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EVIDENCE OF 1122 Hz X-RAY BURST OSCILLATIONS FROM THE NEUTRON STAR X-RAY TRANSIENT XTE J1739−285

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ABSTRACT

We report on millisecond variability from the X-ray transient XTE J1739−285. We detected six X-ray type I bursts and found evidence for oscillations at 1122 ± 0.3 Hz in the brightest X-ray burst. Taking into consideration the power in the oscillations and the number of trials in the search, the detection is significant at the 99.96% confidence level. If the oscillations are confirmed, the oscillation frequency would suggest that XTE J1739−285 contains the fastest rotating neutron star yet found. We also found millisecond quasi-periodic oscillations in the persistent emission with frequencies ranging from 757 to 862 Hz. Using the brightest burst, we derive an upper limit on the source distance of about 10.6 kpc.

Subject headings: accretion, accretion disks — gravitation — relativity — stars: individual (XTE J1739−285) — stars: neutron — X-rays: stars

1. INTRODUCTION

Weakly magnetized neutron stars can be spun up to rates of several 100 Hz by accretion in low-mass X-ray binaries (Alpar et al. 1982). The first direct measurements of millisecond spin rates in actively accreting neutron stars in low-mass X-ray binaries (LMXBs) came from the discovery of oscillations in thermonuclear X-ray bursts occurring on the neutron star surface (Strohmayer et al. 1996). The burst oscillation frequencies were later found to be nearly equal to those of coherent pulsations (in 't Zand et al. 2001; Strohmayer & Markwardt 2002; Chakrabarty et al. 2003; Strohmayer et al. 2003), implying that the burst oscillation frequency indicates the neutron star spin rate. This X-ray technique has no known biases against the detection of very high spin rates, unlike radio pulsation searches, and the sample of X-ray burst oscillation frequencies has been exploited to constrain the neutron star spin rate distribution. Analysis of a sample of 11 X-ray–measured spin frequencies in the range 270–619 Hz suggests a limiting spin rate near 760 Hz if the distribution is uniform and bounded (Chakrabarty et al. 2003). This is below the expected maximum spin frequency possible without centrifugal breakup and has been interpreted as evidence that some physical process, possibly gravitational radiation, limits the maximum possible spin rate. However, the discovery of a radio pulsar spinning at 716 Hz, a frequency above any previously measured in X-rays, suggests that the true maximum spin rate is higher (Hessels et al. 2006).

Here we describe observations made with the *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt et al. 1993) following the detection of X-ray bursts from the transient source XTE J1739−285 as part of a program to search for millisecond oscillations in both X-ray bursts and persistent emission from neutron star X-ray binaries that are newly discovered or found to be active (Kaaret et al. 2002, 2003, 2006). We detected six X-ray bursts and found oscillations at a frequency of 1122 Hz in the brightest burst. This suggests that XTE J1739−285 contains the most rapidly rotating neutron star yet discovered. We describe our observations in § 2, the X-ray bursts in § 3, and the persistent emission and the discovery of kilohertz quasi-periodic oscillations (kHz QPOs) from the source in § 4. We discuss the results in § 5.

2. OBSERVATIONS OF XTE J1739−285

XTE J1739−285 is a transient neutron star (NS) LMXB that was discovered during *RXTE* Proportional Counter Array (PCA) scans of the Galactic bulge on 1999 October 19 (Markwardt et al. 1999) and underwent short outbursts in 2001 May and 2003 October. The source became active again in 2005 August (Bodaghee et al. 2005), and two X-ray bursts were detected with the Joint European Monitor for X-Rays (JEM-X) instrument on *INTEGRAL* on 2005 September 30 and October 4 (Brandt et al. 2005).

Triggered by the detection of the X-ray bursts, we obtained 19 observations using *RXTE* in the period beginning 2005 October 12 and ending 2005 November 16. Data were obtained with the PCA in a spectral mode (standard 2) with 256 energy channels and 16 s time resolution, a low-resolution timing mode (standard 1) with no energy information and 0.125 s time resolution, and a high-resolution timing mode (event mode) with 122 μs time resolution and 64 energy channels (Jahoda et al. 2006).

