The Astrophysical Journal, 523:L51–L55, 1999 September 20

SPIN-DOWN OF PULSATIONS IN THE COOLING TAIL OF AN X-RAY BURST FROM 4U 1636−53

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Received 1999 June 3; accepted 1999 July 21; published 1999 August 19

ABSTRACT

With the proportional counter array on board the *Rossi X-ray Timing Explorer*, we report the discovery of a decrease in the frequency of X-ray brightness oscillations in the cooling tail of an X-ray burst from 4U 1636−53. This is the first direct evidence for a spin-down of the pulsations seen during thermonuclear bursts. We find that the spin-down episode is correlated with the appearance in this burst of an extended tail of emission with a decay timescale much longer than is seen in other bursts from 4U 1636−53 in the same set of observations. We present both time-resolved energy and variability spectra during this burst and compare them with results from a second burst that shows neither a spin-down episode nor an extended tail. A spectral evolution study of the "spin-down" burst reveals a secondary signature of weak radius expansion, which is not seen in other bursts and is correlated with the spin-down episode; this may indicate a secondary thermonuclear energy release. We interpret the spin-down episode in the context of an angular momentum–conserving shell, which is reexpanded and therefore spun down by an additional thermonuclear energy release that could also explain the extended X-ray tail.

Subject headings: stars: individual (4U 1636−53) — stars: neutron — stars: rotation — X-rays: bursts

1. INTRODUCTION

Millisecond oscillations in the X-ray brightness during thermonuclear bursts, "burst oscillations," have been observed from six low-mass X-ray binaries with the *Rossi X-ray Timing Explorer* (Strohmayer, Swank, & Zhang 1998 provide a recent review). Considerable evidence points to rotational modulation as the source of these pulsations (e.g., Strohmayer, Zhang, & Swank 1997b; Strohmayer & Markwardt 1999). Anisotropic X-ray emission caused by either localized or inhomogeneous nuclear burning produces either one or a pair of hot spots on the surface that are then modulated by rotation of the neutron star. A remarkable property of these oscillations is the frequency evolution that occurs in their cooling tails. Recently, Strohmayer & Markwardt (1999) have shown that the frequency in the cooling tails of bursts from 4U 1728−34 and 4U 1702−429 is well described by an exponential chirp model whose frequency increases asymptotically toward a limiting value. Strohmayer et al. (1997a) have argued that this evolution results from the angular momentum conservation of the thermonuclear shell, which cools, shrinks, and spins up as the surface radiates away the thermonuclear energy. To date, only frequency increases have been reported in the cooling tails of bursts, which is consistent with the settling of the shell as its energy is radiated away.

In this Letter, we report observations of a *decreasing* burst-oscillation frequency in the tail of an X-ray burst. We find that an episode of spin-down in the cooling tail of a burst observed in 1996 December 31 at 17:36:52 UTC (hereafter burst A, or the "spin-down" burst) from 4U 1636−53 is correlated with the presence of an extended tail of emission. In § 1, we present an analysis of the frequency evolution in this burst, with emphasis on the spin-down episode. In § 2, we present time-resolved energy spectra of the spin-down burst, and we investigate the energetics of the extended tail. Throughout, we compare the temporal and spectral behavior of the spin-down burst with a different burst observed in 1996 December 29 at 23:26:46 UTC (hereafter burst B) that does not show either a spin-down episode or an extended tail of emission but that is similar to the spin-down burst in most other respects. We conclude in § 3 with a summary and discussion of the spin-down episode and extended emission in the context of an additional, delayed thermonuclear energy release that might reexpand the thermonuclear shell and perhaps account for both the spin-down and the extended tail of thermal emission.

