OSCILLATIONS DURING THERMONUCLEAR X-RAY BURSTS: A NEW PROBE OF NEUTRON STARS

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ABSTRACT

Observations of thermonuclear (also called Type I) X-ray bursts from neutron stars in low mass X-ray binaries (LMXB) with the Rossi X-ray Timing Explorer (RXTE) have revealed large amplitude, high coherence X-ray brightness oscillations with frequencies in the 300 - 600 Hz range. Substantial spectral and timing evidence point to rotational modulation of the X-ray burst flux as the cause of these oscillations, and it is likely that they reveal the spin frequencies of neutron stars in LMXB from which they are detected. Here I review the status of our knowledge of these oscillations and describe how they can be used to constrain the masses and radii of neutron stars as well as the physics of thermonuclear burning on accreting neutron stars.

KEYWORDS: stars: neutron – stars: rotation – X-rays: bursts – equation of state

1. INTRODUCTION

During the past 25 years X-ray astronomers have expended a good deal of effort in an attempt to identify the spin frequencies of neutron stars in LMXB (see for example Wood et al. 1991; Vaughan et al. 1994). These efforts were largely prompted by the discovery in the radio band of rapidly rotating neutron stars, the millisecond radio pulsars (see Backer et al. 1984), and subsequent theoretical work suggesting their origin lie in an accretion-induced spin-up phase of LMXB (see the review by Bhattacharya 1995 and references therein). However, up to the mid-90's there was little or no direct evidence to support the existence of rapidly spinning neutron stars in LMXB. This situation changed dramatically with the launch of the *Rossi X-ray Timing Explorer* (RXTE) in December, 1995. Within a few months of its launch RXTE observations had provided strong evidence suggesting that neutron stars in LMXB are spinning with frequencies ≥ 300 Hz. These first indications came with the discovery of high frequency (millisecond) X-ray brightness oscillations, "burst oscillations," during thermonuclear (Type I) X-ray bursts from several neutron star LMXB systems (see Strohmayer et al. 1996; Smith, Morgan & Bradt 1997; Zhang et al. 1996).

At present these oscillations have been observed from six different LMXB systems (see Strohmayer, Swank & Zhang 1998). The observed frequencies are in the range from $\approx 300 - 600$ Hz, similar to the observed frequency distribution of binary millisecond radio pulsars (Taylor, Manchester & Lyne 1993), and consistent with some theoretical determinations of spin periods which can be reached via accretion-induced spin-up (Webbink, Rappaport & Savonije 1983). In this contribution I will review our observational understanding of these oscillations, with emphasis on how they can be understood in the context of spin modulation of the X-ray burst flux. I will discuss how detailed modelling of the oscillation amplitudes and harmonic structure can be used to place interesting constraints on the masses and radii of neutron stars and therefore the equation of state of supranuclear density matter. Inferences which can be drawn regarding the physics of thermonuclear burning will also be discussed. I will conclude with some outstanding theoretical questions and uncertainties and where future observations and theoretical work may lead.

2. OBSERVATIONAL PROPERTIES OF BURST OSCILLATIONS

Burst oscillations with a frequency of 363 Hz were first discovered from the LMXB 4U 1728-34 by Strohmayer et al. (1996). Since then an additional five sources with burst oscillations have been discoverd. The burst oscillation sources and their observed frequencies are given in table 1. In the remainder of this section I review the important observational properties of these oscillations and attempt to lay out the evidence supporting the spin modulation hypothesis.

2.1. Oscillations at burst onset

Many bursts show detectable oscillations during the $\approx 1-2$ s risetimes typical of thermonuclear bursts. For example, Strohmayer, Zhang & Swank (1997) showed that some bursts from 4U 1728-34 have oscillation amplitudes as large as 43 % within 0.1 s of the observed onset of the burst. They also showed that the oscillation amplitude decreased monotonically as the burst flux increased during the rising portion of the the burst lightcurve. Figure 1 shows this behavior in a burst from 4U 1636-53. This burst had an oscillation amplitude near onset of $\approx$ 80 %, and then showed an episode of radius expansion beginning near the time when the oscillation became undectable (see Strohmayer et al. 1998a). The presence of modulations of the thermal burst flux approaching 100 % right at burst onset fits nicely with the idea that early in the burst there exists a localized hot spot which is then modulated by the spin of the neutron star. In this scenario the largest modulation amplitudes are produced when the spot is smallest, as the spot grows to encompass more of the neutron star surface, the amplitude drops, consistent with the observations.

