4 s, stepped by 0.25 s. For each power spectrum we search for excess power at frequencies > 10 Hz, below which red noise from the burst rise and decay dominates.

We set a detection threshold corresponding to 3σ significance taking into account the number of trials for each window. However, we consider a single detection at this confidence level, or detections in windows that overlap in time, insufficient to confirm a burst oscillation. Robust detections require exceeding our threshold in power spectra from multiple independent time windows, either in the same burst or other bursts from the same source, and at frequencies within a few Hz.

3. RESULTS

We measured power far exceeding the noise level in power spectra of two bursts from EXO 0748−676, on 2007 January 14 14:08:44 UT (MJD 54114.58941) and 2007 December 13 13:29:20 UT (MJD 54447.56204)[5]. In the first burst, a power spectrum of a 1-s window of data beginning 0.125 s before the burst start (here defined as the time at which the burst flux first exceeded 25% of the peak flux, following G08) exhibited a peak Leahy power of 59.68 at a frequency of 552 Hz (Fig. 1). The second burst, occurring almost a year later, in a 2 s window of data beginning 0.5 s before the burst start reached a Leahy power of 48.26 at a frequency of 552.5 Hz.

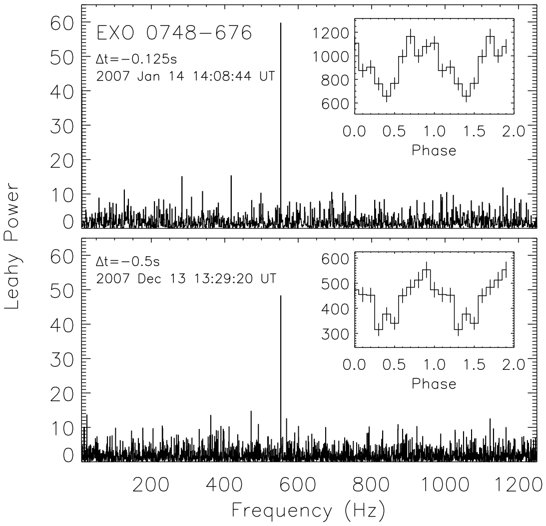

FIG. 1.— Significant power excess at 552 Hz in two bursts from EXO 0748−676. We show the power-density spectra covering a 1-s window beginning 0.125 s before the start of the 2007 January 14 burst (*top panel*), and from a 2-s window of data beginning 0.5 s before the start of the 2007 December 13 burst (*bottom panel*). The inset in each panel shows the folded pulse profile (units of count s^{-1} PCU^{-1}) within each interval; two full cycles are plotted for clarity. The relative phase of the two profiles is arbitrary.

While both these detections are highly significant (with single trial probabilities of 10^{-13} and 10^{-11}) we did not detect the signal in multiple independent (non-overlapping) time windows in either burst. However, the correspondence of the detection frequencies in two separate bursts virtually guarantees the signal is real. We estimated the likelihood of two such peaks separated by less than 1 Hz arising by chance, as the product of the probabilities for each detection, multiplied by the probability related to their separation. Assuming a uniform distribution for noise peaks over the full frequency range of 10–4000 Hz, the probability for two such nearby detections is roughly 2.5×10^{-4}. Taking into account all trials in the blind search covering all 157 bursts from EXO 0748−676 in the extended G08 catalog the estimated null hypothesis probability is 10^{-10}, equivalent to 6.3σ. This estimate includes no correction for the lack of independence between the searches in overlapping time windows; such correction would only increase the significance. We also measured the distribution of noise powers in the absence of a signal for simulated lightcurves matching the observed 0.125-s lightcurve within each time window in which the oscillation was detected. We confirmed that the noise powers are distributed as χ^2 with two degrees of freedom, which supports our estimated significance. Thus, we conclude that the signal is a genuine burst oscillation.

We folded the lightcurve in each time window in which the 552 Hz signal was detected initially, to measure the amplitude and harmonic content of the profile. Since the

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[4] Available from the High-Energy Astrophysics Science Archive Research Center (HEASARC), at \protecthttp://heasarc.gsfc.nasa.gov.

