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Gamma-ray bursts in the *Swift* era

N Gehrels[1], J K Cannizzo[2] and J P Norris
NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
E-mail: gehrels@milkyway.gsfc.nasa.gov

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Abstract. Gamma-ray burst (GRB) research has undergone a revolution in the last two years. The launch of *Swift*, with its rapid slewing capability, has greatly increased the number and quality of GRB localizations and x-ray and optical afterglow lightcurves. Over 160 GRBs have been detected, and nearly all have been followed up with the on-board narrow field telescopes. Advances in our understanding of short GRBs have been spectacular. The detection of x-ray afterglows has led to accurate localizations from ground based observatories, which have given host identifications and redshifts. Theoretical models for short GRB progenitors have, for the first time, been placed on a sound foundation. The hosts for the short GRBs differ in a fundamental way from the long GRB hosts: short GRBs tend to occur in non-star forming galaxies or regions, whereas long GRBs are strongly concentrated within star forming regions. Observations are consistent with a binary neutron star merger model, but other models involving old stellar populations are also viable. *Swift* has greatly increased the redshift range of GRB detection. The highest redshift GRBs, at $z \sim 5$–6, are approaching the era of reionization. Ground-based deep optical spectroscopy of high redshift bursts is giving metallicity measurements and other information on the source environment to much greater distance than other techniques. The localization of GRB 060218 to a nearby galaxy, and association with SN 2006aj, added a valuable member to the class of GRBs with a detected supernova. The prospects for future progress are excellent given the >10 year orbital lifetime of the *Swift* satellite.

[1] Author to whom any correspondence should be addressed.
[2] Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA.

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Contents

1. Introduction

Despite impressive advances over the roughly three decades since GRBs were first discovered [1], the study of bursts remains highly dependent on the capabilities of the observatories which carried out the measurements. The era of the *Compton Gamma Ray Observatory* (CGRO) led to the discovery of more than 2600 bursts in just nine years. Analyses of these data produced the key result that GRBs are isotropic on the sky and occur at a frequency of roughly two per day all sky [2]. The hint from earlier instruments was confirmed that GRBs come in two distinct classes of short and long bursts, with distributions crossing at $\sim$2 s duration [3]. The *BeppoSAX* mission made the critical discovery of x-ray afterglows of long bursts [4]. With the accompanying discoveries by ground-based telescopes of optical [5] and radio [6] afterglows, long GRBs were found to emanate from star forming regions in host galaxies at typical distance of $z = 1$. *BeppoSAX* and the following *HETE-2* mission also found evidence of associations of GRBs with Type Ic supernovae. This supported the growing evidence that long GRBs are caused by 'collapsars' where the central core of a massive star collapses to a black hole (BH) [7].

The next chapter in our understanding of GRBs is being written by the *Swift* mission. In this article, we discuss the findings of the *Swift* mission and their relevance to our understanding of GRBs. We also examine what is being learned about star formation, supernovae and the early Universe from the new results. In each section of the article, we close with a discussion of the prospects for future progress with *Swift* and follow-up observatories. We look ahead in this article to the next five years.

2. The *Swift* observatory

Swift [8] carries 3 instruments, a wide-field burst alert telescope (BAT) [9] that detects GRBs and positions them to arcmin accuracy, and the narrow-field x-ray telescope (XRT) [10] and UV-optical telescope (UVOT) [11] that observe their afterglows and determine positions to arcsec accuracy, all within ∼100 s. BAT is a coded aperture hard x-ray imager with 0.5 m^2 of CdZnTe detectors (32 000 individual sensors) and a 1.4 sr half-coded field of view. XRT is a JET-X Wolter 1 grazing incidence, imaging x-ray telescope with a 0.2–10 keV energy range, 120 cm^2 effective area at 1.5 keV, field of view of $23.6'' \times 23.6''$, and sensitivity of 1 mCrab ($\sim 2 \times 10^{-11}$ erg cm^{-2} s^{-1}) in 104 s. The UVOT is a modified Ritchey–Chrétien reflector with 30 cm aperture, 170–600 nm wavelength range, field of view $17'' \times 17''$, point spread function FWHM of $1.9''$ at 350 nm, and sensitivity of 23rd magnitude in white light in 10^3 s.

The general operations of the *Swift* observatory are as follows. The BAT detects the bursts in the 15–350 keV band and determines a few-arcmin position onboard within 12 s. The position is provided to the spacecraft, built by Spectrum Astro General Dynamics, which repoints to this new position in less than 2 min. The XRT and UVOT then observe the afterglow. Alert data from all three instruments is sent to the ground via NASAs TDRSS relay satellite. The full data set is stored and dumped to the Italian Space Agency equatorial Malindi Ground Station.

The *Swift* mission was built by an international team from the US, UK and Italy. After five years of development, it was launched from Kennedy Space Center on 20 November 2004. The spacecraft and instruments were carefully brought into operational status over an eight week period, followed by a period of calibration and operation verification which ended with the start of normal operations on 5 April 2005.

Swift started detecting GRBs in December 2004 and was actively following afterglows by February 2005. The mission enables ground-based and other space-based follow-ups of GRBs through rapid data distribution by the GCN network (http://gcn.gsfc.nasa.gov/gcn/). This follow-up complements *Swift* instruments by providing deep optical spectroscopy, IR coverage, rapid response, radio observations, and *HST* and *Chandra* imaging. Recently, new observatories have begun searches for very high energy gamma-rays, neutrinos and gravitational waves in conjunction with *Swift* GRBs. A follow-up team of observers affiliated with *Swift* optimizes use of observatories around the world, representing over 40 telescopes (http://swift.gsfc.nasa.gov/docs/swift/teamlist.html#fu_team).

Swift spends 56% of its time observing GRBs and their afterglows, with observations continuing for weeks and even months in some cases. The mission policy is to give highest priority to GRB science. The remaining time is shared between non-GRB planned targets, target of opportunity (ToO) observations of non-GRB transients, and calibration sources. ToOs are open to community proposal, with the decision to observe them made by the *Swift* Principal Investigator based on scientific merit and observational constraints. To date, more than 150 ToO targets have been observed. Afterglow from eight GRBs discovered by other observatories has been detected by XRT.

3. *Swift* GRB observations

As of 31 August 2006, BAT has detected 168 GRBs (annual average rate since December 2004 of ∼100 per year and since August 2005 of ∼110 per year). Approximately 90% of the

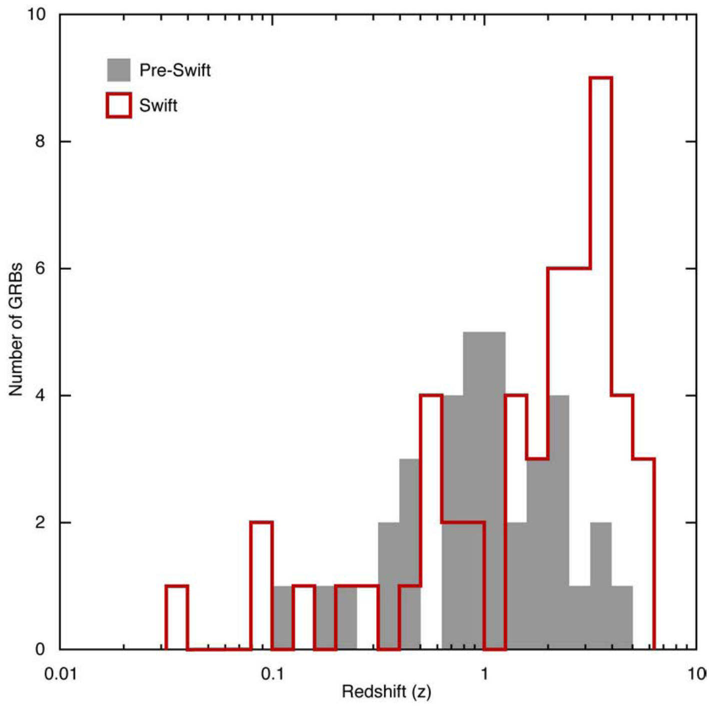

Figure 1. Redshift distribution of *Swift* detected bursts compared to the pre-*Swift* sample.