X-ray spectroscopy during burst rise also suggests that the emission is localized near the onset of bursts. Prior to RXTE few instruments had the collecting area and temporal resolution to study spectral evolution during the short rise times of thermonuclear bursts. Day & Tawara (1990) used GINGA observations of 4U 1728-34 in an attempt to constrain the e-folding spreading time of the burning front to ≈ 0.1 s in two bursts. With RXTE Strohmayer, Zhang & Swank (1997) investigated the spectral evolution of bursts from 4U 1728-34. They fit a black body model to

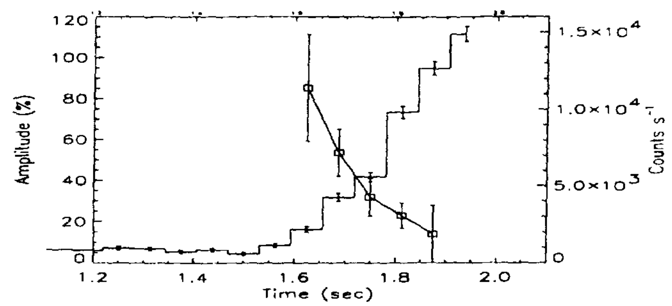

FIGURE 1. The amplitude of oscillations at 580 Hz during the rising phase of a burst from 4U 1636-53. The amplitude is greatest near the onset of the burst and decreases as the burst flux increases.

TABLE 1. Burst oscillation sources and frequencies

Object	Frequency (Hz)
4U 1728-34	363
4U 1636-53	580 (290)
4U 1702-429	330
KS 1731-26	526
Aql X-1	549
Gal. Center	589

intervals during several bursts and plotted the flux F_{bol} versus $F_{bol}^{1/4}/kT_{BB}$. For black body emission from a spherical surface this ratio is a constant proportional to $(R/d)^{1/2}$, where d and R are the source distance and radius, respectively. Figure 2 shows such a plot for a burst from 4U 1728-34. In this plot the solid line connects successive time intervals, with the burst beginning in the lower left and evolving diagonally to the upper right and then across to the left. This evolution indicates that the X-ray emitting area is *not* constant, but *increases* with time during the burst rise. The spectra of type I bursts are not true black bodies (see London, Taam & Howard 1986; Ebisuzaki 1987; Lewin, van Paradijs & Taam 1993), however, the argument here concerns the energetics and not the detailed shape of the spectrum. Since the effect is seen in bursts that do not show photospheric radius expansion the atmosphere is always geometrically thin compared with the stellar radius, so the physics of spectral formation depends only on conditions locally. The most straightforward interpretation is that the deficit in $F_{bol}^{1/4}/kT_{BB}$ evident at burst onset reflects a localized region of X-ray emission which then spreads to encompass the neutron star.

2.2. Expectations from the theory of thermonuclear burning

The thermonuclear instability which triggers an X-ray burst burns in a few seconds the fuel which has been accumulated on the surface over several hours. This $> 10^3$ difference between the accumulation and burning timescales means that it is unlikely that the conditions required to trigger the instability will be achieved simultaneously over the entire stellar surface. This realization, first emphasized by Joss (1978), led to the study of lateral propagation of the burning over the neutron star surface (see Fryxell & Woosley 1982, Nozakura, Ikeuchi & Fujimoto 1984, and Bildsten 1995). The subsecond risetimes of thermonuclear X-ray bursts suggests that convection plays an important role in the physics of the burning front propagation, especially in the low accretion rate regime which leads to large ignition columns (see Bildsten (1998) for a review of thermonuclear burning on neutron stars). Bildsten (1995) has shown that pure helium burning on neutron star surfaces is in general inhomogeneous, displaying a range of behavior which depends on the local accretion rate, with low accretion rates leading to convectively combustible accretion columns and standard type I bursts, while high accretion rates lead to slower, nonconvective propagation which may be manifested in hour long flares. These studies emphasize that the physics of thermonuclear burning is necessarily a multi-dimensional problem and that *localized* burning is to be expected, especially at the onset of bursts. The properties of oscillations near burst onset described above fit well into this picture of thermonuclear burning on neutron stars.

