Swift observations of gamma-ray bursts

BY NEIL GEHRELS*

NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

Since its launch on 20 November 2004, the Swift mission has been detecting approximately 100 gamma-ray bursts (GRBs) each year, and immediately (within approx. 90 s) starting simultaneous X-ray and UV/optical observations of the afterglow. It has already collected an impressive database, including prompt emission to higher sensitivities than BATSE, uniform monitoring of afterglows and a rapid follow-up by other observatories notified through the GCN. Advances in our understanding of short GRBs have been spectacular. The detection of X-ray afterglows has led to accurate localizations and the conclusion that short GRBs can occur in non-star-forming galaxies or regions, whereas long GRBs are strongly concentrated within the star-forming regions. This is consistent with the NS merger model. Swift has greatly increased the redshift range of GRB detection. The highest redshift GRBs, at $z \approx 5–6$, are approaching the era of reionization. Ground-based deep optical spectroscopy of high redshift bursts is giving metalliclicity measurements and other information on the source environment to a much greater distance than other techniques. The localization of GRB 060218 to a nearby galaxy, and the association with SN 2006aj, added a valuable member to the class of GRBs with detected supernova.

Keywords: Gamma-ray bursts; high energy astrophysics; space astrophysics

1. Introduction

Gamma-ray bursts (GRBs) are the most powerful explosions in the Universe and are thought to be the birth cries of black holes. They are a product of the space age, discovered by Vela and observed by satellites for 40 years (Klebesadel et al. 1973). Despite impressive advances over the past three decades, the study of bursts remains highly dependent on the capabilities of the observatories that carried out the measurements.

The era of the Compton Gamma-Ray Observatory (CGRO) led to the discovery of more than 2600 bursts in just 9 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 over the sky (Meegan et al. 1991). The hint from earlier instruments was confirmed by the fact that GRBs fall in two distinct classes, short and long bursts, with distributions crossing at approximately 2 s duration (Kouveliotou et al. 1993). The BeppoSAX mission made the critical discovery of X-ray afterglows of long bursts (Costa et al. 1997). With the accompanying discoveries by ground-based telescopes of optical (van Paradijs et al. 1997) and radio (Frail et al. 1997) afterglows, long GRBs were found to emanate from the star-forming regions in host galaxies.

*neil.gehrels@nasa.gov

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galaxies at a 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 (MacFadyen & Woosley 1999).

Section 2 in our understanding of GRBs is being written by the Swift mission. In this paper, we discuss the findings of Swift 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.

2. Swift GRB operations and observations

Swift (Gehrels et al. 2004) carries three instruments, a wide-field burst alert telescope (BAT; Barthelmy et al. 2005a) that detects GRBs and positions them to arcminute accuracy, and the narrow-field X-ray telescope (XRT; Burrows et al. 2005a) and UV–optical telescope (UVOT; Roming et al. 2005) that observe their afterglows and determine positions to arcsecond accuracy, all within approximately 100 s. The BAT detects the bursts in the 15–350 keV band and determines a few arcminute positions onboard within 12 s. The position is provided to the spacecraft, which is then repointed to the burst location in less than 2 min. The XRT and UVOT then observe the afterglow. Alert data from all the three instruments are sent to the ground via NASA’s TDRSS relay satellite. The full dataset is stored and dumped to the Italian Space Agency’s equatorial Malindi Ground Station.

The Swift mission was built by an international team from the US, the UK and Italy. After 5 years of development, it was launched from Kennedy Space Center on 20 November 2004. Full normal operations commenced on 5 April 2005.

As of August 2006, BAT has detected 168 GRBs (annual average rate of approx. 105 per year). Approximately 90% of the 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 the X-ray afterglow. The fraction of rapid-pointing GRBs that have UVOT detection is approximately 30%. Combined with ground-based optical observations, approximately 50% of Swift GRBs have optical afterglow detection.

The distribution in redshift of the 50 Swift bursts with redshift determination 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 \( \langle z \rangle = 2.3 \), when compared with \( \langle z \rangle = 1.2 \) for the previous observations. It is shown by Jakobsson et al. (2006a) that the Swift redshift distribution is consistent with models where the GRB rate is proportional to the star-formation rate in the Universe.

3. Short GRBs

At Swift’s launch, perhaps 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, Swift provided the first short GRB X-ray afterglow localization. This burst plus the HETE-2 GRB 050709 and Swift GRB 050724 led to a breakthrough in our understanding of short bursts (Gehrels et al. 2005; Bloom et al. 2006;
Barthelmy et al. 2005b; Berger et al. 2005; Fox et al. 2005; Hjorth et al. 2005; Villasenor et al. 2005). BAT has now detected approximately 13 short GRBs, most with XRT detections, and about half with host identifications or redshifts (an additional two GRBs have been detected by HETE-2).

