PHILOSOPHICAL
TRANSACTIONS
OF
THE ROYAL
SOCIETY A

Phil. Trans. R. Soc. A (2007) **365**, 1293–1305
doi:10.1098/rsta.2006.1974

Observations of short gamma-ray bursts

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We review recent observations of short-hard gamma-ray bursts and their afterglows. The launch and successful ongoing operations of the Swift satellite, along with several localizations from the *High-Energy Transient Explorer* mission, have provoked a revolution in short-burst studies: first, by quickly providing high-quality positions to observers; and second, via rapid and sustained observations from the Swift satellite itself. We make a complete accounting of Swift-era short-burst localizations and proposed host galaxies, and discuss the implications of these observations for the distances, energetics and environments of short bursts, and the nature of their progenitors. We then review the physical modelling of short-burst afterglows: while the simplest afterglow models are inadequate to explain the observations, there have been several notable successes. Finally, we address the case of an unusual burst that threatens to upset the simple picture in which long bursts are due to the deaths of massive stars, and short bursts to compact-object merger events.

Keywords: gamma rays: bursts; gamma rays: observations; gravitational waves

1. Introduction

The discovery in 2005 of the first afterglows of short-hard gamma-ray bursts has triggered a long-promised revolution in our understanding of these events. With X-ray (Barthelmy *et al.* 2005*b*; Fox *et al.* 2005*a*; Gehrels *et al.* 2005; Burrows *et al.* 2006), optical (Berger *et al.* 2005; Fox *et al.* 2005*a*; Hjorth *et al.* 2005*b*; Soderberg *et al.* 2006) and radio (Berger *et al.* 2005; Soderberg *et al.* 2006) afterglows of multiple short bursts in-hand, their distance scale ($z \gtrsim 0.1$) and energetics ($E_\gamma \gtrsim 10^{48}$ erg) are now established, and they have been revealed definitively as a cosmological phenomenon.

The presence of short bursts among old stellar populations—in elliptical galaxies (Barthelmy *et al.* 2005*b*; Berger *et al.* 2005), galaxy clusters (Gehrels *et al.* 2005; Bloom *et al.* 2006; Gal-Yam *et al.* 2006) and the outskirts of younger galaxies (Fox *et al.* 2005*a*; Soderberg *et al.* 2006)—along with the absence of associated supernovae to deep limits (Fox *et al.* 2005*a*; Hjorth *et al.* 2005*a*; Soderberg *et al.* 2006; Kulkarni *et al.* submitted) appear to rule out an origin in the deaths of massive stars. This offers a strong contrast to the long-duration gamma-ray bursts (GRBs), whose host galaxies and offsets (Bloom *et al.* 2002), redshifts and associated supernovae (Galama *et al.* 1998; Kulkarni *et al.* 1998; Hjorth *et al.* 2003; Stanek *et al.* 2003) are all consistent with the collapsar-supernova model.

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One contribution of 35 to a Discussion Meeting Issue ‘Gamma-ray bursts’.

The effect of this rapid series of discoveries has been to strongly favour the compact-object merger model for short bursts. In each respect, properties of the bursts that are inconsistent with massive star models conform to theoretical expectations for the coalescence of a compact-object binary, either neutron star–neutron star or neutron star–black hole (Eichler *et al.* 1989; Narayan *et al.* 1992). As a result, the prospects for gravitational-wave detection of these events can now be estimated from the basis of short-burst properties (Belczynski *et al.* 2006; Guetta & Piran 2006; Nakar *et al.* 2006), either with or without reference to population-synthesis models.

In this article, we review short-burst prompt, afterglow and host galaxy observations of the Swift era. We begin with a tabulation of short-burst localizations and host galaxy identifications that have been derived since the launch of the Swift mission (§2). Next, we discuss the implications of these findings for the likely progenitor lifetimes and local rate of short bursts (§3). We then review the state of short-burst afterglow models, including necessary deviations from the simplest fireball models (§4), and conclude with a brief discussion of the recent burst GRB 060614 (§5), which challenges the standard picture in which long bursts result from collapsar-supernovae, and short bursts from compact-object merger events.

2. Localizations and host galaxies

Table 1 presents the prompt emission properties of all well-localized short bursts and short-burst candidates of the Swift era, along with information on the type of afterglow detections that were secured.

