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## A COMPARISON BETWEEN THE RAPID BURSTER AND GRO J1744–28

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### ABSTRACT

Twenty years ago, the Rapid Burster (MXB 1730–335) was discovered. Its most salient feature was the occurrence of rapidly repetitive type II X-ray bursts, the release of gravitational potential energy due to spasmodic accretion onto a compact object. This is almost certainly due to an accretion disk instability whose origin is still not understood. With the recent appearance of GRO J1744–28, the Rapid Burster is no longer the only system to produce such bursts. Both systems are transient low-mass X-ray binaries in which the accretor is a neutron star. The Rapid Burster, located in a globular cluster, also produces type I bursts which are due to thermonuclear flashes on the neutron star's surface; no X-ray pulsations are observed. Its neutron star magnetic field is therefore relatively weak. In contrast, strong X-ray pulsations have been observed in the persistent flux as well as in the type II bursts from GRO J1744–28, but no type I bursts have been observed. Thus, the magnetic field of the neutron star in this system is probably stronger than is the case of the Rapid Burster. The fact that type II bursts occur in both systems may bring us closer to an understanding of the mechanism(s?) that produces them.

*Subject headings:* stars: neutron — X-rays: general — X-rays: bursts

### 1. THE RAPID BURSTER

The Rapid Burster (MXB 1730–335) was discovered in March of 1976 during observations with the *SAS 3* observatory (Lewin et al. 1976). Extensive reviews of this source and its complex behavior are given by Lewin, Van Paradijs, & Taam (1993, 1995); these two reviews are hereafter referred to as LVT93, LVT95. We mention here some of the most salient features of the Rapid Burster and refer the reader largely to LVT93 and LVT95 for references.

The Rapid Burster is located at a distance of  $\sim 10$  kpc in the highly reddened globular cluster Liller 1. It is a low-mass X-ray binary and a recurrent transient. There are  $\sim 125$  known low-mass X-ray binaries (van Paradijs 1995), all produce a persistent flux of X-rays, the result of a release of gravitational potential energy. Approximately 40 of them also exhibit type I bursts which are due to thermonuclear flashes on the surface of a neutron star (LVT93 and LVT95 and references therein).

The Rapid Burster is unique among the low-mass X-ray binaries in that it produces X-ray bursts in quick succession. These are called type II bursts, and they result from a spasmodic release of gravitational potential energy, which is almost certainly due to some unknown accretion disk instability. The burst mechanism can be described as that of a relaxation oscillator. The fluences,  $E$ , are approximately proportional to the time intervals,  $\Delta t$ , following a burst. Burst durations can be as short as  $\sim 2$  s and as long as  $\sim 680$  s with corresponding intervals,  $\Delta t$ , of  $\sim 10$  s and  $\sim 1$  hr, respectively. The Rapid Burster produces not only the rapidly repetitive type II bursts, but also type I bursts, which occur on timescales of several hours (Hoffman, Marshall, & Lewin 1978).

Spasmodic accretion—thus, by definition type II bursts—

has been observed from sources other than the Rapid Burster (e.g., Cyg X-1) as discussed by Lewin & Joss (1981). However, the type II bursts from the Rapid Burster with their unique patterns and evolution make them a distinct class on their own.

The Rapid Burster exhibits a variety of bursting modes and intensities of persistent emission during its active periods. Type I bursts have been observed in concurrence with only type II bursts (Hoffman et al. 1978) and solely with strong persistent emission (no type II bursts; Kunieda et al. 1984; Barr et al. 1987). At times, only type II bursts are observed, with persistent X-ray emission after long (greater than  $\sim 30$  s) type II bursts. This persistent flux emerges gradually after these long type II bursts and disappears before the occurrence of the next type II burst; this is often referred to as “dips” in the persistent emission (Marshall et al. 1979; van Paradijs, Cominsky, & Lewin 1979; Stella et al. 1988b; see Fig. 1c below). Short ( $< 30$  s) type II bursts often show oscillations (“ringing”) during their decay. Bursts within limited duration ranges have profiles that are approximately time invariant (Tawara et al. 1985; Tan et al. 1991).