In stark contrast to long bursts, the evidence to date on short bursts is that they can originate from regions with low star-formation rates. GRBs 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 in that location. This is illustrated in figure 2 where the images of these three short bursts are contrasted to three typical HST images of long bursts showing their coincidence with regions of star formation (Fruchter et al. 2006). 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 or neutron star–black hole (NS–BH) binaries).

A list of short GRBs detected to date since GRB 050509B is given in table 1. The list includes all bursts that researchers have discussed in the context of short events. Some, such as GRBs 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 even higher.

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 approximately 4 than those of long bursts ($\langle z_{\text{short}} \rangle = 0.5$, $\langle z_{\text{long}} \rangle = 2.3$), and their isotropic energies are smaller by a factor of approximately 100.

### 4. Afterglow physics

Swift was specifically designed to investigate GRB afterglows by filling the temporal gap between observations of the prompt emission and the afterglow (O’Brien et al. 2006). The combined power of the BAT and XRT has revealed that in long GRBs, the non-thermal prompt X-ray emission smoothly transitions into the decaying afterglow (figure 3). Often, a steep-to-shallow transition is found, suggesting that the prompt emission and the afterglow are distinct emission components. The early steep-decay phase seen in the majority of GRBs is a surprise. The current best explanation is that we are seeing high-latitude emission due to the termination of central engine activity (Zhang et al. 2006).

Swift has discovered erratic flaring behaviour (figure 3), lasting long after the prompt phase in approximately 25% of X-ray afterglows. The most extreme examples are flares with integrated power similar to or exceeding the initial burst (Burrows et al. 2005b). The rapid rise and decay, multiple flares in the same burst and cases of fluence comparable to the prompt emission suggest that these flares are due to the central engine.

### 5. High redshift GRBs and cosmology

GRBs, as the most brilliant explosions in the Universe, offer us the potential to probe the early Universe into the epoch of reionization. They can trace the star

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1 $E_{\text{iso}}$ in $1-10^4$ keV in source frame. Duration is in $15-150$ keV band. # = HETE-2. ### = IPN.
formation, reionization and metallicity histories of the Universe (Lamb & Reichart 2000; Ciardi & Loeb 2000; Bromm & Loeb 2002; Lamb 2002). GRBs are 100–1000 times brighter at early times than are high redshift QSOs.

Table 1. Short GRBs with afterglow detection or deep limits.

<table>
<thead>
<tr>
<th>name</th>
<th>redshift</th>
<th>afterflow</th>
<th>host</th>
<th>$E_{\text{iso}}/10^{50}$ erg</th>
<th>duration</th>
<th>$T_{90}$</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>050509B</td>
<td>0.225</td>
<td>X</td>
<td>elliptical</td>
<td>0.13</td>
<td>0.03</td>
<td></td>
<td>low SF region</td>
</tr>
<tr>
<td>050709#</td>
<td>0.161</td>
<td>X, O</td>
<td>SF galaxy</td>
<td>0.6</td>
<td>0.07</td>
<td></td>
<td>low SF region</td>
</tr>
<tr>
<td>050724</td>
<td>0.258</td>
<td>X, O, R</td>
<td>elliptical</td>
<td>4.7</td>
<td>3</td>
<td></td>
<td>low SF region</td>
</tr>
<tr>
<td>050813</td>
<td>1.8?</td>
<td>X</td>
<td>galaxy</td>
<td>1.7?</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>050906</td>
<td>0.03?</td>
<td>—</td>
<td>galaxy?</td>
<td>0.001?</td>
<td>0.13</td>
<td></td>
<td>BAT only</td>
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<td>050911</td>
<td>0.165?</td>
<td>—</td>
<td>cluster</td>
<td>0.9?</td>
<td>16</td>
<td></td>
<td>is it short?</td>
</tr>
<tr>
<td>050925</td>
<td>—</td>
<td>—</td>
<td>in gal. plane</td>
<td>—</td>
<td>0.07</td>
<td></td>
<td>non—GRB</td>
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<tr>
<td>051103##</td>
<td>—</td>
<td>—</td>
<td>near M81</td>
<td>—</td>
<td>—</td>
<td></td>
<td>M81 SGR?</td>
</tr>
<tr>
<td>051105A</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.03</td>
<td></td>
<td>—</td>
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<tr>
<td>051210</td>
<td>0.11?</td>
<td>X</td>
<td>cluster?</td>
<td>0.1?</td>
<td>1.4</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>051221A</td>
<td>0.547</td>
<td>X, O, R</td>
<td>SF galaxy</td>
<td>31</td>
<td>1.4</td>
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<td>—</td>
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<tr>
<td>051227</td>
<td>—</td>
<td>X</td>
<td>—</td>
<td>—</td>
<td>0.9</td>
<td></td>
<td>—</td>
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<tr>
<td>060121#</td>
<td>1.5 or 4.5</td>
<td>X, O</td>
<td>galaxy</td>
<td>—</td>
<td>2</td>
<td></td>
<td>—</td>
</tr>
<tr>
<td>060313</td>
<td>—</td>
<td>X, O</td>
<td>cluster?</td>
<td>—</td>
<td>0.7</td>
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<td>—</td>
</tr>
<tr>
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<td>0.287?</td>
<td>X</td>
<td>elliptical?</td>
<td>0.1?</td>
<td>0.09</td>
<td></td>
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<td>060505</td>
<td>0.089</td>
<td>X, O</td>
<td>galaxy</td>
<td>$\sim$0.5</td>
<td>4</td>
<td></td>
<td>is it short?</td>
</tr>
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<td>0.125</td>
<td>X, O</td>
<td>galaxy</td>
<td>3.7</td>
<td>103</td>
<td></td>
<td>is it short?</td>
</tr>
<tr>
<td>060801</td>
<td>0.131</td>
<td>X</td>
<td>galaxy?</td>
<td>$\sim$13</td>
<td>0.5</td>
<td></td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 1. Redshift distribution of Swift-detected bursts, compared with the pre-Swift sample.
(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 $z=3$.

