Swift-BAT results on the prompt emission of short bursts

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This is a brief review of short hard bursts (SHBs) from previous missions and from Swift-BAT; in particular, a review of the developing class of gamma-ray bursts which are similar to SHBs in that they have the short hard initial spike (0.1 to a few seconds), but that they also have a long extended phase of soft emission (50–200 s). Further, we suggest that a class of events discovered by Horvath in the T90 versus hardness ratio plane is this SHB with extended emission.

Keywords: gamma-ray burst; SHB; extended emission; long GRB

1. Introduction

This will be an abbreviated version of the talk given at the Royal Society discussion meeting. This proceedings paper will concentrate only on the observations made on short hard bursts (SHBs) and, in particular, those SHBs with the so-called extended emission (SHBwEE). There will be a brief review of the T90 versus hardness ratio (HR) and spectral lag work, mostly to provide a groundwork for the Burst Alert Telescope (BAT) SHBwEE results. There will also be a brief section on the status of the BAT instrument and its performance. It will not cover (i) the redshift distribution results, (ii) the BAT burst catalogue results that allow a pseudo-redshift determination or (iii) the transition from the prompt gamma-ray emission phase into the X-ray emission phase.

2. Burst duration distributions

The work of Norris (1984) with KONUS-13/14 and ISEE-3 using the durations of bursts gave indications that there were two distinct types or populations of bursts. The work by Kouveliotou et al. (1993) using the much larger BATSE sample of bursts plus spectral information confirmed this. Figure 1 shows the distribution of T90 durations for bursts detected by the CGRO-BATSE instrument. The distribution clearly shows two peaks: one peaking at approximately 0.5 s and the other at approximately 30 s. These are the so-called SHBs and the long bursts (sometimes also called the long soft bursts; LSBs). The hard versus soft spectral aspects will be discussed later. The minimum between these two peaks is at approximately 2 s. It is this minimum that has led to a
general working approximation within the burst community that SHBs have durations less than 2 s and that LSBs have durations longer than 2 s. It should be noted that these two distributions have a significant overlap.

It is important to note that the details of this duration distribution are dependent on the detecting instrument. In particular, they are dependent on the energy window of the instrument and the trigger criteria used. As an example, the BeppoSAX Wide Field Camera did not detect any short bursts during the 6 years of operations. The KONUS-13/14 distribution is similar (Norris 1984). Figure 2 shows the T90 distribution for the Swift-BAT instrument. The ratio of SHB to LSB is much lower in BAT than for BATSE. This ratio difference is generally due to the softer energy range of the BAT trigger (15–150 keV) compared with the BATSE one (50–300 keV).

The spectral differences between the short and the long bursts are seen in figure 3 (ignore the ellipses for the moment; they will be covered in §4c). Here, the HR is plotted against the T90 duration. While the separation of the two populations in the duration (T90) dimension is clearly seen, the separation of the two populations in the spectral (HR) dimension is not so strong. There is a much greater overlap in the HR for the two populations.

3. Short hard bursts

As already mentioned, there are two classical populations of gamma-ray bursts (GRBs): SHB and LSB. Swift-BAT has confidentially detected 15 (and maybe as many as 18) SHBs. They are listed in table 1 along with some related parameters (redshift, lag, host galaxy and comments). For a complete discussion of this table and results, please see Gehrels (2007).
Figure 2. The $T_{90}$ distribution of bursts detected by Swift-BAT. The SHB peak is only weakly present in the BAT-detected bursts.

Figure 3. BATSE $T_{90}$-HR scatterplot with the three populations fitted with two-dimensional Gaussians (shown with ellipses). The original SHB population (upper left), the LSB population (lower right) and the third population fitted by Horvath (middle ellipse). Note that the SHB and LSB have no correlation of $T_{90}$ with HR, but that the ‘third’ population has $T_{90}$ anti-correlated with HR. Adapted from Horvath et al. (2006).
Figure 4 shows the distribution of redshifts of bursts detected by BAT. The short bursts have a clearly lower distribution than the long bursts. This is an instrumental effect based on the lower fluence of soft photons available for the SHB and thus the reduced sensitivity of the BAT triggers.

