DISCOVERY OF A 270 HERTZ X-RAY BURST OSCILLATION IN THE X-RAY DIPPER 4U 1916−053

DUNCAN K. GALLOWAY, DEEPTO CHAKRABARTY, MICHAEL P. MUNO, AND PAVLIN SAVOV
Center for Space Research and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139; duncan@space.mit.edu, deepto@space.mit.edu, muno@space.mit.edu, pavlin@space.mit.edu

Received 2000 October 4; accepted 2000 December 20; published 2001 February 22

ABSTRACT

We report the discovery of a highly coherent oscillation in a type I X-ray burst observed from 4U 1916−053 by the Rossi X-Ray Timing Explorer (RXTE). The oscillation was most strongly detected ∼1 s after the burst onset at a frequency of 269.4 Hz, and it increased in frequency over the following 4 s of the burst decay to a maximum of 272 Hz. The total measured drift of 3.58 ± 0.41 Hz (1 σ) represents the largest fractional change in frequency (1.32% ± 0.15%) yet observed in any burst oscillation. If the asymptotic frequency of the oscillation is interpreted in terms of a decoupled surface burning layer, the implied neutron star spin period is around 3.7 ms. However, the expansion of the burning layer required to explain the frequency drift during the burst is around 80 m, substantially larger than expected theoretically (assuming rigid rotation). The oscillation was not present in the persistent emission before the burst, nor in the initial rise. When detected, its amplitude was 6%−12% (rms) with a roughly sinusoidal profile. The burst containing the oscillation showed no evidence for photospheric radius expansion, while at least five of the other nine bursts observed from the source by RXTE during 1996 and 1998 did. No comparable oscillations were detected in the other bursts. A pair of kilohertz quasi-periodic oscillations (kHz QPOs) has been previously reported from this source with a mean separation of 348 ± 12 Hz. 4U 1916−053 is the first example of a source where the burst oscillation frequency is significantly smaller than the frequency separation of the kHz QPOs.

Subject headings: accretion, accretion disks — stars: individual (4U 1916−053) — stars: neutron — X-rays: bursts

1. INTRODUCTION

Type I X-ray bursts are signatures of unstable nuclear burning on the surface of accreting neutron stars (see Lewin, van Paradijs, & Taam 1995 and Bildsten 1998 for recent reviews). Strong evidence for surface brightness anisotropies during the bursts comes from observations of highly coherent “burst oscillations” in seven sources to date (Strohmayer et al. 1996; see also van der Klis 2000 and references therein). These oscillations have been suggested to result from initially localized nuclear burning, which spreads over the surface of the neutron star during the early stages of the burst (Strohmayer et al. 1996).

As the burst evolves, the oscillations typically increase in frequency by a few Hz; in 4U 1916−053 the increase is ∼5 Hz, the greatest increase seen so far (Wijnands, Strohmayer, & Franco 2000). This frequency drift may occur as a consequence of the burning layer becoming decoupled from the star (Strohmayer et al. 1997; Cumming & Bildsten 2000). In several sources the oscillation approaches an asymptotic frequency that may be the spin frequency νspin of the neutron star. Although many observational characteristics of burst oscillations seem to be consistent with this picture, a growing body of observations points to a substantially more complex underlying mechanism (e.g., Miller 1999; Strohmayer et al. 2000). In this Letter we report the discovery of a new burst oscillation in 4U 1916−053.

The low-mass X-ray binary (LMXB) 4U 1916−053 (l = 31°4, b = −8°5) was discovered by the Uhuru satellite in 1977 (Forman et al. 1978). EXOSAT observations revealed irregular X-ray dipping behavior with a period of ∼50 minutes (Walter et al. 1982; White & Swank 1982), which optical observations of the mγ = 21 companion confirmed was approximately the orbital period (Grindlay et al. 1988).

