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Discovery of the Spin Frequency of 4U 0614+09 with *Swift*/BAT

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ABSTRACT

We report the discovery of burst oscillations at 414.7 Hz during a thermonuclear X-ray burst from the low mass X-ray binary (LMXB) 4U 0614+091 with the Burst Alert Telescope (BAT) onboard *Swift*. In a search of the BAT archive, we found two burst triggers consistent with the position of 4U 0614+091. We searched both bursts for high frequency timing signatures, and found a significant detection at 414.7 Hz during a 5 s interval in the cooling tail of the brighter burst. This result establishes the spin frequency of the neutron star in 4U 0614+091 as ≈ 415 Hz. The oscillation had an average amplitude (rms) of 14%, These results are consistent with those known for burst oscillations seen in other LMXBs. The inferred ratio of the frequency difference between the twin kHz QPOs, and the spin frequency, $\Delta\nu/\nu_s$, in this source is strongly inconsistent with either 0.5 or 1, and tends to support the recent suggestions by Yin et al., and Mendez & Belloni, that the kHz QPO frequency difference may not have a strong connection to the neutron star spin frequency.

Subject headings: stars: neutron—stars: rotation—stars: oscillations—X-rays: bursts—X-rays: binaries–X-rays: individual (4U 0614+091)

1. Introduction

The detection of spin modulation pulsations during thermonuclear X-ray bursts, "burst oscillations," has become an important method for measuring the spin rates of neutron stars in accreting binary systems (see Strohmayer & Bildsten 2006 for a review). To date, almost all of the *a priori* detections of burst oscillations have been made with the Proportional Counter Array (PCA) onboard the *Rossi X-ray Timing Explorer* (RXTE). Indeed, its combination of large collecting area, low background, high time resolution, and high telemetry capacity enabled the first detections of the phenomenon. Pulsations during a bright burst from SAX J1808.4-3568 were detected with the Wide Field Camera (WFC) on *BeppoSAX* at the $\approx 3\sigma$ level, but in this case the spin frequency was already known (in 't Zand et al. 2003).

The Burst Alert Telescope (BAT) onboard *Swift* has a combination of large collecting area (5,200 cm^2) and high time resolution (100 μ-sec) that should, in principle, make it sensitive to burst oscillations from particularly bright X-ray bursts, although the BAT does suffer a significant loss of sensitivity to such oscillations due to its much larger background compared to the PCA. The BAT has a sophisticated triggering system that identifies Gamma-ray bursts (GRBS), and other fast transients, including thermonuclear bursts from accreting neutron stars. When a trigger occurs, an estimate of the source's position is derived onboard the *Swift* spacecraft, where it is checked against an onboard catalog of known objects. If the position is consistent with a source in the catalog, then the trigger is deemed to not be a GRB, and *Swift* will not initiate a direct slew to the position. However, high time resolution data is still accumulated around the trigger time. These data can then be searched for burst oscillations.

Historically, some of the brightest X-ray bursts observed, with fluxes of order 2×10^{-7} ergs cm^2 s^{-1}, have been associated with the low mass X-ray binary (LMXB) 4U 0614+091. Based on the detection of a bright burst with *Watch*, and Eddington limit arguments, Brandt et al. (1992) argued that the distance to 4U 0614+091 is likely < 3 kpc. Several lines of evidence point to the conclusion that 4U 0614+091 is an ultra-compact X-ray binary system. Juett, Psaltis & Chakrabarty (2001) inferred an enhanced neon to oxygen ratio for the system, and based on a comparison of the ratio with known ultra-compact systems, argued that 4U 0614+091 is a similar system. Sensitive optical spectroscopy by Nelemans et al. (2005) found carbon and oxygen emission lines, but no evidence for helium or hydrogen, further strengthening the ultra-compact classification. The optical counterpart to 4U 0614+091, V1055 Ori, is also intrinsically faint, consistent with a compact orbit (Nelemans et al. 2005; van Paradijs & McClintock 1994). The faintness of its persistent X-ray emission and nearby distance suggest a low accretion rate, again consistent with an orbital period < 1 hr (Deloye

& Bildsten 2003). Finally, we note that in 't Zand et al. (2007) cite a report by O'Brien (2005) of a 50 min. optical modulation, that could represent the orbital period.