[5] Observation IDs 92019-01-13-00 & 92019-01-28-02

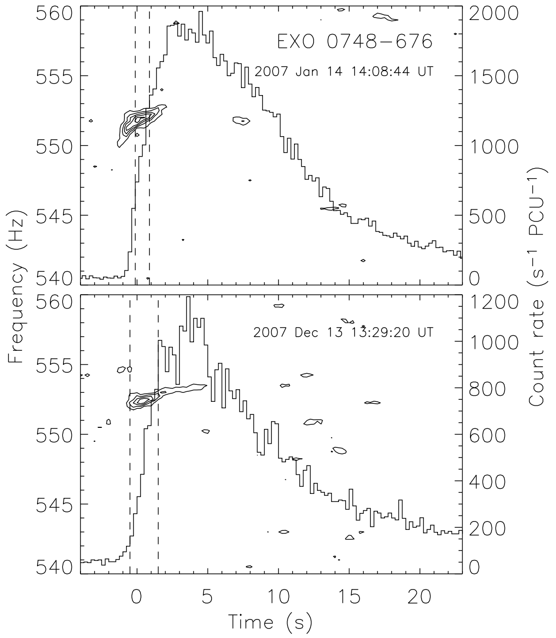

FIG. 2.— Dynamic power density spectra computed from oversampled FFTs covering the two bursts from EXO 0748−676 in which we detected burst oscillations. In each panel the contours show the Leahy power as a function of time and frequency (left-hand y-axis). The contour interval is 10; the overall maximum is slightly lower than in the power spectrum from the blind search because we oversample by a factor of two. The histogram shows the burst (count) profile, binned on 0.25 s (right-hand y-axis). The dashed lines in each panel show the intervals in which the oscillation was first detected in the blind search.

power spectra in each case have rather limited frequency resolution, we folded the data on a grid of frequencies and chose the frequency value which maximised the variance in the folded profile. The corresponding frequency value for the January 14 burst was 552.02 Hz, while for the December 13 burst was 552.45 Hz. We tested for the presence of harmonic content from the power spectrum of the folded pulse profile, following Muno et al. (2002). The maximum Leahy power for the 2007 January burst at 2× the oscillation frequency was 6.47, which was below our detection threshold. The power at 3 or more times the oscillation frequency was comparable or smaller, and even smaller powers were measured for the December burst. Thus, we found no evidence for significant power at the 2nd or higher harmonics during either burst. We fitted each profile with a sinusoidal model, giving fractional rms amplitudes of $15.2 \pm 1.7\%$ and $15 \pm 2\%$ for the January 14 and December 13 bursts, respectively. The uncertainties were estimated by fixing the amplitude on a grid of values, re-fitting the model with the remaining parameters free, and determining the range for which the $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min} < 1$ (for 1-σ error).

To determine the energy dependence of the oscillation we subdivided the PCA energy band in five intervals adjusted to give approximately the same source counts in each. We then created background-subtracted lightcurves for photons within each energy band and folded each lightcurve on the best-fit pulse frequency determined above. The rms pulse fraction (for a single sinusoid) increased steadily from $\approx 10\%$ between 2–4 keV, to 20% above 9 keV, consistently in both bursts. The arrival phase of the pulse varied weakly below ≈ 8 keV, but appeared to arrive earlier by 0.07 ± 0.01 in phase (≈ 0.1 ms) above this energy.

We also computed oversampled FFTs covering each burst to measure the evolution of the oscillation. In both bursts we found evidence of an increase in the signal frequency, which is characteristic of burst oscillations (Fig. 2). The signal appears initially at a lower frequency (approximately 551 Hz) in the January 14 burst and increases in frequency more rapidly. The overall frequency drift for the two bursts was no more than 2 Hz (0.4%).

