The Periods Discovered by RXTE in Thermonuclear Flash Bursts

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Oscillations in the X-ray flux of thermonuclear X-ray bursts have been observed with RXTE from at least 6 low-mass binaries, at frequencies from 330 Hz to 589 Hz. There appear to be preferred relations between the frequencies present during the bursts and those seen in the persistent flux. The amplitude of the oscillations can exceed 50% near burst onset. Except for a systematic increase in oscillation frequency as the burst progresses, the frequency is stable. Time resolved spectra track increases in the X-ray emitting area due to propagation of the burning front over the neutron star surface, as well as radiation driven expansion of the photosphere. The neutron star mass, radius, and distance can be inferred when spectra are compared to theoretical expectations.

1. OSCILLATIONS IN BURST FLUX

Type I (thermonuclear) X-ray bursts from six bursters have been found to have episodic, strong oscillations, without any significant evidence of harmonics. For sources from which multiple bursts have been observed, not all bursts have exhibited the oscillations. The oscillations were first seen in a burst from 4U 1728-34. In an observation of 200 ksec duration when the source was bursting, 12 bursts were seen, 6 of them exhibiting oscillations at about 363 Hz. So far, when a source has multiple bursts with oscillations, the frequencies are almost the same, so that a frequency identifies the source. It is likely that some bursts from many other bursters also exhibit oscillations. In most cases, we have no way, yet, of knowing whether a burster is burst active, so that we have not been able to choose to observe it at such a time. We also do not know for sure why sometimes the oscillations are not seen, although this seems to be correlated with the strength of the bursts and whether they result in radius expansion of the neutron star.

To display properties of the burst oscillations it is convenient to compute the power spectra of 2 s intervals with a new interval sampled every 1/8 s. Figure 1 shows an example of a burst with a typical appearance of the oscillations during the course of a burst, with a slight rise in frequency of about 2 Hz to a value that stays approximately constant during the decline of the burst. Sometimes only a portion of this kind of pattern can be seen. Even with the change of frequency in some bursts, $\Delta \nu / \nu \geq 300$. In the tails of the bursts, it can be $\geq 1000$.

Among the six bursters with burst oscillations four also exhibit twin “kilohertz” quasiperiodic oscillations (QPO), which drift in frequency with
inferred mass accretion rate during an observation. Table 1 gives their burst oscillation periods and Figure 2 summarizes the relations between oscillation frequencies that have been reported to date. The frequencies are plotted with respect to estimated persistent luminosity \([2]\), to emphasize that they are approximately independent of it. For 4U 1728-34 and 4U 1702-43 the difference frequencies of the twin kilohertz peaks are close to the burst frequencies. For 4U 1636-53 and KS 1731-44, the difference frequencies are closer to half the burst frequencies. For Aql X-1 and a burster in the galactic center, X1743-29, possibly the same as a burster seen previously (MXB 1743-29) \([3]\), it has not been possible to date to identify two oscillation frequencies in the persistent emission from which to compute a difference.

Neither of the variable persistent emission QPO frequencies is a candidate for the rotation frequency of the neutron star, but the difference frequencies have been linked to the spin frequency despite the variations in difference frequencies seen for Sco X-1 and 4U 1608-52. A strong case has been made that the burst frequencies are directly related to the stellar spin frequency \([5]\). For the burst oscillations the variations in frequency for a given source are rather small and explanations appear plausible, as we will discuss.

In either case a model in terms of rotation of a neutron star with a non-uniform temperature distribution appears reasonable. There could be

![Figure 2. Kilohertz oscillations in LMXB detected with RXTE. Filled circles are reported maximum QPO frequencies in the persistent emission. Open circles are the difference between the two persistent emission frequencies when both are present. Filled squares are the frequencies seen in bursts. See van der Klis, this volume, for the most recent review of persistent emission results and references.](image-url)

| Source         | Period (ms) | # of Bursts |
|----------------|-------------|-------------|
| 4U1636-53      | 1.72        | 4           |
| 4U 1702-43     | 3.03        | 1           |
| 4U1728-34      | 2.76        | 16          |
| KS 1731-26     | 1.90        | 1           |
| X 1743-29      | 1.70        | 3           |
| Aql X-1        | 1.82        | 1           |
a single hot (or cold) spot giving rise to rotational modulation or perhaps a spot associated with each magnetic pole, even if the magnetic fields are much smaller than the $10^{12}$ G fields of high mass binary accreting neutron stars. In this paper we discuss the evidence that the burst frequencies are the rotation frequencies of the neutron stars in low mass X-ray binaries (LMXB).

Other explanations might have been, a priori possible. When a neutron star is hot because of a thermonuclear flash, oscillations in the inner part of a remnant disk, not blown back by the explosion, could obscure part of the glowing star periodically. We will see, however, that there are associated oscillations in the temperature, rather than the area, making this explanation less probable. The explosion and the transfer of heat to the surface, by a combination of diffusion and convection, could excite oscillation modes of the neutron stars. Such modes have been studied theoretically and some have frequencies in the observed range. However, there is no compelling reason why the frequency spectrum of the modes would be so simple and estimates of the amount of energy that would be in these oscillations are a small fraction of the amplitudes actually observed.