2. EVIDENCE FOR SPIN-DOWN

Oscillations at 580 Hz were discovered in thermonuclear bursts from 4U 1636−53 by Zhang et al. (1996). More recently, Miller (1999a) has reported evidence during the rising phase of bursts of a significant modulation at half the 580 Hz frequency, suggesting that 580 Hz is twice the neutron star spin frequency and that a pair of antipodal spots produces the oscillations. Here we focus on a burst from 4U 1636−53 that shows a unique decrease in the ≈580 Hz oscillation frequency. To study the evolution in frequency of burst oscillations, we employ the Z_n^2 statistic (Buccheri et al. 1983). We have described this method previously, and details can be found in Strohmayer & Markwardt (1999). We first constructed, for both bursts A and B, a dynamic "variability" spectrum by computing Z_1^2 as a function of time on a grid of frequency values in the vicinity of 580 Hz. We used 2 s intervals to compute Z_1^2 and started a new interval every 0.25 s. This variability spectrum is very similar to a standard dynamic power spectrum; however, the Z_1^2 statistic allows for a more densely sampled frequency grid than a standard fast Fourier transform power spectrum would allow. The results are shown in Figure 1 (bursts A and B are in the left and right panels, respectively) as contour maps of constant Z_1^2 through each burst. The contour map for the spin-down burst (*left*) suggests that the oscillation began with a frequency near 579.6 Hz at burst onset, reappeared later in the burst after "touchdown" of the photosphere at an increased frequency, ≈580.7 Hz, but then, beginning near 11 s, dropped to ≈579.6 Hz over several seconds. For comparison, we also show in Figure 1 (*right*) a similar variability spectrum for burst B, which also shows strong oscillations near 580 Hz but shows no evidence of a similar spin-down episode.

To investigate the evolution of the oscillation frequency more

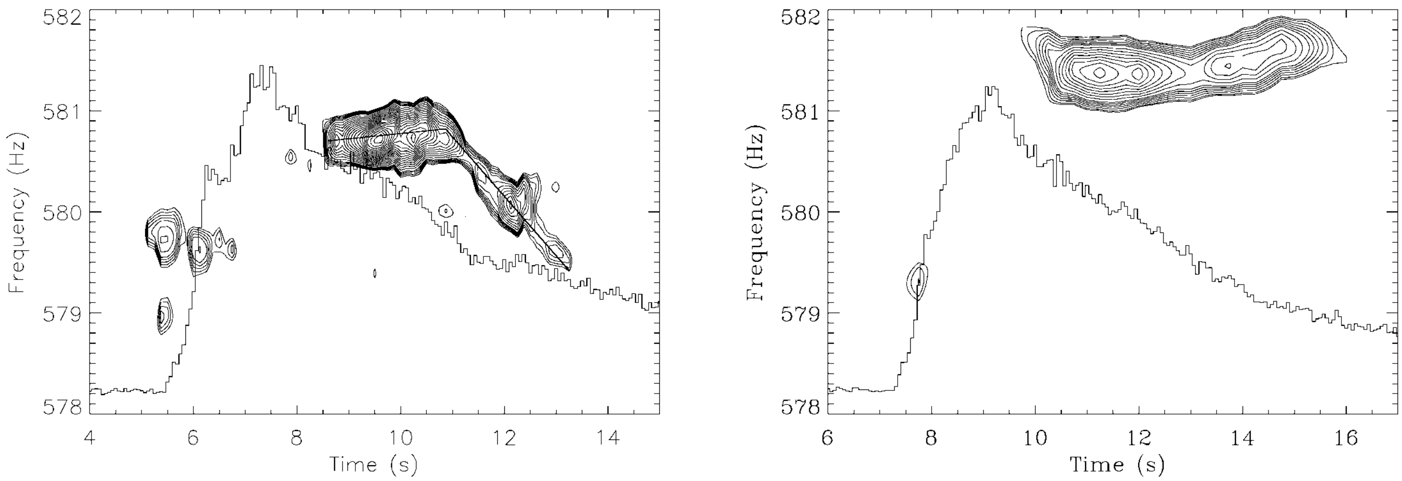

FIG. 1.—Dynamic variability spectra for bursts A (*left*) and B (*right*) from 4U 1636−53. The contours of constant power Z_1^2 computed from 2 s intervals, with a new interval every 0.25 s, are shown. The count rate vs. time in the proportional counter array is also shown. For burst A, the two-segment frequency evolution model is shown as the solid curve. The best-fitting model parameters were $\nu_0 = 580.70$ Hz, $d_\nu^1 = 9.0 \times 10^{-5}$ s^{-1}, $d_\nu^2 = -1.0 \times 10^{-3}$ s^{-1}, and t_b = 10.86 s.

