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Different progenitors of short hard gamma-ray bursts

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ABSTRACT

We consider the spatial offsets of short hard gamma-ray bursts (SHBs) from their host galaxies. We show that all SHBs with extended-duration soft emission components lie very close to their hosts. We suggest that neutron star–black hole binary mergers offer a natural explanation for the properties of this extended-duration/low-offset group. SHBs with large offsets have no observed extended emission components and are less likely to have an optically detected afterglow, properties consistent with neutron star–neutron star binary mergers occurring in low-density environments.

Key words: stars: neutron – gamma-rays: bursts.

1 INTRODUCTION

In the last few years, the successful *Swift* mission (Gehrels et al. 2004) has greatly expanded our knowledge of gamma-ray burst (GRB) phenomenology. In particular, it has transformed the study of short hard gamma-ray bursts (SHBs). The ability to react rapidly to GRB triggers led to the first detection of an SHB X-ray afterglow (GRB 050509B; Gehrels et al. 2005), and, a few months later, to the detection of the first SHB optical counterpart (GRB 050709; Fox et al. 2005; Hjorth et al. 2005). Accurately pinpointing the afterglow position on the sky can link the SHB to its host galaxy, constraining its distance and energetics through the redshift measurement of the galaxy. Identifying SHB hosts can also provide a powerful insight into the progenitor population and formation history. Almost all SHB models invoke close binary systems containing at least one neutron star. The mass loss involved in the supernova (SN) forming the neutron star gives the binary a significant space velocity, depending on its total mass. This can be enhanced if the back reaction ('kick') on the neutron star is anisotropic. There is ample observational evidence (e.g. Wang, Lai & Han 2006, and references therein) for such anisotropic kicks in both single and binary neutron stars.

The analogous inferences for long GRBs (Bloom, Kulkarni & Djorgovski 2002; Fruchter et al. 2006) are well known. For instance, only a few important cases show an observed GRB/SN connection (e.g. GRB 060218/SN 2006aj; Campana et al. 2006a; Pian et al. 2006), but the measured low offsets from the galaxy centres and the preferential location of long GRBs in the bluest regions of these galaxies strengthen the link with massive stars and their collapse. By contrast, associating SHBs with a host is complicated by the faintness of their afterglows and their potential origin in NS binaries which can travel far from their birth sites before coalescence (Bloom, Sigurdsson & Pols 1999; Belczynski et al. 2006; Wang et al. 2006; Lee & Ramirez-Ruiz 2007). Finding the absorption redshifts of SHB afterglows would strengthen the association with their hosts.

Since its launch, in 2004 November, *Swift* has detected 25 GRBs classified as SHBs up to 2007 August. In a significant fraction of them ($\sim$25 per cent) the initial short hard gamma-ray episode is followed by a second spectrally softer emission component, lasting tens of seconds. Despite their long duration, exceeding the canonical cut of 2 s (Kouveliotou et al. 1993), these bursts display all the distinctive features of the SHB class: a first short hard event with zero spectral lag (Norris & Bonnell 2006); a heterogeneous population of host galaxies, in stark contrast to the hosts of long GRBs which are all late type (Covino et al. 2006; Prochaska et al. 2006); and very tight limits on the presence of any accompanying SN, at odds with the standard core-collapse origin of long GRBs (Woosley 1993).

In 18 cases out of 25 ($\sim$70 per cent) there is an X-ray counterpart, and in seven cases ($\sim$28 per cent) the optical afterglow was also detected. Three additional bursts with visible X-ray and optical counterparts were triggered by the *HETE-2* (GRB 050709, GRB 060121; Villasenor et al. 2005; Donaghy et al. 2006) and *INTEGRAL* (GRB 070707; Gotz et al. 2007) satellites. A total of 21 SHBs have arcsecond or subarcsecond localizations, allowing us to infer their hosts and estimate their redshifts with some security.

