X-RAY BURST SOURCES

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For detailed reviews on X-ray burst sources, covering most information that was available prior to 1994, see [1].

Since those reviews there have been very important new developments. First, a surprisingly new animal, GRO J1744−28 (better known as the Bursting Pulsar), made its debut in 1995. Second, but NOT last, in 1996/97 kHz pulsations were discovered in the persistent emission of several burst sources, and near coherent pulsations were detected in type I X-ray bursts.

The Bursting Pulsar. *The name "Bursting Pulsar" is somewhat misleading as it may give the impression that this source is an exception to an empirical rule: "Pulsars don't Burst, and Bursters don't Pulse! If one reads this properly, namely that X-ray sources that exhibit coherent pulsations in their persistent emission do not produce type I X-ray bursts, then GRO J1744−28 is NO exception to the rule as its bursts are NOT of type I (see below).*

GRO J1744−28 was discovered with BATSE on 1995 December 2, when over 80 hard X-ray bursts with durations of 10–30 s were detected [2]. The pulsar period is 467 ms, and pulsations are detected in the persistent emission and in the type II bursts (see [3], [4]). The pulsar is in a nearly circular orbit ($e < 1.1 \times 10^{-3}$) with an 11.8 day orbital period [3]. The very small X-ray mass function indicates that the companion is most likely a low-mass (M $< 1M_{\odot}$) star. GRO J1744−28 joins just 7 other pulsars detected in low-mass X-ray binary (LMXB) systems.

The first major outburst of the source lasted from its discovery on 1995 December 2 until 1995 May. A less intense reactivation was observed during 1995 June–July. The beginning of a second major outburst was detected with BATSE on 1996 December 2, exactly one year after the first detection of the source [5]. The second large outburst is nearly a carbon-copy of the first. The long-term light curves show similar profiles. In both outbursts the rate of repetitive X-ray bursts was 150–200 per day (corrected for Earth occultation and live time) on the first day of activity; thereafter the rate settled down to 30–50 per day for the duration of the outburst [6].

Observations with OSSE on *CGRO* showed that the phase of the 467 ms pulsations during and after bursts *lags* the phase prior to bursts by as much as 90 ms [7]. Observations with *RXTE* confirmed the pulse phase lags after bursts [8] and showed that the persistent emission following bursts is often depressed below its pre-burst level [9]. The *RXTE* PCA spectrum of the source is typical of X-ray pulsars [9]. The brightest bursts observed with *RXTE* in 1996 January had peak intensities of ~75 Crab (although this number is somewhat uncertain due to large dead time corrections). At an assumed distance of 7 kpc this corresponds to an assumed isotropic burst peak luminosity in excess of 50 Eddington luminosities!

Kouveliotou et al. suggested that the repetitive bursts are caused by an instability in the accretion flow onto the neutron star [2]. A thermonuclear flash (type I X-ray burst) model for the repetitive bursts is excluded because the persistent X-ray emission during 1995 December 2 and 1996 December 2 was insufficient to account for the required replenishment of burnt fuel through accretion. The upper limits for the ratio, α, of the 20–100 keV persistent emission to the time-averaged burst emission are $\alpha \leq 4$ (3σ) on 1995 December 2 and $\alpha = 1.5 \pm 1.3$ on 1996 December 2 (see [2], [6]).

Several X-ray binaries have shown isolated burst- and flare-like events attributed to unstable accretion; but the Rapid Burster (MXB 1730−335) is the only source other than GRO J1744−28 which emits rapidly repetitive bursts due to spasmodic accretion (type II X-ray bursts). Lewin et

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al. [10] compared these two sources and concluded that the bursts from GRO J1744−28 must be due to spasmodic accretion based on the very low value of α, the hardness of the burst spectra, the absence of distinct spectral softening during burst decay, and the depressed persistent emission level following bursts. Kommers et al. [11] noted that some type II bursts from both sources are followed by transient quasi-periodic oscillations (QPO) that increase in frequency during their lifetime and occur during a period of spectrally hard emission. These comparisons suggest that the same accretion instability is responsible for the (type II) bursts from the Rapid Burster and from GRO J1744−28. Cannizzo [12] has shown that a thermal-viscous accretion disk instability can reproduce the ~1000 s recurrence times and the ~10 s durations of the bursts from GRO J1744−28 as well as the depressed accretion rate following bursts.

GRO J1744−28 was observed with *ASCA* from 1996 February 26 10:00 (UT) through February 27 2:05 for ~20 ks. The GIS count rate of the persistent emission was about 130 counts s^{-1} in 1–10 keV, which corresponds to ~0.9 Crab. The peak count rate during bursts was 6 to 7 times higher than the persistent emission count rate. A total of 10 bursts were detected with dips in the persistent emission after the bursts. The 467 ms pulsations were clearly present, with a single-peaked sinusoidal profile, and a pulsed fraction $(f_{\rm max} - f_{\rm min})/(f_{\rm max} + f_{\rm min})$ of the persistent emission of ~0.02 at 2 keV, increasing up to 0.1 at 10 keV. During the burst the pulse fraction increased by a factor of 2–4 [13].