quantitatively, we fitted a model for the temporal evolution of the frequency, $\nu(t)$, to the 4.5 s interval during which the oscillation is evident in the dynamic variability spectrum (Fig. 1, *left*). Our model is composed of two linear segments, each with its own slope, joined continuously at a break time t_b. This is similar to the model employed by Miller (1999b) and has four free parameters: the initial frequency ν_0, the two slopes d_ν^1 and d_ν^2, and the break time t_b. We used this frequency model to compute phases ϕ_{t_j} for each X-ray event, viz., $\phi_{t_j} = \int_0^{t_j} \nu(t')dt'$, where the t_j's are the X-ray arrival times, and then we varied the model parameters to maximize the Z_1^2 statistic. We used a downhill simplex method for the maximization (Press et al. 1986). Figure 2 compares Z_1^2 versus ν_0 for the best-fitting two-segment model (*solid histogram*) and a simple constant frequency model [$\nu(t) = \nu_0$, *dashed histogram*]. The two-segment model produces a significant increase in the maximum Z_1^2 of about 40 compared with no frequency evolution, and it also yields a single, narrower peak in the Z_1^2 distribution. The increase of 40 in Z_1^2, which for a purely random process is distributed as χ^2 with 2 degrees of freedom, argues convincingly that the frequency drop is significant. We note that Miller (1999b) has also identified the same spin-down episode during this burst using a different but related method. The best-fitting two-segment model is shown graphically as the solid curve in Figure 1 (*left*).

3. TIME HISTORY, SPECTRAL EVOLUTION, AND BURST ENERGETICS

A comparison of the 2–20 keV time history of the spin-down burst with other bursts from the same observations reveals that this burst is also unique in having an extended tail of thermal emission. This is well illustrated in Figure 3, which compares the 2–20 keV time histories of the spin-down burst and burst B. To investigate the energetics of the thermal burst emission further, we performed a spectral evolution analysis. We accumulated energy spectra for varying time intervals through both bursts. Using XSPEC, we fitted blackbody spectra to each interval by first subtracting a preburst interval as back-

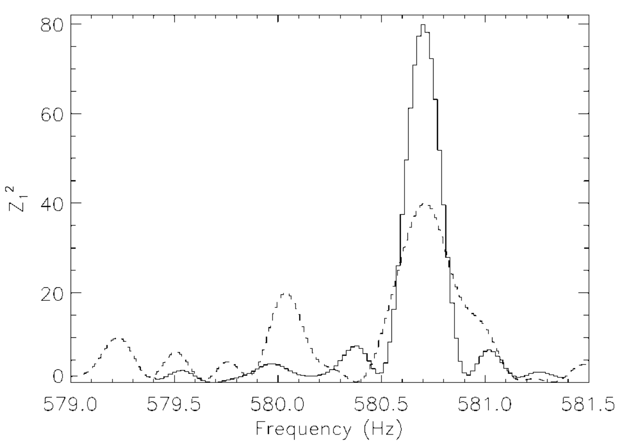

FIG. 2.—A plot of Z_1^2 vs. frequency parameter ν_0 for the spin-down burst (burst A). The solid curve shows the result for the best-fitting two-segment frequency evolution model. The dashed curve was produced assuming no frequency evolution.