In this Letter we report on the full sample of well-localized SHBs and their possible progenitors, focusing on their spatial distribution with respect to their putative hosts. We also estimate the prompt gamma-ray and X-ray afterglow energetics of the available sample. The Letter is organized as follows. In Section 2 we briefly describe the adopted selection criteria and the general properties of the sample, and our results are reported in Section 3. We discuss our findings and their implications for SHB progenitors in Section 4. A summary of our conclusions is given in Section 5. Throughout the Letter we

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have adopted a standard cosmology with Hubble constant $H_0 = 71$ km s^{-1} Mpc^{-1} and parameters $\Omega_\Lambda = 0.73$, $\Omega_M = 0.27$ (Spergel et al. 2007).

2 SAMPLE

We included in our analysis GRBs whose prompt emission follows the original classification ($T_{90} < 2$ s, hard spectrum; Kouveliotou et al. 1993), as well as GRBs that formally have a long duration ($T_{90} \gg 2$ s), but a morphology resembling the short bursts with extended emission, as codified by Norris & Bonnell (2006). We discarded those GRBs without at least an accurate X-ray localization. Among the 21 well-localized ($\lesssim$6 arcsec radius) SHBs, we excluded six other bursts since their hosts and distance scales are not constrained (GRB 050813, 070429B, 070707, 070714B, 070729 and 070809).

In addition, two bursts [GRB 060505 and 060614 (Fynbo et al. 2006; Gehrels et al. 2006)] that display several features of the SHBs class were considered and compared to the sample.

Table 1 lists the properties of our sample of bursts and their putative hosts. In each case we give the probability, $P_{\rm chance}$, that the proposed association is a chance coincidence (column 5). If no value is given in the literature, we simply estimated it as the probability that a galaxy of magnitude $R < R_{\rm host}$ is randomly placed within a certain radius from the GRB centroid position, without regard to the galaxy type or redshift. When the galaxy centroid lies within the error circle position (e.g. GRB 061006), then the GRB cross-section is determined by the size of the uncertainty region. Otherwise, if the galaxy is well outside the position circle (e.g. GRB 061217), it is determined by the angular offset (column 7). We used the results of Hogg et al. (1997) and Huang et al. (2001) to calculate the galaxy sky-density in the R band.

The derived values listed in column 5 reflect the difficulties of identifying SHB hosts. These result from either poor localizations or large offsets (e.g. GRB 061217). The chance of a spurious association obviously increases when only an X-ray position is available, as several galaxies lie within or close to the X-ray error circle. In those cases, the guiding criterion is usually the object brightness, favouring the association with the brightest galaxy. Interestingly, the probability that four associations out of 17 are spurious is $\sim 4 \times 10^{-4}$, and indeed the chance of four or more misidentifications is well below the 3σ confidence level.

The quoted errors are mainly due to the GRB localizations, usually pinpointed within a 90 per cent confidence level error circle. We caution that the offset is a positive-defined quantity, thus the associated uncertainties do not properly reflect a probability distribution, especially in cases of negligible offsets (see Bloom et al. 2002).

Table 1. SHB sample properties.