We report on our studies of properties of the burst oscillations that tend to confirm interpretation in terms of rotation: the sinusoidal pulse shape, the very high amplitude which can occur at the onset of bursts, the correlation with a temperature oscillation, and coherence of the oscillations through the bursts. We have expected theoretically and some have frequencies in the observed range. However, there is no compelling reason why the frequency spectrum of the modes would be so simple and estimates of the amount of energy that would be in these oscillations are a small fraction of the amplitudes actually observed. We report on our studies of properties of the burst oscillations that tend to confirm interpretation in terms of rotation: the sinusoidal pulse shape, the very high amplitude which can occur at the onset of bursts, and coherence of the oscillations through the bursts. We have expected theoretically that these neutron stars are rotating fast and the large population of millisecond radio pulsars has implied the existence of progenitors such as LMXB, so that the theoretical implication that we should find such objects is very strong. Finally, we address briefly the neutron star properties that the burst observations can strongly constrain.

2. BURST OSCILLATION PROPERTIES

2.1. Increasing Area during the Rise

The data allow the pulsed amplitude to be tracked during bursts as a function of energy. The spectra of the bursts during the rise can be fitted every 0.125 s and yield a color temperature and an apparent radius to better than 10% during a period when the apparent radius changes by > 50%. Expected corrections to the spectra would make the scale of radius increase larger.

In some bursts the oscillations are seen very close to the beginning of the rise in flux, within the first 100 ms. Within such time intervals, the oscillations are coherent and can be folded on the period. Fractional amplitudes near and exceeding 50% are seen both in bursts 4U 1728-34, in which the difference frequency of 363 Hz is about the burst frequency, and in bursts from 4U 1636-53, in which the difference frequency of about 255 Hz is closer to half the burst frequency of 581 Hz. The fractional amplitude decreases strongly as the burst flux rises to the peak. This suggests that the thermonuclear burning starts as a localized hot spot on the neutron star and from there spreads around the neutron star. Calculations have suggested the burning is inhomogeneous. Simulations of emission from the surface of a neutron star show that this model can reproduce the observed behavior of the fractional amplitude.

Because the neutron star gravitational field bends light around it the intensity of radiation emitted from a surface hot spot on the neutron star depends on the rotational phase of the spot and the compactness, $M/R$ of the neutron star. Here $M$ and $R$ are the stellar mass and radius, respectively. This is taken into account in simulations of the expected pulse growth and decay. The more compact the neutron star, that is, the higher is $M/R$, the more severe is the bending of light, the more smeared the pulse, and the lower would be the modulation of radiation from the surface. Thus the high level of modulation of the flux that is observed puts a strong constraint on the compactness of the neutron star. The neutron stars must be fairly large. If the intensity is actually from opposing poles of a neutron star, these constraints become almost impossible for known and tested equations of state of nuclear matter. This suggests that the hypothesis of two antipodal spots may be untenable.

We have found no substantial differences between the behavior of the burst oscillations for 4U 1728-34 and 4U 1636-53 to contradict the hy-
hypothesis that the mechanisms are the same. The similarity of the burst rise behavior thus argues in favor of both being the neutron star spin.

Interpretation of the oscillations at the beginning of a burst in terms of a spreading hot spot raises the question of what mechanism causes the oscillations that appear during the decays of bursts. There would have to be a remnant or recurring inhomogeneity on the surface of the neutron star. Possibly what was hot first is now a cooler spot, although conductivity might tend to make the star homogeneous. So far at least, there is no evidence there are different numbers of hot spots arising on the neutron star. This suggests that the occurrence is not random and a magnetic pole is an obvious candidate.

2.2. Temperature versus Area Oscillations

In cases where the duration of coherent oscillations is long enough and the amplitude strong enough, pulse phase spectroscopy is possible. In a burst from 4U 1636-53 shown in Figure 3, the pulsations for 5 s in the burst decay produce a 6 % modulation in the derived blackbody kT.

