New soft gamma-ray bursts in the BATSE records and spectral properties of X-ray rich bursts

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ABSTRACT
A population of X-ray dominated gamma-ray bursts (GRBs) observed by Ginga, BeppoSAX and the High Energy Transient Explorer (HETE-2) should be represented in the Burst and Transient Source Experiment (BATSE) data as presumably soft bursts. We have performed a search for soft GRBs in the BATSE records in the 25–100 keV energy band. The softness of a burst spectrum could explain why it has been missed by the on-board procedure and by the previous searches for untriggered GRBs tuned to the 50–300 keV range. We have found a surprisingly small number (∼20 yr⁻¹) with fluxes down to 0.1 photon cm⁻² s⁻¹) of soft GRBs where the count rate is dominated by the 25–50 keV energy channel. This fact, as well as the analysis of HETE-2 and common BeppoSAX/BATSE GRBs, indicates that the majority of GRBs with a low E_peak have a relatively hard tail with a high-energy power-law photon index β > −3. An exponential cutoff in GRB spectra below 10–15 keV may be a distinguishing feature of non-GRB events.

Key words: methods: data analysis – gamma-rays: bursts.

1 INTRODUCTION
Observations of gamma-ray burst (GRB) prompt emissions, using different instruments, show that their spectra can extend from several keV up to a few MeV (Wheaton et al. 1973; Trombka et al. 1974; Metzger et al. 1974), and sometimes up to GeV range (Sommer et al. 1994). According to recent broadband observations by Ginga (Strohmayer et al. 1998), the High Energy Transient Explorer (HETE-2) (Sakamoto et al. 2005) and combined results of BeppoSAX/BATSE (Kippen et al. 2003) and RXTE/IPN (Smith et al. 2002), most GRBs exhibit a peak in the EF0 spectrum at an energy E_peak in the 50–400 keV range. However, the distribution of E_peak is broad and a large number of events demonstrate a significant X-ray (2–30 keV) emission (X-ray dominated GRBs, X-ray rich GRBs). At present, the study of broadband spectra is complicated because of insufficient statistics accumulated by the broadband instruments and biases arising from different instrument responses.

The BATSE (Paciesas et al. 1999) data from all-sky 9.1-yr (1991–2000) continuous monitoring in the γ-ray range give a unique opportunity for GRB analysis combined with X-ray observations. The BATSE γ-ray detectors were the most sensitive instruments of this type in GRB history. Only the recently launched Swift experiment (Gehrels et al. 2004) has a more sensitive γ-ray detector. However, during the next several years Swift, because of its smaller field of view, cannot accumulate statistics comparable to that of the BATSE. BATSE detected about 2700 GRBs with fluxes down to ∼0.3 ph cm⁻² s⁻¹ (Paciesas et al. 1999). In addition, the off-line scans of the BATSE continuous records almost doubled the number of observed GRBs with fluxes down to ∼0.1 ph cm⁻² s⁻¹ (see Koomers et al. 2001; Stern et al. 2001).

The BATSE detectors were sensitive to photons from ∼25 keV up to ∼1 MeV. However, the on-board procedure and most off-line searches identified GRBs according to the signal in the 50–300 keV range, while GRBs with a soft spectrum could be missed. These soft events can help to outline the place of X-ray dominated bursts in the GRB variety.

The 25–50 keV range was inspected only in the off-line search of Koomers et al. (2001). Their scan has covered six of the 9.1 years of the BATSE data and yielded 50 previously unknown low-energy events, some of which are probably soft GRBs. Even if all of them are GRBs, the number of these events is 50 times smaller than that found in the 50–300 keV range.

1 A non-triggered supplement to the BATSE GRB catalogues is available at http://space.mit.edu/BATSE/intro.html
2 The uniform catalogue of GRBs found in the continuous BATSE daily records is available at http://www.astro.su/se/groups/head/grb archive.html
We performed a search for GRBs, inspecting the 25–50 keV range with a more careful procedure optimized for soft GRBs. The continuous daily 1.024-s time resolution Discriminator Large Area (DISCLA) records of count rate in eight BATSE detectors in four energy channels (25–50, 50–100, 100–300, and 300–1000 keV) were used. We have applied the same technique and the same algorithm as in our scan of the BATSE DISCLA data in the 50–300 keV range (Stern et al. 2001), setting the trigger in the 25–100 keV range (i.e. in the first and second energy channels).