On a related topic to SHB and distance distributions, soft gamma-ray repeaters (SGRs) superflares are also short in duration. On 27 December 2004, BAT detected a superflare from SGR1806-20. Even though these SGR superflare events tend to be softer than SHBs (as are regular SGR outbursts), many authors have noted that some of the SHBs in the upper left cluster in figure 3 (at least the lower portion thereof) could be due to SGR superflares. This is an improbable situation for the BAT instrument because the 041227 superflare event, which is already 100 times more energetic than any of the other two superflares, could not be seen by BAT beyond 40 Mpc (Palmer et al. 2005). All of the detected Swift-BAT SHBs are well beyond the Virgo cluster of galaxies.

(a) Redshift distribution

Table 1. Short bursts detected by Swift-BAT. Question marks indicate uncertainty on that particular entry.

<table>
<thead>
<tr>
<th>name</th>
<th>redshift</th>
<th>afterglow</th>
<th>host</th>
<th>$E_{iso}/(10^{50}$ erg)</th>
<th>duration (s)$^a$</th>
<th>lag (ms)</th>
<th>origin?</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>050509B</td>
<td>0.225</td>
<td>X</td>
<td>elliptical</td>
<td>0.01</td>
<td>0.042</td>
<td>4.3±3.2</td>
<td>NS–NS</td>
<td></td>
</tr>
<tr>
<td>050709$^b$</td>
<td>0.161</td>
<td>X, O</td>
<td>SF galaxy</td>
<td>0.6</td>
<td>0.07</td>
<td>0.0±2.0</td>
<td>NS–NS</td>
<td></td>
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<td></td>
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<td>050813</td>
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<td>X</td>
<td>galaxy$^c$</td>
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<td>0.012</td>
<td>−9.7±14.0</td>
<td>—</td>
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<td>—</td>
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<td>0.162</td>
<td>—</td>
<td>—</td>
<td></td>
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<td>late slew</td>
<td>cluster$^c$</td>
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<td></td>
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<td>—</td>
<td>in galaxy plane</td>
<td>—</td>
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<td>—</td>
<td>new SGR?</td>
<td></td>
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<td>051105A</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>0.028</td>
<td>6.3±5.3</td>
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<td>X, O, R</td>
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<td>0.2</td>
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<td>—</td>
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<td>2±10?</td>
<td>—</td>
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<tr>
<td>060121$^e$</td>
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<td>X, O</td>
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<td>1.97</td>
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<td>cluster$^c$</td>
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<td>—</td>
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<td>galaxy</td>
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<td>4.0</td>
<td>—</td>
<td>is it short?</td>
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<td>103(5)</td>
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<td>~13</td>
<td>0.5</td>
<td>−8±8</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>061006</td>
<td>—</td>
<td>X, O?</td>
<td>no bright galaxy</td>
<td>130</td>
<td>5±3</td>
<td>—</td>
<td>—</td>
<td></td>
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</table>

$^a$T90 in 30–350 (400) keV.$^b$HETE GRB.$^c$Galaxy in cluster.$^d$Soft spectrum.$^e$Not related to massive stars, consistent with NS–NS merger models.

(b) Fast temporal variations in short hard burst

Unlike many SHBs which have a single spike of emission in their lightcurves, figure 5 shows Swift-BAT GRBs 051221a and 060313, which have many separate, statistically significant peaks in their lightcurves. Many of these spikes have rise times less than 1 ms and a few have fall times less than 1 ms.
Norris & Bonnell (2006) have done extensive work on the spectral lag properties of GRBs, in particular, the spectral lag as a tool for separating short from long bursts. Figure 6 shows the lag values for 260 BATSE bursts that have ‘zero lag’ (i.e. anything with a lag in the $\pm 20$ ms range). Figure 6a shows that there is no correlation of lag with peak flux (i.e. neither correlation with an intrinsic brightness of the SHB nor with distance). Figure 6b collapses figure 6a in the flux dimension to produce a histogram of lags for SHB with the x-axis now in sigma units. The distribution is tightly confined around zero with only a small tail on the positive side (demarcated by the blue arrow). These extra bursts with small positive lag values are due to long bursts with extremely small lag values. Norris & Bonnell (2006) estimate that only one or two out of the 20 events seen in this tail are true SHB, yielding that approximately 18 are not true SHBs. The level of contamination is 7%.