3. X-RAY BURSTS

We searched the standard 1 data for X-ray bursts and found six (see Table 1). We examined their evolution by extracting spectra for 0.25 s intervals of event mode data using all Proportional Counter Units (PCUs) that were on during each burst and all layers. The fluxes were corrected for dead-time effects with a maximum correction of 5.5%. To remove the contribution of the persistent emission, we subtracted off a spectrum

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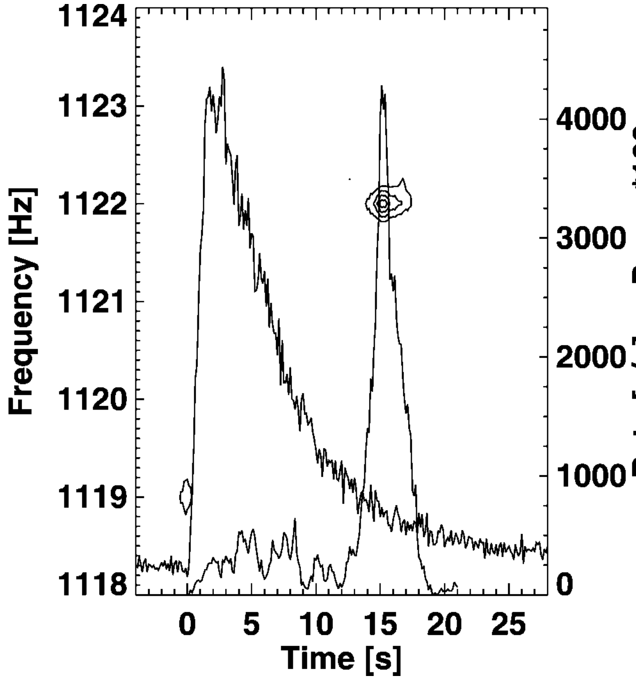

FIG. 1.—Dynamical power spectrum of burst 2 with the burst light curve (count rate) and the power at 1122.0 Hz superposed. The contours are at Leahy powers of 12, 20, 28, and 36. The contours are generated from power spectra for overlapping 4 s intervals of data with the power plotted at the midpoint of the interval. The curve that peaks near 2 s is the rate in the 3–18 keV band from all the PCUs on during the observation (PCU0 and PCU2). The curve that peaks near 15 s is the Leahy power at 1122.0 Hz. The scales for both curves are on the right side. The oscillation is significant at the 99.96% confidence level.

from 10 s of data preceding each burst. Spectra were fitted in the 3–18 keV band (channels 3–24 in the event mode data) with an absorbed blackbody model with the column density fixed to $N_H = 7.5 \times 10^{21}$ cm^{-2}, which is the hydrogen column density along the line of sight in the Milky Way (Dickey & Lockman 1990). We found a burstlike event at November 11 10:27:22 UTC that appears in only one of four PCUs on at the time and is likely a detector breakdown event and not an X-ray burst.

The brightest burst is burst 2, which had a peak bolometric flux, as measured in 0.25 s intervals, of $(2.8 \pm 0.5) \times 10^{-8}$ ergs cm^{-2} s^{-1}. The blackbody temperature rose rapidly during the flux rise, reached a maximum near 2.5 keV, and then decayed as the flux decayed. This behavior is indicative of heating during the rise and cooling during the decay and is characteristic of type I X-ray bursts. Kuulkers et al. (2003) found that the empirical maximum bolometric peak luminosities for photospheric radius expansion bursts from a sample of 12 bursters located in globular clusters with known distances was 3.8×10^{38} ergs s^{-1}, with an accuracy of ~15%. None of our bursts showed evidence of photospheric radius expansion, and thus their luminosities should be below this value. The peak flux of the brightest burst implies an upper limit on the distance to XTE J1739−285 of about 10.6 kpc. This is consistent with, but somewhat closer than, the upper limit of 12 kpc from Torres et al. (2006).