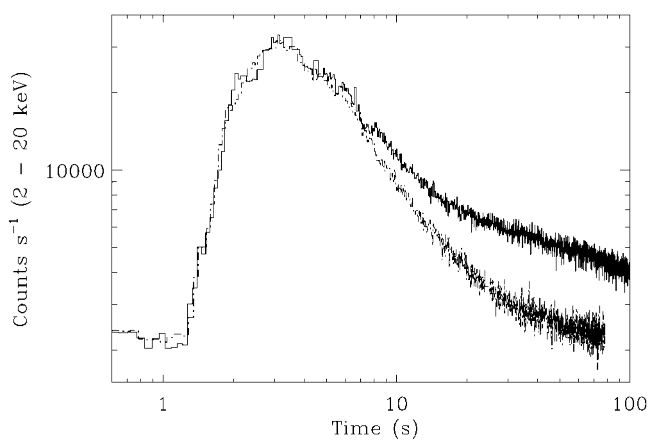

FIG. 3.—The 2–20 keV light curves for bursts A (*solid curve*) and B (*dashed curve*) from 4U 1636−53. Notice the long extended tail in burst A. The preburst and peak count rates were virtually the same for both bursts. The bursts were aligned in time to facilitate direct comparison.

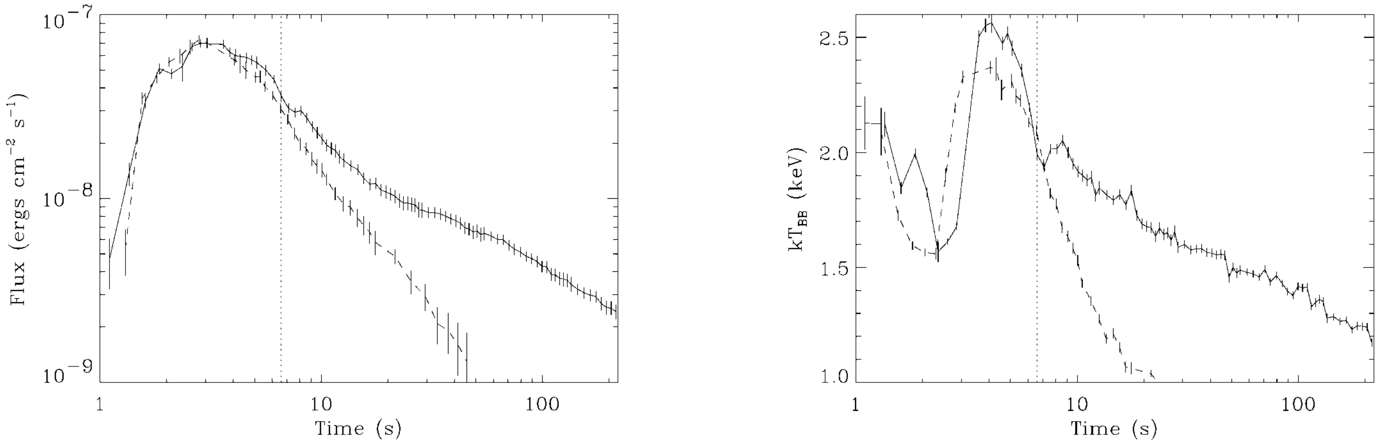

FIG. 4.—Results of the spectral evolution analysis for bursts A and B. The left panel shows the evolution of the bolometric flux deduced from the best-fitting blackbody parameters for bursts A (*solid curve*) and B (*dashed curve*). Note the long tail on burst A, and note that the peak fluxes are consistent. The right panel shows the evolution of the blackbody temperature *kT* for bursts A (*solid curve*) and B (*dashed curve*). The initial drop in *kT*, followed by an increase, is a signature of radiation-driven photospheric expansion. The dotted vertical line marks t_b, which is the break time marking the onset of spin-down (see discussion in text).