Miller (1999) has recently found evidence for a significant 290 Hz subharmonic of the strong 580 Hz oscillation seen in bursts from 4U 1636-53. Evidence for the subharmonic was found by adding together in phase data from the rising intervals of 5 bursts. This result suggests that in 4U 1636-53 the spin frequency is 290 Hz, and that the strong signal at 580 Hz is caused by nearly antipodal hot spots. If correct this result has interesting implications for the physics of nuclear burning, in particular, how the burning can be spread from one pole to the other within a few tenths of seconds, and how fuel is pooled at the poles, perhaps by a magnetic field.

2.3. The coherence of burst oscillations

One of the most interesting aspects of the burst oscillations is the frequency evolution evident in many bursts. The frequency is observed to increase by $\approx 1 - 3$ Hz in the cooling tail, reaching a plateau or asymptotic limit (see Strohmayer et al. 1998a). An example of this behavior in a burst from 4U 1702-429 is shown in figure 3. However, increases in the oscillation frequency are not universal, Strohmayer (1999) and Miller (1999) have recently reported on an episode of *spin down* in the cooling tail of a burst from 4U 1636-53. Frequency evolution has been seen in five of the six burst oscillation sources and appears to be commonly associated with the physics of the modulations. Strohmayer et. al (1997) have argued this evolution results from angular momentum conservation of the thermonuclear shell. The burst expands the shell, increasing its rotational moment of inertia and slowing its spin rate. Near burst onset the shell is thickest and thus the observed frequency lowest.

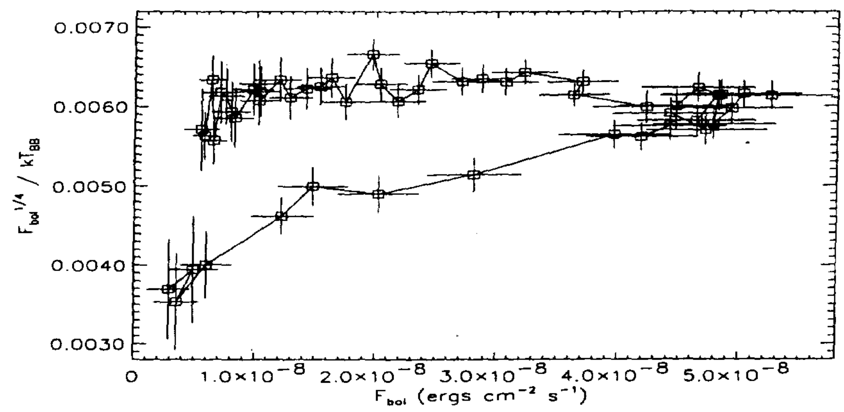

FIGURE 2. Bolometric flux F_{bol} versus $F_{bol}^{1/4}/kT_{BB}$ for a burst from 4U 1728-34. The burst evolves from lower left to upper right and then to the left. This behavior is strong evidence for an increasing X-ray emission area during the burst rise.

The shell then spins back up as it cools and recouples to the bulk of the neutron star. Calculations indicate that the $\sim$ 10 m thick pre-burst shell expands to $\sim$ 30 m during the flash (see Joss 1978; Bildsten 1995), which gives a frequency shift due to angular momentum conservation of $\approx 2\ \nu_{spin}(20\ \mathrm{m}/R)$, where ν_{spin} and R are the stellar spin frequency and radius, respectively. For the several hundred Hz spin frequencies inferred from burst oscillations this gives a shift of $\sim$ 2 Hz, similar to that observed.

