

DISCOVERY OF 442 Hz PULSATIONS FROM AN X-RAY SOURCE IN THE GLOBULAR CLUSTER NGC 6440

FOTIS P. GAVRIIL,¹ TOD E. STROHMAYER, JEAN H. SWANK, AND CRAIG B. MARKWARDT^{2,3}

NASA Goddard Space Flight Center, Astrophysics Science Division, Code 662, X-Ray Astrophysics Laboratory, Greenbelt, MD 20771

Received 2007 July 18; accepted 2007 September 18; published 2007 October 11

ABSTRACT

We report on the serendipitous discovery of a 442 Hz pulsar during a *Rossi X-Ray Timing Explorer* (*RXTE*) observation of the globular cluster NGC 6440. The oscillation is detected following a burstlike event which was decaying at the beginning of the observation. The timescale of the decay suggests we may have seen the tail end of a long-duration burst. Low-mass X-ray binaries (LMXBs) are known to emit thermonuclear X-ray bursts that are sometimes modulated by the spin frequency of the star, the so-called burst oscillations. The pulsations reported here are peculiar if interpreted as canonical burst oscillations. In particular, the pulse train lasted for ~ 500 s, much longer than in standard burst oscillations. The signal was highly coherent and drifted down by $\sim 2 \times 10^{-3}$ Hz, much smaller than the \sim Hz drifts typically observed during normal bursts, but consistent with orbital motion of the neutron star. The pulsations are reminiscent of those observed during the much more energetic “superbursts”; however, the temporal profile and the energetics of the burst suggest that it was not the tail end nor the precursor feature of a superburst. Rather, it is likely that we caught a portion of an outburst from a new “intermittent” accreting millisecond pulsar, a phenomenon which until now had only been seen in HETE J1900.1–2455.

Subject headings: globular clusters: individual (NGC 6440) — stars: neutron — X-rays: bursts

1. INTRODUCTION

The discovery of millisecond spin periods of neutron stars in low-mass X-ray binaries (LMXBs) with the *Rossi X-Ray Timing Explorer* (*RXTE*) has helped elucidate the nature of these sources. Neutron star LMXBs consist of a neutron star accreting from a low-mass companion. As material (mostly H and He) is accreted onto the star and gets compressed, it eventually ignites and burns unstably (see Strohmayer & Bildsten 2006). This phenomenon is observed as a Type I X-ray burst. Type I X-ray bursts have been observed from over ~ 70 LMXBs (see Liu et al. 2006 and references therein). The recurrence time of these bursts varies but in some cases it can be as frequent as every few hours (see Galloway et al. 2007b for examples). Occasionally it is possible to observe the spin of the neutron star modulating the burst emission—the so-called burst oscillations (Strohmayer et al. 1996). Burst oscillations have been observed from ~ 18 LMXBs (see Galloway et al. 2007b for examples).

X-ray bursts from LMXBs have been discovered which are ~ 1000 times longer, and thus, that much more energetic, than canonical Type I X-ray bursts. They are aptly named “superbursts.” Superbursts are believed to occur by the unstable burning of carbon (Strohmayer & Brown 2002; Cumming & Bildsten 2001). Strohmayer & Markwardt (2002) discovered highly coherent pulsations during a superburst from 4U 1636–53. The pulse train lasted for ~ 800 s, as opposed to the ~ 10 s long pulse trains observed in Type I X-ray bursts. Superbursts are much rarer than Type I X-ray bursts. Thus far 10 have been observed from eight LMXBs (see in ’t Zand et al. 2004).