The peak luminosity in type II bursts ranges from  $\sim 5 \times 10^{37}$  to  $\sim 4 \times 10^{38}$  ergs s $^{-1}$  and the integrated burst energies range from  $\sim 1 \times 10^{38}$  to  $\sim 7 \times 10^{40}$  ergs (for assumed isotropic radiation and a distance of 10 kpc). The spectra of the type II bursts can be roughly approximated by that of a blackbody with a constant value of  $kT$  ( $\sim 2$  keV) throughout the type II bursts (for more details, see LVT93, LVT95). This behavior is in striking contrast to type I bursts, which show a very distinct softening during their decay.

Various levels of time-averaged persistent emission between bursts have been observed with intensities ranging from  $\sim 6 \times 10^{36}$  to  $\sim 3 \times 10^{37}$  ergs s $^{-1}$ . This time-averaged luminos-

ity can be as high as  $\sim 50\%$  of the time-averaged luminosity in the type II bursts. Both power-law spectra (photon index  $\Gamma = 2.1 \pm 0.2$ ) and thermal bremsstrahlung ( $kT = 9_{-2}^{+3}$  keV) gave acceptable fits to the 1983 August data when persistent emission and type I (but no type II) bursts were observed (Kunieda et al. 1984; Barr et al. 1987). In 1985 August, the type II burst spectra were harder than the average spectrum of the persistent emission between the bursts (Stella et al. 1988b). Very globally, the spectrum of the persistent emission was very soft during the “dip” just after a burst, then it rapidly increased in hardness, after which it gradually decreased to become very soft again during the “dip” just prior to the next burst.

Quasi-periodic oscillations (QPO) in the range  $\sim 2\text{--}7$  Hz have been observed in the type II bursts and in the persistent emission between the bursts; their behavior is very complex (Tawara et al. 1982; Stella et al. 1988a, b; Dotani et al. 1990; Lubin et al. 1991; Rutledge et al. 1995; LVT93; LVT95). Dotani et al. (1990) showed that during the type II bursts the oscillations are due to a periodic modulation without phase jumps whose frequency changes by up to  $\sim 25\%$ . The frequency shifts can explain the width of the QPO peaks in the power density spectra. The oscillations can be described by changes in the temperature of a blackbody emitter with constant emitting area, but they can equally well be described by changes in the photospheric radius and associated temperature changes. Lewin et al. (1991) have given some arguments why the latter is more likely. Very strong oscillations with a frequency of  $\sim 40$  mHz were observed in the persistent emission shortly after 10 long type II bursts (Lubin et al. 1992; see our Fig. 1c, below, near “Time” = 40). The frequency of these oscillations gradually increased over a timescale of  $\sim 100$  s.

## 2. GRO J1744–28

A transient X-ray burster was discovered on 1995 December 2, with BATSE (Fishman et al. 1995). The bursts were detected up to energies of  $\sim 75$  keV; their intervals were initially several minutes. After 2 days the burst rate had dropped to about one per hour (Kouveliotou et al. 1996b); however, by January 15 the burst rate had increased to  $\sim 40$  bursts per day (corrected for Earth occultation and instrumental lifetime). The burst durations remained about the same (4–6 s FWHM) throughout the BATSE observations (Fishman et al. 1996). A pulsating persistent source (with period 467 ms and  $\sim 40\%$  modulation) was detected a few weeks later (Paciesas et al. 1996; Finger et al. 1996a); the very strong pulsations were also seen in the bursts (Kouveliotou et al. 1996a). Spectra above 8 keV taken with BATSE of both the persistent emission and the bursts could be described by a blackbody with no absorption and with a characteristic temperature  $kT = 6$  keV; the spectra could be equally well described by optically thin thermal bremsstrahlung with a very high value of  $N_{\text{H}}$  (Briggs et al. 1996). The spectra (extending down to  $\sim 2$  keV) taken with *XTE*<sup>1</sup> on 1996 January 18–19 of the persistent emission as well as the bursts are characteristic of bright accreting pulsars; they are consistent with a power law with a photon index of  $\sim 1.2$  and a rollover above 13 keV with an  $e$ -folding energy of 14 keV (Swank 1996). The absorbing column density is at least  $2 \times 10^{22}$  cm<sup>-2</sup> (Augusteijn et al. 1996).