ground, and then we investigated the temporal evolution of the blackbody temperature *kT*, inferred radius R_{BB}, and bolometric flux *F*. In most intervals, we obtained acceptable fits with the blackbody model. The results for both bursts are summarized in Figure 4. We have aligned the burst profiles in time for direct comparison. Both bursts show evidence for radius expansion shortly after onset in that *kT* drops initially and then recovers. Their peak fluxes are also similar, which is consistent with their being Eddington-limited fluxes. Out to about 7 s post-onset, both bursts show the same qualitative behavior; after this, however, the spin-down burst (*solid curve*) shows a much more gradual decrease in both the blackbody temperature *kT* and the bolometric flux *F* than is evident in burst B. We integrated the flux versus time profile for each burst in order to estimate fluences and establish the energy budget in the extended tail. We find fluences of 1.4×10^{-6} and 5.1×10^{-7} ergs cm^{-2} for bursts A and B, respectively. That is, the spin-down burst has about 2.75 times more energy than burst B. Put another way, most of the energy in the spin-down burst is in the extended tail. In Figure 4, we also indicate with a vertical dotted line the time t_b associated with the beginning of the spin-down episode based on our modeling of the 580 Hz oscillations. The spectral evolution analysis indicates that at about the same time the spin-down began, there was also a change in its spectral evolution as compared with burst B. This behavior is evident in Figure 5, which shows the evolution of *kT* (*dashed curve*) and the inferred radius R_{BB} (*solid curve*) for the spin-down burst. Notice the secondary increase in R_{BB} and an associated dip in *kT* near time t_b (*vertical dotted line*). This behavior is similar to the signature of radius expansion seen earlier in both bursts, but at a weaker level it suggests that there may have been an additional thermonuclear energy input in the accreted layers, perhaps at greater depth, which then diffused out on a longer timescale, producing the extended tail. That this spectral signature occurred near the same time as the onset of the spin-down episode suggests that the two events may be causally related.

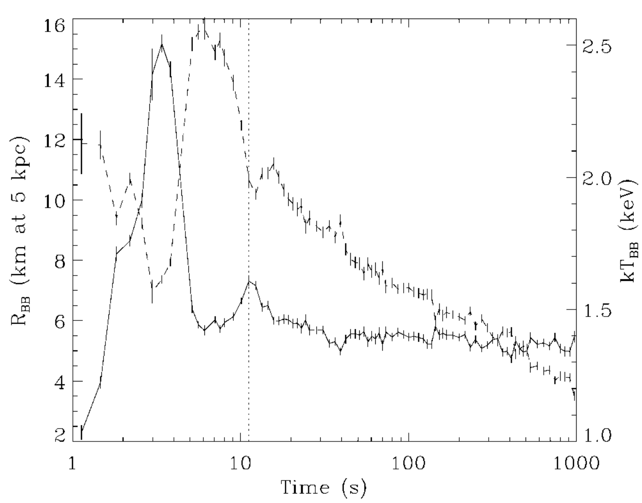

FIG. 5.—Evolution of the blackbody temperature *kT* (*dashed curve*) and inferred radius R_{BB} (*solid curve*) for the spin-down burst (burst A). The dotted vertical line marks t_b, which is the break time marking the onset of spin-down (see discussion in text). The burst begins with an episode of photospheric radius expansion, marked by the simultaneous decrease in temperature and increase in radius. Notice the secondary signature of a weak radius expansion event near time t_b (*dotted vertical line*).