Bursts 1 and 4–6 have similar peak fluxes, while bursts 2 and 3 were brighter (see Table 1). Burst 3 had a rise time near 3 s, while the other rise times were near 1 s. Burst 6 had a relatively broad maximum extending over 5 s. The decay (*e*-folding) times are in the range 3–6 s. The fact that the bursts have fast rises and durations of tens of seconds suggests that they are typical helium bursts.

TABLE 1
PROPERTIES OF X-RAY BURSTS

Number	Time	Peak Flux	Decay
1	Oct 31 (07:59:09)	1.6 ± 0.3	5.0
2	Nov 4 (11:34:23)	2.8 ± 0.5	5.4
3	Nov 7 (05:34:04)	2.2 ± 0.4	5.0
4	Nov 7 (07:30:53)	1.1 ± 0.3	3.0
5	Nov 8 (08:19:08)	1.0 ± 0.2	3.1
6	Nov 11 (09:47:10)	1.2 ± 0.3	5.7

NOTES.—Col. (2): Time (UTC) at the start of each burst (all bursts occurred in 2005). Col. (3): The bolometric peak flux corrected for absorption in units of 10^{-8} ergs cm^{-2} s^{-1}. Col. (4): Decay (*e*-folding) time in seconds.

Using high time resolution data, we computed power spectra for overlapping 4 s intervals with 0.125 s between the starts of successive intervals using events in the event mode energy channels 4–24, inclusive, for PCU0 and 3–24 for all other PCUs; these correspond to standard 2 mode energy channel ranges of 9–43 and 8–43, respectively. The background, particularly at low energies, is higher in PCU0 due to the loss of its propane layer. We searched over the duration of each burst defined as the interval where the total counting rate exceeds the background plus persistent counting rate, measured a few seconds before the burst, by at least a factor of 2. We searched for excess power in the range 20–2000 Hz, corresponding to 7920 frequency bins in the 4 s fast Fourier transforms (FFTs). We found oscillations in the second burst with a Leahy-normalized power (Leahy et al. 1983) of 42.82 at a frequency of 1122 ± 0.3 Hz, occurring in the burst decay 15 s after the burst rise (see Fig. 1). The four consecutive FFTs around the one with the peak power all have powers above 40.31 at 1122.0 Hz.

To evaluate the significance of the signal, we used a Monte Carlo simulation that generates Poisson-distributed events following the light curve from burst 2 in 0.125 s bins after smoothing with a moving average over nine bins. The deadtime of

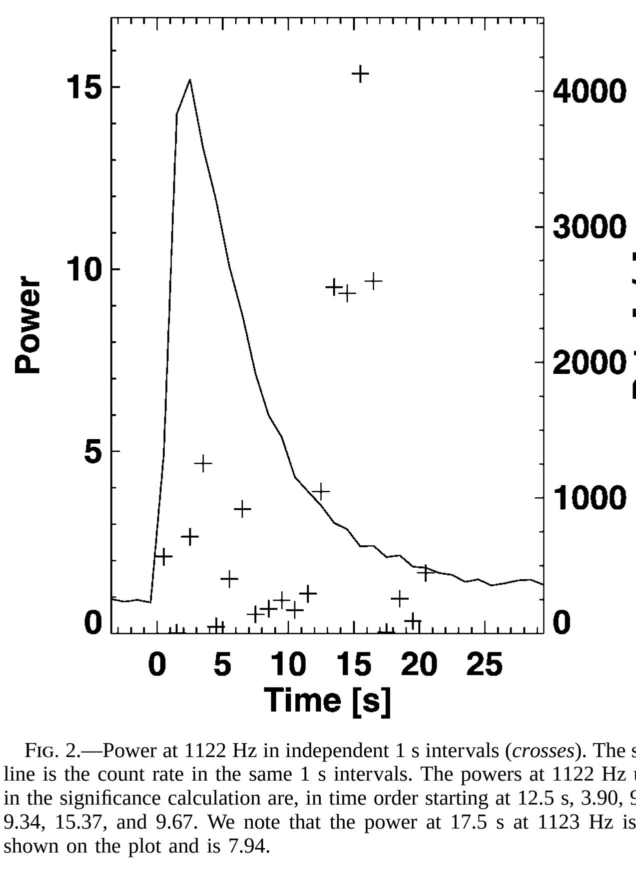

FIG. 2.—Power at 1122 Hz in independent 1 s intervals (*crosses*). The solid line is the count rate in the same 1 s intervals. The powers at 1122 Hz used in the significance calculation are, in time order starting at 12.5 s, 3.90, 9.51, 9.34, 15.37, and 9.67. We note that the power at 17.5 s at 1123 Hz is not shown on the plot and is 7.94.