Between mid-December of 1995 and mid-January of 1996,

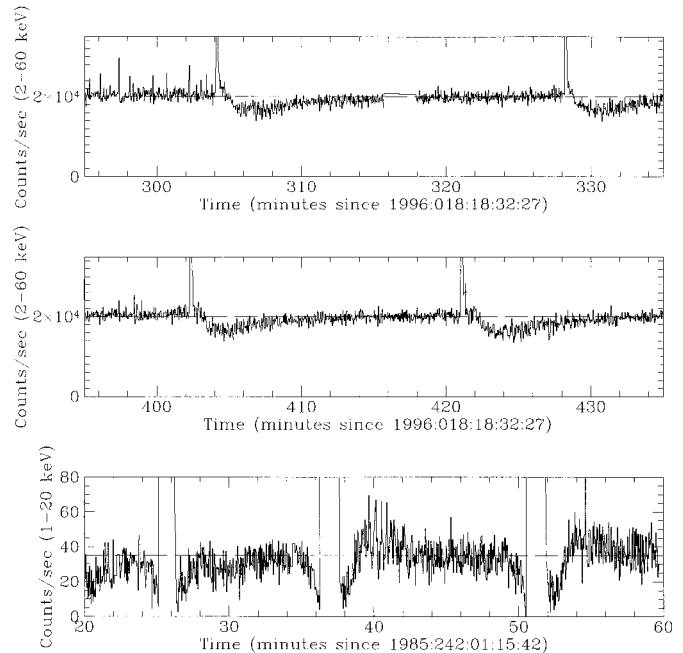


FIG. 1.—Light curves of GRO J1744–28 (*a* and *b*) and the Rapid Burster (*c*). Data for GRO J1744–28 is the 2–60 keV count rate in the 5 *XTE*/PCA detectors for four of the nine bursts observed with *XTE* during the 1996 January 18 observations, with a nominal background count rate of 80 counts s<sup>-1</sup> subtracted; deadtime correction has not been applied. Data for the Rapid Burster is the 1–20 keV count rate in the *EXOSAT*/ME instrument (Turner, Smith, & Zimmermann 1981), with a nominal background count rate of 70 counts s<sup>-1</sup> subtracted; no deadtime correction has been applied. Time resolution of the data shown is 2 s. The vertical scale has been enlarged, cutting off the peak count rates of the bursts, to show the postburst “dips” in some detail. Horizontal lines in each of the panels at arbitrary count rate values to accentuate the magnitude of the postburst “dips” and the slow rise of the persistent emission. Flickering in GRO J1744–28 (minibursts?) is evident before the first burst in the top panel. 40 mHz oscillations in the Rapid Burster (Lubin et al. 1992) can be seen at time = 40 minutes (*c*). Data for (*a*) and (*b*) are from HEASARC/Office of Guest Investigator Programs, 1996.

the peak burst flux and the burst fluence of individual bursts increased by about a factor of 6. On January 15, their average values (20–50 keV) were  $\sim 2 \times 10^{-7}$  ergs cm<sup>-2</sup> s<sup>-1</sup> [corresponding to a luminosity of  $\sim 2.4 \times 10^{37}$  (d/kpc)<sup>2</sup> ergs s<sup>-1</sup> for assumed isotropic emission] and  $\sim 7 \times 10^{-7}$  ergs cm<sup>-2</sup>, respectively (Fishman et al. 1996). By mid-January, the intensity of the persistent emission had reached a level of 2.5 Crab in the range 20–100 keV and  $4.4 \pm 0.3$  Crab in the range 8–20 keV (Sazonov & Sunyaev 1996). Following each burst, the flux is suppressed to below its preburst level and takes a few minutes to recover (Swank 1996). In Figure 1 (*top two panels*) we show some of the *XTE* data which show the “dips” in the persistent emission after the bursts.

During observations with the Very Large Array (VLA) observatory on 1996 February 2–8, a variable radio source was found (Frail et al. 1996) in an *XTE* error box (Strohmayer, Jahoda, & Marshall 1996). The source increased from less than 170  $\mu$ Jy ( $3 \sigma$ ) to  $540 \pm 30$   $\mu$ Jy during three observations over 6 days at 8.4 GHz; there was also evidence of variability on a timescale of  $\sim 1$  hr. On February 13.6 UT the source flux density was less than 195  $\mu$ Jy (D. Frail, private communication). The VLA observations yielded a subarcsecond position for the variable radio source. It is unclear yet whether the radio source and GRO J1744–28 are the same source.

