X-ray Observations of Neutron Star Binaries: Evidence for Millisecond Spins

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Abstract.
High amplitude X-ray brightness oscillations during thermonuclear X-ray bursts were discovered with the Rossi X-ray Timing Explorer (RXTE) in early 1996. Spectral and timing evidence strongly supports the conclusion that these oscillations are caused by rotational modulation of the burst emission and that they reveal the spin frequency of neutron stars in low mass X-ray binaries (LMXB), a long sought goal of X-ray astronomy. I will briefly review the status of our knowledge of these oscillations. So far 10 neutron star systems have been observed to produce burst oscillations, interestingly, the observed frequencies cluster in a fairly narrow range from $\sim 300 - 600$ Hz, well below the break-up frequency for most modern neutron star equations of state (EOS). This has led to suggestions that their spin frequencies may be limited by the loss of angular momentum due to gravitational wave emission. Connections with gravity wave rotational instabilities will be briefly described.

INTRODUCTION
X-ray binaries are potentially among the most interesting sources of gravitational wave emission which current and future gravity wave detectors will attempt to study. The high frequency gravity wave signal produced during binary inspiral and ring down of black hole and neutron star binaries contains detailed information on the properties of the compact object as well as the structure of spacetime in its vicinity (see Lee; Faber & Rasio; these proceedings). These objects will be prime targets for ground based detectors such as LIGO which because of seismic noise are only sensitive in the high frequency range above $\sim 100$ Hz (see Barish, these proceedings).
Neutron stars are compelling targets of investigation because of the extreme physical conditions which exist in their interiors and immediate environs. For example, the gravity wave signals produced by inspiral of a neutron star depend on the equation of state (EOS) at supranuclear density, a quantity which is still not precisely constrained by currently available astrophysics and nuclear physics.
data (see for example Heiselberg & Hjorth-Jensen 1999). Moreover, fundamental properties of the star, such as its mass, can be extracted if the gravity wave signal can be measured. Thus gravity wave astronomy can in principle provide new probes of fundamental physics as well as advancing neutron star astrophysics.

Radio observations provided the first indications that some neutron stars are spinning with periods approaching 1.5 ms (Backer et al. 1982). These rapidly rotating neutron stars are observed as either isolated or binary radio pulsars. Binary evolution models indicate that neutron stars accreting mass from a companion can be spun up, or ‘recycled’, to millisecond periods (see for example Webbink, Rappaport & Savonije 1983). This formation mechanism likely accounts for a substantial fraction of the observed population of millisecond radio pulsars, however, other formation scenarios have also been proposed (van den Heuvel & Bitzaraki 1995; van Paradijs et al. 1997). In recent years direct evidence linking the formation of rapidly rotating neutron stars to accreting X-ray binaries has been provided by data from the Rossi X-ray Timing Explorer (RXTE). The first evidence came from the discovery of high amplitude, nearly coherent X-ray brightness oscillations (so called ‘burst oscillations’) during thermonuclear flashes from several neutron star binaries (see Strohmayer 2000 for a recent review). These oscillations likely result from spin modulation of either one or a pair of antipodal ‘hot spots’ generated as a result of the thermonuclear burning of matter accreted on the neutron star surface. Indisputable evidence that neutron stars in X-ray binaries can indeed be rotating rapidly then came with the discovery of the first accreting millisecond X-ray pulsar SAX J1808-369 (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998), which is spinning at 401 Hz.

The observed distribution of burst oscillation frequencies and the 401 Hz pulsar is very similar to the observed distribution of millisecond radio pulsars. The RXTE observations suggest that the spin frequencies of neutron stars in accreting binaries span a relatively narrow range from ∼ 300 – 600 Hz. Moreover, these observed frequencies are significantly less than the maximum neutron star spin rates for almost all but the stiffest neutron star equations of state (Cook, Shapiro & Teukolsky 1994). This has led to the suggestion that some mechanism may limit the spin periods of these accreting neutron stars. Bildsten (1998) recently proposed that the angular momentum gain from accretion could be offset by gravitational radiation losses if a misaligned quadrupole moment of order $10^{-8} - 10^{-7} I_{NS}$ could be sustained in the neutron star crust. Here $I_{NS}$ is the moment of inertia of the neutron star. In this scenario the strong spin frequency dependence of the gravitational radiation losses sets the limit on the observed spin frequencies. Recent theoretical work has also shown that an $r$-mode instability in rotating neutron stars may also be important in limiting the spins of neutron stars via gravity wave emission (see Ushomirsky, Bildsten & Cutler 2000; Bildsten 1998; Levin 1999; Andersson, Kokkotas, & Stergioulas 1999).