2. OBSERVATIONS

The data presented here were acquired from the Proportional Counter Array (PCA) on board *RXTE*. The PCA consists of

five identical and independent proportional counter units (PCUs). Each PCU is a 90% xenon/10% methane gas filled proportional counter, with a collimated $1^\circ \times 1^\circ$ field of view, 256 spectral channels in the 2–60 keV range, and a limiting temporal resolution of $\sim 1 \mu$ s. Between 2005 March 7 and 2005 July 21 the PCA Galactic Bulge Scan Survey⁴ discovered an outburst from the direction of the globular cluster NGC 6440. A follow up 1.8 ks long pointed *RXTE* observation (observation identification number 91050-03-07-00) was initiated on 2005 June 14. Only two PCUs (PCU 0 and PCU 2) were operational throughout the span of the observation. The data were taken in E_125us_64M_0_1s mode, which returns events to a limiting resolution of 125 μ s and with moderate (64 channels as opposed to the full 256 channels) spectral resolution. This mode was used because it is not as susceptible to buffer overflows during high count rate data as compared to the less restrictive modes (e.g., GoodXenon). Using the pointing of the observation ($17^h48^m52.8^s$, $-20^\circ21'32''$) and the planetary ephemeris DE200, the times of raw events were corrected to the solar system barycenter. Binning the events into a 1 s resolution light curve reveals a quickly decaying burst (Fig. 1).

3. ANALYSIS AND RESULTS

This burst was reminiscent of canonical Type I X-ray bursts from LMXBs; therefore we searched this event for burst oscillations. We rebinned the raw events using the full spectral band pass into a time series with 0.5/1024 s resolution, which yields an equivalent Nyquist frequency of 1024 Hz. A Leahy normalized (see Leahy et al. 1983) power density spectrum (PDS) is displayed in Figure 1 (*inset*). A prominent peak is clearly seen at 442 Hz. The probability of this peak occurring by chance after accounting for the number of trials (the total number of frequency bins in our PDS) is $\sim 2 \times 10^{-9}$. The discovery of the pulsar was first presented in Gavriil et al. (2006).

¹ NPP Fellow; Oak Ridge Associated Universities, Oak Ridge, TN.

² CRESST.

³ Department of Astronomy, University of Maryland, College Park, MD 20742.

⁴ See <http://lheawww.gsfc.nasa.gov/users/craigm/galscan>.

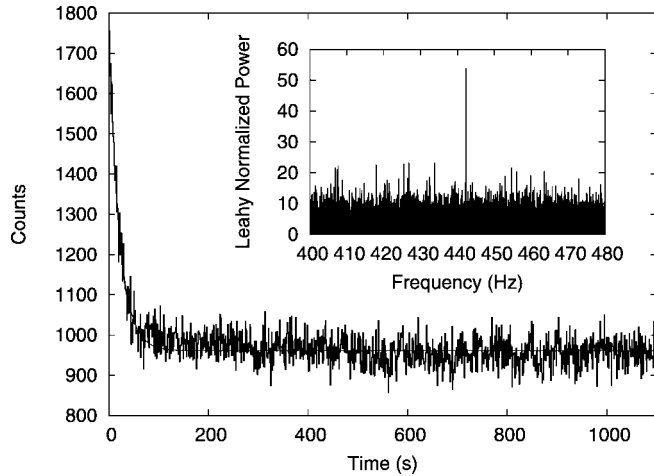


FIG. 1.—Burst light curve binned with 1 s resolution and using the full PCA bandpass. Inset: Leahy normalized (Leahy et al. 1983) power spectrum of the entire observation. Notice the significant peak at 442 Hz.

3.1. The NGC 6440 Field

NGC 6440 harbors the bright X-ray transient SAX J1748.9–2021, from which Kaaret et al. (2003) claimed a detection of burst oscillations at 409.7 Hz. However, there are many other X-ray sources in the cluster (see Fig. 2). *Chandra* X-Ray Observatory imaging by Pooley et al. (2002) revealed 24 X-ray sources in NGC 6440, and they concluded that 4–5 of these sources are likely quiescent LMXBs. Thus, if the Kaaret et al. (2003) claim is valid, the oscillations we discovered would very likely have to be from a different object in the cluster.