BAT-detected GRBs have repointings within 5 min (the remaining 10% have spacecraft constraints that prevent rapid slewing). Of those, virtually all bursts observed promptly have detected x-ray afterglow, the only exceptions being three short GRBs (050906, 050925, 051105A). The fraction of rapid-pointing GRBs that have UVOT detection is ∼30%. Combined with ground-based optical observations, about 50% of *Swift* GRBs have optical afterglow detection.

There are 57 *Swift* GRBs with redshifts as listed in table 1. This total from the first 1.7 years of *Swift* operations is more than the number found from all previous observations since 1997. The distribution in redshift is given in figure 1. It is seen that *Swift* is detecting GRBs at higher redshift than previous missions due to its higher sensitivity and rapid afterglow observations. The average redshift for the *Swift* GRBs is $\langle z \rangle = 2.3$ compared to $\langle z \rangle = 1.2$ for previous observations. Jakobsson *et al* [12] find that the *Swift* redshift distribution is consistent with models where the GRB rate is proportional to the star formation rate in the Universe.

Another way of considering the distances of GRBs is to plot the distribution of their look-back time. This is done for the *Swift* bursts with redshift determinations in figure 2. The era of *Swift* GRBs is seen to have peaked at >10 Gyr in the past.

The duration distribution of *Swift* detected GRBs is shown in figure 3. *Swift's* short-burst fraction is ∼10%, which is smaller than BATSE's ∼25%, because *Swift* has a lower energy range than BATSE and short GRBs have hard spectra. Still, the detection rate of short bursts is 10 per year and high enough for considerable progress as discussed in the following section. Figure 4 shows the duration distribution in the source frame for those bursts with redshift determinations. The typical duration in the source frame is a factor of ∼3 less than that in the observer frame as one would expect from the $(1 + z)$ time dilation and average redshift of ∼2.3. Long GRBs have true physical durations of typically 10–20 s and not 30–60 s that we observe.

Table 1. *Swift* GRBs with redshift determinations.

GRB	BAT fluence (10^{-7} erg cm^{-2})	BAT T90 (s)	XRT flux (10^{-11} erg cm^{-2} s^{-1})	Optical flux (magnitude)	Redshift	Notes
060218	68	∼1500	560@153 s	$V = 17.8$@152 s (U)	0.033 (Md,V,G,K)	
051109B	2.7	15	17@87 s	–	0.080 (K)	1
060505	6.2	4	0.05@14 h	$g \sim 21.5$@27 h (G)	0.089 (G)	2
060614	217	102	6000@91 s	$V = 19.54$@101 s (U)	0.125 (G,V)	
050509B	0.130	0.04	0.1@62 s	–	0.225 (K)	3
050724	11.8	3	530@74 s	$I = 8.4\,\mu$Jy@12 h (Sw)	0.258 (G,K)	4
060502B	0.4	90	∼0.1@70 s	$R = 21.6$@15 h (Md)	0.287 (K)	5
050803	22.3	85	150@180 s	$I \sim 22$@23.5 h (Ma)	0.422 (K)	6
060512	2.3	8.6	26@102 s	$V = 15.88$@94 s (U)	0.4428 (K)	
060729	27	116	7700@124 s	$V = 17.30$@135 s (U)	0.54 (G)	
051221A	11.6	1.4	20@92 s	$r' = 21$@3 h (G)	0.547 (G)	7
050223	6.40	23	0.076@0.8 h	–	0.5915 (Ma)	8
050525A	156	8.8	130@130 s	$V = 14.97$@65 s (U)	0.606 (G)	
050416A	4.31	2.4	1.7@78 s	$V = 19.38$@65 s (U)	0.6535 (K)	
060904B	17	192	43@69 s	$V = 18.64$@71 s (U)	0.703 (V)	
050824	2.92	25	0.12@1.7 h	$V = 20.02$@6093 s (U)	0.83 (V)	
051016B	1.7	4.0	0.415@75 s	$R = 21.5$@1.5–2 h (Lu)	0.9364 (K)	9
060912	13	5.0	2.9@109 s	$V = 17.4$@113 s (U)	0.937 (V)	10
060123	3.0	900	0.070@21 h	–	1.099 (G)	11
050126	8.60	26	2.5 @131 s	–	1.29 (K)	
050318	13.1	32	1.0@0.9 h	$V = 19.7$@3279 s (U)	1.44 (Ma)	
060418	81	52	1600@78 s	$V = 14.99$@88 s (U)	1.490 (Ma,V)	
060502A	22	33	130@76 s	$V = 18.70$@84 s (U)	∼1.51 (G)	
051111	39	47	1.8@∼1.4 h	$V = 19.33$@6459 s (U)	1.549 (K)	
050802	22.0	13	15@300 s	$V = 17.07$@286 s (U)	1.71 (N)	
050813	0.428	0.6	0.6@73 s	–	1.8	12
050315	32.3	96	2.0@84 s	r band@11.3 h (Ma)	1.949 (Ma)	13
060108	3.7	14.4	1.13@91 s	$V = 21.7$@320 s (F)	2.03 (Lv)	14
050922C	17	5	1.5@108 s	$V = 14.60$@111 s (U)	2.199 (N,T,V)	
060124	4.6	∼700	660 @106 s	$V = 17.08$@184 s (U)	2.296 (Md,K)	15
051109A	21	36	32@120 s	$V = 16.49$@109 s (U)	2.346 (H)	
060908	29	19.3	8.9@72 s	$V = 16.85$@80 s (U)	2.43 (G)	
050406	0.806	3	2.8@106 s	$V = 19.0$@88 s (U)	2.44 (U)	
050820A	4.01	26	50@90s	$V = 18.2$@80 s (U)	2.611 (K,V)	
060604	1.3	10	290@109 s	$V = 21.2$ (2.4σ)@99 s (U)	2.68 (N)	
060714	30	115	1000@99 s	$V = 18.6$@109 s (U)	2.71 (V)	
050603	76.3	∼13	0.22@10.8 h	$V = 18.2$@9.1 h (U)	2.821 (Ma)	
050401	85.5	33	65@120	16.80@33.2 s (R)	2.9 (V)	16
060607A	26	100	330@65 s	$V = 15.35$@179 s (U)	3.082 (V)	
060926	2.2	8.0	6@60 s	$V = 19.0$@57 s (U)	3.208 (V)	
060526	4.9	13.8	17@73 s	$V = 17.2$@81 s (U)	3.21 (Ma)	
050319	6.25	10	150@100 s	$V = 17.5$@90 s (U)	3.24 (N)	

Table 1. Contd.