Six of the eight highest redshift GRBs ever seen were discovered by Swift, including bursts at redshifts $z=5.3$ and 6.3 (Haislip et al. 2006; Jakobsson et al. 2006b;)

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Kawai et al. 2006). Of the GRBs with measured redshift, we find that 4 out of 50 or approximately 8% of Swift GRBs lie at $z>5$, consistent with model predictions (Jakobsson et al. 2006a; Bromm & Loeb 2006). 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 rapidly recognize such bursts and obtain redshifts with large ground-based IR spectrographs.

Figure 4 shows the time evolution of gamma-ray and X-ray fluxes of four high-$z$ GRBs. All of these bursts are exceptionally luminous and long-lasting, and their evolution can be very complex.

6. Probing the GRB–SN connection

(a) 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 any previous burst 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 multi-wavelength observations of the supernova from the time of the initial core collapse.

The spectral peak in prompt emission at approximately 5 keV places GRB 060218 in the XRF (X-ray flash) category of GRBs (Campana et al. 2006), the first such association for a GRB–SN event. SN 2006aj was dimmer by a factor of approximately 2 than the previous SNe associated with GRBs, but still approximately two to three times brighter than the normal SN Ic not associated with GRBs (Pian et al. 2006). Combined BAT–XRT–UVOT observations provided the first direct observation of shock breakout in an SN (Campana et al. 2006; Mazzali et al. 2006). This is inferred from the evolution of a soft thermal component in the X-ray and UV spectra, and early-time luminosity variations.

GRB 060218 was an underluminous burst, as were two of the other three previous cases. Owing to the low luminosity, these events are only detected when nearby and are therefore rare occurrences. However, they are actually approximately 10 times more common in the Universe than the normal GRBs (Soderberg et al. 2006).

(b) 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 $2.2 \times 10^{-5}$ erg cm$^{-2}$) and well studied in the X-ray and optical spectroscopies. With a $T_{90}$ duration of 102 s, it seemingly falls squarely in the long-burst category. A host galaxy was found (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006) at $z=0.125$ and deep searches made for a coincident supernova. All other well-observed nearby GRBs have had supernovae detected, but this one did not to limits greater than 100 times fainter than previous detections (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006).

We have found that GRB 060614 shares some characteristics with short bursts (Gehrels et al. 2006). The BAT light curve shows a first short, hard-spectrum episode of emission (lasting 5 s) followed by an extended and somewhat softer
Figure 4. Light curves (BAT–XRT) of four high-z Swift bursts.

Figure 5. 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. The green data points are the four nearby long GRBs associated with the SNe. Three of the four SNe-associated underluminous nearby GRBs (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 Gehrels et al. (2006).
episode (lasting approx. 100 s). The total energy content of the second episode is five times that of the first. This light curve shape 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 (Norris & Bonnell 2006). 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 (Gehrels et al. 2006). Figure 5 shows the peak luminosity ($L_{\text{peak}}$) in Swift GRBs as a function of their spectral lag ($t_{\text{lag}}$) between the 50–100 keV and 15–25 keV bands. For long bursts, there is an anti-correlation between $t_{\text{lag}}$ and $L_{\text{peak}}$, whereas short bursts have small $t_{\text{lag}}$ and small $L_{\text{peak}}$ and occupy a separate area of parameter space. The lag for GRB 060614 for the first 5 s is $3 \pm 6$ 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 GRB 060614 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 as 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 an NS–BH scenario. In any case, this peculiar burst is challenging our classifications of GRBs.

7. 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 within approximately 1 min of 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 breakthroughs in our understanding of short GRBs, extended our knowledge of the high redshift Universe, elucidated the physics taking place in the highly relativistic GRB fireball outflows and added significantly to the study of the connection between the GRBs and SNe. The Swift mission has an orbital lifetime of greater than 10 years and no expendable resources on board, and so is likely to greatly expand on these results with detailed observations of greater than 1000 bursts.

References


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