Following the detection, we performed a narrowband search for the signal in all 154 other bursts detected by *RXTE* from EXO 0748−676, and for which high time resolution data was available. As in G08, we computed FFTs of each 1 s interval of data for the first 16 s of the burst, and searched for signals within 5 Hz of the 552 Hz oscillation frequency. We considered a signal to be a detection if it had less than a 1% chance of occurring due to noise given the 160 trial frequencies searched for each burst, and also if it persisted for two adjacent (independent) time and frequency bins with a chance probability of $< (6 \times 10^{-5})^{1/2}/6 = 1.3 \times 10^{-3}$, or if it occurred in the first second of a burst with a chance probability of $< 10^{-3}$. With these criteria we found two additional (albeit weak) detections, in bursts on 2007 May 19 12:55:55 UT and 2007 Dec 5 12:15:34 UT. In the May 19 burst oscillations were detected weakly in the peak (defined as the interval during which the count rate exceeded 90% of the maximum) and tail (from the peak onwards), whereas in the December 5 burst the oscillations were detected in the rise, as with the initial detections.

We also revisited the analysis of Villarreal & Strohmayer (2004), to measure the significance of the 45 Hz signal in the full sample of 157 bursts observed by *RXTE* from EXO 0748−676 to date. We first reproduced the analysis of Villarreal & Strohmayer (2004) with their original sample of 38 bursts and the same energy selection and lightcurve rebinning strategy, obtaining similar results for the 45 Hz peak and its significance. Next, we applied the same technique to the larger sample of 157 bursts now available, but did not detect the signal (using a detection threshold corresponding to 2σ single-trial significance). Finally, noting that the 38 bursts used by Villarreal & Strohmayer (2004) all occurred at times when the persistent flux (measured by the *RXTE*/ASM daily average count rates) was atypically low, mostly below 1 count s^{-1}. Therefore, we also searched the subset of 129 bursts from the full sample that also occurred during such low flux intervals and applied the same search technique. However, the 45 Hz signal was again not detected.

4. DISCUSSION

There are substantial differences in the characteristics of the two burst oscillations (45 Hz and 552 Hz) now detected in EXO 0748−676. The 45 Hz signal had a fractional amplitude of $\approx 3\%$ (rms) and was detected in the summed power spectrum of 38 bursts, rebinned by a factor of (typically) 64 or 128 to give a resolution of 1 Hz, calculated from light curves selecting photons within the energy range 6–60 keV, and covering intervals of typically 64 or 128 s of the burst decay. In contrast, the 552 Hz signal has a fractional amplitude of 15% (rms), was detected separately in unbinned power spectra calculated from 1- and 2-s light curves extracted over the full PCA energy range ($\approx$ 2–60 keV) during the rise of two individual bursts, separated by 11 months. Additionally, the dynamic power density spectra give evidence for frequency evolution while the 552 Hz signal was present, similar to that observed in other burst oscillation sources. The key question is, which of these two signals traces the neutron star spin?

We consider three alternatives. First, assuming both signals are genuine, the 45 Hz signal may arise from the neutron star spin, in which case the 552 Hz signal may arise from a high-order ($m \approx$ 12–13) radial mode (Cumming & Bildsten 2000; see also Heyl 2004; Piro & Bildsten 2005). However, the appearance of this mode alone is difficult to explain; one would expect the excitation of many different modes, rather than just two with widely-separated orders. Second, if both signals are real but the 552 Hz signal instead indicates the neutron star spin, there is no known mechanism that can give rise to a 45 Hz signal from the neutron star surface. As suggested by Balman (2009), the 45 Hz oscillation may instead arise in the boundary layer between the disk and neutron star.

Third, the lack of a detection of the 45 Hz signal in the larger sample of bursts detected since 2004 suggests that the 45 Hz signal may have arisen from statistical fluctuations. Our analysis shows that including many more bursts in the power spectral sum has the effect only of reducing the detection significance to well below any conservative detection threshold. The signal power is also quite sensitive to other parameters of the data selection. Thus, while it is possible that the 45 Hz oscillation is transient and has not been detectable since, it is also difficult to rule out an origin in statistical noise with any confidence.