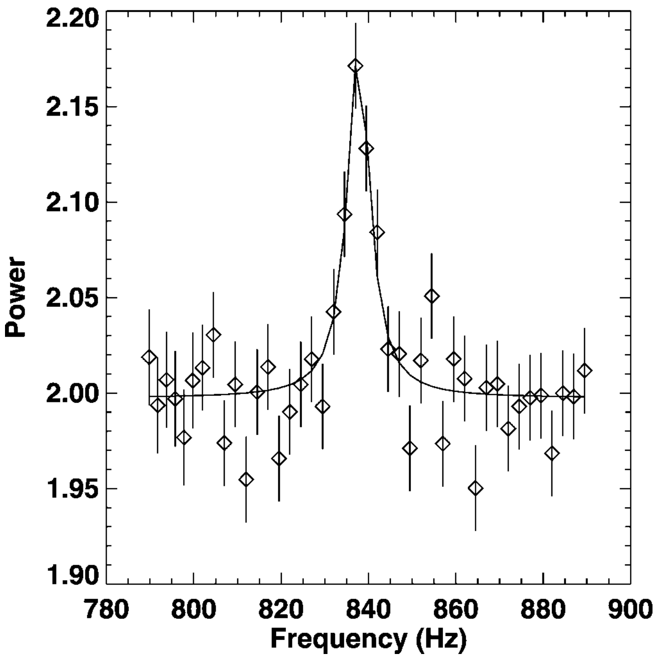

FIG. 3.—Power spectrum showing a kHz QPO from October 31. The power is Leahy-normalized.

the PCA is modeled by removing any event that occurs within 10 μs after a previous event (Jahoda et al. 2006). The number of events generated in each time bin is larger than the observed counts so that after the deadtime correction the number matches that in the actual light curve within Poisson fluctuations. We generated 400,000 trial bursts. Each simulated burst was analyzed using exactly the same analysis done on the real data, specifically by calculating 4 s FFTs at overlapping intervals with starts each 0.125 s and searching for power in the 20–2000 Hz interval. The chance probability of occurrence of the observed signal is calculated by counting the fraction of trial bursts with powers equal to or exceeding those observed. This procedure eliminates the ambiguity in estimating the equivalent number of independent trials for the overlapping FFTs. We found 58 bursts with at least one power above 42.82 of which 14 had at least four consecutive powers above 40.31 at the same frequency. We estimate the chance probability of occurrence of the observed signal to be 3.5×10^{-5}. Allowing two trials for two energy bands, the probability is 7.0×10^{-5}, equivalent to a 3.97 σ confidence level.

The signal at 1122 Hz was detected in the brightest burst. Since the bursts are not a uniform sample and the presence of oscillations may depend on burst properties and/or accretion history (e.g., Watts et al. 2005), one can reasonably argue that the significance should be evaluated for each burst individually, particularly in this case since the brightest burst is the most likely to give a detectable signal. However, a more conservative approach is to consider the full set of six bursts. The durations of the bursts, as defined above, are 21, 21, 22, 10, 11, and 18 s for bursts 1–6, respectively. To account for all the trials in all the bursts, we multiply the number of trials by an additional factor of $103/21 = 4.9$ for a chance probability of 3.4×10^{-4}. The oscillation is detected at a confidence level of 99.966%, equivalent to a 3.6 σ significance.