Although 4U 0614+091 has been extensively studied with RXTE, it has not yet observed any X-ray bursts from the source. Ford et al. (1997) reported the discovery of kHz quasiperiodic oscillations (QPOs) from the source using RXTE data. They found a maximum QPO frequency of $\approx 1,145$ Hz, and a mean frequency separation of 323 ± 4 Hz between the upper and lower kHz oscillations (see van der Klis 2006, for a review of kHz QPOs). Based on this frequency separation they suggested a spin frequency of ≈ 323 Hz. Recent studies, however, have suggested that the frequency separation between the kHz QPOs may be more or less independent of the neutron star spin frequency (Yin et al. 2007; Mendez & Belloni 2007).

In this Letter we report the discovery of 415 Hz burst oscillations in a burst from 4U 0614+091 observed with the BAT instrument onboard *Swift*. In §2 we describe our timing study of bursts from 4U 0614+091 with BAT and summarize their basic properties. In §3 we discuss our results in the context of recent efforts to understand the relationship (if any) between the kHz QPOs and the spin frequencies of neutron stars in LMXBs.

2. Observations and Data Analysis

We searched the BAT archives for triggered events consistent with the position of 4U 0614+091, and found two; triggers 234849, and 273106. These events ocurred on October 21, 2006 and March 30, 2007, respectively. For imaging the BAT has a point spread function of 22 arcmin, but centroiding for source localization is typically accurate to 1 - 6 arcmin, based on the detection significance. The BAT-derived positions for each trigger were offset by 1.5 and 1.0 arcmin, respectively, from the well known position of 4U 0614+091, confirming it as the source of the bursts. The BAT data consist of X-ray event times with 100 μ-sec resolution as well as energy measurements for 43 seconds around each burst. BAT's nominal energy band is 15 - 150 keV, and the bursts are not detected above about 30 keV, which is consistent with a thermonuclear origin. Figure 1 shows mask-weighted (background subtracted) lightcurves of each burst in the 12 - 25 keV energy band. The 2006 October 21 burst was observed at $\approx 20.6°$ from the BAT pointing axis, so the source countrate was substantially higher for this event than the 2007 March 30 burst, which was at 51.3°. Indeed, the peak 12 - 20 keV raw countrates were 4,100 and 2,620 s^{-1} for the 2006 October and 2007 March bursts, respectively. Time resolved spectroscopy of these bursts indicates that they both had peak fluxes of $\approx 2 \times 10^{-7}$ ergs cm^2 s^{-1} (Kuulkers et al. 2007, in preparation). These values are comparable to peak fluxes reported from earlier burst observations (Brandt et al. 1992; Swank et al. 1978). There is no strong indication for photospheric radius expansion in either burst.

The signal to noise ratio, n_σ, in a timing signature (such as a QPO) is proportional to $S^2/(S + B)$, where S and B are the source and background countrates, respectively. Thus, to search most sensitively for an oscillation signal one should attempt to minimize the background and maximize the source countrate. With the present BAT data we do this by restricting our timing study to events in the energy band from 13 - 20 keV. We selected this range because it effectively maximized the ratio of burst countrate to total countrate. That is, most of the events above 20 keV are not associated with the thermal burst emission, and simply add background, while the BAT does not have much effective area below about 15 keV. To search for burst oscillations we computed power spectra for 10 second intervals, and we stepped the interval by 2 seconds through each burst. We searched in the frequency band from 1 - 2048 Hz, at successive resolutions of 0.2, 0.4, and 0.8 Hz. We began our study with the 2006 October burst since this burst had the higher observed countrate of the two events.

Our study revealed a significant signal at 415 Hz in the cooling tail of the 2006 October burst. Figure 2 shows a power spectrum computed from a 10 s interval beginning 24.5 s from the beginning of the event data. The frequency resolution is 0.2 Hz, and a strong peak in the power spectrum is present at 414.75 Hz. The single trial probability to obtain a peak this strong (25.78) in this power spectrum is 1.7×10^{-10}. We searched 10,240 frequency bins in this power spectrum (to 2048 Hz at 0.2 Hz resolution), and a total of 14 similar power spectra through the burst tail. To account for the number of trials searched we take the total number of power spectral bins in each time interval, and at each resolution. This gives $10,240 \times 14 \times (1+0.5+0.25) = 250,880$ trials, and yields a detection significance of 4.3×10^{-5}, which is a 4σ detection. We note that this is a conservative estimate of the significance, since not all the bins at 0.4 and 0.8 Hz resolution are independent of those in the 0.2 Hz spectrum. The pulsed amplitude associated with the signal in this power spectrum is 12.3% (rms). This is the fractional modulation associated with the burst emission only, under the assumption that the pre-burst level is a reasonable indicator of the non-burst background.