In bursts where frequency drift is evident the drift broadens the peak in the power spectrum, producing quality factors $Q \equiv \nu_0/\Delta\nu_{FWHM} \approx 300$. In some bursts a relatively short train of pulses is observed during which there is no strong evidence for a varying frequency. Recently, Strohmayer & Markwardt (1999) have shown that with accurate modeling of the frequency drift quality factors as high as $Q \sim 4,000$ are achieved in some bursts. They modelled the frequency drift and showed that a simple exponential "chirp" model of the form $\nu(t) = \nu_0(1 - \delta_\nu \exp(-t/\tau))$, works remarkably well. The resulting quality factors derived from the frequency modelling are very nearly consistent with the factors expected from a perfectly coherent signal of finite duration equal to the length of the data trains in the bursts. These results argue strongly that the mechanism which produces the modulations is a highly coherent process, such as stellar rotation, and that the asymptotic frequencies observed during bursts represent the spin frequency of the neutron star.

2.4. The long-term stability of burst oscillation frequencies

The accretion-induced rate of change of the neutron star spin frequency in a LMXB is approximately 1.8×10^{-6} Hz yr^{-1} for typical neutron star and LMXB parameters.

The Doppler shift due to orbital motion of the binary can produce a frequency shift of magnitude $\Delta\nu/\nu = v \sin i/c \approx 2.05 \times 10^{-3}$, again for canonical LMXB system parameters. This doppler shift easily dominates over any possible accretion-induced spin change on orbital to several year timescales. Therefore the extent to which the observed burst oscillation frequencies are consistent with possible orbital Doppler shifts, but otherwise stable over $\approx$ year timescales, provides strong support for a highly coherent mechanism which sets the observed frequency.

At present, the best source available to study the long term stability of burst oscillations is 4U 1728-34. Strohmayer et al. (1998b) compared the observed asymptotic frequencies in the decaying tails of bursts separated in time by $\approx$ 1.6 years. They found the burst frequency to be highly stable, with an estimated time scale to change the oscillation period of about 23,000 year. It was also suggested that the stability of the asymptotic periods might be used to infer the X-ray mass function of LMXB by comparing the observed asymptotic period distribution of many bursts and searching for an orbital Doppler shift.

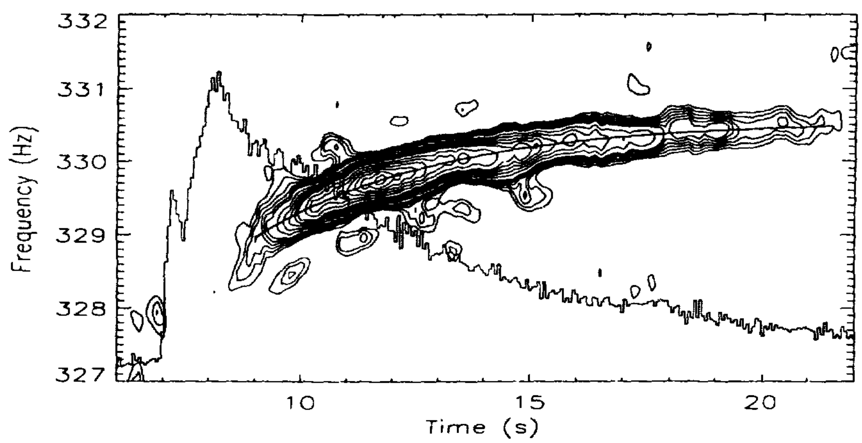

FIGURE 3. A dynamic power density spectrum of a burst from 4U 1702-429 showing frequency drift toward an asymptotic limit. The solid curve is a best fit using an exponential recovery.

3. BURST OSCILLATIONS AS PROBES OF NEUTRON STARS

Detailed studies of the burst oscillation phenomenon hold great promise for providing new insights into a variety of physics issues related to the structure and evolution of neutron stars. In particular, the burst oscillations have given astronomers their first direct method to investigate the two dimensional nature of nuclear flame front propagation. In this section I will outline how the burst oscillations can be used to probe neutron stars.