We present the results of our search for soft BATSE GRBs in Section 2 and discuss new data together with the recent GRB observations by BeppoSAX and HETE-2 in Section 3.

2 SEARCH FOR SOFT GRBS IN THE BATSE RECORDS

We have performed a scan of the BATSE DISCLA records available at the FTP archive at the NASA Goddard Space Flight Center for the time period from 1998 July 6 until 2000 May 26 (TJDs 11000–11699: files for TJDs 11047, 11048, 11354, 11355–11359, 11519–11521 are missing). We have restricted our search to the time interval not covered by the search of Kommers et al. (2001). Our preliminary results show that the extension of the scan to the whole BATSE operation time would hardly modify the conclusions of this work. The applied algorithm and technique are described in Stern et al. (2001).

The applied algorithm and technique are described in Stern et al. (2001). Only the 25–100 keV range (first and second channels) was checked. The 1024-ms time resolution DISCLA data are not suitable for studies of short (<2 s) GRBs and we did not consider 1-bin events. This allowed us to avoid scintillation from heavy nuclei and the outbursts of soft gamma-ray repeaters (SGR). We also excluded events located in the vicinity of the Galactic Centre, the Sun, the four known SGRs and other persistent sources, as well as those events that appeared near and/or below the Earth’s horizon. We recorded only new GRBs missing from the catalogues of Paciesas et al. (1999) and Stern et al. (2001).

We have found, and classified as GRBs, 21 new events. Table 1 presents their time identifiers, intensities, hardness, location and duration. In the previous scan in the 50–300 keV band (Stern et al. 2001) for the same time period we have detected about 800 long GRBs. The hardness–intensity diagram (Fig. 1) shows that although GRBs from the new sample are softer on average, the samples do overlap. Actually, 13 out of 21 GRBs in the new sample (Table 1) and 23 out of ~800 long GRBs in the old sample (Stern et al. 2001, and see Table 2) have a peak count rate in the 25–50 keV band higher than that in the 50–300 keV band. According to this somewhat arbitrary criterion, we consider these 36 events to be a sample of soft, long (>2 s) BATSE GRBs.

These 36 soft GRBs have typical light curves, last up to about 100 s and do not demonstrate any significant anisotropy on the sky. Soft BATSE GRBs selected with the above criteria constitute about 5 per cent of the observed long GRB sample (about 20 per year with peak fluxes down to ~0.1 photon cm$^{-2}$ s$^{-1}$).

Our scan (as well as an alternative scan by Kommers et al. 2001) in the BATSE records in the 25–50 keV range has yielded a surprisingly

### Table 1. Long (>2 s) GRBs found in the present scan of the BATSE DISCLA records (TJD 11000–11699) in the 25–100 keV band.