We next computed a dynamic power spectrum through the burst using the Z^2 statistic (see Strohmayer & Markwardt 2002, for a discussion of the method). We used 4 s intervals, and stepped the intervals at 0.25 s. The dynamic spectrum is shown in Figure 3 and indicates that the oscillation signal is present during an ≈ 5 s interval beginning about 22 s after the onset of the burst. The vertical dashed lines in Figure 3 mark the interval used to compute the power spectrum shown in Figure 2. The presence of oscillations after the burst peak, during the cooling tail, is consistent with other burst oscillation sources, and further supports the interpretation that we are seeing burst oscillations in 4U 0614+091. The oscillation amplitude is also within the characteristic range seen in other sources.

We next searched the March 2007 burst in a manner similar to that described above, however, having detected a signal in the October 2006 burst, we narrowed the search in frequency to within a few Hz on either side of 415 Hz. We did not detect any significant signal. We are not too suprised by this, however, since the peak burst countrate is almost a factor of 3 lower in the March 2007 event than the October 2006 burst. This greatly reduces the sensitivity to pulsations in this burst. Quantitatively, $S^2/(S+B)$ is reduced by a factor of ~ 5, which would erase a 4σ detection, thus a non-detection is not particularly surprising.

3. Discussion

We have found strong evidence for a burst oscillation at 414.75 Hz in a thermonuclear burst from 4U 0614+091 with the BAT onboard *Swift*. This is the first detection of burst oscillations with BAT and demonstrates its potential in this regard, particularly for relatively nearby (read bright) burst sources. This detection implies a spin frequency of about 415 Hz for the neutron star in this system. Since the discovery of kHz QPOs and burst oscillations, there has been a suggested link between the neutron star spin frequency, ν_s, (as indicated by burst oscillation frequencies, or persistent pulsation frequencies, or both) and the frequency difference of the twin kHz QPOs, $\Delta\nu/\nu_s$. Initial discoveries suggested that the kHz QPO frequency separation was consistent with the spin frequency, but subsequent observations have revealed a more complex picture (Strohmayer et al. 1996; van der Klis 2006). The tentative consensus at present is that the frequency separation is related to the spin frequency (at least in some sources), in the sense that $\Delta\nu/\nu_s$ can be close to either 1 or 0.5. While this description fits reasonably well with several of the observed systems, it is not universally precise, in the sense that some objects show statistically significant deviations from 1 or 0.5, and that the frequency separation is known to vary in some objects. Recently, Mendez & Belloni (2007), and Yin et al. (2007) have re-examined the existing measurements of neutron star spin frequencies and kHz QPO, and suggest that there may be only a weak connection between the QPO frequency difference and the spin frequency. Indeed, Mendez & Belloni (2007) hypothesize that the frequency difference may be more or less constant, essentially independent of the spin frequency.

With the detection of the spin frequency in 4U 0614+091 we now have an additional source in which to closely evaluate the relationship between kHz QPOs and spin. Interestingly, the burst oscillation frequency we have found is very significantly different from the frequency separation of 323 ± 4 Hz of the twin kHz QPOs reported for the system (Ford et al. 1997). In this case the QPO difference frequency was quite accurately determined, and since the spin frequency is not thought to differ from observed burst oscillation frequencies by more than a few Hz, this is a strong demonstration that the kHz QPO difference frequency and spin frequency in 4U 0614+091 do not follow the "consensus" model. Assuming that the spin frequency is within 4 Hz of our measured burst oscillation frequency, then we arrive at $\Delta\nu/\nu_s = 0.78 \pm 0.02$, which is inconsistent with both 0.5 and 1 at very high confidence. Interestingly, this value lies much closer to the two alternative relations suggested by Yin et al. (2007, $\Delta\nu = 390$ Hz $- 0.2\nu_s$), and Mendez & Belloni (2007, $\Delta\nu = 308$ Hz), although it stills fall about 2σ away from these as well. Since these relations were derived and or suggested prior to our discovery, the spin meausurement reported here can be thought of as an independent check on those models, and it appears they provide a much better description of the data than the "consensus" model, further supporting the notion that it may be past time to re-think the relationship between the kHz QPOs and neutron star spin, or to at least adopt the working hypothesis that the relationship does not hold for all sources, or at all times.