3.1. Mass - Radius constraints and the EOS of dense matter

Using the rotating hot spot model it is possible to determine constraints on the mass and radius of the neutron star from measurements of the maximum observed modulation amplitudes during X-ray bursts as well as the harmonic content of the pulses. The physics that makes such constraints possible is the bending of photon trajectories in a strong gravitational field. The strength of the deflection is a function of the stellar compactness, GM/c^2R, with more compact stars producing greater deflections and therefore weaker spin modulations. An upper limit on the compactness can be set since a star more compact than this limit would not be able to produce a modulation as large as that observed. Complementary information comes from the pulse shape, which can be inferred from the strength of harmonics. Information on both the amplitude and harmonic content can thus be used to bound the compactness. Detailed modelling, during burst rise for example, can then be used to determine a confidence region in the mass - radius plane for neutron stars. Miller & Lamb (1998) have investigated the amplitude of rotational modulation pulsations as well as harmonic content assuming emission from a point-like hot spot. They also show that knowledge of the angular and spectral dependence of the emissivity from the neutron star surface can have important consequences for the derived constraints. More theoretical as well as data modelling in this area are required.

3.2. Doppler shifts and pulse phase spectroscopy

Stellar rotation will also play a role in the observed properties of spin modulation pulsations. For example, a 10 km radius neutron star spinning at 400 Hz has a surface velocity of $v_{spin}/c \leq 2\pi\nu_{spin}R \approx 0.084$ at the rotational equator. This motion of the hot spot produces a Doppler shift of magnitude $\Delta E/E \approx v_{spin}/c$, thus the observed spectrum is a function of pulse phase (see Chen & Shaham 1989). Measurement of a pulse phase dependent Doppler shift in the X-ray spectrum would provide additional evidence supporting the spin modulation model and also yields a means of constraining the neutron star radius, perhaps one of the few direct methods to infer this quantity for neutron stars.

The rotationally induced velocity also produces a relativistic aberration which results in asymmetric pulses, thus the pulse shapes also contain information on the spin velocity and therefore the stellar radius (Chen & Shaham 1989). The component of the spin velocity along the line of site is proportional to $\cos\theta$, where θ is the latitude of the hotspot measured with respect to the rotational equator. The modulation amplitude also depends on the latitude of the hotspot, as spots near the rotational poles produce smaller amplitudes than those at the equator. Thus a correlation between the observed oscillation amplitude and the size of any pulse phase dependent Doppler shift is to be expected. Dectection of such a correlation in a sample of bursts would provide strong confirmation of the rotational modulation hypothesis.

Searches for a Doppler shift signature are just beginning to be carried out. Studies in single bursts have shown that spectral variations with pulse phase can be detected (see Strohmayer, Swank, & Zhang 1998). The varations with pulse phase show a 4-5 % modulation of the fitted black body temperature, consistent with the idea that a temperature gradient is present on the stellar surface, which when rotated produces the flux modulations. Ford (1999) has analysed data during a burst from Aql X-1 and finds that the softer photons lag higher energy photons in a manner which is qualitatively similar to that expected from a rotating hot spot. Strohmayer & Markwardt (1999) have shown that signals from multiple bursts can be added in phase by modelling the frequency drifts present in individual bursts. This provides a stronger signal with which to test for Doppler shift effects. So far, burst oscillation signals from 4U 1702-429 have been added in phase in an attempt to identify a rotational Doppler shift. A difficulty in analysing the phase resolved spectra from bursts is the systematic change in the black body temperature produced as the surface cools. A simpler measure of the spectral hardness, rather than the black body temperature, is the mean energy channel of the spectrum. I computed the distribution of mean channels in the RXTE proportional counter array (PCA) as a function of pulse phase using spectra from 4 different bursts from 4U 1702-429. Figure 4 shows the results. A strong modulation of the mean PCA channel is clearly seen. There is a hint of an asymmetry in that the leading edge of the pulse appears harder (as expected for a rotational Doppler shift) than the trailing edge, but the difference does not have a high statistical significance. More data will be required to decide the rotational Doppler shift issue.