To obtain an estimate of the significance of the oscillations that does not depend on a simulation, we calculated FFTs in independent 4, 2, and 1 s intervals of data from burst 2. There are five successive 1 s FFTs with power at 1122 Hz (see Fig. 2). The single trial probability for having five powers at or above the observed levels in the 1 s FFTs is 4.2×10^{-11}. Accounting for all sequential combinations of FFTs of fixed length of 1, 2, or 4 s with a total duration of 5 s or less covering the 20–2000 Hz range in two energy bands, we estimate a total of 605,880 trials: $(17 + 18 + 19 + 20 + 21) \times 1980 \times 2 + (9 + 10) \times 3960 \times 2 + 5 \times 7920 \times 2$. The chance probability, taking into account the number of trials in the one burst, is then 2.5×10^{-5} (4.2 σ). Accounting for the other bursts, the chance probability is 1.2×10^{-4} (3.8 σ). This probability agrees within a factor of 3 with that in the previous paragraph.

In the 4 s interval with the maximum power, the fractional rms amplitude of the 1122.0 Hz oscillation is 0.13 ± 0.02. The quality factor, $Q = \nu/\Delta\nu$, of the oscillation in burst 2 is $Q > 1000$. This is consistent with the values found in burst oscillations and inconsistent with the values found in high-frequency QPOs in the persistent emission. We searched for oscillations near half the frequency. The strongest signal has a Leahy power of 13.6 at 561.25 Hz and occurs 7.75 s after the burst rise. This is not a significant signal; the chance probability of occurrence within the narrow window searched, 562.5–558.5 Hz, is 0.09. At the time of the maximum strength of the 1122 Hz signal, the Leahy power near 561 Hz is less than 6.

4. PERSISTENT EMISSION

To study the persistent emission spectra, we used standard 2 data from PCU2, removing data around the X-ray bursts, and estimating the background using bright source background files. The source was in a relatively hard state, with a hard X-ray color, HC, defined as the count rate in the 9.7–16 keV band divided by the 6.0–9.7 keV rate, of HC > 0.35 for all observations before October 25. The flux was roughly constant and near 4×10^{-10} ergs cm^{-2} s^{-1} in the 2–20 keV band. The spectra were adequately described by the absorbed ($N_{\rm H} = 7.5 \times 10^{21}$ cm^{-2}) sum of a power law with a photon index near 2 and a Gaussian emission line with a centroid of 6.7 keV and a flux consistent with that from Galactic ridge emission at the source position (Revnivtsev et al. 2006). After October 25, the source stayed in a softer state, HC < 0.35. The flux varied by a factor of 2, with the maximum near 1.4×10^{-9} ergs cm^{-2} s^{-1} in the 2–20 keV band. The spectra showed distinct curvature at high energies and were adequately fitted with the absorbed sum of a Comptonization model (`compst` in `xspec`) with a temperature in the range 4–12 keV and an optical depth in the range 3–10, a blackbody with a temperature near 1.6 keV, and a Gaussian emission line with a centroid of 6.7 keV, a width less than 0.9 keV, and an equivalent width of 100–300 eV, in some cases larger than the expected Galactic ridge emission. The blackbody component was not required for some lower flux observations. The spectra are similar to those of other moderate-luminosity NS LMXBs (Kaaret et al. 2002, 2003).

TABLE 2
HIGH-FREQUENCY PEAKS IN THE PERSISTENT EMISSION

Time (UTC)	Centroid (Hz)	Width (Hz)	Amplitude (%)
Oct 31 (06:22:11)	837.9 ± 0.3	5.3 ± 0.9	1.7 ± 0.2
Nov 01 (02:48:14)	784.6 ± 1.1	14 ± 3	2.4 ± 0.4
Nov 08 (04:37:47)	814.4 ± 3.2	36 ± 9	3.1 ± 0.6
Nov 08 (09:46:31)	756.7 ± 0.7	9 ± 3	2.1 ± 0.4
Nov 10 (08:30:35)	861.8 ± 0.7	13 ± 2	2.7 ± 0.3
Nov 10 (10:04:43)	846.0 ± 2.9	33 ± 8	2.7 ± 0.5

NOTE.—Col. (1): Time at the beginning of the observation. All observations were in 2005. Cols. (2) and (3): Centroid and width of the fitted Lorentzian. Col. (4): rms fractional amplitude of the fitted Lorentzian.