In order to make an assessment of whether each burst is likely to be associated with the distinct short-hard or long-soft burst populations identified by the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma-Ray Observatory* (Kouveliotou *et al.* 1993), we fit the distribution of durations (T_{90} values) and hardness ratios ($H_{32}=S(100-300\ \text{keV})/S(50\text{–}100\ \text{keV})$ for 1179 bursts from the BATSE catalogue (http://www.batse.msfc.nasa.gov/batse/grb/catalog/current/); i.e. those with good measurements for both quantities) with two bivariate lognormal functions, using maximum-likelihood methods. We find that this functional form provides a satisfactory reproduction of the distribution (figure 1); a typical fit has the short-burst distribution (with 319 bursts in the population) centred at $\log T_{90}=-0.36$, $\log H_{32}=0.75$, with widths of $(\sigma_1, \sigma_2)=(0.51, 0.26)$ along two orthogonal axes that make an angle of 3° with the T_{90} and H_{32} axes; and a long burst distribution (with 860 members of the population) centred at $\log T_{90}=1.46$, $\log H_{32}=0.40$, with widths of $(\sigma_1, \sigma_2)=(0.50, 0.24)$ along orthogonal axes making an angle of 5° with the T_{90} and H_{32} axes. Contours of this model distribution are shown in figure 1.

We then calculate the odds for any observed burst to belong to the BATSE-delineated short-burst distribution, by comparing the values of the two model distributions at the point defined by the particular duration and hardness ratio of that burst (table 1). The tabulated durations and spectral fits (from which we calculate fluences and hardness ratios) thus determine the 'odds of shortness' for each burst. The uncertainty range is determined by bootstrap Monte Carlo methods—resampling the BATSE catalogue, refitting our model distribution function and calculating odds for each candidate short burst on each iteration.

Table 1. Short-burst localizations in the Swift era. Sat, detecting satellite; S, Swift; H, HETE; K, Konus–Wind; λ_A, afterglow detections; X, X-ray; O, UV/optical/IR; R, radio; α_{J2000}, right ascension; δ_{J2000}, declination of burst or afterglow; Δ, coordinate uncertainty (radial, 90% confidence); T_{90}, time-interval containing 90% of counts above background; Γ, power-law photon index of the time-averaged spectrum (some bursts have exponential cut-off spectra, see notes); Lag, temporal lag measured between the indicated bands: 31 (50-100 keV: 15-25 keV), 42 (100-350 keV: 25-50 keV), or 56 (80-400 keV: 40-80 keV); SE, presence (S) or absence (N) of extended soft emission; log (odds), logarithm of the odds that the burst is 'short' (see text for details).

GRB name	Sat	λ_A	α_{J2000}	δ_{J2000}	Δ	T_{90} (s)	Γ	Lag (ms)	SE	log (odds)
050202	S	—	19:22:18.00	−38:44:06.0	$4'$	0.080	1.4 (3)	—	—	5.0 (5)
050509B	S	X	12:36:13.68	+28:58:57.0	$3''.6$	0.040 (4)	1.5 (4)	1, 8 [31]	N	5.9 (6)
050709^{a}	H	XO	23:01:26.96	−38:58:39.3	$0''.3$	0.070 (10)	0.82 (14)	−2.0, 2.5 [56]	S	3.9 (6)
050724^{b}	S	XOR	16:24:44.37	−27:32:27.5	$0''.2$	0.25 (5)	1.71 (16)	−11,4 [31]	S	2.8 (3)
050813	S	X	16:07:57.12	+11:14:52.8	$10''$	0.6 (1)	1.19 (33)	−21, 4 [42]	N	2.2 (3)
050906^{c}	S	—	03:31:21.84	−14:39:07.2	$2'.6$	0.128 (16)	1.91 (42)	—	N	3.6 (4)
050911^{d}	S	—	00:54:52.32	−38:51:43.2	$2'.8$	1.0 (2)	1.90 (33)	∼0 [31]	N	0.5 (3)
050925^{e}	S	—	20:13:54.24	+34:19:55.2	$1'.5$	0.068 (27)	1.74 (17)	2, 15 [31]	N	4.8 (5)
051105A	S	—	17:41:06.48	+34:56:56.4	$2'.5$	0.028 (4)	1.33 (35)	1, 12 [31]	N	6.7 (7)
051114	S	—	15:05:03.84	+60:09:21.6	$2'$	2.2 (3)	1.22 (27)	—	—	0.2 (3)
051210	S	X	22:00:41.28	−57:36:46.8	$4''.2$	1.27 (5)	1.1 (3)	−27, 19 [42]	N	1.1 (2)
051211^{f}	H	—	06:56:12.96	+32:40:44.4	$1''.3$	4.2 (6)	0.07 (50)	−25, 21 [56]	S	−1.7 (4)
051221A	S	XOR	21:54:48.63	+16:53:27.4	$0''.2$	1.4 (2)	1.39 (6)	−0.4, 0.4 [31]	N	0.6 (3)
051227^{g}	S, H	XO	08:20:58.11	+31:55:31.9	$0''.2$	4.0 (2)	1.31 (22)	−8, 12 [42]	S	−1.8 (4)
060121^{h}	H	XO	09:09:52.03	+45:39:46.1	$0''.5$	1.97 (6)	0.79 (12)	−12, 31 [56]	S	−0.7 (4)
060313^{i}	S, K	XO	04:26:28.44	−10:50:39.1	$0''.6$	0.7 (1)	0.61 (10)	−0.4, 1.0 [42]	S	2.8 (3)
060502B	S	X	18:35:45.84	+52:37:51.6	$4''.4$	0.090 (20)	0.92 (23)	−2.6, 3.0 [31]	N	5.5 (5)