<sup>1</sup> The *XTE* observatory is now called the *Bruno Rossi X-Ray Timing Explorer*.

Possible optical counterparts of the radio source have been suggested; however, no behavior (e.g., optical variability or strong H $\alpha$  lines) that would support an identification of any of these objects as a pulsating X-ray binary has been observed yet (Miller et al. 1996; Cole et al. 1996; Zytkow & Irwin 1996; Vanden Berk et al. 1996; Miller 1996).

The orbital period of the binary is  $\sim 11.8$  days with an upper limit to the eccentricity of 0.026. The X-ray mass function is  $(1.31 \pm 0.04) \times 10^{-4} M_{\odot}$ . For a  $1.4 M_{\odot}$  neutron star and an orbital inclination larger than  $30^{\circ}$ , the mass of the donor is  $0.065$ – $0.14 M_{\odot}$ , with a Roche lobe radius of 4.1–5.2 solar radii (Finger, Wilson, & van Paradijs 1996b).

GRO J1744–28 and the so-called soft gamma-ray repeaters (hereafter SGRs; Kouveliotou et al. 1993, 1994) both emit repeated outbursts in the 20–60 keV energy range; both are transients, but the similarities stop there. The bursts from GRO J1744–28 have already persisted for over 2 months, whereas SGRs are active for much shorter episodes separated by several years. SGR burst durations are very short (with an average in the tens of milliseconds) compared to the burst durations of GRO J1744–28. Bursts from SGRs have simple light curves without substructure, whereas the bursts from GRO J1744–28 show single similar envelopes heavily modulated by the pulsed emission from the neutron star.

### 3. A COMPARISON

In comparing the Rapid Burster with GRO J1744–28, the first striking similarity is the occurrence of repetitive bursts. The bursts from GRO J1744–28 are almost certainly not type I bursts (thermonuclear flashes) for several reasons. (1) In early 1995 December, when the burst intervals were  $\sim 3$  minutes, the  $3\sigma$  upper limit of the ratio of integrated energy (20–50 keV) in the persistent flux to that in bursts as observed with BATSE was  $\sim 4$  (A. Harmon provided us with the upper limits to the persistent flux). This is too low by a large factor (LVT93; LVT95 and references therein). One could perhaps argue that a much larger fraction of the energy in the persistent emission was “hiding” in the energy range below 20 keV than was the case for the burst emission. However, that is very unlikely as the spectrum of both the bursts and the persistent emission is characteristic of that of an X-ray pulsar, thus very hard (Paciesas et al. 1996; Briggs et al. 1996; Sazonov & Sunyaev 1996; Swank 1996). (2) Spectral softening, so very characteristic of type I bursts (LVT93; LVT95) is not present in the bursts of GRO J1744–28. (3) The spectra of type I bursts can be approximately represented by blackbody radiation that reaches peak values for  $kT$  of  $\sim 2$  keV (representing the Eddington limit to the blackbody temperature of a neutron star; LVT93; LVT95). The burst spectra from GRO J1744–28 are much harder than that (one can probably get around this third argument since GRO J1744–28 is a pulsar with a relatively strong magnetic field).

We believe that there is little doubt that the bursts from GRO J1744–28 are due to gravitational potential energy (thus type II bursts). In strong support of this conclusion is the fact that the spectra of the bursts and the persistent emission are nearly identical, suggesting a similar mechanism for both (Briggs et al. 1996). In addition, type II bursts from the Rapid Burster (those longer than  $\sim 30$  s) are followed by a distinct “dip” in the persistent emission (see Fig. 1c), and such “dips” are also observed after bursts from GRO J1744–28 (Fig. 1).

Apart from the occurrence of type II bursts in both sources,

there are more similarities. Both systems are transient low-mass X-ray binaries, and the accretor in both is a neutron star. There are also some striking differences: GRO J1744–28 is a pulsar (thus the neutron star has a relatively strong magnetic field) with a characteristically hard spectrum and no observed type I bursts. In contrast, type I bursts have been observed from the Rapid Burster, but no pulsations. Thus the neutron star in the Rapid Burster probably has a relatively weak magnetic field.