4. DISCUSSION AND SUMMARY

The observation of thermonuclear bursts with extended tails is not a new phenomenon. Czerny, Czerny, & Grindlay (1987) reported on a burst from the soft X-ray transient Aql X-1 that showed a long, relatively flat X-ray tail. Bursts following this one were found to have much shorter, weaker tails. Fushiki et al. (1992) argued that such long tails were caused by an extended phase of hydrogen burning that was due to electron captures at high density ($\rho \approx 10^7$ g cm^{-3}) in the accreted envelope. Such behavior is made possible because of the long time required to accumulate an unstable pile of hydrogen-rich thermonuclear fuel when the neutron star is relatively cool ($\approx 10^7$ K) prior to the onset of accretion. This, they argued, could occur in transients such as Aql X-1, which have long quiescent periods during which the neutron star envelope can cool, and thus the first thermonuclear burst after the onset of an accretion-driven outburst should show the longest extended tail. Other researchers have shown that the thermal state of the neutron star envelope, the abundance of CNO materials in the accreted matter, and variations in the mass accretion rate all can have profound effects on the character of bursts produced during an accretion-driven outburst (Taam et al. 1993; Woosley & Weaver 1984; Ayasli & Joss 1982; and references therein). For example, Taam et al. (1993) show that for low CNO abundances and cool neutron star envelopes, the subsequent bursting behavior can be extremely erratic, with burst recurrence times varying by as much as 2 orders of magnitude. They also show that such conditions produce dwarf bursts, with short recurrence times and peak fluxes less than a tenth Eddington, and that many bursts do not burn all the fuel previously accumulated. Thus, residual fuel, in particular hydrogen, can survive and provide energy for subsequent bursts. These effects lead to a great diversity in the properties of X-ray bursts observed from a single accreting neutron star. Some of these effects were likely at work during the 1996 December observations of 4U 1636−53 discussed here since both a burst with a long extended tail and a dwarf burst were observed (Miller 1999b).

The spin-up of burst oscillations in the cooling tails of thermonuclear bursts from 4U 1728−34 and 4U 1702−429 has been discussed in terms of the angular momentum conservation of the thermonuclear shell (Strohmayer et al. 1997a; Strohmayer & Markwardt 1999). Expanded at burst onset by the initial thermonuclear energy release, the shell spins down because of its larger rotational moment of inertia compared with its preburst value. As the accreted layer subsequently cools, its scale height decreases, and it comes back into corotation with the neutron star over ≈10 s. To date, the putative initial spin-down at burst onset has not been observationally confirmed, perhaps because of the radiative diffusion delay, on the order of a second, which can hide the oscillations until after the shell has expanded and spun down (Bildsten 1998). However, we continue to search for such a signature. Although the initial spin-down at burst onset has not been seen, the observation of a spin-down episode in the *tail* of a burst begs the question: can it be understood in a similar context, that is, by invoking a second thermal expansion of the burning layers? The supporting evidence is the presence of spin-down associated with the spectral evidence for an additional energy source, the extended tail, as well as the spectral variation observed at the time the spin-down commenced (see Fig. 5). Based on these observations, we suggest that the spin-down began with a second episode of thermonuclear energy release, perhaps in a hydrogen-rich layer underlying that responsible for the initial instability, and built up over several preceding bursts. Such a scenario is not so unlikely based on previous theoretical work (Taam et al. 1993; Fushiki et al. 1992). The observed rate of spin-down, $d_\nu^2 = -1.01 \times 10^{-3}\ \mathrm{s^{-1}}$, interpreted as an increase in the height of the angular momentum–conserving shell gives $dr/dt \approx (\Delta\nu/2\Delta T\nu_0)R \approx 5.25\ \mathrm{m\ s^{-1}}$ for a neutron star radius of $R = 10$ km. Calculations predict increases in the scale height of the bursting layer on the order of 20–30 m during thermonuclear flashes (Joss 1978; Bildsten 1995). Based on this and the energy evident in the extended tail, the additional expansion of about 12 m does not appear overly excessive. If correct, this scenario would require that the frequency eventually increase again later in the tail. Unfortunately, the oscillation dies away before another increase is seen.

It is interesting to note that bursts from 4U 1636−53 do not appear to show the same systematic evolution of the oscillation frequency as is evident in bursts from 4U 1728−34 and 4U 1702−429 (Miller 1999b; Strohmayer & Markwardt 1999). In particular, there is no strong evidence for an exponential-like recovery that is often seen in 4U 1728−34 and 4U 1702−429. Rather, in 4U 1636−53, when the burst-oscillation frequency reappears after photospheric touchdown, in many bursts it appears almost immediately at the higher frequency. In the context of a spinning shell, this might suggest that the shell recouples to the underlying star more quickly than in 4U 1728−34 or 4U 1702−429. Interestingly, 4U 1636−53 is also the only source to show significant pulsations at the subharmonic of the strongest oscillation frequency, and this has been interpreted as revealing the presence of a pair of antipodal hot spots (Miller 1999a). These properties may be related and could, for example, indicate the presence of a stronger magnetic field in 4U 1636−53 than in the other sources.