3.2. Timing Analysis

To study the frequency evolution of the pulse we calculated a dynamic Z^2 statistic. The Z^2 statistic is analogous to the Fourier power spectrum, with the advantage that the data need not be binned, thus allowing us to oversample our data (Buccheri et al. 1983). The Z^2 statistic is defined as

$$Z_{N_{\text{harm}}}^2 = \frac{2}{N_{\gamma}} \sum_{k=0}^{N_{\text{harm}}} \sum_{i=0}^{N_{\gamma}} |e^{i2\pi k\nu_j t_i}|^2, \quad (1)$$

where N_{γ} is the total number of photons in each interval, N_{harm} is the total number of harmonics that one deems significant, ν_j is the frequency searched over, and t_i is the event time. The factor in front of the summations normalizes the Z^2 statistics in an analogous way to Leahy normalizing a PDS. We calculated the dynamic Z^2 power spectrum using a 200 s long window, which was translated across the observation with a step size of 16 s. Our dynamic Z^2 power spectrum is displayed in Figure 3. Note that the pulsations were highly significant for 576 s. As is common for canonical X-ray bursts, the frequency drifts; however, unlike the ~ 1 –2 Hz drifts seen in those, the pulsation here drifts down in frequency only by $\sim 2.1 \times 10^{-3}$ Hz in 576 s.

To further quantify this frequency evolution we determined how the phase of the pulsations varies as a function of time. For each interval with $Z_1^2 > 16$ we generated a pulse profile by folding the events in that interval on the frequency determined from the Z^2 statistic. We then cross correlated these pulse profiles with a sinusoid of fixed phase to determine the pulse phase

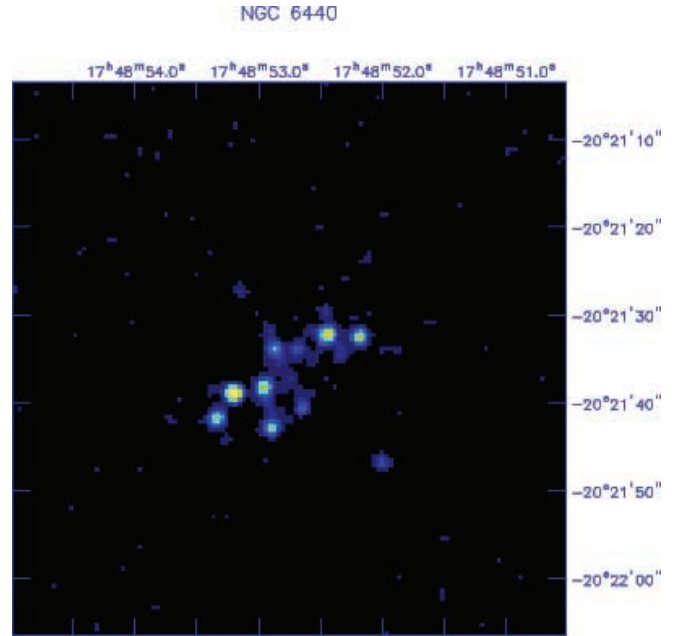


FIG. 2.—Archival *Chandra* image of NGC 6440. Note that the cluster contains many X-ray point sources.

as a function of time. We can model the pulse phase (ϕ) at a given time (t) by the following Taylor expansion:

$$\phi(t) = \phi(t_0) + \nu(t_0)(t - t_0) + \frac{1}{2} \dot{\nu}(t_0)(t - t_0)^2 + \dots, \quad (2)$$

where ν is the barycentric frequency, $\dot{\nu}$ is the frequency derivative, and t_0 is some reference epoch. We were able to whiten our phase residuals with just a frequency derivative (see Fig. 3,