During the past 2 decades no one has succeeded in producing a satisfying model that explains the type II bursts and the complex bursting modes observed from the Rapid Burster. Models that require a weak magnetic field clearly cannot apply to GRO J1744–28. For example, one model proposed for the Rapid Burster (Hanawa, Hirofani, & Kawai 1989) argues that only at a field strength of  $B \sim 10^8$  G is the magnetosphere both larger than the neutron star (so that magnetohydrodynamic instabilities can occur) and also small enough that the accreted matter is not funneled onto the polar caps.

Other models assume a weak magnetic field a priori. These models include those invoking viscous and thermal instabilities in the disk (Taam & Lin 1984), radiation feedback mechanisms (Milgrom 1987; Walker 1992), and the instability associated with a magnetosphere-accretion disk interaction operating in concert with a centrifugal barrier gating mechanism (Spruit & Taam 1993; LVT93; LVT95). It remains to be seen whether these models can also accommodate the magnetic field strength of an X-ray pulsar.

The well-known relation (observed in the Rapid Burster) between burst fluence,  $E$ , and waiting time,  $\Delta t$ , to the next burst has been only partially reproduced in some models. The viscous and thermal instability, radiation feedback, and magnetosphere-accretion disk-centrifugal barrier schemes can all produce periodic bursts, but the  $E - \Delta t$  relationship is produced only by varying the global mass-transfer rate in the disk or by varying the viscosity from burst to burst (Taam & Lin 1984; Walker 1992; Spruit & Taam 1993; LVT93; LVT95). On the other hand, an  $E - \Delta t$  relationship as observed in the Rapid Burster is not present in GRO J1744–28 for which burst fluences remained approximately constant while the burst intervals changed by factors of  $\sim 4$  (Kouveliotou et al. 1996b).

To date, no adequate explanation exists for the very complex type II burst behavior from the Rapid Burster. One of the main problems is perhaps the fact that the Rapid Burster was one of a kind for 20 years (among some 125 low-mass X-ray binaries; see § 1). In 1983 August the source behaved for a few days like an “ordinary” low-mass X-ray binary (of which  $\sim 40$  systems exist) in that it produced persistent emission and type I bursts (Kunieda et al. 1984; Barr et al. 1987). Thus the Rapid Burster is almost “normal,” imposing a large constraint on the allowed models (LVT93; LVT95). With the appearance of GRO J1744–28, we hope that the situation will change in that we will be able to get more insight into the type II burst mechanism.

It seems reasonable to suggest that the behavior of the Rapid Burster can be viewed through a simple, qualitative model involving a reservoir of matter. The “dips” after the type II bursts (Fig. 1) can be understood in terms of depletion of this reservoir (the disk) once a burst has occurred. We envision that an inner portion (“ring”) of the disk breaks off (due to an unknown instability), resulting in a type II burst. (The mass of this ring is  $\sim 5 \times 10^{20}$  g for the most energetic

bursts of  $\sim 7 \times 10^{40}$  ergs). It takes time to replenish the now “empty” ring; the more massive that this ring is, the larger is the fluence of the type II burst, and the longer is the time to replenish the empty ring; thus, the longer it takes for the next burst to occur. This model provides a natural explanation for the observed  $E - \Delta t$  relation in the Rapid Burster and perhaps a natural explanation for why the persistent emission is initially suppressed after the burst. Such a scenario, however, cannot explain the “dips” before the bursts in the Rapid Burster. Such “dips,” which apparently foresee the onset of a burst (see Fig. 1c) are more difficult to understand. The situation is even more complex, as this scenario cannot explain the type II burst mechanism in GRO J1744–28 since it does not exhibit the  $E - \Delta t$  relation.

It appears quite possible that the mechanism for the accretion instability that causes the type II bursts is different for

sources that have neutron stars with different magnetic field strengths. It is hoped that GRO J1744–28 will stay “on” for many more months (it has now already been active for over 2 months), and that the Rapid Burster will become active at least once during *XTE*’s and *ASCA*’s lifetimes. Detailed spectra, as can be obtained with *ASCA*, and fast timing, as can be obtained with *XTE*, may tell the story.

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