GRB	BAT fluence (10^{-7} erg cm^{-2})	BAT T90 (s)	XRT flux (10^{-11} erg cm^{-2} s^{-1})	Optical flux (magnitude)	Redshift	Notes
050908	4.91	20	20@120 s	V = 19.3@104.6 s (U)	3.344 (V,G,K)	
060707	17	68	0.55@122 s	V = 19.65@126 s (U)	3.43 (V)	
060115	18	142	410@113 s	Rc = 19.1@6 min (Mi)	3.53 (V)	17
060906	22.1	43.6	1.37@148 s	R ~ 19.0@12 min (P)	3.685 (V)	18
060605	4.6	15	0.75@93 s	V = 16.53@97 s (U)	3.711 (A)	
060210	77	255	130@95 s	R = 18.1@63 s (K)	3.91 (G)	19
050730	24.2	155	150@130 s	V = 17.842@119 s (U)	3.968 (Ma,W,V)	
060206	8.4	7	~8@58 s	V = 18.8@57 s (U)	4.045 (N,Lk,S)	
050505	24.9	60	4@~0.8 h	I = 20.51@6.1 h (K)	4.27 (K)	20
060223A	6.8	11	2@150 s	V = 17.7@72 s (U)	4.41 (K)	
060510B	42	276	190@119 s	R ~ 22.5@26 min (Md)	4.9 (G)	21
060522	11	69	40@140 s	R = 20.6@1.5 h (T)	5.11 (K)	22
050814	18.3	65	0.476@138 s	R = 23.2@13.5 h (N)	5.3 (N)	23
060927	11	22.6	0.56@65 s	16.5@16.5 s (R)	5.6 (V)	24
050904	50.7	225	180@161 s	I = 15.22@150 s (Ta)	6.29 (V,S)	25

Notes: A = Australian National University, C = Calar Alto, F = Faulkes North, G = Gemini, H = HET, K = Keck, Lk = Lick, Lv = Liverpool, Lu = Lulin, K = KAIT, Md = MDM, Mi = MITSuME, Ma = Magellan, N = Nordic Optical Tel., P = Palomar, R = ROTSE-IIIa, Sa = South African Large Tel., Su = Subaru, Sw = Swope, T = TNG, Ta = TAROT, U = U, V=VLT W=William Herschel Tel.
1 = host redshift.
2 = untriggered burst found in ground processing; Optical flux ref GCN 5123.
3 = redshift probable, not definitive; inferred by possible association with galaxy cluster at reported z..
4 = Optical flux ref [13].
5 = T90, first spike/extended emission; candidate redshift; Optical flux ref GCN 5066.
6 = possible redshift; Optical flux ref GCN 3753.
7 = ref [14].
8 = host redshift.
9 = Optical flux ref GCN 4105.
10 = probably host redshift.
11 = probable redshift of host.
12 = ref [15].
13 = Optical flux ref GCN 3100.
14 = Optical flux ref [16].
15 = BAT precursor 500 s before main burst with ~100 s duration.
16 = Optical flux ref [17] (assuming the ROTSE-IIIa unfiltered magnitudes are roughly equivalent to the Rc-band system).
17 = Optical flux ref GCN 4517.
18 = Optical flux ref GCN 5529.
19 = Optical flux ref GCN 4723.
20 = Optical flux ref [18].
21 = Optical flux ref GCN 5097.
22 = Optical flux ref GCN 5151.
23 = Optical flux ref GCN 3809.
24 = Optical flux ref GCN 5629.
25 = Optical flux ref [19].
26 = except as noted, data in the table from http://swift.gsfc.nasa.gov/docs/swift/archive/grb_table/.

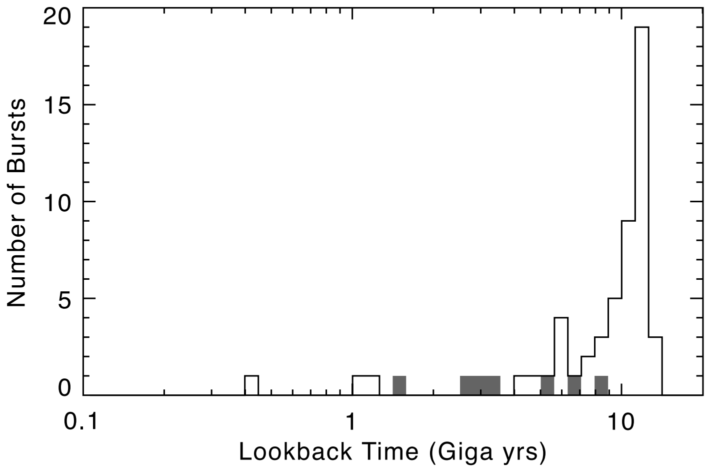

Figure 2. The look-back time distribution of *Swift* detected bursts. The short bursts are shown as the solid part of the histogram. A standard cosmology of $H_0 = 71\ \mathrm{s}^{-1}\ \mathrm{Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ is assumed to convert the observed redshift to look-back time.

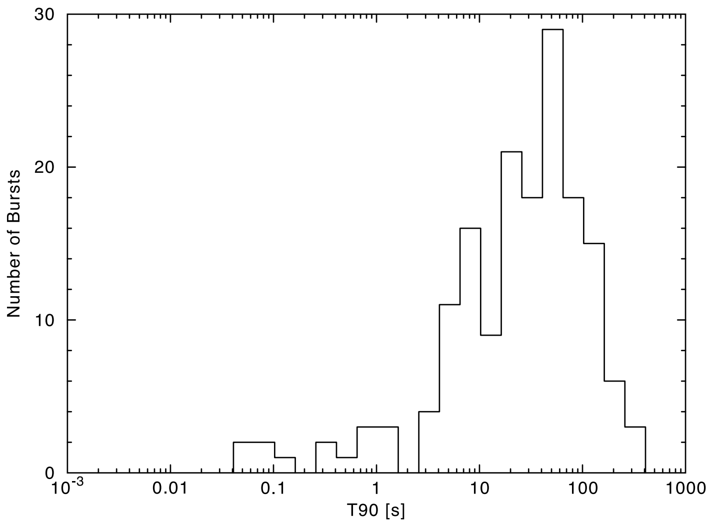

Figure 3. Duration distribution of *Swift* detected bursts. Plotted is the distribution of the parameter T_{90} which is the length of time in which 90% of the burst fluence is observed.

4. Short GRBs

At the time of *Swift's* launch, the greatest mystery of GRB astronomy was the nature of short-duration, hard-spectrum bursts. Although more than 50 long GRBs had afterglow detections, no afterglow had been found for any short burst. In May 2005 (GRB 050509B), *Swift* provided the first short GRB x-ray afterglow localization [20]. This burst plus the *HETE-2* GRB 050709 and *Swift* GRB 050724 led to a breakthrough in our understanding [13], [20]–[25] of short bursts. BAT has now detected ~13 short GRBs, most of which with XRT detections, and about half of which with host identifications or redshifts (an additional two have been detected by *HETE-2*).