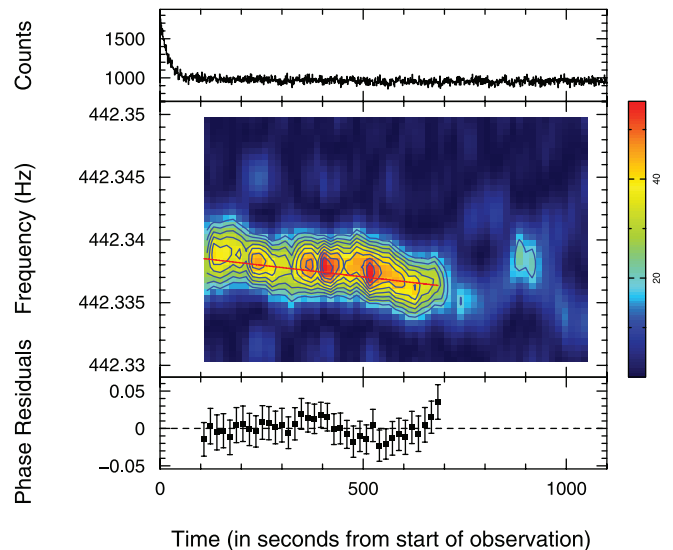


FIG. 3.—Pulse frequency evolution. *Top*: The burst light curve as shown in Fig. 1. *Middle*: Dynamic Z^2 power spectrum. Note that the pulsations remain highly significant (with $Z_1^2 > 16$) for 576 s. The solid line represents our best-fit frequency model consisting of just a frequency and a frequency derivative term. *Bottom*: Phase residuals after subtracting our best-fit frequency model. Note that the pulsations are highly coherent.

bottom). We find $\nu = 442.33850(5)$ Hz, $\dot{\nu} = 3.7(2) \times 10^{-6}$ Hz s $^{-1}$ at $t_0 = 53,535.463215$ MJD (UTC). The phase residuals after subtracting the model given by equation (2) are shown in Figure 3 (bottom). Note that the pulse train lasts for 576 s; this is quite long when compared to those of Type I X-ray bursts. We folded all the events within the 576 s pulse train using our best-fit ν and $\dot{\nu}$, and the resulting pulse profile is shown in Figure 4. Note that the pulse profile is highly sinusoidal. Fitting a sinusoid to the pulse profile returned a reduced χ^2 value of 0.76 for 13 degrees of freedom, affirming the absence of any harmonic content. From the fit we obtain a fractional pulse amplitude of $2.1\% \pm 0.1\%$.

It is possible that the frequency drift we have observed is entirely due to orbital motion. The observed spin frequency of a neutron star in a circular orbit is given by

$$\nu = \nu_0 \left[1 - \frac{v_{\text{ns}} \sin i}{c} \sin \left(\frac{2\pi t}{T} + \phi_0 \right) \right], \quad (3)$$

where ν_0 is the barycentric frequency at time $t = t_0$, $v_{\text{ns}} \sin i$ is the projected velocity of the neutron star, T is the orbital period, and ϕ_0 is the orbital phase at time $t = t_0$. Unfortunately we do not have a long enough data set to place interesting constraints on T or $v_{\text{ns}} \sin i$; however, we can determine whether orbital modulation is consistent with the observed frequency drift. For example, if we assume, for solely demonstrative purposes, that this system has a projected velocity comparable to the one found by Strohmayer & Markwardt (2002) for 4U 1636–53 ($v_{\text{ns}} \sin i = 136$ km s $^{-1}$), then fitting equation (3) to our frequency time series yields a good fit with a reasonable orbital period, i.e., $T = 7 \pm 1$ hr. Hence, binary motion can account for the observed frequency drift.

3.3. Spectral Analysis

The timing analysis seems to suggest that this event is in fact very different from a canonical burst oscillation. To study it further we performed a spectral analysis. We analyzed the spectral evolution of the burst by breaking the burst up into 10 intervals. The exposure of each interval was selected by demanding that each one contained an equal number of photons. Using the last interval as an estimator of the persistent emission, we fit each interval to a simple photoelectrically absorbed blackbody model while holding the column density fixed to the value found by Pooley et al. (2002) for the optical reddening. We find only subtle evidence for spectral softening, significant only at the 1σ level.

