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 NS–BH 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 NS–NS binary mergers occurring in low density environments.

Key words: gamma rays: bursts; stars: neutron.

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 SHBs. The ability to react rapidly to GRBs triggers led to the first detection of a SHB X-ray afterglow (GRB 050509; Gehrels et al. 2005), and, a few months later, to the detection of the first SHB optical counterpart (GRB 050709; Fox et al. 2003; 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 galaxy’s redshift measurement. 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 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 et al. 2002; Fruchter et al. 2004) are well known. For instance, only a few important cases show an observed GRB/supernova (SN) connection (e.g. GRB 060218/SN2006aj; 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. 2002; 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 November 2004, Swift has detected 25 GRBs classified as SHBs up to August 2007. In a significant fraction of them (∼25%) the initial short hard γ-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 SHBs class: a first short-hard event with zero spectral lag (Nottis & 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); 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 (∼70%) there is an X-ray counterpart, and in 7 cases (∼28%) 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 sub-arcsecond 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, focussing...
Table 1. SHBs sample properties.

| GRB       | T<sub>90</sub> (s) | z | Putative host magnitude | Afterglow angular offset arcsec | Projected offset kpc |Refs. |
|-----------|------------------|---|------------------------|-------------------------------|---------------------|-----|
| 050509B...| 0.03 [0.01]      | 0.225 | 16.8 | 5.0×10<sup>-3</sup> | 17.87 | 3.40 | 64| 12 | 1–3 |
| 050709....| 130 [7]<sup>a</sup> | 0.161 | 21.2 | 2.0×10<sup>-3</sup> | 1.30 | 0.10 | 3.57 | 0.27 | 4–6 |
| 050724....| 152 [9]          | 0.258 | 19.8 | 1.0×10<sup>-5</sup> | 0.64 | 0.02 | 2.57 | 0.08 | 7–9 |
| 051210....| 1.4 [0.2]        | >1.4 | 23.8 | 1.0×10<sup>-1</sup> | 2.80 | 2.90 | <50 | – | 3, 10, 11 |
| 051221A...| 1.27 [0.05]      | 0.546 | 22.0 | 2.4×10<sup>-4</sup> | 0.12 | 0.04 | 0.76 | 0.25 | 12, 13 |
| 051227....| 110 [10]         | – | 25.6 | 2.0×10<sup>-4</sup> | 0.05 | 0.02 | <0.7 | – | 11, 14 |
| 060121....| 1.97 [0.06]<sup>b</sup> | >1.7 | 26.6 | 1.3×10<sup>-2</sup> | 0.32 | 0.10 | <4 | – | 15–17 |
| 060313....| 0.7 [0.1]        | <1.1 | 25.0 | 4.0×10<sup>-3</sup> | 0.40 | 0.56 | <8 | – | 11, 18 |
| 060502B...| 0.09 [0.02]      | 0.287<sup>c</sup> | 18.7 | <5.0×10<sup>-2</sup> | 16.33 | 3.70 | 70 | 16 | 3, 19 |
| 060505....| 4 [1]            | 0.089 | 17.9 | 1.0×10<sup>-4</sup> | 0.45 | 0.32 | 7.45 | 0.53 | 20, 21 |
| 060614....| 103 [5]          | 0.125 | 22.5 | 6.0×10<sup>-6</sup> | 0.50 | – | 1.10 | – | 22–24 |
| 060801....| 0.5 [0.1]        | 1.131 | 23.0 | 4.1×10<sup>-2</sup> | 2.39 | 2.40 | 19.7 | 19.8 | 3, 11 |
| 061006....| 130 [10]        | 0.438 | 23.7 | 1.8×10<sup>-3</sup> | 0.32 | 0.50 | 1.8 | 2.8 | 11, 26 |
| 061201....| 0.8 [0.1]        | 0.111 | 19.0 | 3.8×10<sup>-2</sup> | 17.00 | 0.20 | 33.9 | 0.4 | 27 |
| 061210....| 85 [5]          | 0.410 | 21.1 | 4.7×10<sup>-3</sup> | 1.99 | 1.80 | 10.7 | 9.7 | 3, 11, 28 |
| 061217....| 0.30 [0.05]      | 0.827 | 23.4 | 3.9×10<sup>-1</sup> | 7.41 | 3.80 | 55 | 28 | 3, 11, 29 |
| 070724A...| 0.40 [0.04]      | 0.457 | ~21<sup>d</sup> | ~5×10<sup>-3</sup> | 0.72 | 2.10 | 4 | 12 | 3, 30 |

Notes: Col. (1): GRB name; Col. (2): T<sub>90</sub> duration and its error in the 15-350 keV energy band; Col. (3): Redshift of the putative host galaxy; Col. (4): Observed R magnitude of the putative host galaxy; Col. (5): Probability that the association is a chance of coincidence; Col. (6): Detection of the GRB counterpart in different energy band (X - X-ray; O - optical; R - radio); Col. (7)-(8): Angular offset between the afterglow position and the associated galaxy centroid, and its error, respectively; Col. (9) and (10): Projected physical offset and its error, respectively; Col. (11): Reference to publications of the presented data.