Analysis of Rossi X-Ray Timing Explorer (RXTE) observations during 1996 shows that the source is a member of the “atoll” class (Bloser et al. 2000; Boirin et al. 2000). Both high- (≥100 Hz) and low-frequency quasi-periodic oscillations (QPOs) were detected in the power spectra of the source as measured by RXTE. In particular, a pair of high-frequency QPOs (“kilohertz QPOs”) with a mean separation of 348 ± 12 Hz was simultaneously detected on five occasions (Boirin et al. 2000). On four of these occasions, the observed separation was consistent with the mean value, but on one occasion it was only 290 ± 5 Hz. X-ray bursts exhibiting photospheric radius expansion resulting from super-Eddington luminosities indicate a source distance of 8.4−10.8 kpc (Smale et al. 1988). The X-ray bursts observed by RXTE during 1996 were searched for high-frequency oscillations, but none were found to a 3 σ limit of 3% rms amplitude (Boirin et al. 2000). Here we present the results of a more comprehensive timing study of X-ray bursts in 4U 1916−053 observed by RXTE, including both the previously analyzed 1996 data and more recent observations made during 1998.

2. OBSERVATIONS AND ANALYSIS

4U 1916−053 was observed using the RXTE proportional counter array (PCA; Jahoda et al. 1996) throughout 1996 and during 1998 June–August.

These observations comprise 40 separate pointings with a total exposure time of 323 ks. The data were screened to exclude Earth occultations and intervals of unstable pointing, with the maximum allowed offset 0°01. A search of the Standard 1 mode data (2−60 keV, 0.125 s time resolution, no energy resolution) revealed four type I bursts during 1996 and six during 19981 (see Table 1). It is possible that one or more of the

1 An apparent weak burst on 1996 March 13 was on closer examination present in only one of the five proportional counter units (PCUs). We attribute this to a detector breakdown in PCU 3, the earliest example of which was previously thought to occur several days later.
observed bursts originated from a source other than 4U 1916–053 in the PCA field (FWHM = 1°). The nearest (∼1°) known source from the Simbad catalog is RXS 192242.1–051559, from which no bursts have been reported. We consider the likelihood of an unknown bursting source within the PCA field of view at this relatively high Galactic latitude remote. As already noted by Chou, Grindlay, & Bloser (2001), the 1996 bursts are clustered in binary phase near the X-ray dip. Interestingly, the 1998 bursts do not show the same evidence for clustering, although the Chou et al. ephemeris still correctly predicts the X-ray dip times in the 1998 data.

The burst profiles typically exhibit a broad and somewhat flat-topped peak, often followed by one or more narrow dips during the decay. Uninterrupted PCA data from high time resolution modes (typically the E_125us_64M_0_1s mode with 122 μs time resolution and 64 channel energy resolution) were available for eight of the 10 bursts observed. The spectral characteristics of these bursts were measured by fitting absorbed blackbody spectra in the 2.5–40 keV range to 0.25 s segments of data covering the burst. Spectral fitting was undertaken with XSPEC version 11 (Arnaud 1996). A spectrum extracted from a short interval of data immediately before the burst was used as the background. Five of the bursts showed an increase in the fitted blackbody radius coupled with a decrease in the effective temperature during the first 10 s. This strongly suggests that photospheric radius expansion occurred during these bursts. No evidence for radius expansion was found for the bursts on 1998 July 24, August 1, and August 10.

Subintervals of the high time resolution data covering each of the bursts were searched for oscillations in the 0–4000 Hz range. We computed 8 times oversampled Fourier power spectra for 0.5 s lengths of data spaced at 0.25 s intervals and searched for statistically significant pulsed signals. A strong, highly significant (chance probability for 2000 independent frequencies 5 × 10⁻¹⁰, equivalent to 4.6 σ) oscillation at $f_{\text{burst}} \approx 270$ Hz was detected 0.75 s after the burst rise during the 1998 August 1 burst (Fig. 1). Weaker oscillations were measured at a gradually increasing frequency over the next ≈5 s, except for the interval between 2 and 3 s following the burst rise when no significant oscillation was detected in the 220–320 Hz range (Fig. 2a). When the oscillation reappeared 3 s after the burst rise, we initially detected two peaks of approximately equal strength separated by ≈3 Hz, although clearly only one was consistent with the continuing evolution of the initial signal. We note that the presence of these two closely separated peaks has also been observed in 4U 1636–536 (Miller 2000). The oscillation was not detected in the persistent emission prior to the burst, nor during the burst rise itself. The frequency and rms amplitude for the oscillation corresponding to each peak was measured from the oversampled Fourier power spectra (e.g., Middleditch & Nelson 1976). The difference between the initial and final frequencies at which the oscillation was detected (268.45 ± 0.34 and 272.03 ± 0.24 Hz, respectively) was 3.58 ± 0.41 Hz (1 σ error; Fig. 2b). The rms amplitude for the full PCA energy range (2–60 keV) peaked at ≈12% around 1 s following the burst rise, and then decreased within 0.5 s to unmeasurable levels. When the oscillation returned ≈3 s following the burst rise, the measured amplitude was in the 6%–11% range. The rms amplitudes were also calculated in the 2–8 and 8–20 keV energy ranges separately. The amplitude was generally significantly greater in the 8–20 keV energy band, at 6%–12%. However, at times the amplitude in the 2–8 keV band reached that of the higher energy band, suggesting spectral variations in the pulsed emission. We note