| Date of TJD | Seconds | TJD | $P^a$ | HR$^b$ | $a^c$ | $b^c$ | $R^d$ | $T^f_{90}$ | $N^f_{90}$ |
|------------|---------|-----|-------|-------|-------|-------|-------|----------|-----------|
| 980726 | 63036 | 11020 | 0.11 | 0.57 | 255.8 | −54.8 | 9.7 | 56 | 29 |
| 980804 | 50914 | 11029 | 0.46 | 0.87 | 173.3 | −52.7 | 7.3 | 13 | 5 |
| 980927 | 6133 | 11083 | 0.33 | 0.89 | 9.6 | −54.5 | 11.4 | 6 | 4 |
| 981225 | 76754 | 11172 | 0.22 | 0.45 | 161.9 | −61.3 | 17.0 | 25 | 4 |
| 990304 | 77277 | 11241 | 1.85 | 0.83 | 31.6 | −26.7 | 4.6 | 4 | 2 |
| 990513 | 2453 | 11311 | 0.18 | 0.30 | 236.4 | −59.6 | 16.5 | 15 | 2 |
| 990610 | 20227 | 11339 | 0.11 | 0.43 | 234.8 | 16.6 | 17.3 | 80 | 11 |
| 990804 | 39065 | 11394 | 0.05 | 0.92 | 44.1 | 21.2 | 36.6 | 38 | 10 |
| 990907 | 75723 | 11428 | 0.06 | 0.66 | 301.0 | −39.3 | 8.3 | 126 | 33 |
| 991003 | 30847 | 11454 | 0.16 | 0.60 | 253.8 | 33.2 | 21.1 | 13 | 6 |
| 991009 | 30691 | 11460 | 0.10 | 0.47 | 107.9 | 3.5 | 12.9 | 24 | 8 |
| 991106 | 59880 | 11488 | 0.10 | 0.33 | 284.7 | −58.2 | 20.5 | 39 | 11 |
| 990107 | 8784 | 11550 | 0.12 | 0.91 | 74.9 | −61.6 | 16.1 | 73 | 12 |

### Notes:

$^a$Peak count rate in the 25–300 keV band, in units of count cm$^{-2}$ s$^{-1}$.

$^b$Hardness ratio of the peak count rates in the 50–300 keV band higher than that in the 50–300 keV band.

$^c$Coordinates.

$^d$Error radius.

$^e$Duration.

$^f$Number of 1.024-s bins where the signal exceeds 50 per cent of the peak value.

$^3$An FTP archive at the Goddard Space Flight Center is available at ftp://coss.gsc.nasa.gov/compton/data/batse/daily
small number of new soft GRBs. Moreover, there are no events with a hardness ratio (HR) below 0.3, while much softer events like outbursts of Vela X-1 can be confidently detected (see Fig. 1). We have considered a sample of 50 events classified by Kommers et al. (2001) as unknown because of their softness. When excluding short events they again have HR > 0.3 except the two events from the direction of Vela X-1.

Why do we not see softer GRBs despite the fact that there exist X-ray dominated bursts with the peak energy below the BATSE window? We approximated GRB spectra with the Band function (Band et al. 1993) and folded them with the BATSE Detector Response Matrix (DRM) (Pendleton et al. 1999). We present in Fig. 2 the dependence of the hardness ratio on the spectral index β for different values of $E_{\text{peak}}$ with α fixed at the most probable value $\alpha = -1$ (Preece et al. 2000; Kippen et al. 2003; Sakamoto et al. 2005). The hardness ratio is not very sensitive to $\alpha$ at low $E_{\text{peak}}$. The low hardness ratio (HR < 1) of our soft events is consistent with a wide variety of spectral parameters $E_{\text{peak}}$, low- and high-energy spectral indices $\alpha$ and $\beta$, for example with $E_{\text{peak}} < 20$ keV and $\beta < -3$ (see Figs 1 and 2). It is also evident that the sufficient condition for a GRB to give HR > 1, and thus to look like a typical GRB in the BATSE data (with a larger signal above 50 keV), is $\beta > -3$ independently of $E_{\text{peak}}$. The combination of a low $E_{\text{peak}}$ with a very steep $\beta$ would give a hardness ratio below 0.3, which we do not observe. The fact that all events with HR < 0.3 have an obvious non-GRB origin (solar flares, Vela X-1 pulsar, etc.) implies that a spectral cutoff below ~10–15 keV may be a distinguishing feature by which to separate the non-GRB sources.

Table 2. Soft long (>2 s) GRBs found by our previous scan of the BATSE DISCLA records (TJD 11000–11699) in the 50–300 keV band (Stern et al. 2001, location and duration data from that catalogue), GRB980924, GRB981015 and GRB991006 are bright and were first detected by the on-board procedure (Paciesas et al. 1999). GRB990304 was also detected by Konus and Ulysses; GRB991127 and GRB000405 were observed by Ulysses.