Refs.: (1) Gehrels et al. 2002; (2) Bloom et al. 2006; (3) Butler 2007; (4) Hjorth et al. 2003; (5) Fox et al. 2005; (6) Villasenor et al. 2003; (7) Campana et al. 2006; (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. 2006; (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) O’Leary et al. 2007; (21) Levesque & Kewley 2007; (22) Gal-Yam et al. 2004; (23) Gehrels et al. 2006; (24) Mangano et al. 2007; (25) Sato et al. 2006; (26) Malesani et al. 2007; (27) Marshall et al. 2004; (28) Cannizzo et al. 2008; (29) Ziaeepour et al. 2008; (30) Ziaeepour et al. 2007.

Notes:

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 4.5σ.

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<sub>chance</sub>~70%), corresponding to 34±30 kpc at z~1.

d We assume R–I<1

2 SAMPLE

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

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

Table lists the properties of our sample of bursts and their putative hosts. In each case we give the probability, P<sub>chance</sub>, that the proposed association is a chance coincidence (col. 5). If no value is given in the literature, we simply estimated it as the probability that a galaxy of magnitude R&lt;R<sub>K</sub>host is randomly placed within a certain radius from the GRB centroid position, without regard to the galaxy type or on their spatial distribution with respect to their putative hosts. We also estimate the prompt γ-ray and X-ray afterglow energetics of the available sample. The paper is organized as follows: in § 2 we briefly describe the adopted selection criteria and the general properties of the sample; our results are reported in § 3. We discuss our findings and their implication for SHBs progenitors in § 4. A summary of our conclusions is given in § 5. Throughout the paper we have adopted a standard cosmology with Hubble constant H<sub>0</sub>=71 km s<sup>-1</sup> Mpc<sup>-1</sup> and parameters Ω<sub>Λ</sub> = 0.73, Ω<sub>M</sub> = 0.27 (Spergel et al. 2007).
Figure 1. Left 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 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 ($\sim1.3$ 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 panel. Two main features emerge from the plot: 1) bursts with prompt emission extending up to $\sim100-200$ 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 the X-ray energies are calculated in the 15–150 keV and the 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 Tab. 1).

The $\gamma$-ray energy radiated during the short hard spike and over the total $T_{90}$ are reported in the top panel and in the middle panel 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 fit lightcurve 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 GRB 051210, the X-ray afterglow was below the detection limit in this temporal range. To estimate their energetics we assumed temporal slope $\alpha\sim1$ and spectral index $\beta\sim-1$ ($F_\nu \propto \nu^{-\alpha} t^{-\beta}$). 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.

Even given the small number of SHBs detected so far, it is clear that large offset bursts (GRB 050509B,
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 duration have a mean offset a factor of 15 larger. Though the low statistic does not allow us to firmly 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 $2\sigma$ 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 Tab 1 col. 2). Accepting the usual arguments that the short duration/large offset group are probably 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 WD mergers, collapsars, and 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 $v_{\text{kick}} \sim 100$ 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 et al. 2007) of extended duration and no supernovae, but is likely to have similar merger times and kicks as 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 et al. 2007) to explain both the very different light curves and the lack of supernovae 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 & Rodríguez (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.) Second, the gravitational radiation merger times $t_{\text{GR}}$ for BH–NS and NS–NS binaries of a given initial separation scale as $\sim (M_{\text{BH}}/M_{\text{NS}})^{-2} \sim 0.01$ for typical masses $M_{\text{BH}} = 14$ M$\odot$, $M_{\text{NS}} = 1.4$ M$\odot$. Together these two effects show that some BH–NS 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.
Figure 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% merge within 30 kpc according to Bloom et al. 1999. These bursts should have populated the empty short duration/small offsets region in Fig. 1. We note that five other very short bursts (GRB 050906, GRB 050925, GRB 051105A, GRB 070209, GRB 070810B, T ∼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.