In the remainder of this contribution I will present an overview of the RXTE data and lay out the evidence for the conclusion that the observed burst oscillation frequencies are a manifestation of the spin frequencies of neutron stars (or perhaps
twice the spin frequency in a few cases). I will summarize the status of current X-ray measurements of neutron star spin periods and the implications for gravity wave emission.

BURST OSCILLATIONS: OBSERVATIONAL OVERVIEW

Burst oscillations with a frequency of 363 Hz were first discovered from the LMXB 4U 1728-34 by Strohmayer et al. (1996). Oscillations in an additional nine sources have since been reported, with four of these only appearing in the last few months. The sources and their observed frequencies are given in Table 1. In the remainder of this section I will briefly review the important observational properties of these oscillations and summarize the evidence supporting spin modulation as the mechanism. Because of the rapid pace of developments this will no doubt be an incomplete review.

Oscillation Amplitudes near Burst Onset

Some bursts show large amplitude oscillations during the $\approx 1-2$ s rises commonly seen in thermonuclear bursts. An example of this behavior in a burst from 4U 1636-53 is shown in figure 1. 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 burst lightcurve. Strohmayer et al (1998a) reported on strong pulsations in 4U 1636-53 at 580 Hz with an amplitude of $\approx 75\%$ only $\sim 0.1$ s after detection of burst onset. The presence of modulations of the thermal burst flux which can approach nearly 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 should be produced when the spot is smallest, and as the spot grows to encompass more of the neutron star surface, the amplitude decreases. This behavior is consistent with the observations. X-ray spectroscopy during burst rise also indicates that the X-ray emission is localized on the neutron star near the onset of bursts. Strohmayer, Zhang, & Swank (1997) found that during burst rise the flux is underluminous compared with intervals later in the burst which have the same observed black body temperature, and suggested that during the rise a localized, but growing segment of the surface of the neutron star is producing the X-ray emission. As the burst progresses the burning area increases in size until the entire surface is involved.
The observed oscillation frequency during a burst is usually not constant. Often 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. 1998b). This behavior is common to all the burst oscillation sources, and it would appear that the same physical mechanism is involved, however, there have been reports of decreases in the oscillation frequency with time. For example, Strohmayer (1999) and Miller (2000) identified a burst from 4U 1636-53 with a spin down of the oscillations in the decaying tail. This burst also had an unusually long decaying tail which may have been related to the spin down episode. Muno et al. (2000) reported an episode of spin down in a burst from KS 1731-24.

Strohmayer et. al (1997) have suggested that the time evolution of the burst oscillation frequency 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. The shell spins back up as it cools and recouples to the underlying neutron star. Calculations indicate that the $\sim 10$ m thick pre-burst shell expands to $\sim 30 - 40$ m during the flash (see Joss 1978; Bildsten 1995; Cumming & Bildsten 2000), which gives a frequency shift of $\approx 2 \nu_{\text{spin}} (20 \text{ m}/R)$, where $\nu_{\text{spin}}$ 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. Recently, Galloway et al. (2000) reported the discovery of a 270 Hz

![Figure 1](image-url)
Table 1. Burst Oscillation Sources and Properties

| Sources     | Frequency (Hz) | ∆ν (kHz QPO, in Hz) | References |
|-------------|----------------|---------------------|------------|
| 4U 1728-34  | 363            | 363 - 280           | 1, 2, 3, 4, 5, 13, 14 |
| 4U 1636-53  | 290, 580       | 251                 | 6, 7       |
| 4U 1702-429 | 330            | 315 - 344           | 4, 9       |
| KS 1731-260 | 524            | 260                 | 10, 11, 12 |
| Galactic Center | 589     | Unknown             | 15         |
| Aql X-1     | 549            | Unknown             | 16, 17     |
| X1658-298   | 567            | Unknown             | 18         |
| 4U 1916-053 | 270            | 290 - 348           | 19, 20     |
| 4U 1608-52  | 619            | 225 - 325           | 8, 21      |
| SAX J1808-369 | 401      | Unknown             | 22, 23     |