(*Continued.*)

Table 1. (*Continued.*)

GRB name	Sat	λ_A	α_{J2000}	δ_{J2000}	Δ	T_{90} (s)	Γ	Lag (ms)	SE	log (odds)
060505	S	XO	22:07:03.44	−27:48:51.6	$0''.5$	4 (1)	1.3 (3)	—	—	−0.8 (3)
060801	S	X	14:12:01.68	+16:58:55.2	$3''.7$	0.5 (1)	0.47 (24)	−16, 0 [42]	N	3.5 (3)
061006[j]	S, K	XO	07:24:07.66	−79:11:55.1	$0''.5$	0.5 (1)	0.62 (21)	—	S	2.9 (3)

[a] HETE exponential cut-off spectrum, $\Gamma = 0.82 \pm 0.14$, $E_p = 86.5^{+16}_{-11}$ keV. [b] Soft emission contributes to the BAT burst duration of $T_{90} = 3.0$ s, while the evolving spectrum of the burst suggests a BATSE-equivalent duration of $T_{90} = 0.25$ s. [c] A possible X-ray afterglow detection was reported for this burst. [d] Soft emission contributes to the BAT burst duration of $T_{90} = 16$ s, while the evolving spectrum of the burst suggests a BATSE-equivalent duration of $T_{90} < 1.0$ s; also, the lag is reported to be consistent with zero, but without being specified. [e] Possible SGR event, located in plane of the Milky Way. [f] HETE exponential cut-off spectrum, $\Gamma = 0.07^{+0.50}_{-0.41}$, $E_p = 121^{+33}_{-20}$ keV. [g] Soft emission contributes to the BAT burst duration of $T_{90} = 8.0$ s, with $T_{90} < 4.0$ s at higher energies; also, HETE+BAT exponential cut-off spectrum, $\Gamma = 1.3 \pm 0.4$ and $E_p = 100^{+219}_{-41}$ keV. [h] HETE exponential cut-off spectrum, $\Gamma = 0.79 \pm 0.12$, $E_p = 114^{+14}_{-11}$ keV. [i] BAT+Konus–Wind exponential cut-off spectrum, $\Gamma = 0.61 \pm 0.10$, $E_p = 947^{+224}_{-173}$. [j] BAT observed the $T_{90} = 130 \pm 10$ s soft component of this burst; tabulated duration and spectral parameters are from Konus–Wind; exponential cut-off spectrum, $\Gamma = 0.62^{+0.18}_{-0.21}$ and $E_p = 664^{+227}_{-144}$. References: 050202 (Sakamoto *et al.* 2005*b*), 050509B (Gehrels *et al.* 2005; Bloom *et al.* 2006; Norris & Bonnell 2006), 050709 (Fox *et al.* 2005*a*; Hjorth *et al.* 2005*b*; Villasenor *et al.* 2005), 050724 (Barthelmy *et al.* 2005*b*; Berger *et al.* 2005; Norris & Bonnell 2006), 050813 (Morris *et al.* 2005; Norris & Bonnell 2006; Sato *et al.* 2005), 050906 (Parsons *et al.* 2005; Fox *et al.* 2005*b*), 050911 (Page *et al.* 2006), 050925 (Markwardt *et al.* 2005; Norris & Bonnell 2006), 051105A (Barbier *et al.* 2005; Norris & Bonnell 2006), 051114 (Sakamoto *et al.* 2005*c*), 051210 (La Parola *et al.* 2006; Norris & Bonnell 2006), 051211 (Donaghy *et al.* submitted; Kawai *et al.* 2005; Norris & Bonnell 2006), 051221A (Norris *et al.* 2005; Soderberg *et al.* 2006; Burrows *et al.* in press), 051227 (Barthelmy *et al.* 2005*a*; Hullinger *et al.* 2005; Sakamoto *et al.* 2005*d*), 060121 (Donaghy *et al.* submitted; de Ugarte Postigo *et al.* 2006), 060313 (Roming *et al.* 2006), 060502B (Sato *et al.* 2006*a*), 060505 (Hullinger *et al.* 2006; Ofek *et al.* 2006), 060801 (Sato *et al.* 2006*b*), 061006 (Golenetskii *et al.* 2006; Malesani *et al.* 2006; Schady *et al.* 2006).