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 (T90 ∼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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REFERENCES

Belczynski, K., Perna, R., Bulik, T., Kalogera, V., Ivanova, N., & Lamb, D. Q. 2006, ApJ, 648, 1110
Berger, E., et al. 2007, ApJ, 664, 1000
Berger, E., et al. 2005, Nature, 438, 988
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bloom, J. S., et al. 2007, ApJ, 654, 878
Bloom, J. S., et al. 2006, ApJ, 638, 354
Bloom, J. S., Sigurdsson, S., & Pols, O. R. 1999, MNRAS, 305, 763
Burrows, D. N., et al. 2006, ApJ, 653, 468
Butler, N. R. 2007, AJ, 133, 1027
Campana, S., et al. 2006a, Nature, 442, 1008
Campana, S., et al. 2006b, A&A, 454, 113
Cannizzo, J. K., et al. 2006, GCNR, 20, 1
Covino, S., et al. 2006, A&A, 447, L5
de Ugarte Postigo, A., et al. 2006, ApJ, 648, L83
Dhawan, V., Mirabel, I. F., Ribó, M., & Rodrigues, I. 2007, ApJ, 668, 430
Donaghy, T. Q., et al. 2006, arXiv: astro-ph/0605570
Fox, D. B., et al. 2005, Nature, 437, 845
Fruchter, A. S., et al. 2006, Nature, 441, 463
Fryer, C. L., Hungerford, A. L., & Young, P. A. 2007, ApJ, 662, L55
Fryer, C. L. & Kalogera, V. 2001, ApJ, 554, 548
Fynbo, J. P. U., et al. 2006, Nature, 444, 1047
Gal-Yam, A., et al. 2006, Nature, 444, 1053
Gehrels, N., et al. 2004, ApJ, 611, 1005
Gehrels, N., et al. 2006, Nature, 444, 1044
Gehrels, N., et al. 2005, Nature, 437, 851
Gotz, D., Beckmann, V., Mereghetti, S., & Paizis, A. 2007, GRB Coordinate Network, 6608
Hjorth, J., et al. 2005, Nature, 437, 859
Hogg, D. W., Pahre, M. A., McCarthy, J. K., Cohen, J. G., Blundell, R., Smail, I., & Soifer, B. T. 1997, MNRAS, 288, 404
Huang, J.-S., et al. 2001, A&A, 368, 787
King, A., Olsson, E., & Davies, M. B. 2007, MNRAS, 374, L34
Kouveliotou, C., Meegan, C. A., Fishman, G. J., Bhat, N. P., Briggs, M. S., Koshut, T. M., Paciesas, W. S., & Pendleton, G. N. 1993, ApJ, 413, L101
La Parola, V., et al. 2006, A&A, 454, 753
Lee, W. H. & Ramirez-Ruiz, E. 2007, New Journal of Physics, 9, 17
Levan, A. J., et al. 2006, ApJ, 648, L9
Levan, A. J., et al. 2007, MNRAS, accepted, arXiv: astro-ph/0705.1705
Levesque, E. M. & Kewley, L. J. 2007, ApJ, 667, L121
Malesani, D., et al. 2007, A&A, 473, 77
Malesani, D., Stella, L., D’Avanzo, P., Covino, S., Jehin, E., Lidman, C., Naef, D., & Schady, P. 2006, GRB Coordinates Network, 5718
Mangano, V., et al. 2007, A&A, 470, 105
Marshall, F., Perri, M., Stratta, G., Barthelmy, S. D., Krimm, H., Burrows, D. N., Roming, P., & Gehrels, N. 2006, GCNR, 18, 1
Mirabel, I. F. & Rodrigues, I. 2003, Science, 300, 1119
Nakar, E. 2007, Phys. Rep., 442, 166
Norris, J. P. & Bonnell, J. T. 2006, ApJ, 643, 266
Ofek, E. O., et al. 2007, ApJ, 662, 1129
Pian, E., et al. 2006, Nature, 442, 1011
Prochaska, J. X., et al. 2006, ApJ, 642, 989
Roming, P. W. A., et al. 2006, ApJ, 651, 985
Rosswog, S. 2007, MNRAS, 376, L48
Sakamoto, T., et al. 2007, arXiv e-prints, 707
Sato, G., et al. 2006, GRB Coordinates Network, 5381
Soderberg, A. M., et al. 2006, ApJ, 650, 261
Spergel, D. N., et al. 2007, ApJS, 170, 377
Villasenor, J. S., et al. 2005, Nature, 437, 855
Wang, C., Lai, D., & Han, J. L. 2006, ApJ, 639, 1007
Woosley, S. E. 1993, ApJ, 405, 273
Ziaeepour, H., et al. 2006, GCNR, 21, 2

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Ziaeepour, H., Barthelmy, S. D., Parsons, A., Page, K. L.,
De Pasquale, M., & Schady, P. 2007, GCNR, 74, 2