1References: (1) Strohmayer et al. (1996); (2) Strohmayer, Zhang, & Swank (1997); (3) Mendez & van der Klis (1999); (4) Strohmayer & Markwardt (1999); (5) Strohmayer et al. (1998b); (6) Strohmayer et al. (1998a); (7) Miller (1999); (8) Mendez et al. (1998); (9) Markwardt, Strohmayer & Swank (1999) (10) Smith, Morgan, & Bradt (1997); (11) Wijnands & van der Klis (1997); (12) Muno et al. (2000); (13) van Straaten et al. (2000); (14) Franco (2000); (15) Strohmayer et al (1997); (16) Zhang et al. (1998); (17) Ford (1999); (18) Wijnands, Strohmayer & Franco (2000); (19) Boirin et al. (2000); (20) Galloway et al. (2000); (21) Chakrabarty (2000); (22) Heise (2000); (23) Ford (2000)

Burst oscillations have a much higher coherence than is typical for other quasiperiodic X-ray variations observed from neutron star systems. For example, the kHz QPO seen in many LMXBs have maximum coherence values, \( Q \equiv \nu/\Delta \nu \sim 100 \). Strohmayer & Markwardt (1999) showed that the frequency evolution of burst oscillations in 4U 1728-34 and 4U 1702-429 is highly phase coherent. They modelled the frequency drift and showed that a simple exponential “chirp” model of the form \( \nu(t) = \nu_0(1 - \delta_v \exp(-t/\tau)) \), works remarkably well, producing quality factors \( Q \equiv \nu_0/\Delta \nu_{FWHM} \sim 4,000 \). Muno et al. (2000) performed a similar analysis on bursts from KS 1731-26 and concluded that the burst oscillations from this source were also phase coherent. These results argue strongly that the mechanism which produces the modulations is intrinsically a highly coherent one.

The accretion-induced rate of change of the neutron star spin frequency in a LMXB is approximately \( 1.8 \times 10^{-6} \) 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 repre-
sentative 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 \( \approx 1 \) 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. We illustrate this behavior in figure 2 which compares the observed burst oscillation frequency of two bursts from 4U 1728-34 which occurred \( \sim 3 \) years apart. van Straaten et al. (2000) showed evidence that the frequency track made by a given burst from 4U 1728-34 is dependent on the position in the X-ray color - color diagram (a surrogate for mass accretion rate). The two bursts shown in figure 2 have similar frequency tracks and there closeness in frequency over a span of 3 years argues for a highly stable process, such as rotation, as the mechanism which sets the frequency.

Strohmayer et al. (1998b) 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. The source 4U 1636-53 is a good candidate for such an effort because its orbital period is known (3.8 hrs). Strohmayer et al. (1998b) compared the highest observed frequencies in three different bursts from 4U 1636-53. The frequencies in these bursts alone were consistent with a typical orbital velocity for the neutron star. However, study of additional bursts reveals a greater range of highest frequencies than can likely be accounted for by orbital motion alone (see Giles & Strohmayer 2001). A possible explanation of this within the context of the spin modulation scenario is that not every burst has relaxed to the asymptotic value before the oscillations fade below the detection level. Nevertheless, the observed distribution does suggest the existence of an upper limit, which can naturally be associated with the spin frequency (Giles & Strohmayer 2001).