2.3. Coherence of Burst Oscillations

For the burst oscillations to represent the rotation period of the neutron stars, there must be an explanation for the 1-2 Hz change in frequency observed during bursts, since this cannot represent a real change in the angular momentum of the entire neutron star on such a short time scale. A model which has been discussed is that the heated burning layer expands on the order of 10–30 m and is not rigidly attached to the neutron star, so that conservation of angular momentum causes the expanded hot material to rotate more slowly than material deeper in. It might then wrap around the neutron star about once during the initial second of the burst rise. A crude estimate of the height above the surface that the material would have to rise in order to produce such an effect is given by equating the angular momentum of a thin shell at the stellar surface, \( R \), and at a slightly higher altitude, \( R + \Delta R \), including the correction introduced by the gravita-

Figure 3. Oscillations in a burst observed from 4U 1636-54 by I. Lapidus. Contours of Fourier power with the burst profile overlaid (top). Epoch folded pulse profile, blackbody kT, and apparent radius (bottom). Note the 6 % change in the blackbody temperature with pulse phase associated with the 20 % amplitude in luminosity. A small asymmetry due to Doppler shifts would be expected and a confirmed measurement would be important.
tional time dilation from different radii.

\[
\frac{(R + \Delta R)^2}{R^2} = \sqrt{\frac{1 - \frac{R_s}{R + \Delta R} \nu_{0,\infty}}{1 - \frac{R_s}{R} \nu_{0,\infty}}} \quad (1)
\]

Here, \(\nu_{0,\infty}\) and \(\nu_{1,\infty}\) are the frequencies measured near burst onset and burst decay, respectively. An observed frequency lower by 1 Hz than a final frequency of 500 Hz would correspond to a 10-20 m expansion during the rising part of the burst in comparison to the tail of the burst. Whatever the exact explanation, this serves to illustrate that modest changes in the source of a modulation near the neutron star surface could cause the amount of frequency change observed.

In this model, gradual changes in the pulse peak phases would be seen. Given a frequency during the tail of the burst and a frequency at the beginning, a frequency derivative can always bridge a gap. But for a given frequency change, the pulses need not remain in phase. In fact, Zhang et al. [10] apply the frequency derivative seen in a burst from Aql X-1, correct the times to that of the neutron star and find that almost all of the power in the oscillation is recovered, consistent with coherence of the underlying clock.

3. MILLISECOND PULSAR PROGENITORS

The LMXB are part of the old population of stars in the Galaxy. They have been accreting for a long time compared to high mass X-ray binaries [11]. It was speculated when the low magnetic field millisecond radio pulsars were found that they were recycled pulsars spun up by accretion in LMXB. The periods we find are certainly in the approximate region of the periods of the millisecond radio pulsars as shown in Figure 4. We do not have firm measurements of the magnetic fields but they have been expected to have surface fields of \(\approx 10^8 - 10^9\) G and the current data can be interpreted in terms of upper limits on the field of that order [4]. However, careful estimates of the number of low field millisecond radio pulsars [12] (5 \(\times\) 10^4) imply a birthrate about 10 times the birthrate of LMXB. The long time needed for LMXB to spin up the neutron star (8 \(\times\) 10^7) yr when accreting at the observed luminosities of only 0.01 – 0.1 of the Eddington limit imply a birth rate insufficient to be responsible for the observed millisecond radio pulsars. A large part of that population may have a different origin, perhaps accreting low mass binaries which have a phase of accretion so strong that they are not seen as X-ray sources (+), perhaps actually formed with low magnetic fields.

4. PROPERTIES OF THE BURST NEUTRON STARS

A radius expansion burst from 4U 1820-30 illustrates the possible information that can be obtained from the bursts. Spectral fits per 0.125 s show the pattern of temperature and radius changes associated with the flux rising to the Eddington limit for hydrogen poor material and then a decay at approximately constant apparent radius after the photosphere has presumably returned to the surface of the neutron star. Taking the flux at the start of this decay to give the observed Eddington limit at the neutron star ra-
radius, the flux and color temperature run during the decay can be fit to the relation calculated by Ebisuzaki and Nakamura [14] for the value of the effective temperature at the Eddington limit. This temperature constrains the mass and radius:

$$kT_E = [(c/\sigma_{\text{eq}})(GM/R^2)]^{1/4}(1-2GM/Rc^2)^{3/8}$$

Figure 5 shows the results.

![Figure 5](image)

Figure 5. Mass versus radius constraints derived from a radius expansion burst from 4U 1820-30. The set of three curves rising from the lower left corner are derived by fitting for the Eddington effective temperature using the observed blackbody parameters and the theoretical pure helium atmosphere calculations of Ebisuzaki and Nakamura (1988). The dot-dash line from the compactness limit constrains the values to its right.

5. CONCLUSIONS

Many, but not all bursts from some sources show possible coherent strong oscillations. A correlative is that bursts that are observed without oscillations do not imply that oscillations will not be seen on other occasions. The period range of $3 - 1.7 \text{ ms}$ is about right for these sources eventually becoming some of the recycled millisecond radio pulsars. The behavior at onset of the burst suggests probably a single expanding hot spot. In all cases so far analyzed, the burst tail frequency is no more than a couple of Hz different from the rise frequency, so that the geometry of the emission region must remain essentially the same. Spectral analysis indicates the parameter varying is the average temperature in view. Coherence during the burst and the rationale for the small frequency changes needs further study to answer outstanding questions. The possibility of using burst spectra and the oscillations to constrain the mass, radius, composition, and distance of the neutron stars holds great promise.

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