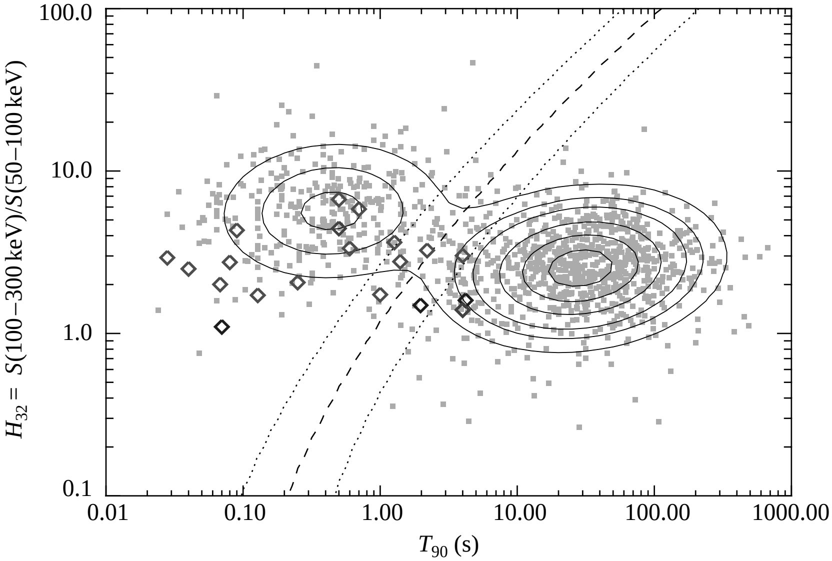

Figure 1. Prompt emission properties of 20 Swift-era short bursts (diamonds) in the context of the BATSE population (grey squares) and corresponding population models (contours). Burst durations (T_{90}) and hardness ratios (H_{32}) for the Swift-era bursts are drawn from table 1; BATSE burst properties are from the current catalogue. Solid contours outline the two bivariate lognormal distributions for one of our model fits. The dashed line traces the locus for bursts with even odds of being drawn from either population in this model, and dotted lines trace the loci for bursts with 10 : 1 odds of being drawn from one population (short bursts, on the left) or the other (long bursts, on the right).

This approach does not address known selection effects associated with the BATSE observations (Sakamoto *et al.* 2005*a*); however, to the extent that such effects act within the duration–hardness plane we do not expect them to selectively enrich the long- or short-burst populations in any particular region; our calculated odds will not be affected. We avoid including additional pieces of information in our analysis, for example, lag measurements and properties of the afterglow or proposed host galaxies (cf. Donaghy *et al.* submitted), in order to maintain as much as possible the original definition of the two populations. This should also help us to avoid prejudicing comparative studies of the long- and short-burst populations, as in the case of GRB 060614 (§5).

Figure 1 shows the 20 short bursts from table 1 in the context of the full BATSE population. The distribution of Swift-era short bursts is concentrated at lower hardness ratios than the BATSE sample due to the lower-energy nature of the detectors in use. Several bursts from HETE and Swift, discussed as possible or probable short bursts in the literature, are seen to have low ‘odds of shortness’ according to our analysis, being below even odds in several cases and less than 1 : 10 in two (GRBs 051211 and 051227). Analyses of the short-burst population as a whole should be wary of these likely long or borderline-long events, and consider whether their conclusions are robust to the exclusion of these bursts from the sample.

Table 2 presents the properties of proposed candidate host galaxies for short bursts in table 1 with known or constrained redshifts. Without direct afterglow spectroscopy, association of these short bursts with candidate host galaxies and

Table 2. Short-burst host properties. z, redshift; host type, E (early), L (late) or C (cluster); m_{host}, host galaxy apparent magnitude; L_{host}, host luminosity; $\mathrm{SFR}_{\mathrm{host}}$, host star formation rate; offset, offset from centre of host galaxy; p_{assoc}, chance probability of association (single trial).