GRB (1)	T_{90} (s) (2)	z (3)	Putative host R (mag) (4)	$P_{\rm chance}$ (5)	Afterglow (6)	Angular offset (arcsec) (7)	Error (arcsec) (8)	Projected offset (kpc) (9)	Error (kpc) (10)	Refs. (11)
050509B...	0.03 [0.01]	0.225	16.8	5.0×10^{-3}	X – –	17.87	3.40	64	12	1–3
050709.....	130 [7] [a]	0.161	21.2	2.0×10^{-3}	X,O –	1.30	0.10	3.57	0.27	4–6
050724.....	152 [9]	0.258	19.8	1.0×10^{-5}	X,O,R	0.64	0.02	2.57	0.08	7–9
051210.....	1.4 [0.2]	>1.4	23.8	1.0×10^{-1}	X – –	2.80	2.90	<50	–	3, 10, 11
051221A.....	1.27 [0.05]	0.546	22.0	2.4×10^{-4}	X,O,R	0.12	0.04	0.76	0.25	12, 13
051227.....	110 [10]	–	25.6	2.0×10^{-4}	X,O –	0.05	0.02	<0.7	–	11, 14
060121.....	1.97 [0.06] [b]	>1.7	26.6	1.3×10^{-2}	X,O –	0.32	0.10	<4	–	15–17
060313.....	0.7 [0.1]	<1.1	25.0	4.0×10^{-3}	X,O –	0.40	0.56	<8	–	11, 18
060502B...	0.09 [0.02]	0.287 ? [c]	18.7	$<5.0 \times 10^{-2}$	X – –	16.33	3.70	70	16	3, 19
060505.....	4 [1]	0.089	17.9	1.0×10^{-4}	X,O –	4.53	0.32	7.45	0.53	20, 21
060614.....	103 [5]	0.125	22.5	6.0×10^{-6}	X,O –	0.50	–	1.10	–	22–24
060801.....	0.5 [0.1]	1.131	23.0	4.1×10^{-2}	X – –	2.39	2.40	19.7	19.8	3, 11, 25
061006.....	130 [10]	0.438	23.7	1.8×10^{-3}	X,O –	0.32	0.50	1.8	2.8	11, 26
061201.....	0.8 [0.1]	0.111	19.0	3.8×10^{-2}	X,O –	17.00	0.20	33.9	0.4	27
061210.....	85 [5]	0.410	21.1	4.7×10^{-3}	X – –	1.99	1.80	10.7	9.7	3, 11, 28
061217.....	0.30 [0.05]	0.827	23.4	3.9×10^{-1}	X – –	7.41	3.80	55	28	3, 11, 29
070724A...	0.40 [0.04]	0.457	$\sim$21 [d]	$\sim 5 \times 10^{-3}$	X – –	0.72	2.10	4	12	3, 30

Notes: column (1): GRB name; column (2): T_{90} duration and its error in the 15–350 keV energy band; column (3): redshift of the putative host galaxy; column (4): observed R magnitude of the putative host galaxy; column (5): probability that the association is a chance coincidence; column (6): detection of the GRB counterpart in different energy bands (X – X-ray; O – optical; R – radio); columns (7)–(8): angular offset between the afterglow position and the associated galaxy centroid, and its error, respectively; columns (9) and (10): projected physical offset and its error, respectively; column (11): reference to publications of the presented data.

References: (1) Gehrels et al. (2005); (2) Bloom et al. (2006); (3) Butler (2007); (4) Hjorth et al. (2005); (5) Fox et al. (2005); (6) Villasenor et al. (2005); (7) Campana et al. (2006b); (8) Berger et al. (2005); (9) Prochaska et al. (2006); (10) La Parola et al. (2006); (11) Berger et al. (2007); (12) Burrows et al. (2006); (13) Soderberg et al. (2006); (14) Sakamoto et al. (2007); (15) Donaghy et al. (2006); (16) de Ugarte Postigo et al. (2006); (17) Levan et al. (2006); (18) Roming et al. (2006); (19) Bloom et al. (2007); (20) Ofek et al. (2007); (21) Levesque & Kewley (2007); (22) Gal-Yam et al. (2006); (23) Gehrels et al. (2006); (24) Mangano et al. (2007); (25) Sato et al. (2006); (26) Malesani et al. (2006); (27) Marshall et al. (2006); (28) Cannizzo et al. (2006); (29) Ziaeepour et al. (2006); (30) Ziaeepour et al. (2007).

[a] *Hete-2* trigger. The duration is given in the 2–25 keV energy band. [b] *Hete-2* trigger. The duration is given in the 30–400 keV energy band. Donaghy et al. (2006) detected a faint and long-lasting soft bump of emission at a significance level of $\sim 4.5\sigma$. [c] A faint ($R = 26$ mag) object (S2 in Bloom et al. 2007) has been proposed as the high-redshift host galaxy. The measured angular offset is 4.2 ± 3.7 arcsec ($P_{\rm chance} \sim 70$ per cent), corresponding to 34 ± 30 kpc at $z \sim 1$.
[d] We assume $R - I \sim 1$.