4. Summary

We have found the first evidence for burst oscillations in the LMXB 4U 0614+091 at 414.75 Hz, the first such detection with the BAT instrument onboard *Swift*. The inferred spin frequency of $\approx$ 415 Hz is fairly typical for such sources, but it is inconsistent with the kHz QPO frequency separation, or half of that, measured for the source by Ford et al. (1997).

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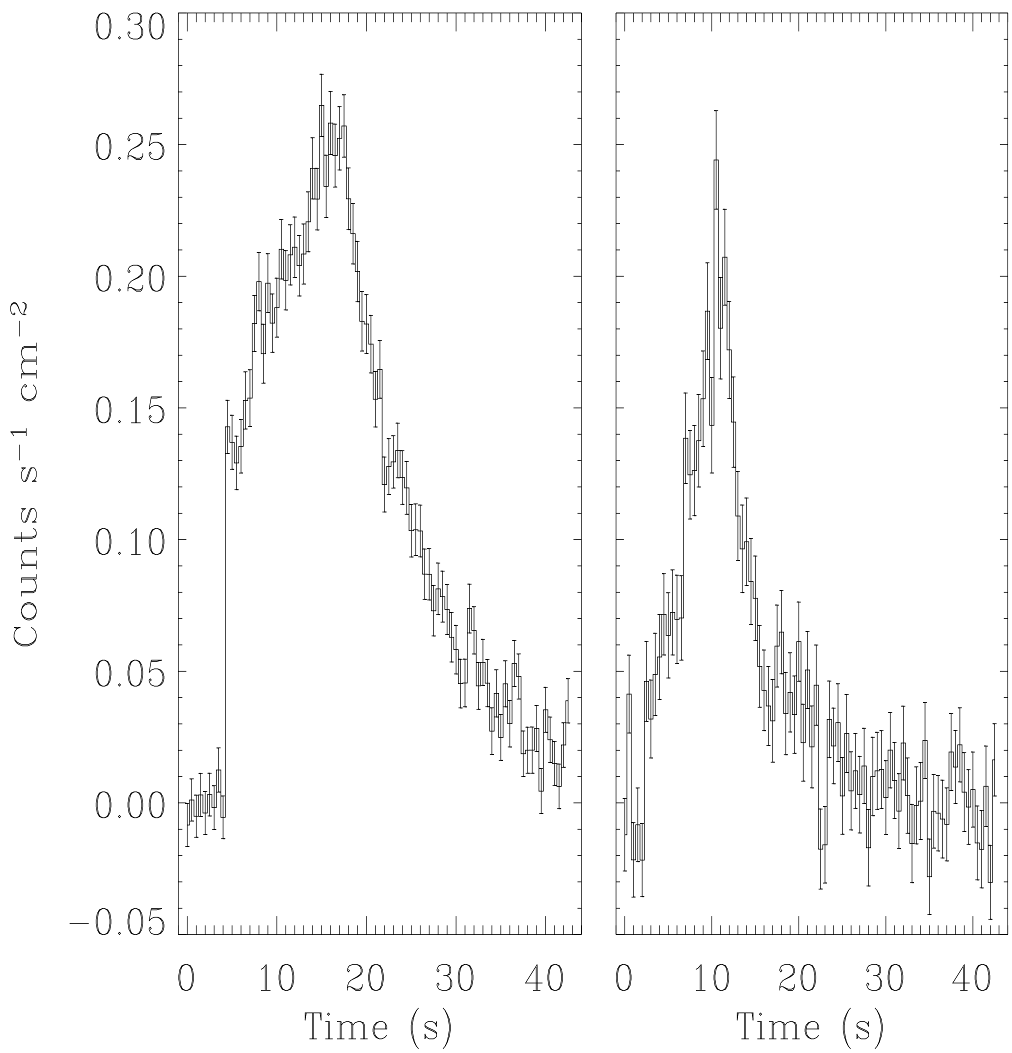

Figure 1: Mask-weighted light curves in the 12 - 25 keV band of the two thermonuclear bursts observed by BAT from 4U 0614+091. The left panel shows the burst from 2006 October (trigger #234849), and the right panel that from 2007 March (trigger #273106). The time bin size is 0.5 s. Mask-weighted BAT light curves have the background subtracted, and are corrected approximately to the on-axis effective count rate.