![Fig. 1.—Leahy-normalized power spectrum from RXTE observations of 4U 1916–053 on 1998 August 1. The 8 times oversampled power spectrum is calculated from 0.5 s segments of data, with frequency resolution 0.25 Hz. (a) Power spectrum from 0.5 s segment beginning 0.75 s after the start of the burst. The largest peak is at a significance level of 99.99% and indicates a burst oscillation at 269.4 Hz. Expected positions of the $n = 2, 3, 4$ harmonics and the first subharmonic are indicated by the arrows. (b) Power spectrum for the 0.5 s segment beginning 2.5 s after the start of the burst. The less significant marked peak is close to the (single) peaks observed in subsequent power spectra.](Image)
that when two significant peaks close to 270 Hz were measured in the Fourier spectrum (at around 2.5 s following the burst onset) only the higher frequency oscillation was present to a significant level in the 8–20 keV energy band. The pulse profile was generally consistent with a sinusoid.

No significant persistent oscillations were observed in the other nine bursts detected from the source in 1996 and 1998. A more sensitive search was undertaken on those bursts by averaging power spectra over 1 s segments of data within intervals of varying length covering the burst peak, but this too resulted in no detections. In several of the bursts (1996 August 16 in particular), peaks representing detections at greater than 90% confidence around 256 or 270 Hz were found in single power spectra as early as 2 s prior to the burst or coincident with the burst rise. These peaks did not persist for more than 0.5 s, nor were they as significant in power spectra of longer stretches of data. The most significant peak (3σ equivalent for 4000 independent frequencies) was found in both the 0.5 and 1 s power spectra around 4 s before the 1996 August 16 burst, with frequency 278.01 ± 0.07 Hz (1σ) and estimated rms amplitude 24%. We include these results for completeness; without repeated detections or greater significance their authenticity is questionable.

3. DISCUSSION

We have conclusively detected a highly coherent ≈270 Hz oscillation during a type I X-ray burst from 4U 1916−053, bringing the total number of known burst oscillation sources to eight. If we interpret the frequency evolution of the oscillation during the burst in terms of a decoupled burning layer, then the maximum observed frequency implies a neutron star spin period of ≈3.7 ms. However, the large change in frequency during this burst (3.58 ± 0.41 Hz or 1.32% ± 0.15%) would require an ≈80 m expansion of the burning layer (assuming rigid rotation). The maximum peak flux of all the bursts observed is a lower limit to the Eddington flux $F_{\text{Edd}}$ for the source, in which case the peak flux for the 1998 August 1 burst (in which the burst oscillation was observed) is at most 0.5$F_{\text{Edd}}$. The maximum expansion predicted for a mixed H/He burst at this flux level is only 20 m (Cumming & Bildsten 2000), different from our measurement at the 7σ level. That the binary period of the source is shorter than 80 minutes indicates that the mass donor must be very hydrogen-poor (Nelson, Rapaport, & Joss 1986), suggesting a predominantly He burning layer. Interestingly, Cumming & Bildsten (2000) predict an even smaller expansion in that case.

The limited sample available suggests that burst oscillations in 4U 1916−053 are more likely to be present in atypically weak bursts which do not exhibit photospheric radius expansion (see Table 1). The other two sources with ∼300 Hz burst oscillations (4U 1728−34 and 4U 1702−429) also show this tendency, while the sources with higher frequency oscillations behave in a distinctly different manner (Muno et al. 2001).