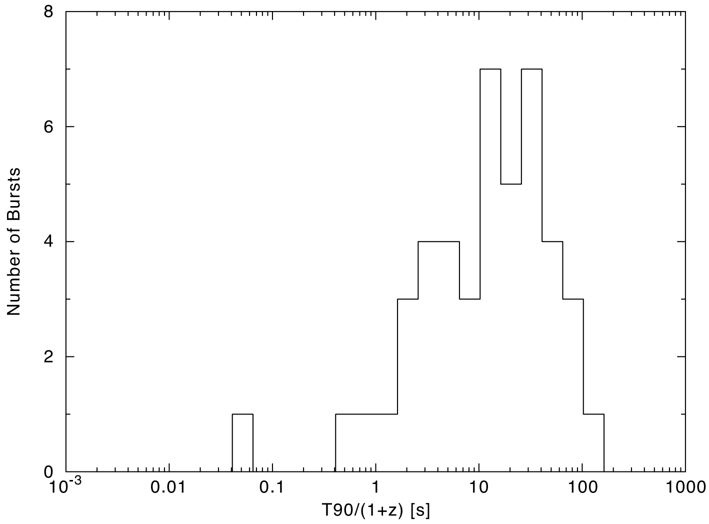

Figure 4. The distribution of durations, transposed to the source frame, for those *Swift* bursts with redshift determinations.

In stark contrast to long bursts, the evidence to date on short bursts is that they typically originate from regions with low star formation rate. GRB 050509B and 050724 were from elliptical galaxies with low current star formation rates, while GRB 050709 was from a region of a star forming galaxy with no nebulosity or evidence of recent star formation activity. This is illustrated in figure 5 where the images of these three short bursts are contrasted to three typical *HST* images of long bursts showing them coincident with regions of star formation [27]. Taken together, these results support the interpretation that short bursts are associated with an old stellar population, and may arise from mergers of compact binaries (i.e. double neutron star (NS) or NS-BH).

A list of short GRBs detected to date since GRB 050509B is given in table 2. The list includes all bursts that researchers have discussed in the context of short events. Some, such as GRB 050911, 060505 and 060614, are uncertain as to their long or short classification. From the five definite short events with firm redshifts, the concentration is seen to be near $z = 0.2$, but with some events as far away as $z = 2$, or possibly higher. It has been suggested [28] that there are separate populations of short bursts that are nearby ($z < 0.5$) and farther away ($z > 1$). With the caveat that statistics are poor and the population appears diverse, the redshifts for short bursts are smaller on average by a factor of $\sim$4 than those of long bursts ($\langle z_{\rm short}\rangle = 0.5$, $\langle z_{\rm long}\rangle = 2.3$), and their isotropic energies are smaller by a factor of $\sim$100.

Measurements or constraining limits on beaming from light curve break searches have been hard to obtain, given the typically weak afterglow of short GRBs. Figure 6 shows the best data available comparing the inferred beaming angle distributions for long and short GRBs. Based on the limited statistics available, and bearing in mind the large uncertainties involved in determining reliable breaks for the short GRB light curves, it appears short GRBs have larger beaming angles on average than for long GRBs.

Swift observations also reveal new and puzzling features. Prolonged emission (lasting $\sim$100 s), characterized by softer spectra than that of the initial burst, is seen to follow the prompt emission for about 25% of short bursts [33, 34]. Also, x-ray flares on late timescales

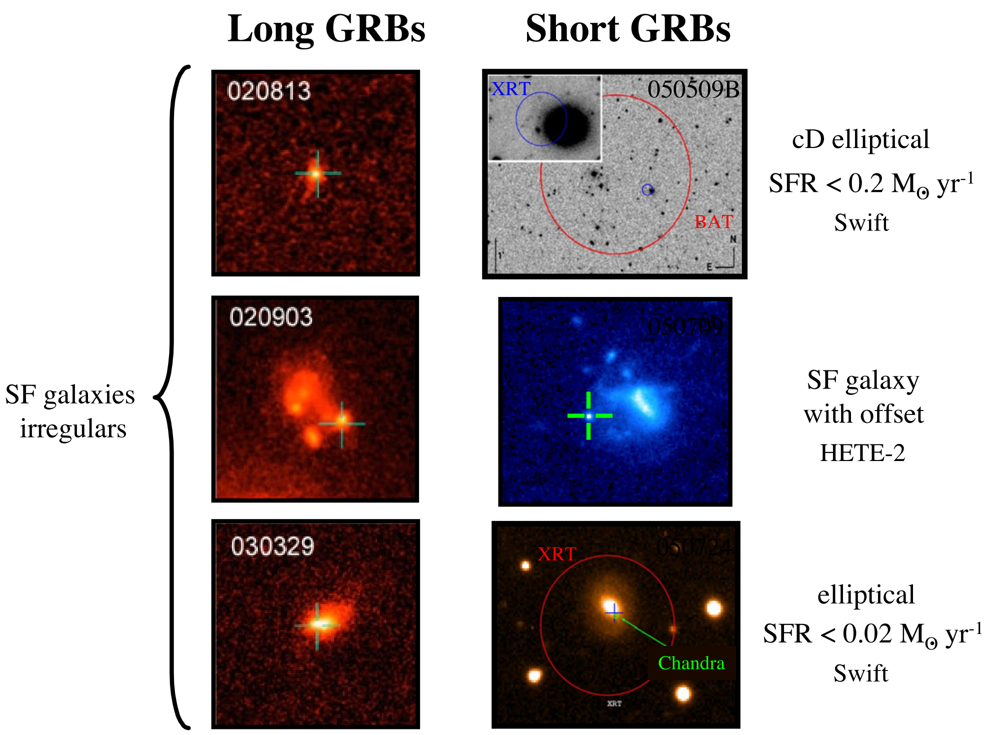

Figure 5. Images of three short GRBs compared to 3 typical long GRBs. The short GRBs and image references are GRB 050509B [20], GRB 050709 [22] and GRB 050724 [13]. The long burst images are from Fruchter *et al* [26].

in the afterglow [35] are not easily explained by the standard coalescence model. Perhaps these flares result from a complex energy extraction process from the nascent BH, or self-gravitational clumping instabilities at large radii in the fall-back disk [36], or other possibilities [37]. GRB 060614 is a particularly interesting case that may or may not be a short burst with a exceptionally bright tail as discussed in subsection 7.2.

Swift localization of a short GRB increases the sensitivity of gravitational wave interferometers to detect gravitational waves from that GRB by a large factor due to the much narrower search window that can be used [38]. Detection of gravitational waves from a *Swift* GRB would be an enormous discovery with great scientific payoff for merger physics, progenitor types, and NS equations of state. Short GRBs are also 'cosmic sirens' that can provide constraints on the properties of dark energy, if they are detected by gravitational wave detectors [39]. Even if this requires advanced LIGO in 2012, it is feasible for *Swift* to be operating at that time.

We already know from the 27 December 2004 extremely luminous giant flare from SGR 1806-20 that such events could be detected to ~60 Mpc and would look identical to short GRBs [40]. With *Swift*, we can determine whether some short GRBs are magnetar flares or if the SGR 1806-20 giant flare was an extremely rare event. A recent study [26] that searched for nearby galaxies ($z < 0.025$) within the error boxes of six well-localized, pre-*Swift* short GRBs failed to find any plausible hosts as would be expected from magnetar progenitors, and concludes that magnetar hyperflares constitute $<15\%$ of all short GRBs.

Table 2. Short GRBs with afterglow detection or deep limits.