Using the distance estimate to the cluster found by Ortolani et al. (1994), $d = 8.5 \pm 0.4$ kpc, we were able to calculate the luminosity of the burst. At the start of the observation the flux was $\sim 2 \times 10^{37}$ erg s $^{-1}$, which is $\sim 0.1 L_{\text{Edd}}$, where L_{Edd} is the Eddington luminosity for a canonical $1.4 M_{\odot}$ neutron star. The burst light curve was well fit by an exponential with a decay timescale of 22 s. Unfortunately the observation only caught the tail end of the burstlike event; we could not therefore characterize the peak luminosity of the burst.

4. DISCUSSION

The timing properties of the pulsations are similar to those observed during a superburst from 4U 1636–53, but our spectral analysis makes this interpretation problematic. Recently Galloway et al. (2007a) discovered “intermittent” pulsations

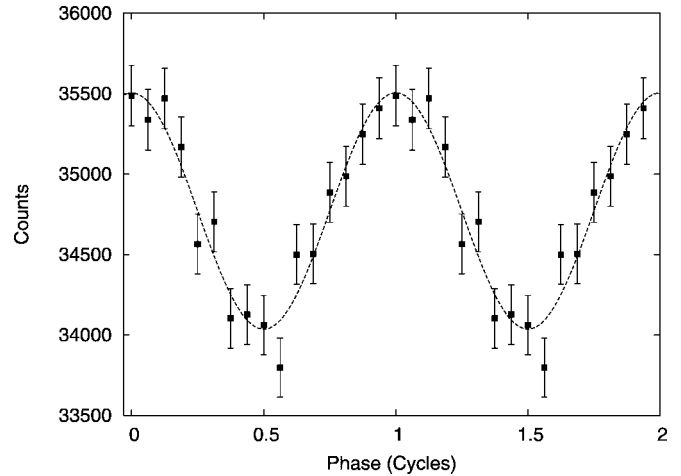


FIG. 4.—Pulse profile obtained by folding all events in the 576 s long pulse train (i.e., the interval where the pulsations were highly significant as determined from the Z^2 power spectrum) on the ephemeris determined in our timing analysis. The pulse shape is highly sinusoidal. The solid line represents the best-fit sinusoid. The fit yielded $\chi^2 = 0.76$ for 13 degrees of freedom, affirming the absence of any harmonic content.

from the accretion-powered millisecond pulsar (AMP) HETE J1900.1–2455. They found that the properties of this pulsar differed from those of the other six known AMPs. For example, the pulsations were only present in the first few months of its outburst as opposed to other AMPs which show pulsations throughout (see Wijnands 2004 for a review). In addition, the pulsed amplitude increased at three points in time that were almost coincident with the times of thermonuclear bursts. The pulsed amplitude subsequently decayed after the bursts. Thus, it is plausible that we have observed a similar phenomenon. Following the theoretical work of Cumming et al. (2001) and Payne & Melatos (2006), Galloway et al. (2007a) suggest that the reason why the pulsations in HETE J1900.1–2455 sometimes “switch off” is because the magnetic field is buried by accreted material, and thus it cannot channel the flow which gives rise to the pulsations in the first place. In contrast with HETE J1900.1–245, these pulsations were not present at the beginning of the outburst but well into it. However, given that the pulsations occurred after a burst implies that the material burying the field was expelled allowing pulsations to be observed again. Given that the pulsations ceased 576 s after the burst, and given the accretion rate following the burst, we can estimate the amount of matter required to bury the field anew. In that case, we estimate that only $\sim 10^{-14} M_{\odot}$ of matter is required to bury the field, much less than the $10^{-10} M_{\odot}$ required for HETE J1900.1–2455 as estimated by Galloway et al. (2007a).

5. CONCLUSIONS

We discovered a 442 Hz pulsation during a burst from an X-ray source in NGC 6440. We could not establish the energetics of the burst as *RXTE* only caught the tail end of the event. Based on the timing properties of the pulsation we conclude that it was not a standard burst oscillation. In particular, the pulse train lasted for 576 s, as opposed to the ~ 10 s long pulse trains observed in regular thermonuclear bursts, and the frequency drifted down by only 2.1×10^{-3} Hz, much smaller than is the case for normal burst oscillations, but consistent with what could be produced by orbital motion of the neutron

star. We conclude that the long pulse train is most likely an “intermittent” pulsation from an accreting millisecond pulsar such as those seen only in HETE J1900.1-2455 thus far (Galloway et al. 2007a).