To further investigate the source state, we produced low-frequency power spectra using event mode data from all PCUs on during each observation. The sum power spectrum for observations with $HC > 0.35$ shows very low frequency noise (VLFN) and so-called high-frequency noise (HFN). The total noise power in the 0.01–100 Hz band is 1.0% fractional rms. We fit the power spectrum with a model consisting of a power law to describe the VLFN and an exponentially cutoff power law for the HFN (van der Klis 1995). The best-fit parameters are a power-law index for the VLFN of 1.81 ± 0.13 and a power-law index of 0.8 ± 0.1 and a cutoff frequency in the range of 20–60 Hz for the HFN. The weakness of the signal at high frequencies prevents an accurate determination of the HFN parameters, but a HFN noise component is required, $\Delta\chi^2 = 49$. This power spectrum is consistent with those in the "lower banana" state. There is no detectable HFN in the power spectrum from the observations with the softer hard color, $HC < 0.35$. The total noise power in the 0.01–100 Hz band is 0.2% fractional rms and the spectrum is adequately described by a single power law with an index of 1.08 ± 0.02. The shape of the power spectrum is consistent with those seen in the "upper banana" state, but the total noise power is lower than usual and spectrally the state would be classified as the lower banana (van der Klis 1995).

Based on the timing and color information, we identify XTE J1739−285 as an atoll source. The source appears to have been in the "banana" state during all of the observations analyzed here, although its evolution along the banana appears somewhat unusual.

We searched for high-frequency QPOs in each uninterrupted *RXTE* observation window. We calculated averages of 2 s power spectra for PCA events in the 4.2–20.4 keV energy band (channels 6–26 in the event mode data). We searched for peaks in the range from 100 to 3000 Hz and fit any peak found with a Lorentzian plus a constant equal to the calculated Poisson noise level. There were several strong QPO detections (see Table 2). The second most significant detection occurred on October 31 and is shown in Fig. 3. Allowing for 1102 trials, which is calculated by dividing the search interval of 2900 Hz by the QPO trial widths of 5, 10, 20, 50, and 100 Hz, we estimate a chance probability of occurrence of 1.2×10^{-13} for this QPO. The chance probabilities of occurrence, taking into account the number of trials, of all the other QPOs listed in the table are less than 1×10^{-4}. These QPO detections establish XTE J1739−285 as a new member of the class of neutron star low-mass X-ray binaries producing kHz QPOs. We did not detect two simultaneous kHz QPOs in any observation.

5. DISCUSSION

These observations establish that XTE J1739−285 exhibits millisecond oscillations in its persistent X-ray emission. The properties of the source are generally similar to those of other atoll neutron star X-ray binaries, although the evolution of the timing noise in the banana state is unusual.

The signal at 1122 Hz present in burst 2 is significant at the 99.96% confidence level. If this signal represents a true burst oscillation, then it would be of substantial interest. The near equality of the burst oscillation frequency with the frequency of coherent pulsations in the millisecond pulsars SAX J1808.4−3658 (in 't Zand et al. 2001; Chakrabarty et al. 2003) and XTE J1814−338 (Strohmayer et al. 2003), and the frequency of coherent pulsations in a superburst from 4U 1636−536 (Strohmayer & Markwardt 2002), strongly suggests that the burst oscillation frequency indicates the neutron star spin frequency. The lack of any significant signal near 561 Hz in the burst from XTE J1739−285 supports this interpretation and suggests that the possible 1122 Hz oscillation would be most naturally interpreted as the spin rate of the neutron star.

If the burst oscillation frequency of 1122 Hz is the spin rate of the neutron star, then XTE J1739−285 contains the most rapidly rotating neutron star yet discovered. This spin rate is close to the centrifugal breakup limit for some equations of state of nuclear matter (Burgio et al. 2003) and, therefore, may remove the motivation for a physical limit on neutron star spin other than the centrifugal breakup limit. Furthermore, such a high spin rate would place constraints on the nuclear equation of state, particularly if combined with a measurement of the mass and/or radius of the neutron star.

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