**Burst Oscillations and Mass Accretion Rate**

Recent studies have focused on how the presence and properties of burst oscillations correlate with other properties of these sources, for example, their spectral state and inferred mass accretion rates. Muno et al. (2000) were the first to conduct such a study and found that bursts from KS 1731-26 with oscillations appear to only occur when the source is on the banana branch in the X-ray color-color diagram. They also found that these bursts were all photospheric radius expansion bursts. Cumming & Bildsten (2000) suggested that such bursts were likely pure Helium flashes and that it would be more likely for these to show oscillations because the radiative diffusion time is short compared to the inferred shearing time.
of the thermonuclear burning layer, making it more likely that a modulation would survive. Franco (2000) and van Straaten et al. (2000) showed that bursts from 4U 1728-34 with oscillations also occur preferentially on the banana branch, but they did not find a similar relationship with radius expansion as for KS 1731-26. They also found that the portion of a full frequency track which is present in a burst appears to also depend on mass accretion rate. Franco (2000) also found that for 4U 1728-34 the strength of oscillations was correlated with position in the color-color diagram. Since other burst properties, such as peak flux, fluence and durations, are also known to correlate with mass accretion rate it is not surprising, given the fact that the physics of thermonuclear burning is dependent on mass accretion rate, that the properties of burst oscillations appear also to be strongly dependent on mass accretion rate.

Theoretical Expectations

The notion that X-ray bursts are caused by thermonuclear instabilities in the accreted layer on the surface of a neutron star is now universally accepted. There is no doubt that interesting puzzles remain and our detailed understanding is incomplete, but the basic model is firmly established. 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 makes it very unlikely that the conditions required to trigger the instability will be achieved simultaneously over the entire stellar surface. This notion, first emphasized by Joss (1978), led to the study of lateral propagation of the burning front over the neutron star surface (see Fryxell & Woosley 1982, Nozakura, Ikeuchi & Fujimoto 1984, and Bildsten 1995).

FIGURE 2. Burst oscillations in two bursts from 4U 1728-34 separated in time by ~ 3 yr. The frequency tracks are almost identical and suggests that the mechanism which sets the frequency is highly stable. The burst on the left was observed in Feb. 1996 while that on the right was seen in Feb. 1999.
The short risetimes of thermonuclear X-ray bursts suggest 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 recent review of thermonuclear burning on neutron stars). These studies emphasized 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 nicely with this picture of thermonuclear burning on neutron stars.

**IMPLICATIONS FOR GRAVITY WAVE EMISSION**

The strong $\nu^6_s$ frequency dependence of the energy radiated by gravitational waves means that rapidly rotating neutron stars with misaligned quadrupole moments might have observationally interesting gravitational wave amplitudes. The spin periods of neutron stars inferred from burst oscillations cluster rather tightly in the range from $\sim 300 – 600$ Hz. As pointed out earlier, these frequencies are well below the maximum break-up frequencies for most modern neutron star equations of state (Cook, Shapiro & Teukolsky 1994). White & Zhang (1997) suggested that the observed range of spin frequencies could be produced if these neutron stars were spinning in magnetic equilibrium. However, in order for the observed frequencies to be similar would require that $\dot{M}$ and the magnetic moment $\mu_b$ be correlated. It is not presently known if such a correlation is to be naturally expected based on theoretical grounds.

**Crustal Deformation Quadrupole Moments**

An alternative model has been proposed by Bildsten (1998). He suggested that the spins of these neutron stars may be limited by the emission of gravity waves. The spin down torque due to gravitational wave emission is proportional to $\nu^5_s$ so that one would expect a critical spin frequency above which accretion torques are cancelled out by gravity wave losses. By equating the characteristic accretion torque with the gravity wave torque one can determine the average quadrupole moment required to maintain the critical frequency. For the mass accretion rates characteristic of LMXBs and a critical spin frequency of 300 Hz one obtains a quadrupole $Q \sim 4.5 \times 10^{37}$ g cm$^2$, or about $5 \times 10^{-8} I_{NS}$ (see Bildsten 1998). The question that remains is whether or not such a quadrupole moment can be routinely generated in a neutron star.