GRB name	z	host type	m_{host} (mag)	L_{host} (L^*)	$\mathrm{SFR}_{\mathrm{host}}$ ($M_{\odot}\mathrm{yr}^{-1}$)	offset (kpc)	p_{assoc}
050509B	0.2248	EC	$K\approx 14.1$	1.5	<0.1	44^{+12}_{-23}	10^{-3}
050709	0.1606	L	$V=21.35$ (7)	0.10	0.2	3.8	$<10^{-3}$
			$I=20.63$ (8)				
050724	0.258	E	$R=19.58$ (3)	1.6	<0.03	2.6	$<10^{-3}$
			$K\approx 15.3$				
050813	0.722	E	$K\approx 19$	0.5	—	~ 50	—
	1.8[a]	C	—	—	—	—	—
050906	0.0308	L	$K\approx 11.5$	1	—	—	10^{-3}
050911	0.165	C	$K=13.5$ (1)	3	—	—	$\lesssim 0.01$
051221A	0.5458	E	$R=21.99$ (9)	0.3	1.6 (4)	0.76 (3)	$<10^{-3}$
			$z=22.0$ (4)				
051227	>0.7	—	$R=25.5$ (2)	—	—	—	—
060121	4.6	L	$R=26.3$ (3)	—	—	2.0 (6)	0.01
	1.7[b]					2.6 (9)	
060313	<1.1[c]	—	$r>22$	—	—	—	—
060502B	0.287	E	$R=18.71$ (1)	1.6	~ 0.8	73 (20)	0.03
			$K=15.23$ (5)				
	—	—	$R=25.83$ (5)[d]	—	—	—	—
060505	0.0894	L	$B\approx 19.6$	3.6	~ 1	7.1	$<10^{-3}$
060801	1.131	L	$R=23.0$ (1)	1	—	—	—

[a] Two or three candidate host galaxies lie at $z=0.7$, and the candidate host cluster is at $z=1.8$ (photometric redshift). [b] $z=1.7$ is less probable than $z=4.6$ for this burst. [c] $z=0.75$ is the most likely redshift. [d] Alternate host identification for this event does not have a measured redshift, but is likely at $z\approx 1$. References: 050509B (Fox *et al.* 2005*a*; Gehrels *et al.* 2005; Pedersen *et al.* 2005; Bloom *et al.* 2006), 050709 (Fox *et al.* 2005*a*; Hjorth *et al.* 2005*b*; Covino *et al.* 2006;), 050724 (Barthelmy *et al.* 2005*b*; Berger *et al.* 2005; Fox *et al.* 2005*a*; Gorosabel *et al.* 2006), 050813 (Berger 2005*a*; Fox *et al.* 2005*a*; Gladders *et al.* 2005; Prochaska *et al.* 2006), 050906 (Levan & Tanvir 2005; Parsons *et al.* 2005), 050911 (Berger 2005*b*; Page *et al.* 2006; Berger *et al.* submitted *b*), 051221A (Soderberg *et al.* 2006), 051227 (Berger & Soderberg 2005), 060121 (de Ugarte Postigo *et al.* 2006; Levan *et al.* 2006), 060313 (Roming *et al.* 2006), 060502B (Berger *et al.* submitted *a*; Bloom *et al.* in press), 060505 (Ofek *et al.* 2006; Fynbo *et al.* 2006), 060801 (Cucchiara *et al.* 2006; Piranomonte *et al.* 2006; Berger *et al.* submitted *a*).

host galaxy clusters must be approached probabilistically. In cases where a well-localized afterglow falls on a luminous region of the candidate host, or within a high-mass (or high redshift) cluster, the association can probably be considered secure; however, in other cases, an *a posteriori* estimate of the probability of association must be made. Such estimates are known to be strongly dependent on input assumptions. For example: What lifetime and kick velocity distributions might be appropriate for progenitor binary systems? What about other possible progenitor classes? One must be careful not to fall into circular reasoning, wherein the initial assumptions regarding these questions suggest an association, which is then used as evidence in favour of the assumptions. With that caveat, we present probabilities of association for candidate hosts where these are available.

The recent identification of a class of short bursts associated with faint galaxies at $z \gtrsim 1$ (Berger *et al.* submitted *a*) confirms that the identification of short-burst host galaxies, and the collection of their redshifts, will be an observational challenge. Indeed, unless the short bursts are similar to the long bursts in always occurring within or near their host galaxies, the routine association of every well-localized burst with its nearest galaxy—whether at low redshift or $z \gtrsim 1$—is certain to lead to some erroneous associations. Further analysis of the short bursts as a population should therefore strive to be robust to a modest rate of such errors.