After submitting our Letter, we became aware of the work of Altamirano et al. (2007) that reports on a study of additional outbursts from NGC 6440. Their Letter had not yet been submitted at the time we submitted our Letter. They report the detection of several additional episodes of intermittent pulsations at 442 Hz that enabled them to deduce an orbital period of 8.7 hr for the pulsar. In addition, most of these new episodes clearly followed thermonuclear bursts, in a fashion similar to the pulsations we describe here. These additional results clearly establish the 442 Hz pulsar in NGC 6440 as a new “intermittent” accreting millisecond pulsar. In addition, Altamirano et al. (2007) reanalyzed the 409.7 Hz burst oscillation claimed

by Kaaret et al. (2003) and argue that these authors overestimated the significance of the detection. Based on this they suggest that the 442 Hz pulsar is very likely SAX J1748.9–2021, and probably not a different source in NGC 6440. Moreover, a third Letter was recently submitted to the Journal by Casella et al. (2007) that reports the discovery of an episode of intermittent pulsations in the transient LMXB Aql X-1.

F. P. G. is supported by the NASA Postdoctoral Program administered by Oak Ridge Associated Universities at NASA Goddard Space Flight Center. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA Goddard Space Flight Center.

REFERENCES

- Altamirano, D., Casella, P., Patruno, A., Wijnands, R., & van der Klis, M. 2007, *ApJ*, in press (arXiv:0708.1316)
- Buccheri, R., et al. 1983, *A&A*, 128, 245
- Casella, P., Altamirano, D., Wijnands, R., & van der Klis, M. 2007, *ApJ*, in press (arXiv:0708.1110v1)
- Cumming, A., & Bildsten, L. 2001, *ApJ*, 559, L127
- Cumming, A., Zweibel, E., & Bildsten, L. 2001, *ApJ*, 557, 958
- Galloway, D. K., Morgan, E. H., Krauss, M. I., Kaaret, P., & Chakrabarty, D. 2007a, *ApJ*, 654, L73
- Galloway, D. K., Muno, M. P., Hartman, J. M., Savov, P., Psaltis, D., & Chakrabarty, D. 2007b, *ApJ*, in press (astro-ph/0608259)
- Gavriil, F. P., Strohmayer, T. E., Swank, J. H., & Markwardt, C. B. 2006, *BAAS*, 38, 336
- in 't Zand, J. J. M., Cornelisse, R., & Cumming, A. 2004, *A&A*, 426, 257
- Kaaret, P., in 't Zand, J. J. M., Heise, J., & Tomsick, J. A. 2003, *ApJ*, 598, 481
- Leahy, D. A., Darbro, W., Elsner, R. F., Weisskopf, M. C., Kahn, S., Sutherland, P. G., & Grindlay, J. E. 1983, *ApJ*, 266, 160
- Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2006, *A&A*, 455, 1165
- Ortolani, S., Barbuy, B., & Bica, E. 1994, *A&AS*, 108, 653
- Payne, D. J. B., & Melatos, A. 2006, *ApJ*, 652, 597
- Pooley, D., et al. 2002, *ApJ*, 573, 184
- Strohmayer, T. E., & Bildsten, L. 2006, in *Compact Stellar X-Ray Sources*, ed. W. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 113
- Strohmayer, T. E., & Brown, E. F. 2002, *ApJ*, 566, 1045
- Strohmayer, T. E., & Markwardt, C. B. 2002, *ApJ*, 577, 337
- Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, A., Titarchuk, L., Day, C., & Lee, U. 1996, *ApJ*, 469, L9
- Wijnands, R. 2004, *Nucl. Phys. B (Proc. Suppl.)*, 132, 496