| Date       | Seconds of TJD | TJDa  | $P_b$ | HRc  | $\alpha$ | $\beta$ | $R_f$ | $T_{90}$ | $N_50$f |
|------------|----------------|-------|------|------|----------|--------|------|---------|---------|
| 980924     | 54626          | 11080b| 0.95 | 0.93 | 61.8     | -22.0  | 8.8  | 10      | 2       |
| 981015     | 46766          | 11101c| 1.36 | 0.69 | 122.9    | 22.1   | 5.4  | 34      | 6       |
| 981115     | 21438          | 11132b| 0.80 | 0.80 | 284.0    | 10.0   | 10.6 | 41      | 1       |
| 981117     | 11629          | 11134a| 0.41 | 0.98 | 217.6    | -65.7  | 23.7 | 8       | 3       |
| 981118     | 2533           | 11135a| 0.48 | 0.97 | 186.9    | 60.6   | 23.0 | 6       | 2       |
| 981128     | 74360          | 11145c| 0.18 | 0.97 | 60.3     | 38.4   | 33.2 | 36      | 3       |
| 981204     | 37850          | 11151a| 0.16 | 1.00 | 53.4     | -55.9  | 21.5 | 9       | 3       |
| 981222     | 58180          | 11169b| 0.30 | 0.89 | 145.9    | 67.1   | 28.7 | 11      | 5       |
| 990112     | 7066           | 11190a| 0.20 | 0.63 | 118.6    | -45.6  | 17.7 | 85      | 14      |
| 990207     | 55697          | 11216e| 0.49 | 0.95 | 152.9    | -9.7   | 16.7 | 17      | 2       |
| 990218     | 73752          | 11227b| 0.35 | 0.98 | 72.9     | 37.7   | 17.8 | 89      | 7       |
| 990413     | 32497          | 11281d| 0.39 | 0.94 | 302.1    | 55.5   | 12.8 | 6       | 6       |
| 990506     | 42666          | 11304c| 0.19 | 0.89 | 186.9    | 9.6    | 21.3 | 61      | 15      |
| 990610     | 56705          | 11339c| 0.45 | 0.99 | 105.7    | -16.6  | 8.4  | 109     | 18      |
| 990915     | 58755          | 11436c| 0.64 | 0.78 | 273.2    | -21.9  | 5.0  | 50      | 12      |
| 991006     | 8176           | 11457b| 0.76 | 0.99 | 104.0    | 11.7   | 3.8  | 73      | 27      |
| 991213     | 1802           | 11513a| 0.09 | 0.98 | 167.9    | -10.9  | 12.3 | 19      | 13      |
| 991217     | 37909          | 11529b| 0.36 | 0.49 | 64.8     | -12.7  | 16.8 | 8       | 1       |
| 991231     | 28492          | 11543a| 0.22 | 0.96 | 39.3     | 32.3   | 11.3 | 14      | 5       |
| 990014     | 51441          | 11557a| 1.17 | 0.99 | 107.4    | -25.3  | 3.8  | 5       | 2       |
| 990206     | 74873          | 11580g| 0.22 | 0.98 | 255.7    | 78.5   | 10.7 | 26      | 7       |
| 990405     | 77386          | 11639b| 0.92 | 0.96 | 226.9    | -52.5  | 2.1  | 35      | 7       |
| 990416     | 52380          | 11650c| 0.17 | 0.70 | 258.5    | -65.7  | 14.7 | 9       | 5       |

aLetter next to TJD means a name in the uniform catalogue of Stern et al. (2001). bPeak count rate in the 25–300 keV band, in units of cnt cm$^{-2}$ s$^{-1}$. cHardness ratio of the peak count rates in the 50–300 keV as compared to those in the 25–50 keV band. dCoordinates. eError radius. fDuration. gNumber of 1.024 s bins where the signal exceeds 50 per cent of the peak value.
Figure 2. Hardness ratio of GRBs depending on different parameters of the simulated incident photon spectra. The spectra are approximated with the Band function (Band et al. 1993) and folded with the BATSE detector response matrix (Pendleton et al. 1999). $\alpha$ and $\beta$ are the low- and high-energy photon spectral indices, respectively.