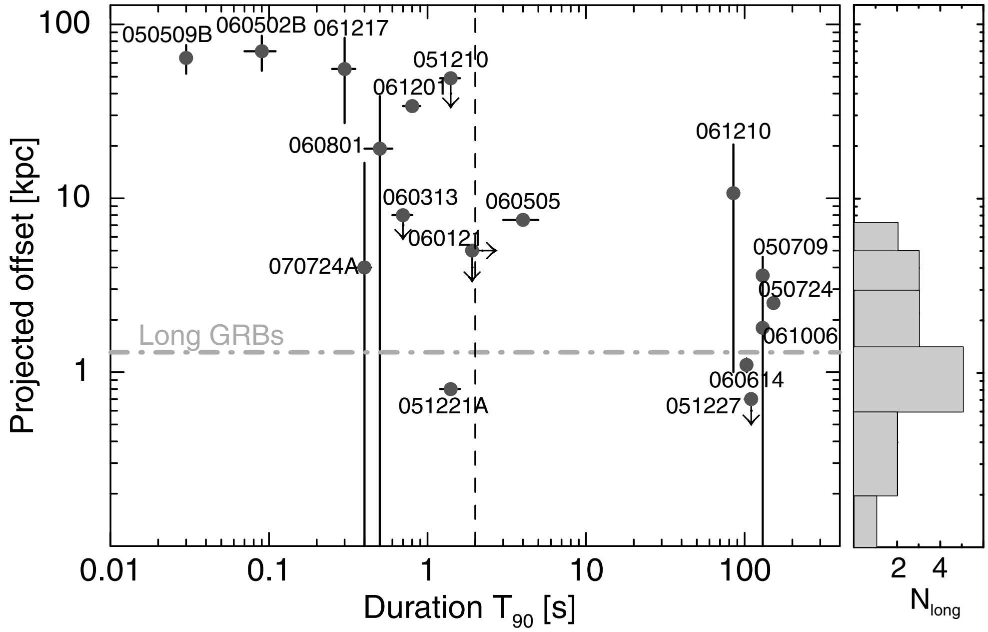

Figure 1. Left-hand panel: projected physical offsets as a function of the burst duration (T_{90}) in the gamma-ray band. The vertical dashed line marks the canonical temporal division between long and short hard bursts. The horizontal dot–dashed line reports the median offset for a sample of long GRBs with known redshift (from Bloom et al. 2002). Right-hand panel: offsets histogram for the same sample of long GRBs.

3 RESULTS

Fig. 1 presents the projected galactocentric offset of SHBs as a function of the burst duration in the gamma-ray band (observer frame). For comparison, the median offset value for long bursts ($\sim$1.3 kpc; Bloom et al. 2002) is traced by the horizontal line. The frequency histogram of long bursts as a function of the projected offset is shown in the narrow right-hand panel. Two main features emerge from the plot: (1) bursts with prompt emission extending up to $\sim$100–200 s tend to be clustered very close to their host galaxy, while short bursts display a more heterogeneous displacement around the host; in particular (2) the shortest duration bursts seem to prefer much higher offsets than the rest of the sample.

In Fig. 2 the prompt and the afterglow energetics are shown as functions of offset. In all cases we assumed isotropic emission. The gamma-ray and X-ray energies are calculated in the 15–150 and 0.3–10 keV bands respectively. To refer our results to the same rest-frame energy band we derived a *k*-correction from the burst spectral parameters (see references in Table 1).

The gamma-ray energies radiated during the short hard spike and over the total T_{90} are reported in the top and middle panels of Fig. 2, respectively. Bursts with extended emission are on average more energetic than bursts with $T_{90} < 2$ s, as shown in Fig. 2 (middle panel), but no clear distinction emerges if we consider only the energy of the initial hard event (top panel).

The bottom panel of Fig. 2 shows the X-ray isotropic energy, calculated by integrating the best-fitting light curve between 400 s and 500 ks after the trigger (rest-frame time), when the central engine activity does not dominate the total X-ray emission. In two cases, GRB 060801 and 051210, the X-ray afterglow was below the detection limit in this temporal range. To estimate their energetics we assumed temporal slope $\alpha \sim 1$ and spectral index $\beta \sim 1$ ($F_{\nu,t} \propto \nu^{-\alpha}\, t^{-\beta}$). The normalizations were determined by the upper limits from *Swift*/XRT observations. Filled symbols indicate those bursts with a detected optical counterpart, empty symbols those lacking an optical detection.