3. Rates and lifetimes

The measurement of redshifts and luminosities for short bursts has enabled the first estimates of the progenitor lifetimes and local rate of these events. Given the consistency of short-burst prompt emission and afterglow properties with the compact-object merger model, these estimates are expected to translate directly into event rates for ground-based gravitational-wave detectors, including the Laser Interferometer Gravitational-Wave Observatory (LIGO). These detectors are now coming online, with the current LIGO science run (begun in December 2005) being the first to achieve that facility's design sensitivity.

Previous estimates of the lifetimes and local rates of compact-object merger events have been derived from population-synthesis models, which are primarily constrained by the observed properties of relativistic pulsar-compact-object binaries within the Milky Way (e.g. Kalogera *et al.* 2004). These observations suggest that binary lifetimes are distributed as $p(\tau) \sim \tau^{-1}$, implying equal numbers of mergers per logarithmic time-interval. There is no single characteristic lifetime for such a distribution, but in this picture, a substantial fraction of mergers should be associated with active or recent star formation. Separately, the recently hypothesized branch of binary evolution described by Belczyński & Kalogera (2001) could contribute a significant population of very short-lived ($\tau \lesssim 100$ Myr) binaries.

The first papers to investigate these questions from the short-burst perspective concluded that short progenitor lifetimes were disfavoured on several grounds. Gal-Yam *et al.* (submitted) argued that the high fraction of elliptical host galaxies (and host galaxy clusters) indicated a mean lifetime significantly longer than for type Ia supernovae, $\bar{\tau} \gtrsim 3$ Gyr. In two similar analyses, Guetta & Piran (2006) and Nakar *et al.* (2006) used the first four short-burst redshifts and luminosities to predict fluence distributions for comparison with the BATSE short-burst catalogue, investigating a range of luminosity functions and progenitor lifetime distributions. While Nakar *et al.* (2006) found that these fits required $\bar{\tau} \gtrsim 4$ Gyr or $n > -0.5$ for power-law distributions $p(\tau) \sim \tau^{n}$, Guetta & Piran (2006) argued that $n = -1$ could not yet be rejected. Both analyses predicted local merger rates of $\mathcal{R} \gtrsim 10\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$, with the exact number depending on the average beaming correction and the overall range of luminosities. The corresponding event rates for LIGO are at the high end of previous estimates, perhaps as high as $0.3\ \mathrm{yr}^{-1}$.

Additional short-burst host demographic studies also provide support for a long progenitor lifetime: Zheng & Ramirez-Ruiz (submitted) found that $n \gtrsim 1.5$ by comparing the numbers of late- and early-type host galaxies, while Shin &

Berger (submitted) derived $0 \lesssim n \lesssim 1$ from the fraction of early type host galaxies found in galaxy clusters.

An intriguing hypothesis that may explain a long mean lifetime for short-burst progenitors appeals to three-body (binary–single star) interactions in globular clusters to produce a significant fraction of all compact-object mergers (Grindlay *et al.* 2006). As Hopman *et al.* (2006) point out, the rate of such interactions spikes at the epoch of core collapse; since core collapse occurs on a time-scale $\tau \sim 10$ Gyr this supplies a natural delay from star formation to compact-object merger.

Belczynski *et al.* (2006) put forward a contrary position, arguing that the presence of short bursts in low-mass star-forming galaxies, as well as in large elliptical galaxies and galaxy clusters, already suggests a bimodal distribution of progenitor lifetimes. Using population-synthesis methods, they predict a spike of mergers at short timescales, $\tau \lesssim 100$ Myr after star formation, followed by a dominant merger population with a τ^{-1} lifetime distribution. Thus, they predicted, more $z \gtrsim 1$ short bursts like GRB 050813 would be identified in the future.

By identifying a likely collection of such $z \gtrsim 1$ short bursts, Berger *et al.* (submitted *a*) have provided the first support for this prediction. However, with a limited number of redshift measurements in this regime, the data remain consistent with a range of models, including broad lognormal lifetime distributions. Specifically, the τ^{-1} lifetime distribution is now consistent with the full set of bursts, and the addition of higher-luminosity events from higher redshift to the relatively low-redshift, low-luminosity bursts prominent in the early sample has resulted in shorter lifetimes and a reduction by a factor of approximately 3 in the local event rate, by comparison with earlier analyses.

4. Afterglow modelling

The mere observation of broadband afterglows of short bursts, exhibiting non-thermal broadband spectra and power-law temporal decays, can already be considered a notable success of the fireball model. Short-burst afterglows have now been detected in the X-ray, UV/optical/infrared and radio bands; sophisticated model fits, and precise constraints on the physical parameters of the blastwave and surrounding environment, should thus be possible. However, as with the study of long-burst afterglows in the Swift era, several factors have conspired to restrict the ambitions of these efforts.