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4. Short hard bursts with extended emission

There is a growing body of evidence that there is a class of events that is at least observationally different, if not intrinsically, from the SHB and LSB classical populations of GRBs. This putative new class starts out like a SHB (the initial short pulse), but then it has ongoing emission—well beyond the 2 s, or even few seconds, durations that have previously been defined as the duration limit for SHBs. This ongoing (extended) emission is softer than the initial emission of the initial spike. Using this observational-based definition, I will call these events SHBs with extended emission (SHBwEE).

(a) Swift-BAT SHBwEE

Figures 7 and 8 show the lightcurves for GRBs 050724 and 060614, respectively. Swift-BAT has detected two other SHBwEEs: GRBs 051227 and 061006, plus 10 traditional SHBs (i.e. no extended emission above the BAT background level). This 4 out of 14 ratio is much higher than the 8 out of 260 ratio that Norris & Bonnell (2006) found in BATSE. This difference is probably due to the somewhat softer energy window that BAT has over BATSE, and that BAT has an image-trigger capability which BATSE did not (note that GRB 061006 was not detected by BAT using a rate trigger on the initial spike, but rather using an image trigger on the extended emission phase because the initial spike occurred during a spacecraft slew manoeuvre when all triggers are disabled).

(b) BATSE, KONUS and HETE SHBwEEs

Figure 9 shows the lightcurves of eight SHBwEEs that Norris & Bonnell (2006) identified from the BATSE catalogue. All eight have zero lag (figure 6)
and are therefore, in the Norris & Bonnell (2006) definition, true short bursts. These eight bursts were previously classified as long bursts by the BATSE team because they were using only T90 and HR; no spectral lag information was used. It is only recently that the spectral lag factor is being incorporated into the

Figure 7. Lightcurve of Swift-BAT GRB 050724, a SHBwEE. The initial spike at $T+0$ s is suppressed in amplitude compared with the extended emission phase owing to the time binning. The extended emission starts to rise at approximately $T+20$ s, peaks around $T+80$ s and returns to instrumental background around $T+200$ s.

Figure 8. Lightcurve of Swift-BAT GRB 060614, a SHBwEE. The extended emission starts to rise at approximately $T+10$ s, peaks around $T+45$ s and returns to instrumental background around $T+150$ s. The spectral lag for the spike phase is $9 \pm 6$ and $3 \pm 6$ ms for the extended emission phase. The apparent periodic structure in the extended emission is not statistically significant (Gehrels et al. 2006).

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classification method. Given that there is a 7% chance of contamination (§3c), it is improbable that any of these eight are long bursts. Note that all eight have the same basic lightcurve envelope: they start with an initial intense and short spike (0.5–2 s), then a hiatus of emission, followed by the onset of the soft emission for 50–100 s. HETE GRB 050709 (figure 10) shows the identical temporal envelope. Figure 11 shows three KONUS bursts that are clearly in the same SHBwEE temporal and spectral envelope. Additionally, KONUS has six more bursts with nearly the same signature (Mazets et al. 2002)—the only difference is that there is no clear hiatus of emission immediately after the initial spike. Given that four instruments have seen these SHBwEEs and at least one BAT SHBwEE would have been classified as a traditional SHB (i.e. the extended emission would not have been detectable in BATSE; Barthelmy et al. 2005b), it seems probable that this is a new (sub)class of bursts.

Figure 9. BATSE SHBwEE. Out of the 260 short bursts found by using the ‘zero-lag’ test on the BATSE catalogue of burst, these are eight that have extended emission and still have a zero-lag value. Adapted from Norris & Bonnell (2006).
The Horvath third class of bursts

Horvath has performed fits in the HR–T90 plane with two-dimensional Gaussians (the three ellipses in figure 3) and finds a third population of burst to be 11% of the total. While the traditional SHB and LSB populations have no significant correlation between T90 and HR, his third population clearly shows an anti-correlation. The longer the burst (i.e. the larger the T90 value), the softer the HR. While Horvath states that he does not know of a reason for this anti-correlation, it seems reasonable that this third population is SHBwEE. The extended emission part of the burst is softer than the initial spike phase of the

Figure 10. HETE SHBwEE. This is the lightcurve of GRB 050709 that was detected by HETE. This burst has the same profile of a SHB (the initial spike of intense spectrally hard emission, followed by a hiatus of emission, then increasing spectrally soft emission, peaking and then decreasing back to instrumental background). Note that in this plot, there is variable-width time binning to preserve the narrowness of the initial spike.