Name	Redshift	Afterglow	Host	E^{a}_{iso} (10^{50} erg)	Duration[b] T_{90}(s)	Comments
050509B	0.225	X	Elliptical	0.13	0.03	Low SF region
050709[c]	0.161	X,O	SF Galaxy	0.6	0.07	Low SF region
050724	0.258	X,O,R	Elliptical	4.7	3.0	Low SF region
050813	1.8?	X	Galaxy	17?	0.60	–
050906	0.03?	–	?Galaxy	0.001?	0.13	BAT only
050911	0.165?		Cluster	0.9?	16.	Is it short?
050925	–	–	In gal. plane	–	0.07	Non-GRB?
051103[d]	–	–	Near M81/M83	–		M81 SGR?
051105A	–	–	–	–	0.03	–
051210	0.11?	X	?cluster	0.1?	1.4	–
051221A	0.547	X,O,R	SF Galaxy	31.	1.4	–
051227	–	X	–	–	0.9	–
060121[c]	1.5 or 4.5	X,O	Galaxy	–	2.	–
060313	–	X,O	?Cluster	–	0.7	–
060502B	0.287?	X	?Elliptical	0.1?	0.09	–
060505	0.089	X,O	Galaxy	~0.5	4.	Is it short?
060614	0.125	X,O	Galaxy	3.7	103.	Is it short?
060801	1.131	X	Galaxy?	~13.	0.5	–

[a] E_{iso} in 1–10 000 keV band in source frame.
[b] Duration in 15–150 keV band.
[c] HETE-2.
[d] IPN.

4.1. Short GRB future progress

Swift will provide a statistically significant sample of short GRBs as it continues to operate, with prompt emission and afterglow observations for dozens of short bursts over five years. The key topics that will be addressed are as follows.

1. Origin of short GRBs. Secure galaxy localizations for short GRBs now total less than 6, and hint at an older population than for long GRBs. The basic scenario of short GRBs as NS–NS mergers is supported, but many other models are also viable [41]. Increased statistics of the hosts are badly needed. The few bright, well observed bursts that *Swift* will provide over the coming years will lead to the most progress.
2. Sub-classes. Two of the short GRBs, 050813 and 060121, have potential host galaxies at cosmological redshifts $z > 1$. The existence of a new class of short GRB lying at much greater distance may reveal a new class of more energetic phenomena [28]. At the other extreme, the magnetar giant flare event of 27 December 2004, with its short duration, hard spectrum, and total energy ~0.01 that of a typical short GRB, also indicates the possibility of at least one additional sub-class existing at lower luminosities. Again, more statistics are needed.
3. Prompt emission tails. The observation of soft emission lasting 10s of seconds after the prompt hard episode is a discovery that will have profound implications for models.

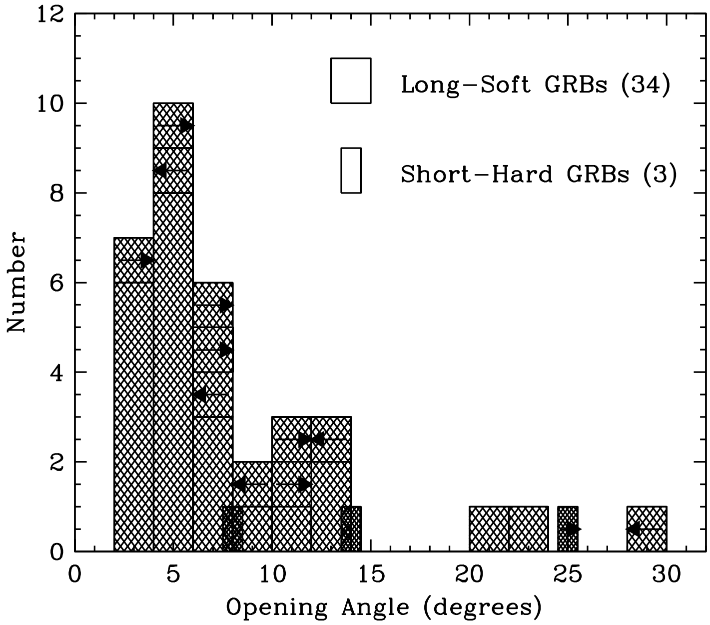

Figure 6. Jet opening angles for short and long GRBs as estimated from observations of jet breaks (e.g., see [29]) in the light curves. Update of Soderberg *et al* [30] study. Short burst data are for GRB 051221 (8° [31]), 050709 (14° [22]), and 050724 (>25° [32]).

A sample size twice as big as the current one is need to firmly establish the observational characteristics of this feature.

5. Afterglow physics

Swift was specifically designed to investigate GRB afterglows by filling the temporal gap between observations of the prompt emission and the later, fading afterglow [34]. The combined power of the BAT and XRT has revealed that in long GRBs the prompt x-ray emission smoothly transitions into the decaying afterglow (figures 7 and 8). Often, a steep-to-shallow transition (phases I–II in figure 7) is found suggesting that prompt emission and the afterglow are distinct emission components. This also seems to be the case for short bursts [20, 22].

The early steep-decay phase seen in the majority of GRBs is a real surprise. The current best explanation is that we are seeing high-latitude emission due to termination of central engine activity [42]–[44]. This phase is usually followed by an equally unexpected shallow decay phase with that begins within the first hour. The shallow phase can last for up to a day, and, although faint, is energetically very significant. It is likely due to the forward shock being constantly refreshed [42, 45, 46] by either late central engine activity or less relativistic material emitted during the prompt phase. Granot *et al* [47] show how the two-component jet model [48] in which a narrow, initially highly relativistic conical jet (producing the prompt emission) embedded within a mildly relativistic coaxial cone that decelerates markedly as it plows into the CSM, can account for the early-time, flat decay (following the initial steep decay) in the XRT light curves.

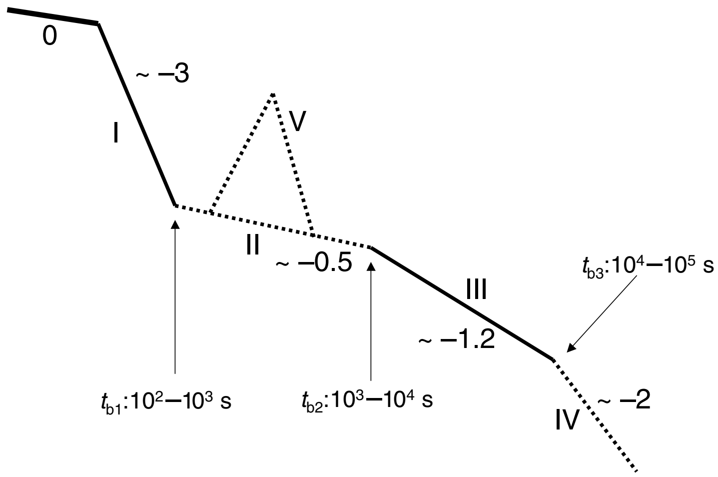

Figure 7. Schematic of the log flux-log time relation of various afterglow phases seen in GRBs (taken from [42]). The prompt phase (0) is often followed by a steep decline afterglow (I) which can then break to a shallower decline (II), a standard afterglow phase (III), and possibly, a jet break (IV). Sometimes an x-ray flare is seen (V).