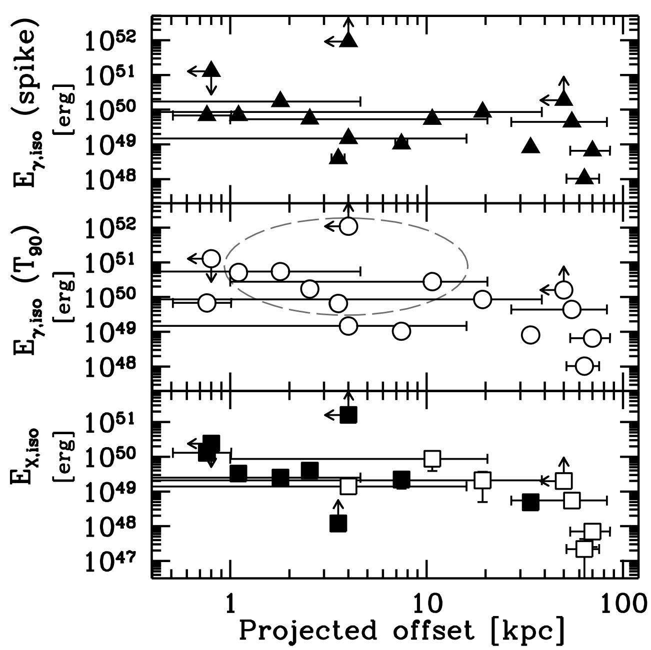

Figure 2. Prompt and afterglow energetics (source rest frame) as functions of the projected physical offset. Top panel: isotropic energy (15–150 keV) released over the initial short hard gamma-ray event only (spike). Middle panel: isotropic energy (15–150 keV) over the T_{90} duration. Bursts with a long-lasting emission are enclosed by the dashed ellipse. Bottom panel: isotropic energy (0.3–10 keV) released over the temporal range 400 s–500 ks. Filled and empty symbols indicate GRBs with and without a detected optical afterglow, respectively.

Even given the small number of SHBs detected so far, it is clear that large-offset bursts (GRB 050509B, 060502B, 061201 and

061217) lie on the lower part of the bottom panel of Fig. 2, while small-offset bursts instead have on average more energetic X-ray afterglows and a much higher chance of a detectable optical afterglow. Malesani et al. (2007) noticed that optical counterparts of SHBs with extended emission are more frequently detected. Our Fig. 2 suggests that this is an enviromental property, since these bursts seem to happen closer to their hosts, and hence presumably in denser interstellar environments.

4 DISCUSSION

As shown in Fig. 1, short GRBs with measured offsets appear qualitatively divided into two groups. The group with extended durations all lie very close to their hosts, while the group with short durations have a mean offset a factor of 15 larger. Although the low-number statistics do not allow us firmly to assess that the proposed groups belong to two distinct offset distributions, a Kolmogorov–Smirnov test, run on the current sample of bursts, excludes at the 2σ confidence level that they are drawn from the same distribution. Furthermore, we point out that the two groups are characterized by very different observational features, which are hard to explain if they originate from the same parent population.

The two groups (extended duration/small offset, short duration/large offset) have similar redshift distributions (see Table 1, column 3). Accepting the usual arguments that the short-duration/large-offset group are probably neutron star–neutron star (NS–NS) mergers, we then have four a priori possibilities for explaining the extended-duration/small-offset group. These are: a different class of NS–NS mergers, NS–massive white dwarf (WD) mergers, collapsars, and neutron star–black hole (NS–BH) mergers. We consider these in turn.