Figure 11. KONUS SHBwEE. This shows three of the best examples of SHBwEE from the KONUS catalogue (Mazets et al. 2002). These three bursts also show the profile of initial spike, followed by a hiatus of emission, then increasing soft emission, peaking and then decreasing emission.

(c) The Horvath third class of bursts

(c) The Horvath third class of bursts
GRB. For a given short burst, as the soft extended emission phase extends longer and longer, the total HR will be decreased. This is the same as the anti-correlation behaviour seen in the Horvath third population.

(d) Conclusions on short hard bursts

We have shown that there is a sizable and distinct population of bursts whose lightcurves and spectral evolutions are different than the traditional short and long bursts. There are two differences. Firstly, they have an initial spectral hard and very short (less than a couple of seconds) emission phase which is identical to the SHBs. And secondly, they have an extended emission phase (lasting as much as 100–200 s) which is spectrally softer and is very close to the duration and spectral properties of the LSBs. Owing to this combination of properties of both the short and the long bursts, these SHBwEEs have been misidentified (owing to a lack of sufficient low-energy response) as to a type in previous missions (i.e. they were most commonly classified as LSB). This plus the results of Horvath (§4c) suggest that there is a third class or population of bursts (which we call SHBwEE). However, we cannot rule out the possibility that (i) there are still only two populations, (ii) all SHBs have extended emission, and (iii) the ratio of initial, hard emission to extended, soft emission has a large dynamic range such that most SHBs have such a low ratio that the extended emission is not detected by the past and the current missions.

5. Status of the Swift-BAT instrument

The BAT on Swift is fully described in Barthelmy et al. (2005a) and the top-level instrumental parameters are shown in table 2. BAT has and continues to operate flawlessly since it was turned on and commissioned on 17 December 2004. Between then and 16 September 2006, there have been a total of 12.7 days (2% downtime) when BAT was not in a fully operational and triggerable state. This downtime was due to two computer crashes (both early in the mission and the cause has been fixed), two flight software upload sessions, a time when one of the two redundant loop heatpipes temporarily shutdown, and finally due to a handful of times when the spacecraft went into safehold state. In addition to these system downtimes, the BAT instrument is not triggerable to GRB (or hard X-ray transients) while in the SAA or while the spacecraft is in slew mode (each approximately 15% of the total time). There have been 173 GRBs detected, localized and distributed to the world

<table>
<thead>
<tr>
<th>item</th>
<th>value</th>
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<tbody>
<tr>
<td>energy range</td>
<td>12–300 keV</td>
</tr>
<tr>
<td>energy resolution</td>
<td>5 keV (at 60 keV)</td>
</tr>
<tr>
<td>location accuracy</td>
<td>1–3 arcmin (1σ, depends on rising edge of burst)</td>
</tr>
<tr>
<td>field of view</td>
<td>2 sr</td>
</tr>
<tr>
<td>detectors</td>
<td>5200 cm^2 of CZT, 32 768 elements</td>
</tr>
</tbody>
</table>

Table 2. BAT basic characteristics.
community which yields an annual rate of $100 \pm 8 \text{GRBs yr}^{-1}$. Of these, approximately 10 per year are short GRBs. There have been slight increases due to two refinements in the triggering system. The first involved a change in the threshold levels in the short rate trigger criteria (4–32 ms duration triggers) and other trigger control parameters. The second involved a bug in the BAT flight software that allowed the long image triggers (5–43 min) to be enabled. Since launch, approximately 16% of the 32 768 CZT detectors have become permanently or semi-permanently noisy and had to be disabled.

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References