The X-ray spectrum of GRO J1744−28 is well described by a power law with a very strong low-energy cut-off ($N_{\rm H} = 5 \times 10^{22}$ cm^{-2}). There is additional structure around 7 keV which may be related to Fe K-shell emission and absorption. The spectra of the bursts, persistent emission, and post-burst dips are quite similar. The average burst spectrum is slightly harder than that of the persistent emission, which in turn is marginally harder than that observed during the dips. The 7 keV structure in the persistent emission spectrum can be reproduced by a partial-covering model. If a partial covering model is used with a power law continuum, one gets a covering fraction of 0.45±0.02, a column density of absorbing matter of $(5.4 \pm 0.2) \times 10^{23}$ cm^{-2}, and a photon index of 1.3 [13].

There were no observations made with *ASCA* during the second major outburst which lasted from 1996 December to 1997 April.

Near Coherent Pulsations in Type I X–ray Bursts. The most important discovery made with *RXTE* is, in my opinion, the discovery of "kHz" oscillations in fourteen (as per Oct. 15, 1997) low-mass X-ray binaries (LMXB); "kHz" refers here to the frequency range above 200 Hz.

The kHz oscillations fall into two classes: (i) those that produce twin peaks in the power density spectra whose centroid frequencies increase as the acrretion rate increases, and (ii) near coherent oscillations observed during type I bursts (thermonuclear flashes on the surface of neutron stars).

Following the early discoveries by Strohmayer et al. [14] and Van der Klis et al. [15] in 1728-34 and Sco X-1, respectively, the "kHz fever" broke out, and we have now reached the point that a pattern is evolving. For a recent review see Van der Klis [16].

Two narrow QPO peaks have been detected in the power density spectra of six atoll sources and four Z sources. I will call the QPO peak with the highest (of the two) frequency the HF-peak, and the peak with the lowest frequency the LF-peak. The two peaks are not always detected simultaneously, but when they are detected simultaneously, the LF peak in most cases (not in the case of Sco X-1 and 1608-52 [17]) tracks the HF peak in that the difference frequency remains constant within the uncertainty of the measurements.

The centroid frequency of the HF peak has been seen to wander as much as ~600 Hz between ~500 Hz and ~1100 Hz in the case of 0614+09 and 1728-34. In 1636-53 and KS1731-260 the centroid frequency of the HF peak reached values in excess of 1200 Hz.

Coherent (or near coherent) oscillations have been detected with *RXTE* in type I bursts from: 1636-53, 1728-34, KS1731-34, MXB1743-29, Aql X-1 (see [14], [18], [19], [20]), and in 1702-43 (Swank, private communication). Not all bursts show these oscillations. Except in Aql X-1, twin peaks have been observed in the power density spectra of these burst sources. In the case of 1728-34 [14] the frequency of the near coherent oscillations in the type I bursts is the same (within the uncertainty of the measurements) as the difference frequency between the HF and the LF peaks; it is twice that for 1636-53 [18] and KS1731-260 [19].

It is very suggestive that the frequency of the oscillations observed in the type I bursts reflects directly the rotation frequency of the neutron star [14]. In the case of 1728-34 the rotation period is then $\sim$2.75 msec [14]; for 1636-53 and KS1731-260, the rotation frequencies are probably half the frequency observed in the type I bursts which translates into spin periods of $\sim$3.45 msec and 3.82 msec, respectively (see [18], [20]).

The fact that the HF and the LF peaks track each other suggests that one peak is due to a beat phenomenon between the neutron star rotation frequency and the frequency of the other peak [14]. *It is important, however, to keep in mind that the difference frequency between the HF and the LF peaks is not constant in the case of Sco X-1 and 1608-52, and that during the observations the luminosity of 1608-52 was about an order of magnitude lower than that of Sco X-1.*

The HF oscillations may well be due to the Keplerian frequency at a preferred distance to the neutron star. The origin of the HF oscillations, however, is still unknown, though there have been some interesting suggestions, and there is the potential to obtain important information about the equation of state of the neutron stars (see [16], [21], [22], [23]).

The origin of the oscillations observed during the type I bursts may be due to a hot spot on the neutron star that results from a localization of the thermonuclear flash[14]. One would then expect to see the oscillations early on in a burst as has been observed (Strohmayer, private communication). However, it is puzzling why these oscillations in several cases have been observed only during the decay portion of the bursts (see [14], [19]), and, which is even more surprising, during the post contraction portion of bursts that showed radius expansion (see [14], [19], [20]). It is also not clear why in two sources the observed frequency in the type I bursts is twice that of the difference frequency between the HF and the LF peak. To assume the presence of two hot spots on the neutron star (resulting from a nuclear flash) seems abit ad hoc. The oscillations observed during the type I bursts can have very small drifts ($<$1.5 Hz) in frequency; it is unclear what causes these small drifts (see [16], [20]).

There seems little doubt in my mind that the long-sought-after milli-second rotation periods of neutron stars in LMXB have finally shown up! These spin periods strongly support the idea that at least some LMXB are the progenitors of the millisecond radio pulsars. The holy grail may have been found, at last!

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