The first multi-band short-burst afterglow fits were presented by Fox *et al.* (2005*a*). Owing to a delayed alert from the HETE satellite, the X-ray and optical afterglow observations were not extensive; moreover, Very Large Array (VLA) radio observations yielded only upper limits. Afterglow models were thus consistent with observations for a range of blastwave parameters; however, among the more robust measured quantities are the collimation angle, $\theta \approx 20^\circ$, and the blastwave kinetic energy, $E_{\mathrm{K}} \approx 5 \times 10^{48}$ erg, roughly equal to the beaming-corrected prompt emission energy in gamma-ray and X-ray.

This simple afterglow model leaves some intriguing aspects of the GRB 050709 afterglow unexplained. First, the bright 100 s X-ray flare that followed the burst by $\delta t \approx 100$ s (and enabled the precision localization by HETE), was more than an order of magnitude brighter than expected for X-ray afterglow emission at that epoch. Second, the factor of approximately 10 variability seen in the second Chandra observation remains one of the most extreme examples of late-time X-ray flaring seen during the Swift era—occurring at an epoch more than 10^7 times the burst duration.

GRB 050724 was the first short-burst afterglow detected at X-ray, optical/NIR and radio wavelengths, and as such inspired several modelling efforts. The early time X-ray variability of this afterglow, mapped out in detail by fast-response Swift observations (Barthelmy *et al.* 2005*b*), established flaring activity as a common feature of short and long bursts observed by Swift. At later times, the X-ray lightcurve showed a prominent flare from 0.2 to 3 days after the burst, which proved a complication for models.

Berger *et al.* (2005) interpreted the fast decay of NIR and radio emission at the epoch of the X-ray flare as a jet break signature, implying collimation to $\theta \approx 10°$. Panaitescu (2006) presents two models, one treating the flare as independent emission, and another treating it as an energy injection. In either case, a jet break accounts for the radio decay, and the blastwave kinetic energy is $E_K \approx 4 \times 10^{49}$ erg, roughly equal to the beaming-corrected prompt gamma-ray energy; the circumburst density in this case is constrained to lie between 10^{-1} and 10^3 cm^{-3}.

Subsequent observations with Chandra showed a continuing power-law decay of the GRB 050724 X-ray flux to late times, 22 days after the burst (Grupe *et al.* in press). Grupe *et al.* (in press), therefore, suggest that the fast decay of NIR and radio emission was associated with the X-ray flare, and was not due to a jet break; they derive a limit of $\theta > 25°$ for the collimation of this burst, increasing the energy budget by a factor of more than 6.

The next broadband afterglow of a short burst, the Swift-detected GRB 051221A, was also the subject of modelling studies. The Swift X-ray lightcurve, more or less free of flaring activity, shows a 'plateau' from 1.4 to 3.4 h after the burst that is interpreted as due to energy injection at the blastwave, either from late-time engine activity or from slow-moving and late-arriving ejecta from the initial explosion. Burrows *et al.* (in press) present the extended X-ray lightcurve from their Chandra observations, which shows a break at 4 days after the burst, implying a collimation to $\theta \approx 6°$ in this event. Incorporating optical and radio data from Soderberg *et al.* (2006) into their model, they measure a blastwave kinetic energy $E_K \approx 2 \times 10^{49}$ erg and find the circumburst density to lie between 10^{-4} and 10^{-1} cm^{-3}.

Soderberg *et al.* (2006) present optical and radio observations of GRB 051221A, and model these data in concert with the X-ray data from Burrows *et al.* (in press). They find a beaming-corrected kinetic energy of $E_K \approx 8 \times 10^{49}$ erg and a burst energy of $E_\gamma \approx 1.5 \times 10^{49}$ erg. Interpreting the single radio detection as a reverse shock signature, they find that the circumburst density $n \approx 10^{-3}$ cm^{-3}.

GRB 060313 was a bright short burst detected by Swift (as well as Konus–Wind), with an optical afterglow detected in all UVOT filters, and an X-ray and UV/optical lightcurve from Swift observations that extends for more than a day after the burst (figure 2). Roming *et al.* (2006) investigate afterglow models for GRB 060313, and find that low-density surroundings, $n \sim 10^{-3}$ cm^{-3}, are preferred. Intriguingly, this low density may be seen as consistent with the absence of a host galaxy identification for this event, since the burst redshift has been constrained to $z < 1.1$ (90% confidence) through model fits to the UVOT and XRT data. The significant variability in the X-ray and UV lightcurves suggests