In the four burst sources from which both a kHz QPO pair and a burst oscillation were previously known, the burst oscillation frequency $\nu_{\text{burst}}$ is comparable to (or else nearly twice) the peak separation of the kHz QPOs’ $\Delta \nu$ (see Table 2). Precise measurements of $\Delta \nu$ have been made for two of these sources, and these detailed measurements show clearly that

$$\nu_{\text{burst}} \equiv n \Delta \nu$$

with $n = 1$ or 2.

(Méndez, van der Klis, & van Paradijs 1998; Méndez & van der Klis 1999). For the other two sources, one can only con-
clude that $\Delta \nu$ and $\nu_{\text{burst}}$ are equal within their uncertainties. The relationship between $\nu_{\text{burst}}$ and $\Delta \nu$ given in equation (1) has been interpreted in terms of a beat frequency model for the kHz QPOs (Strohmayer et al. 1996; Miller, Lamb, & Psaltis 1998). In the original sonic-point beat frequency model of Miller et al. (1998), the upper kHz QPO appears at the Keplerian frequency of the accretion flow’s sonic point, and the lower kHz QPO appears at the beat between this frequency and $\nu_{\text{pin}}$. In this simple picture, we expect $\Delta \nu = \nu_{\text{pin}}$. More recent calculations by Lamb & Miller (2000) have shown that the accreting material’s inward drift decreases the upper kHz QPO frequency below the sonic point’s Keplerian frequency and increases the lower kHz QPO frequency above the beat frequency, resulting in $\Delta \nu \leq \nu_{\text{pin}}$. This is consistent with the observed relation (1) if we have $\nu_{\text{burst}} \approx n \nu_{\text{pin}}$ with $n = 1$ or 2, as in the decoupled burning layer model for the burst oscillations.

Our study of 4U 1916–053 has revealed the first example of a source where $\nu_{\text{burst}} < \Delta \nu$ to high significance ($\geq 7 \sigma$ for the range of values of $\Delta \nu$ reported in Boirin et al. 2000). It is unclear how to understand this result in terms of the sonic-point model, which would require the frequency of the upper kHz QPO to be higher than the Keplerian orbital frequency in order to match our observation. The numerical simulations presented by Lamb & Miller (2000) do not show this trend, but such a possibility cannot be excluded a priori. A different explanation for the kHz QPOs involving relativistic precession of the accretion disk has also been proposed. Here, the upper kHz QPO appears at the Keplerian frequency at some characteristic disk radius, and the lower kHz QPO occurs at the periastron precession frequency at the same radius (Stella & Vietri 1998; Psaltis & Norman 2000). In this picture, $\Delta \nu$ is approximately equal to the radial epicyclic frequency and is not inherently related to $\nu_{\text{pin}}$ so that the striking observed similarity between $\nu_{\text{burst}}$ and $\Delta \nu$ (or $2 \Delta \nu$) is not explicitly addressed. An additional model is therefore required to understand the burst oscillations in conjunction with the relativistic precession models for the kHz QPOs.

The requirements for such a model have been discussed, although none has yet been developed quantitatively. If we assume that $\nu_{\text{burst}} \approx \nu_{\text{pin}}$, then it must be that $\nu_{\text{pin}}$ is driven toward the maximum epicyclic frequency (Stella 1999) or else that the kHz QPOs reach detectable amplitudes only when $\Delta \nu \approx \nu_{\text{pin}}$ or $\Delta \nu \approx \nu_{\text{pin}}/2$ due to a resonance effect (Psaltis 2000) Alternatively, $\nu_{\text{burst}}$ might not be related to $\nu_{\text{pin}}$ at all but might instead be related to an accretion disk mode that occurs near the maximum epicyclic frequency at the innermost stable orbit (Tutukchuk, Lapidus, & Muslimov 1998; Psaltis & Norman 2000), such as the $g$-modes predicted in the case of accreting black holes (see, e.g., Kato 1990; Nowak & Wagoner 1991). Unfortunately, the absence of a detailed link between the burst oscillations and the relativistic precession model makes it impossible to constrain this model using our results.