The properties of the 552 Hz oscillation closely resemble those of the burst oscillations observed in other systems, that are believed to trace the neutron star spin to within a few Hz. In contrast, the properties of the 45 Hz oscillation are quite distinct, especially its low frequency and the inability to detect it in individual bursts. Thus, we conclude that the 552 Hz signal almost certainly traces the neutron star spin in EXO 0748−676; since the signal appears to increase by up to 2 Hz during the burst rise, we expect that the true spin frequency may be a few Hz higher.

The energy dependence of the 552 Hz oscillation amplitude in EXO 0748−676 was similar to that of other burst oscillation sources (Muno et al. 2003), although the overall amplitudes were higher. The suggestion of the hard ($\gtrsim$ 8 keV) photons arriving earlier than the soft photons is however contrary to previous observations. In that respect we note that the previous analysis focussed principally on oscillations present throughout the tails of bursts, whereas the oscillations in EXO 0748−676 were present only in the rise. It is not known whether the two types of oscillations have characteristically different variation of pulse arrival time with energy.

The duty cycle of the 552 Hz oscillation (the number of bursts in which it was detected compared to the total number observed) is extremely small at $\approx$ 1.2%, the smallest yet for all the burst oscillation sources (e.g. G08). The unprecedented scarcity of the oscillation raises the question of what was so unusual about the bursts that exhibited them. Compared to the entire sample of bursts observed by *RXTE* from EXO 0748−676, the bursts on January 14 and December 13 had somewhat shorter timescales (calculated as the ratio of peak flux to fluence) τ = 12–13 s, while the typical range is 15–30 s. Similarly, the rises were of shorter duration than average, at 2–4 s. Shorter burst timescales suggest a smaller proportion of hydrogen in the burst fuel than usual. Correspondingly, while the fluences were rather typical, the bursts reached higher than average peak fluxes. However, other bursts were observed with similar properties which did not exibit oscillations, so these properties do not uniquely determine their observeability. The January 14 burst occurred only 11.4 min after the previous event, and had a fluence only about 77% lower. Such short recurrence time bursts are common for EXO 0748−676, and many examples have been detected by *RXTE* (e.g. G08) as well as *XMM-Newton* (Boirin et al. 2007). However, the second burst in these pairs is typically much fainter than the first. Interestingly, it is also possible that the December 13 burst was the second in a closely-spaced pair, as a data gap (due to the 90 min satellite orbit) prevented observations until approximately 7 min before the event. Again, timing analysis of other such examples did not reveal any additional oscillations, however.

We also compared the properties of the persistent emission at the time when the bursts with oscillations occurred, to other public *RXTE* observations of the source (from G08). The persistent flux in both observations was $\approx 3 \times 10^{-10}$ erg cm^{-2} s^{-1} (2.5–25 keV), approximately equal to the 50th percentile value of the flux distribution. Similarly, the hard and soft spectral colors[6] were in the middle of the observed range, at $\approx$ 0.8 and $\approx$ 1.6, respectively. Thus, we found no evidence for an unusual spectral or intensity state at the time of the bursts with oscillations.

A 552 Hz spin frequency for EXO 0748−676 means that spectral features arising from the neutron star surface will be significantly Doppler broadened, as well as reducing the central line depth to only $\lesssim$ 5% of the continuum level (e.g. Chang et al. 2005). Narrow lines from such rapidly-rotating objects can only arise if the system is viewed at extremely low inclinations; however, the eclipses and dipping activity in EXO 0748−676 unambiguously indicate a high system inclination. Thus, the narrow ($\approx$ 0.1 Å) spectral features reported by Cottam et al. (2002) could not arise from the neutron star surface. This conclusion is corroborated by other recent work, including the absence of lines in a deeper *XMM-Newton* spectrum (Cottam et al. 2008), as well as difficulties explaining the inferred Fe column (Chang et al. 2005). However, the narrow spectral features are difficult to identify otherwise (e.g. Kong et al. 2007), and a satisfactory explanation remains elusive.

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[6] Defined as in G08 as the ratio of the background-subtracted detector counts in the (8.6–18.0)/(5.0–8.6) keV and the (3.6–5.0)/(2.2–3.6) keV energy bands, respectively

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