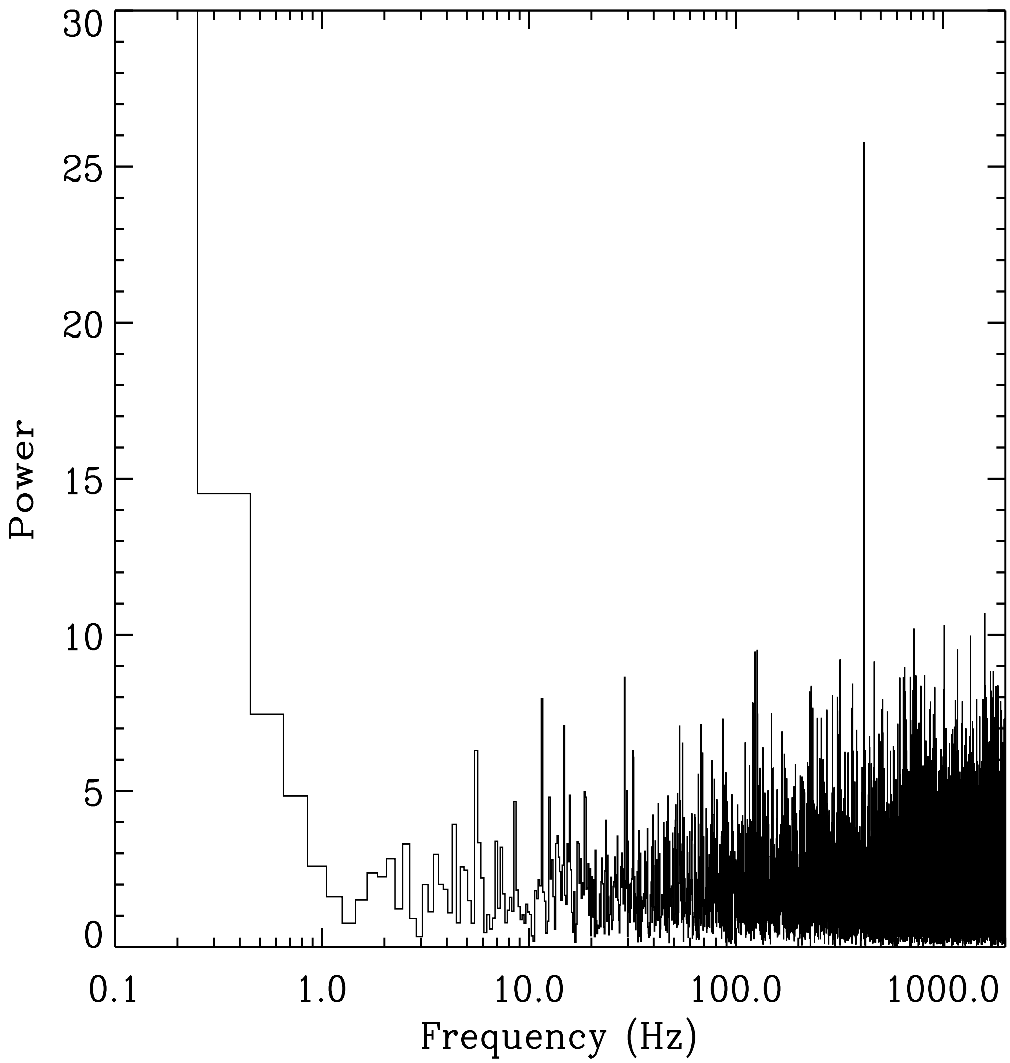

Figure 2: Power spectrum from the decaying tail of the 2006 October burst. The spectrum was computed from a 10 s interval beginning 22.5 s from the start of the data stream (time zero in Figures 2 and 3). For this spectrum we used events in the 13 - 20 keV band, and the frequency resolution is 0.2 Hz. The strong peak at $\approx$ 415 Hz is evident. See the text for a detailed discussion.