3.3. Physics of thermonuclear burning

The properties of burst oscillations can tell us a great deal about the processes of nuclear burning on neutron stars. The amplitude evolution during the rising phase of bursts contains information on how rapidly the flame front is propagating. If the anitpodal spot hypothesis to explain the presence of a subharmonic in 4U 1636-53 is correct, then it has important implications for the propagation of the instability from one pole to another in ≈ 0.2 s (see Miller 1999). In addition, a two pole flux anistropy suggests that the nuclear fuel is likely pooled by some mechanism, perhaps associated with the magnetic field of star. Further detections and study of the subharmonic in 4U 1636-53 could shed more light on these issues.

Until recently, much of the work concerning burst oscillations has concentrated on studies of the pulsations themselves and their relation to individual bursts. With the samples of bursts growing it is now possible to concieve of more global studies which correlate the properties of oscillations with other measures of these sources, for example, their spectral state and mass accretion rate. This will allow researchers to investigate the system parameters which determine the likelihood of producing bursts which show oscillations. Such investigations will provide insight into how the

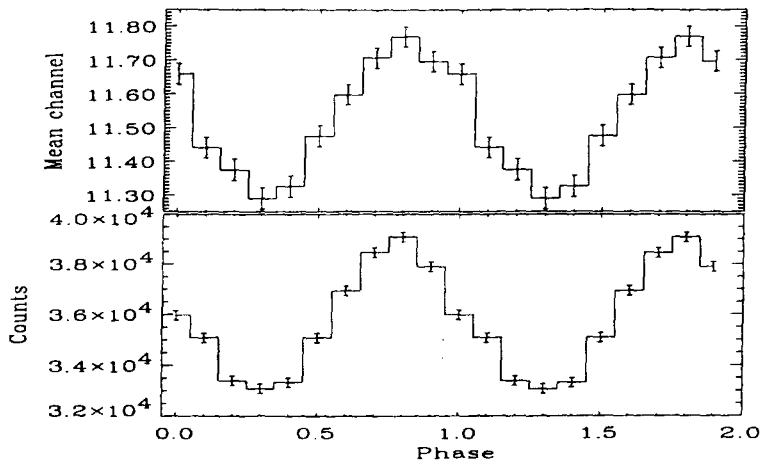

FIGURE 4. Pulse phase spectral variations in bursts from 4U 1702-429. The top panel shows the mean PCA energy channel as a function of pulse phase for 4 bursts which were co-added in phase. The bottom panel shows the pulse profile in the 2 - 24 keV band.

properties of thermonuclear burning (as evidenced in the presence or absence of oscillations) are influenced by other properties of the system. Furthermore, we can test if theoretical predictions of how the burning should behave are consistent with the hypothesis that the oscillations result from rotational modulation of nonuniformities produced by thermonuclear burning. Initial work in this regard suggests that bursts which occur at higher mass accretion rates show stronger burst oscillations more often (see Franco et al. 1999). Although preliminary this result appears roughly consistent with theoretical descriptions of the thermonuclear burning which indicates an evolution from vigorous, rapid (thus uniform) burning at lower mass accretion rates (lower persistent count rates) to weaker, slower burning (thus more non-uniform) at higher mass accretion rates (see Bildsten 1995, for example).

4. REMAINING PUZZLES AND THE FUTURE

Although much of the burst oscillation phenomenology is well described by the spin modulation hypothesis several important hypotheses need to be confronted with more detailed theoretical investigations. Perhaps the most interesting is the mechanism which causes the observed frequency drifts. Expressed as a phase slip the frequency drifts seen during the longest pulse trains correspond to about 5 - 10 revolutions around the star. Whether or not a shear layer can persist that long needs to be further investigated. The recent observation of a, so far unique, spin down in the decaying tail of a burst from 4U 1636-53 (see Strohmayer 1999), which might be the first detection of the spin down caused by thermal expansion of the burning layers, needs to be better understood in the context of thermonuclear energy release at late times in bursts. Another perplexing issue is the mechanism which allows flux asymmetries to both form and then persist at late times in bursts.

Although RXTE provided the technical advancements required to discover the burst oscillations, it may take future, larger area instruments such as Constellation-X or a successor timing mission to RXTE to fully exploit their potential for unlocking the remaining secrets of neutron stars.

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