We thank Ed Morgan and Dimitrios Psaltis for useful discussions and Josh Grindlay for making a source ephemeres available prior to publication. This work was supported in part by the NASA Long Term Space Astrophysics program under grant NAG 5-9184.

REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. Jacoby & J. Barnes (San Francisco: ASP), 17

Bildsten, L. 1998, in The Many Faces of Neutron Stars, ed. R. Buccheri, J. van Paradijs, & A. Alpar (Dordrecht: Kluwer), 419

Bloser, P. F., Grindlay, J. E., Barret, D., & Boirin, L. 2000, ApJ, 542, 989

Boirin, L., Barret, D., Olive, J. F., Bloser, P. F., & Grindlay, J. E. 2000, A&A, 361, 121

Chou, Y., Grindlay, J. E., & Boirin, P. F. 2001, ApJ, in press (astro-ph/0104655)

Cumming, A., & Bildsten, L. 2000, ApJ, 544, 453

Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H., & Giacconi, R. 1978, ApJS, 38, 357

Grindlay, J. E., Bailyn, C. D., Cohn, H., Lugger, P. M., Thorstensen, J. R., & Wegner, G. 1988, ApJ, 334, L25

Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayer, T., Zhang, W., & Morgan, E. H. 1996, Proc. SPIE, 2808, 59

Kato, S. 1990, PASJ, 42, 99

Lamb, F. K., & Miller, C. M. 2000, ApJ, submitted (astro-ph/0007460)

Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 175

Markwardt, C. B., Strohmayer, T. E., & Swank, J. H. 1999, ApJ, 512, L125

Méndez, M., & van der Klis, M. 1999, ApJ, 517, L51

Méndez, M., van der Klis, M., & van Paradijs, J. 1998, ApJ, 506, L117

Middlewitch, D., & Nelson, J. 1976, ApJ, 208, 567

Miller, M. C. 1999, ApJ, 515, L77

———. 2000, ApJ, 531, 458

Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, ApJ, 508, 791

Muno, M. P. Chakrabarty, D., Galloway, D., & Savoy, P. 2001, ApJL, submitted

Nelson, L. A., Rappaport, S. A., & Joss, P. C. 1986, ApJ, 304, 231

Nowak, M. A., & Wagoner, R. V. 1991, ApJ, 378, 656

Psaltis, D. 2000, Adv. Space Res., in press (astro-ph/0012251)

Psaltis, D., & Norman, C. 2000, ApJ, submitted (astro-ph/0001391)

Smale, A. P., Mason, K. O., White, N. E., & Gottwald, M. 1988, MNRAS, 232, 647

Smith, D. A., Morgan, E. H., & Bradt, H. 1997, ApJ, 479, L137

Stella, L. 1999, talk at the Aspen Summer Workshop on X-Ray Probes of Relativistic Effects Near Neutron Stars and Black Holes, Aspen Center for Physics

Stella, L., & Vietri, M. 1998, ApJ, 492, L59

Strohmayer, T. E., Giles, A. B., Wachter, S., & Hill, K. 2000, in Rossi 2000: Astrophysics with the Rossi X-Ray Timing Explorer (Greenbelt: NASA), E71

Strohmayer, T. E., Jahoda, K., Giles, A. B., & Lee, U. 1997, ApJ, 486, 355

Strohmayer, T. E., & Markwardt, C. B. 1999, ApJ, 516, L81

Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, A., Titarchuk, L., Day, C., & Lee, U. 1996, ApJ, 469, L9

Strohmayer, T. E., Zhang, W., Swank, J. H., White, N. E., & Lapidus, I. 1998, ApJ, 498, L135

Titarchuk, L., Lapidus, I., & Muslimov, A. 1998, ApJ, 499, 315

van der Klis, M. 2000, ARA&A, 38, 717

Walter, F. M., Mason, K. O., Clarke, J. T., Halpern, J., Grindlay, J. E., Bowyer, S., & Henry, J. P. 1982, ApJ, 253, L67

White, N. E., & Swank, J. H. 1982, ApJ, 253, L61

Wijnands, R., Strohmayer, T., & Franco, L. M. 2000, ApJ, submitted (astro-ph/0008526)

Wijnands, R. A. D., & van der Klis, M. 1997, ApJ, 482, L65