4.1 A different class of NS–NS mergers

The obvious possibility here is ultracompact NS–NS binaries, which for suitable binary kick velocities $v_{\rm kick} \sim 100$ km s^{-1} can produce rather small offsets from certain types of host (cf. Belczynski et al. 2006, fig. 3). The problem here is that the initial (pre-afterglow) NS–NS merger process should be exactly the same as for NS–NS binaries starting from wider separations. Yet the small-offset group have rather distinct features (e.g. a prompt extended tail of emission, a higher energetic budget) which cannot result from environmental effects.

4.2 NS–massive WD mergers

This group has the desirable properties (King, Olsson & Davies 2007) of extended duration and no SNe, but is likely to have similar merger times and kicks to the standard NS–NS group. It therefore cannot explain the small offsets.

4.3 Collapsars

Collapsars offer a simple explanation of the small offsets, but have other problems. In particular one would have change the model (e. g. Fryer, Hungerford & Young 2007) to explain both the very different light curves and the lack of SNe in the extended-duration/small-offset group. Moreover, at least one observed member of this group is hosted by an elliptical galaxy (GRB 050724; Berger et al. 2005; Malesani et al. 2007), which is hard to reconcile with a collapsar origin.

4.4 NS–BH mergers

Low offsets are expected for NS–BH mergers on two quite general grounds. First, there is mounting observational evidence that at least some black holes do not receive natal kicks. Mirabel & Rodrigues (2003) show that the 10-$M_{\odot}$ BH binary Cyg X-1 has a peculiar velocity of <10 km s^{-1}, and Dhawan et al. (2007) show that the kick in the BH binary GRS 1915+105 was probably similarly small. These may therefore be examples of direct collapse to a black hole (Fryer & Kalogera 2001). (Direct collapse to a neutron star is not possible, as this has far lower entropy than its progenitor, unlike a black hole.) Secondly, the gravitational radiation merger times $t_{\rm GR}$ for NS–BH and NS–NS binaries of a given initial separation scale as $\sim(M_{\rm BH}/M_{\rm NS})^{-2} \sim 0.01$ for typical masses $M_{\rm BH} = 14\,{\rm M}_{\odot}$, $M_{\rm NS} = 1.4\,{\rm M}_{\odot}$. Together these two effects show that some NS–BH binaries would move very little before merging to produce a short GRB.

The advantage of the latter explanation of the low offsets is of course that it offers natural interpretations of the peculiar features of the group of SHBs with extended emission. Rosswog (2007) proposed that if a significant fraction of the shredded NS is not immediately accreted, but remains in bound orbits around the central object, the fallback accretion of the NS remnants can inject power up to late times ($\lesssim$1 d after the burst). The derived theoretical light curves (fig. 3 of Rosswog 2007) show that NS–BH binaries are able to produce much higher luminosities and longer durations than NS–NS mergers.

Fig. 1 shows a further surprise, in the form of its empty bottom-left corner. Models of standard NS–NS mergers predict that an appreciable fraction of such binaries are ejected far from the host, but most remain bound to it. Thus 80–90 per cent merge within 30 kpc according to Bloom et al. (1999). These bursts should have populated the empty short-duration/small-offset region in Fig. 1. We note that five other very short bursts (GRB 050906, 050925, 051105A, 070209 and 070810B, $T_{90} \lesssim 0.1$ s) lack an X-ray counterpart, despite very prompt *Swift*/XRT follow-up observations (79, 92, 68, 78 and 62 s after the bursts, respectively). We speculate that the expected low density of the intergalactic environment may explain the faint X-ray afterglows, placing these X-ray dark bursts in the upper-left side of Fig. 1. However, other mechanisms, related to the microphysics of the shocks and the initial Lorentz factor, could suppress the early X-ray emission (see Nakar 2007). Also, a magnetar origin, as debated for GRB 050906 (Levan et al. 2008) and GRB 050925, might explain the lack of detection.

5 CONCLUSIONS

The offset distribution of SHBs displays several interesting features suggesting two types of progenitor. Most strikingly we found that SHBs with extended soft emission ($T_{90} \sim 100$ s) tend to remain close to their host galaxies. NS–BH mergers naturally account for these properties, although other explanations are still possible. SHBs with large offsets have properties consistent with NS–NS mergers occurring in low-density environments.

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