3 GRB SPECTRA AS OBSERVED BY BATSE/BEPPOSAX/HETE-2

BeppoSAX has observed 20 X-ray dominated GRBs that were detected by the Wide Field Camera (2–26 keV) but have not activated the trigger of the Gamma-Ray Monitor (40–400 keV). Their counterparts were found in the BATSE records for almost all observable events (Kippen et al. 2001; in’t Zand et al. 2003). Most of them have been detected previously as classic GRBs by our scan of the BATSE data in the 50–300 keV band (Stern et al. 2001). These events have a high hardness ratio similar to typical GRBs (see Fig. 3a). The hardness ratio 100–300/50–100 keV for the common BeppoSAX/BATSE events shows a similar picture: seven out of eight events have a hardness typical of weak GRBs, and only one event is softer. Thus this distribution is also consistent with the extrapolated hardness–intensity trend for long GRBs (Kippen et al. 2001). These facts support our conclusion that the majority of the X-ray dominated GRBs should have a hard tail with $\beta > -3$ in the BATSE window 25–1000 keV (see Fig. 2).

HETE-2 observed 45 GRBs in the 2–400 keV band and their spectral fits are given in Sakamoto et al. (2005). In order to check how the HETE-2 results are related to our data we folded the HETE-2 spectra with the BATSE detector response matrix and obtained the corresponding counts in the BATSE channels (see Fig. 3b). The fraction of soft events in the HETE-2 sample is about three times larger than in the BATSE sample, which can be explained by different instrument responses. However, only one out of 45 HETE-2 events gives a lower hardness ratio than we see in the BATSE GRB sample. Nine out of 45 HETE-2 events are below the BATSE sensitivity threshold. The BATSE sample, however, probably represents the whole GRB spectral variety.

Sakamoto et al. (2005) fitted HETE-2 spectra by three functions: a power law, a power law with an exponential cutoff, and the Band function. They started from a power-law fit and used more parametric expressions only if a fit was inconsistent with the data at the 0.01 significance level. From Fig. 3b one can see that a power-law fit was acceptable only for weak events. Relatively bright bursts gave good fits to a power law with an exponential cutoff. However, this does not mean that these events could not be fitted by the Band function. Moreover, among the HETE-2 GRBs with the fluence $\geq 100$ photon cm$^{-2}$ in the 2–400 keV range (with reliable spectral fits), there are no events that are fitted with a power law with an exponential cutoff.
cutoff and show $E_{\text{peak}} \lesssim 25$ keV. This supports our conclusion that the existence of GRBs with a sharp spectral cutoff is questionable for events with low $E_{\text{peak}}$. Indeed, events with $E_{\text{peak}} \sim 10$–20 keV would give a very low hardness ratio which we do not observe in the BATSE data. Note that, as shown by Preece et al. (2000), only a few per cent of GRBs with high $E_{\text{peak}}$ are better described by a power law with an exponential cutoff. If the dispersion in $E_{\text{peak}}$ is due to variations in the redshift/blueshift in the source, then the spectral shape would be stable and our conclusion could refer to all GRBs.

4 CONCLUSIONS

(i) Despite the wealth of the X-ray dominated GRBs observed by *Ginga*, *BeppoSAX* and *HETE-2*, the number of soft GRBs in the BATSE data is relatively small. The fraction of events with a count rate in the 25–50 keV band that is higher than that above 50 keV is $\sim 5$ per cent (20 per year with flux down to 0.1 photon cm$^{-2}$ s$^{-1}$).

(ii) The hardness distribution of the X-ray dominated GRBs in the BATSE band is consistent with that of weak classic GRBs. In the case of a low $E_{\text{peak}}$, the main fraction of GRBs should have a relatively hard high-energy tail with a power-law slope $\beta > -3$. Only a few per cent of the X-ray rich GRBs have a tail with $\beta < -3$, but which is still harder than the exponential one. This fact clarifies the deficiency of soft events in the BATSE data.

(iii) An exponential cutoff in the GRB spectra, if it exists, is probably a rare phenomenon. Therefore, a spectral cutoff with the e-folding energy below $\sim 10$–15 keV may be a distinguishing feature of non-GRB events.

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