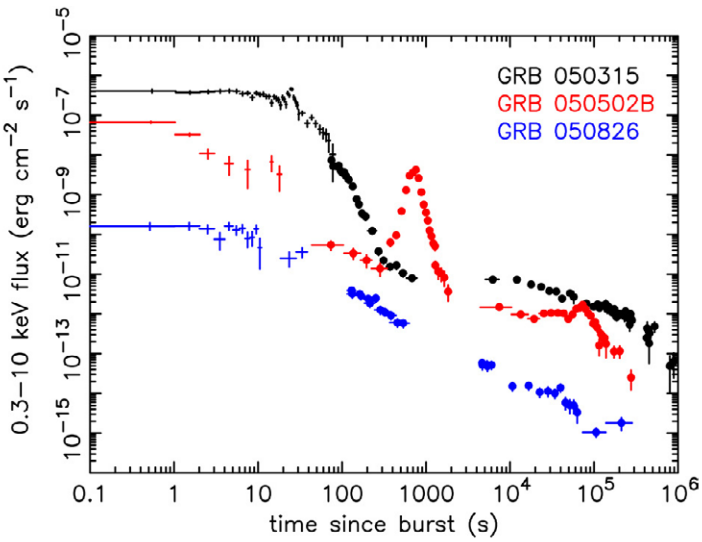

Figure 8. Example GRBs with steep-to-shallow transition (GRB 050315), large x-ray flare (GRB 050502B) and more gradually declining afterglow (GRB 050826; flux scale divided by 100 for clarity).

Most *Swift*-localized GRBs are optically faint at early times [15], in contrast to pre-*Swift* expectations. In some GRBs, the afterglow decays more gradually after the prompt emission. These tend to be the GRBs that are detected early with the UVOT. Here, the afterglow emission may be dominated by the external shock, as expected prior to *Swift* (phase III in figure 7).

Swift has found erratic flaring behaviour (phase V in figure 7), lasting long after the prompt phase, in some cases for several hours after the burst. The most extreme examples are flares with integrated power similar to or exceeding the initial burst [35]. The rapid rise and decay, multiple

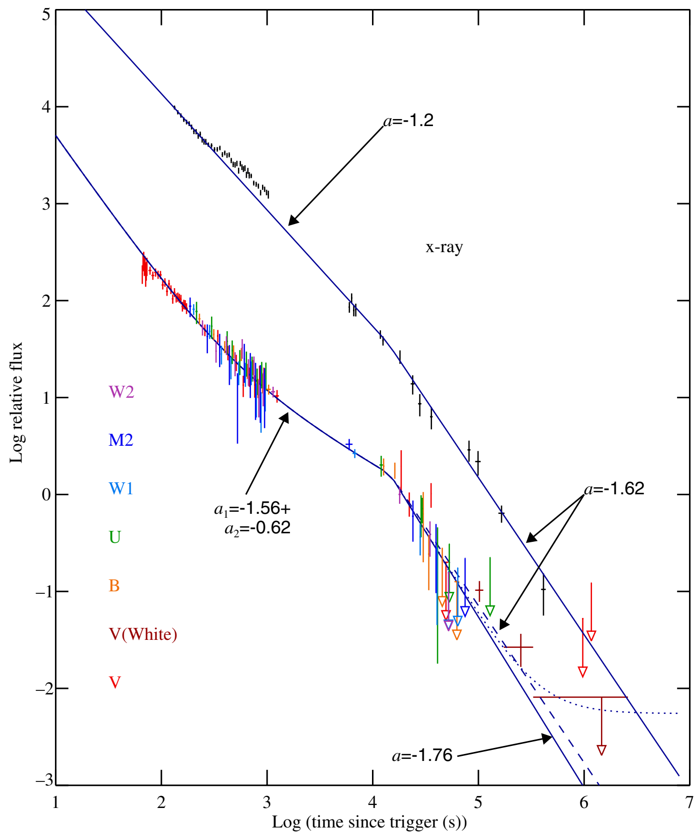

Figure 9. XRT (top curve) and UVOT (bottom curve) observations of GRB 050525A [52].

flares in the same burst, and cases of fluence comparable with the prompt emission suggest that these flares are due to continuing activity of the central engine.

There is a lack of evidence for jet breaks (breaks in temporal decay slope, phase III–IV transition in figure 7) in the *Swift* x-ray afterglow [49, 50]. Although possible jet breaks have been measured in some bursts, the number of bursts in which such breaks are seen is small and they do not satisfy the empirical relations previously found from optical observations [29, 51]. We have detected one textbook version of an achromatic jet break in both x-ray and optical (GRB 050525A, figure 9). Whether these results invalidate the jet picture inferred from earlier optical observations remains to be seen.

5.1. Afterglow physics future progress

Results obtained with *Swift* so far have led to significant progress in understanding GRB outflows, but most issues are far from settled. In the next few years *Swift* will address the following topics.

1. Afterglow origin. Long-duration monitoring of additional bursts will address whether the radiative efficiency in the prompt phase is much higher than in the afterglow, providing clues as to whether the prompt emission requires a Poynting-dominated ejecta and whether the afterglow efficiency or shock microphysics varies in time. The late evolution of the light

curve will also allow searches for unambiguous achromatic jet breaks to constrain jet width and intrinsic luminosity [29].

2. Rare bright optical GRBs. Detection of more bright optical bursts will test whether prompt optical emission is correlated with a high isotropic luminosity. Based on experience from years 1 and 2, *Swift* will detect ~2 of these bursts per year. Comparison of bright optical-flash GRBs with a large sample of early UVOT detections and severe upper limits, combined with detailed modelling of forward shock and reverse shock emission, directly addresses whether GRB fireballs are baryonic or magnetic in origin (e.g. [53]–[56]).
3. High redshift fireballs. A large sample of high redshift bursts will determine whether their fireball physics is similar to that of nearby bursts, or whether it evolves as a function of redshift.
4. X-ray flares. A large sample of bursts with x-ray flares will constrain how flares evolve during an individual burst and how they correlate with other GRB properties. Such correlations test if the flares are powered by the central engine. This will also test disk models with fragmentation or magneto-hydrodynamically-dominated accretion as the explanation of flaring behaviour.
5. Central engine. Monitoring the temporal and spectral evolution of large numbers of GRBs during the shallow decay phase will constrain the possible late ejection of and/or the range in initial Lorentz factor of the entrained material in the relativistic jet. These data can be compared to detailed numerical simulations of the various GRB progenitors to study the behaviour of the central engine.

6. High redshift GRBs and cosmology

GRBs, insofar as they represent the most brilliant explosions known, offer the potential to probe the early Universe into the epoch of reionization. They can trace the star formation, re-ionization, and metallicity histories of the Universe [57]–[62]. GRBs are 100–1000 times brighter at early times than are high redshift QSOs (the near infrared afterglow of GRB 050904 was $J = 17.6$ at 3.5 h). Also, they are expected to occur out to $z > 10$, whereas QSOs drop off beyond $z = 3$. Another benefit is that GRB afterglows produce no 'proximity effects' on intergalactic distances scales, and have simple power-law spectra with no emission lines. Thus GRBs are 'clean' probes of the intergalactic medium (IGM).