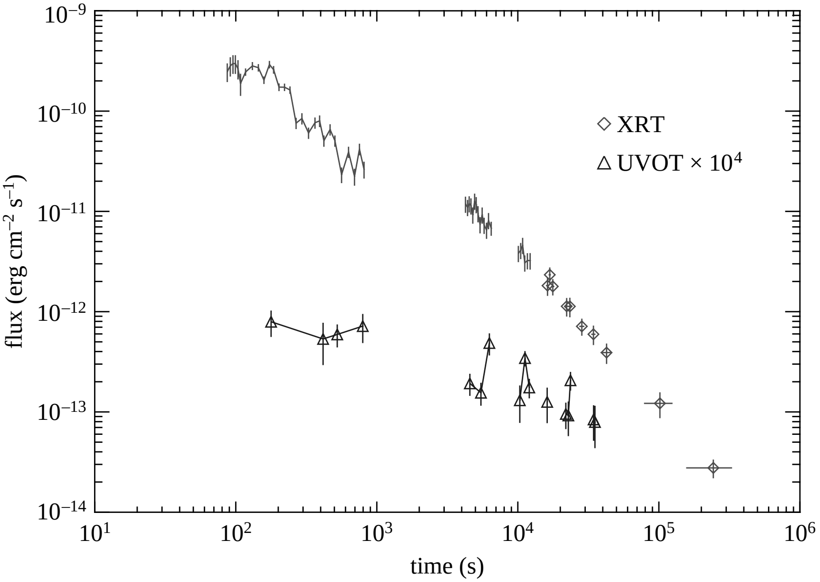

Figure 2. Swift X-ray (XRT; 0.3–10 keV) and UV/optical (UVOT; U-band) lightcurves for the afterglow of GRB 060313. UVOT measurements are converted from a variety of filters using the measured spectral index of the afterglow, and are shown multiplied by 10^4 for ease of presentation. Contiguous flux measurements within a single orbit are connected by lines; multi-orbit averages are shown with horizontal error bars. Substantial non-Poissonian variability is observed in the X-ray over the course of the first and the second orbits, and in the UV from 3 to 30 ks post-burst; this may be due to ongoing engine activity or density inhomogeneities of the surrounding medium. See text or Roming *et al.* (2006) for further discussion.

either ongoing energy input, perhaps due to late-time engine activity, or density variations in the medium surrounding the burst. The idea that the medium surrounding a short burst could be both low-density and exhibit large density inhomogeneities, across a range of length-scales, is an unanticipated and curious feature of this event.

5. An unusual burst

The Swift BAT detected GRB 060614 as a 100 s long burst with prompt autonomous follow-up revealing bright X-ray and optical afterglow emission (Gehrels *et al.* 2006). Given the numerous associations of low-redshift long bursts with supernovae, the measurement of the redshift of the burst's host galaxy, $z=0.125$ (Price *et al.* 2006), stimulated several deep searches for an associated supernova of this event. Despite the sensitivity of these searches (Della Valle *et al.* 2006; Fynbo *et al.* 2006; Gal-Yam *et al.* 2006), however, no supernova was found; the most constraining limits, from the Hubble Space Telescope observations of Gal-Yam *et al.* (2006), give an upper limit of less than 1% the peak brightness of SN 1998bw.

Gehrels *et al.* (2006) go to some length to understand how this peculiar event can be understood in the larger context of the short and long bursts. The prompt emission from the event is clearly long. However, the spectral lag for the burst is consistent with zero—a recently demonstrated property of short bursts (Norris & Bonnell 2006). In addition, the first 5 s of burst emission are spectrally harder and brighter than the remaining 100 s.

If the 100 s of prompt emission really represent more or less continuous engine activity, then it is hard to understand how the burst could be produced in a compact-object merger, where the dynamical time-scale is less than a millisecond and the accretion disc is expected to last a second or two at most (Narayan *et al.* 2001).

At the same time, the absence of an associated supernova is not the only evidence that contradicts a massive star origin for GRB 060614. The host galaxy itself has very little ongoing star formation, less than $0.0035 M_{\odot}\ \mathrm{yr}^{-1}$, and the burst is located on the galaxy outskirts (Fynbo *et al.* 2006; Gal-Yam *et al.* 2006)—not within the brightest parts of the galaxy, as typically found for long bursts (Bloom *et al.* 2002).

Thus, neither of the two leading gamma-ray burst progenitor models are easily accommodated to the data for this event, and development of a third progenitor model may be called for.

We are extremely grateful for the efforts and guidance of our collaborators, including the Swift team and collaborators at Caltech, Carnegie Observatories, NRAO, the Australia National University and the University of Hawaii. We also acknowledge productive discussions with T. Piran and J. Bloom.

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