Another physical process that could alter the observed frequency is related to general relativistic (GR) time stretching. If the burst evolution modulates the location in radius of the photosphere, then the rotation at that radius, as seen by a distant observer, is affected by a redshift such that $\Delta r/R = (R/r_g)(1 - r_g/R)\,[1 - 1/(\nu_h/\nu_l)^2]$, where Δr is the change in height of the photosphere, $r_g = 2GM/c^2$ is the Schwarzschild radius, and ν_h/ν_l is the ratio of the highest and the lowest observed frequencies. If this were the sole cause of the frequency changes, then it would imply a height change for the photosphere of ≈120 m, which is much larger than the increases predicted theoretically for bursting shells. Note that this effect works counter to the angular momentum conservation of the shell, since increasing the height makes the frequency higher compared with deeper layers. Since the thicknesses of pre- and postburst shells are on the order of 20–50 m, we estimate from the above that the GR correction amounts to about 10%–20% of the observed frequency change and, if the angular momentum conservation effect is at work, requires a modest *increase* in the height of the shell over that estimated nonrelativistically.

We have reported in detail on the first observations of a spin-down in the frequency of X-ray brightness oscillations in an X-ray burst. We have shown that this event is coincident with the occurrence of an extended tail as well as a spectral signature, and these both suggest a secondary release of thermonuclear energy in the accreted layer. It is always difficult to draw conclusions based on a single event; however, if the association of spin-down episodes with an extended X-ray tail can be confirmed in additional bursts, this will provide strong evidence in support of the hypothesis that the angular momentum conservation of the thermonuclear shell is responsible for the observed frequency variations during bursts. The combination of spectral and timing studies during bursts with oscillations can then give us a unique new probe of the physics of thermonuclear burning on neutron stars.

We thank Craig Markwardt and Jean Swank for many helpful discussions.

REFERENCES

Ayasli, S., & Joss, P. C. 1982, ApJ, 256, 637

Bildsten, L. 1995, ApJ, 438, 852

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

Buccheri, R., et al. 1983, A&A, 128, 245

Czerny, M., Czerny, B., & Grindlay, J. E. 1987, ApJ, 312, 122

Fushiki, I., Taam, R. E., Woosley, S. E., & Lamb, D. Q. 1992, ApJ, 390, 634

Joss, P. C. 1978, ApJ, 225, L123

Miller, M. C. 1999a, ApJ, 515, L77
———. 1999b, ApJ, submitted (astro-ph/9904093)
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1986, Numerical Recipes (Cambridge: Cambridge Univ. Press)
Strohmayer, T. E., Jahoda, K., Giles, A. B., & Lee, U. 1997a, ApJ, 486, 355
Strohmayer, T. E., & Markwardt, C. B. 1999, ApJ, 516, L81
Strohmayer, T. E., Swank, J. H., & Zhang, W. 1998, Nucl. Phys. B (Proc. Suppl.), 69(1–3), 129
Strohmayer, T. E., Zhang, W., & Swank, J. H. 1997b, ApJ, 487, L77
Taam, R. E., Woosley, S. E., Weaver, T. A., & Lamb, D. Q. 1993, ApJ, 413, 324
Woosley, S. E., & Weaver, T. A. 1984, in AIP Conf. Proc. 115, High Energy Transients in Astrophysics, ed. S. E. Woosley (New York: AIP), 273
Zhang, W., Lapidus, I., Swank, J. H., White, N. E., & Titarchuk, L. 1996, IAU Circ. 6541