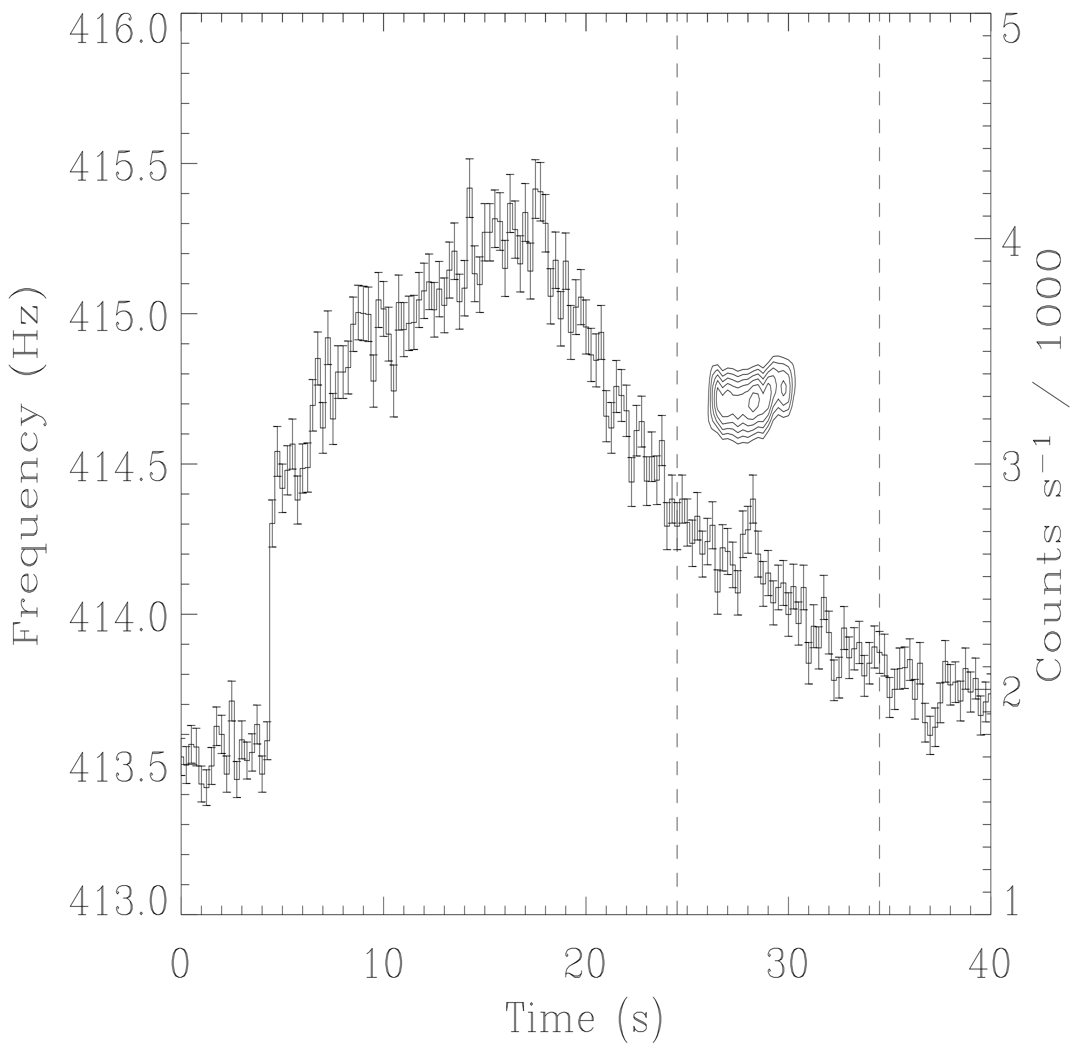

Figure 3: Dynamic Z^2 power spectrum of the burst from 2006 October. We computed Z_1^2 power spectra using 4 s intervals, and stepped the intervals by 0.25 s. We used only events in the 13 - 20 keV range. Six Z_1^2 contour levels are plotted, starting at 16 and spaced in steps of 4. The vertical dashed lines denote the time interval used to compute the power spectrum displayed in Figure 2. The burst light curve in the 13 - 20 keV band with 0.25 s time bins is also superposed. The pulsation signal is evident in the cooling tail of the burst.