The idea that the spin frequencies of neutron stars might be limited by gravitational radiation losses was initially proposed by Papaloizou & Pringle (1978) and Wagoner (1984). Wagoner (1984) argued that the Chandrasekhar - Friedman - Schutz instability would excite non-axisymmetric modes which would radiate gravity waves and limit the spin frequency. However, Lindblom (1995) and Lindblom & Mendell (1995) showed that this instability will only set in near the break-up
frequency, which is at much higher frequency than the observed burst oscillations for most modern equations of state. Bildsten (1998) has suggested that electron captures on heavy nuclei in the neutron star crust might be able to produce a quadrupole of the required amount. The basic idea is that the electron capture process produces density jumps in the crust. Since the electron capture rate is temperature sensitive in the crust a lateral temperature gradient could lead to density jumps which as a function of lateral position occur at slightly different depths in the crust. Ushomirsky, Cutler, & Bildsten (2000) have investigated this process in more detail and concluded that electron captures could produce the observed quadrupole if there are $\sim 5\%$ lateral temperature variations at crustal depths where the density is in excess of $10^{12}$ g cm$^{-3}$. They also computed the dimensionless strain $\sigma$ which gives a quadrupole sufficient to balance the accretion torque and found that $\sigma \sim 10^{-2}$ at near Eddington accretion rates. Although promising, more theoretical work will be required to convincingly establish whether this mechanism can produce a sufficient quadrupole moment to balance the accretion torque.

Regardless of the mechanism, if the accretion torque is indeed balanced by gravity wave losses then the amplitude of the gravitational radiation can be calculated (see Wagoner 1984; Bildsten 1998). The dimensionless strain $h$ is in the range from $h \sim 10^{-27} - 10^{-26}$. Although this strain is significantly less than the estimated sensitivity for LIGO I, one can greatly improve the sensitivity by pulse folding if the rotational ephemeris of the neutron star is known (see Brady & Creighton 1999; Ushomirsky, Bildsten & Cutler 2000). Current estimates indicate that a narrow band configuration for LIGO-II will reach interesting search limits for these neutron stars, especially for the brightest of the LMXBs, for example, Sco X-1 (Ushomirsky, Bildsten & Cutler 2000). This also provides strong motivation for additional deep X-ray timing searches in order to detect coherent pulsations in more LMXBs and to measure the pulse ephemerides so as to improve searches for gravity wave emission. It also illustrates the strong synergism between X-ray and gravity wave astronomy in the context of neutron star binaries.

**R-Mode Instability**

Andersson (1998) recently discovered that the $r$-modes of rotating relativistic stars are excited by gravitational radiation at all rotation frequencies (see also Friedman & Morsink 1998). Shear and bulk viscosity damps these modes, so whether or not they can attain significant amplitudes depends on the competition between gravitational radiation excitation and viscous damping. This discovery has led to a flurry of theoretical activity to try and understand the implications of the $r$-mode instability for rapidly rotating neutron stars. Here I will only give a brief summary. See the contribution by Ushomirsky (2001, these proceedings) for all the details.

For accreting neutron stars the basic idea is that a star will be spun up by accretion to some critical frequency at which the $r$-mode instability sets in. Work by Andersson, Kokkotas & Stergioulas (1999) suggested that the star would spin
up to this critical frequency and then remain in equilibrium at this frequency with the accretion torque balanced by angular momentum losses from the excited $r$-modes. However, Levin (1999) and Spruit (1999) showed that this evolution is not possible because the $r$-modes heat the stellar interior which reduces the viscosity and increases the growth rate. Thus the $r$-modes would grow rapidly and spin the star down on a very short timescale ($\sim$ a few months), much shorter in fact than the timescale to spin the star up via accretion. During this time the star would be a powerful source of gravity waves, however, the timescale is so short that the effective event rate is very low (see Levin 1999; Andersson et al. 2000).

Recent efforts have focused on studying the sources of viscous damping, most importantly the influence of the solid crust of the neutron star. Bildsten & Ushomirsky (2000) estimated the effect the solid crust would have on the damping and concluded the crust dissipation would greatly exceed that from standard viscosity in the core. More recently, Andersson et al. (2000) have revised these estimates and argue that the damping is not as strong as suggested by Bildsten & Ushomirsky (2000). They conclude that the $r$-mode instability could explain the observations of most millisecond pulsars with periods between about 1.5 and 6 ms as well as the lack of any pulsars spinning faster than $\sim$ 1.5 ms.

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