Figure 1 and table 1 show that six of the eight highest redshift GRBs ever seen were discovered by *Swift*, including bursts at redshifts $z = 5.3$ and 6.3 [63]–[65]. Of the GRBs with measured redshift, we find that 4 out of 50 or ~8% of *Swift* GRBs lie at $z > 5$, consistent with model predictions [12, 60]. These same models predict that *Swift* can detect GRBs to redshifts of $z > 8$. A great deal of effort is currently being invested in order to recognize rapidly such bursts and obtain redshifts with large ground-based IR spectrographs. The time evolution of gamma-ray and x-ray fluxes of four high–z GRBs is shown in figure 10. All of these bursts are exceptionally luminous and long-lasting, and their evolution can be very complex.

Swift's rapid localizations have provided new opportunities for spectroscopy of high-redshift GRB afterglows. Observed at low resolution, the host galaxy appears as a damped Ly$-\alpha$ (DLA) system along with a rich array of metallic lines which can be used to infer metal abundances. At high resolution, the host absorption lines split into an array of fine-structure transitions,

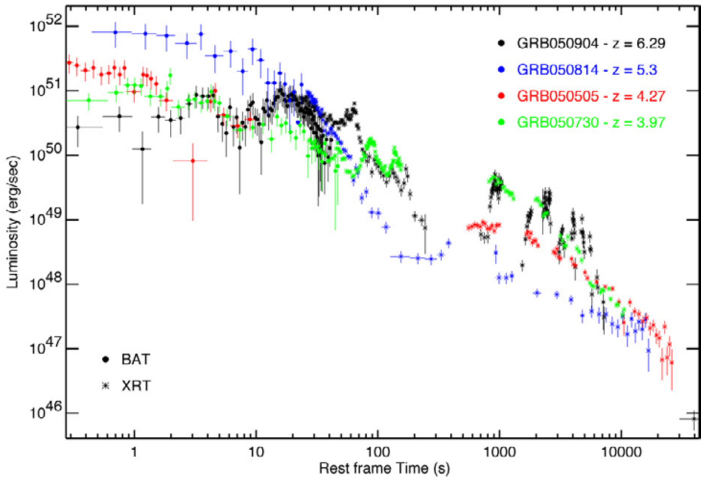

Figure 10. Light curves (BAT-XRT) of four high–z *Swift* bursts.

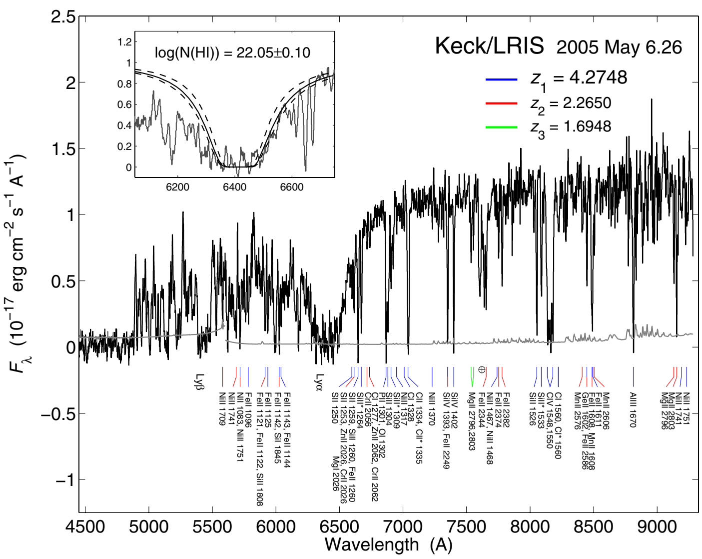

Figure 11. GRB 050505 optical spectrum. Lines are seen from the host galaxy at $z = 4.275$ as well as two foreground absorbers [67].

which allows the inference of gas densities and even of diffuse radiative conditions in the host galaxy [66, 67].

Figure 11 is an example of an optical spectrum for a high redshift ($z = 4.3$) GRB [67]. Countless lines are evident in the spectrum, including a DLA feature corresponding to a neutral hydrogen column density of $10^{22}\,\mathrm{cm}^{-2}$. The lines imply a density of $100\,\mathrm{cm}^{-3}$ in the source region. Absorption lines observed in infrared spectroscopic observations of GRB 050904 gave a metallicity measurement of 5% solar [65], the first metallicity determination at such high redshift, demonstrating that the observed evolution in the mass- and luminosity-metallicity relationships from $z = 0$ to 2 continues to $z > 6$ [68].

6.1. High redshift GRB future progress

We consider here the important cosmological topics that *Swift* observations of GRBs and their afterglows can address over the next few years.

1. Reionization. Observation of one *Swift* GRB at $z > 7$ would provide more information about reionization than all of the SDSS quasars combined. It is impressive that these studies will probe the IGM less than 1 Gyr after the Big Bang. In no other way can such unique observations be made.
2. Star formation rate. The connection between long GRBs and supernovae (SNe) opens the possibility of using the redshifts of long GRBs to infer the cosmological star formation history, with relatively minor (or in any case unique) selection effects [57, 60, 69, 70]. Preliminary estimates of the star formation rate derived from *Swift* bursts [71] shows a flat or (at the highest redshifts) slowly-declining star formation rate, consistent with colour-selected galaxy observations [72].
3. The first generation of stars. Whether massive population III stars can produce GRBs is not yet known [73]–[75]. If such stars, perhaps stripped of their outer envelopes by a binary companion, do produce GRBs, *Swift* may detect them for two reasons: first, because GRBs are so bright; and second, because metal enrichment of the IGM is expected to be heterogeneous. Regions of low metallicity are consequently expected to survive for a substantial period of time—possibly to $z = 10$, or even $z = 6$. Detection of a GRB from the collapse of a massive Pop III star would provide a demonstration of the existence of such stars.

7. Probing the GRB–SN connection

The inferred all-sky supernova rate of $\sim 6\,\mathrm{s}^{-1}$ [76] compares with a universal GRB rate of $\sim 0.02\,\mathrm{s}^{-1}$, taking $\sim 300\,\mathrm{GRBs\,yr}^{-1}$ observed at Earth and adopting a beaming factor of $1/300$ [29]. Thus, supernovae are roughly 300 times more common than GRBs, and therefore GRB progenitors must represent a special subset of all SN progenitors [77]. Both low metallicity and a high rate mass-loss are implicated: theoretical considerations indicate that more massive progenitors favour explosions that produce BHs, and furthermore a high rotation rate is needed to make a GRB [77]. If the mass loss rate is too great, the progenitor mass decreases too much, and expansion of the deeper layers of the progenitor slows the rotation [77]. The fraction of Wolf–Rayet stars that produce GRBs is unknown, however, Wolf–Rayet stars exhibit a strong dependence of mass-loss rate on metallicity [78]—consistent with the notion that low metallicity, a large progenitor mass, and a high angular momentum are common factors needed for a GRB progenitor [77].

7.1. Observations of GRB 060218/SN 2006aj

On 18 February 2006 *Swift* detected the remarkable burst GRB 060218 that provided considerable new information on the connection between SNe and GRBs. It lasted longer than and was softer than any previous burst, and was associated with SN 2006aj at only $z = 0.033$. The BAT trigger enabled XRT and UVOT observations during the prompt phase of the GRB and initiated multiwavelength observations of the supernova starting at the time of the initial core collapse.

The spectral peak in prompt emission at ∼5 keV places GRB 060218 in the x-ray flash category of GRBs [79]. Combined BAT-XRT-UVOT observations provided the first direct observation of shock-breakout in a SN [79]. This is inferred from the evolution of a soft thermal component in the x-ray and UV spectra, and early-time luminosity variations. At maximum, the UV to IR bolometric flux from SN 2006aj was dimmer by a factor ∼2 than the previous SNe associated with GRBs, but still ∼2–3 times brighter than normal SN Ic not associated with GRBs [80, 81].

GRB 060218 was an underluminous burst, as were two of the other three previous cases. Because of the low luminosity, these events are only detected when nearby and are therefore rare occurrences. However, they are actually ∼10 times more common in the Universe than normal GRBs [82].

7.2. The peculiar case of GRB 060614

GRB 060614 was a low-redshift, long-duration burst with no detection of a coincident supernova to deep limits. It was a bright burst (fluence in 15–150 keV band of 2.2×10^{-5} erg cm^{-2}) and well studied in the x-ray and optical. With a T_{90} duration of 102 s, it seemingly falls squarely in the long burst category. A host galaxy was found [83]–[85] at $z = 0.125$ and deep searches were made for a coincident supernova. All other well-observed nearby GRBs have had supernovae detected, but this one did not to limits >100 times fainter than previous detections [83]–[85].

We have found that GRB 060614 shares some characteristics with short bursts [86]. The BAT light curve shows a first short, hard-spectrum episode of emission (lasting 5 s) followed by an extended and somewhat softer episode (lasting ∼100 s). The total energy content of the second episode is five times that of the first (fluence of $(1.69 \pm 0.02) \times 10^{-5}$ erg cm^{-2} and $(3.3 \pm 0.1) \times 10^{-6}$ erg cm^{-2}, respectively, in the 15–350 keV band). The light curve appearance (short hard episode followed by long soft emission) is similar in many respects to that of several recent *Swift* and *HETE-2* short-duration bursts (GRB 050709, 050724, 050911, 051227) and a subclass of BATSE short bursts [87]. There are differences in that the short episode of this burst is longer than the previous examples and the soft episode is relatively brighter.

Another similarity with short bursts comes from a lag analysis of GRB 060614 [86]. Figure 12 shows the peak luminosity (L_{peak}) in *Swift* GRBs as a function of their spectral lag (t_{lag}) between the 50–100 keV and 15–25 keV bands. It is possible for the first time to include short bursts in such a plot with the redshift determinations for several short events from the past 2 years. For long bursts there is an anti-correlation between t_{lag} and L_{peak}, whereas short bursts have small t_{lag} and small L_{peak} and occupy a separate area of parameter space. The lag for GRB 060614 for the first 5 s is 3 ± 6 ms which falls in the same region of the lag-luminosity plot as short bursts.

It is difficult to determine unambiguously which category of burst the well-observed GRB060614 falls into. It is a long event by the traditional definition, but it lacks an associated SN as had been seen in all other nearby long GRBs. It shares some similarities with *Swift* short bursts, but has important differences such the brightness of the extended soft episode. If it is due to a collapsar, it is the first indication that some massive star collapses either fail as supernovae or highly underproduce ^{56}Ni. If it is due to a merger, then the bright long-lived soft episode is hard to explain for a clean NS–NS merger where little accretion is expected at late time but might fit in a NS–BH scenario. In any case, this peculiar burst is challenging our classifications of GRBs.

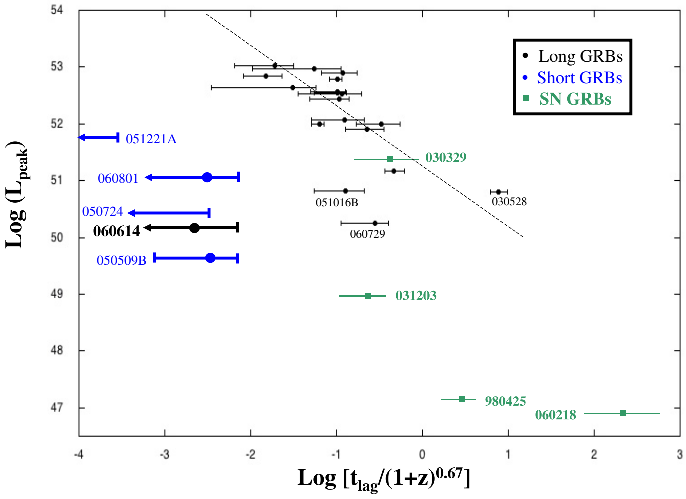

Figure 12. Spectral lag as a function of peak luminosity showing GRB 060614 in the region of short GRBs. The lags and peak luminosities are corrected to the source frame of the GRB. The data points labelled as long bursts are from *Swift*, with the exception of GRB 030528 which is a very long-lagged *HETE-2* burst. The blue data points for short bursts are from *Swift*. In green are the 4 nearby long GRBs with associated SNe. The three of the four (980425, 031203 and 060218) fall below the long-burst correlation, while the only SN-associated GRB with normal luminosity (030329) falls near the long-burst line. From [86].

We note that GRB 060505 appears to also be another nearby long GRB with no coincident SN [88]. It was an untriggered *Swift* burst found in ground processing, and so does not have much data from the on-board instruments aside from a BAT light curve and XRT position. The duration was $T_{90} = 4.0$ s. Ground-based studies of the optical afterglow gave an association with a galaxy at $z = 0.089$ and no coincident supernova to deep limits.

7.3. GRB–SN connection future progress

Although the average redshift of *Swift* bursts is large, there are still a good number of events detected at small enough distance for sensitive supernova searches. Table 1 shows that 3 events have $z < 0.1$, giving a nearby-burst detection rate of more than one per year. It is probable that *Swift* will detect 2 or more GRBs with well-observed coincident supernovae (or deep limits) over the next five years. The *Swift* supernova–GRB data set will then be about as large as all previous detections. In addition, the rapid response of the satellite will give coverage to the full supernova light curve from core collapse through the fading of the ^{56}Co decay. Key topics to address in the coming years are as follows.

1. Population of underluminous GRBs. Although rarely detected, the nearby weak bursts with coincident SN greatly outnumber normal GRBs. A uniform search for such events with *Swift* over many years will give a much better determination of the population size.
2. GRB–SN relationship. A key open question is whether all long GRBs have coincident SNe associated with them. Observations over several years with deep optical searches for

SNe will answer this question. There is already a hint from GRB 060614 and 060505 that some long bursts have no associated SN or very faint ones—or perhaps we do not yet know how to distinguish mergers from collapsars.

3. GRB jet physics. Supernova GRBs observed at low redshift provide unique observations of the emergence of jets from the stellar envelope. The *Swift* data are particularly valuable because they start at the time of the collapse and give multiwavelength coverage of the jet emergence. It is anticipated that *Swift* will make such observations about once every two years.

8. Conclusions

Our understanding of GRBs has advanced greatly in the past 2 years. *Swift* is providing rapid and accurate localizations, which lead to intensive observing campaigns by *Swift* and ground-based observatories starting $\sim$1 min after the GRB trigger. Uniform multiwavelength afterglow light curves are available for the first time for a large number of bursts. The data have led to a break-through in our understanding of short GRBs, have extended our knowledge of the high redshift Universe, have elucidated the physics taking place in the highly relativistic GRB fireball outflows and have added significantly to the study of the connection between GRBs and SNe. The *Swift* mission has an orbital lifetime of $>$10 years and no expendable resources on board, and so is likely to expand greatly on these results with detailed observations of $>$1000 bursts.

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