

GAMMA-RAY BURST: DISCOVERIES WITH *Swift*

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Gamma Ray Bursts (GRBs) are bright, brief flashes of high energy photons and are the most powerful explosions since the Big Bang, with typical energies up to around 10^{51} ergs. Their outbursts persist for durations ranging from milliseconds to tens of seconds or more. In these brief moments the explosions radiate more energy than the Sun will release in its entire 10 billion year lifetime. They come in two classes: long ($\gtrsim 2$ s), soft spectrum bursts and short, hard events. Current theories attribute these phenomena to the final collapse of a massive star, or the coalescence of a binary system induced by gravity wave emission.

New results from Swift and related programmes offer fresh understanding of the physics of gamma-ray bursts and of the local environments and host galaxies of burst progenitors. Bursts found at very high red-shifts are new tools for exploring the intergalactic medium, the first stars and the earliest stages of galaxy formation.

1. Introduction

Gamma Ray Bursts (GRBs) were first discovered in the late 1960s (Klebesadel et al. 1973). They come in two classes: long ($\gtrsim 2$ s), soft spectrum bursts and short, hard events (Kouveliotou et al. 1993). Results from the Compton Gamma-ray Observatory (CGRO) showed them to be distributed isotropically over the sky occurring at a rate of about 300 per year (Meehan et al. 1991). The BeppoSAX mission made the important discovery of X-ray afterglows associated with long bursts. (Costa et al. 1997). Follow-up observations found afterglows at optical (van Paradijs et al. 1997) and radio (Frail et al, 1997) wavelengths and provided redshift (and hence distance) measurements to place upper bounds on the total energy ($\lesssim 10^{51}$ ergs/s) of the bursts. Identification of the hosts showed—at least for the Deposal sample—that long GRBs emanated from regions of high star formation rate in high redshift galaxies. The afterglow observations provided compelling evidence in support of the fireball model which associates the burst and

the subsequent afterglow with shocks generated within highly relativistic jets ejected from the progenitor (Meszaros & Rees, 1997). Deposal and HETE-2 between them found a small sample of closer GRBs, most notably GRB030329/SN2003d, in association with Type 1c supernovae pointing to collapse of the central core of a massive early type star and formation of a black hole as the precursor to the GRB outburst. (MacFadyen & Woosley, 1999). However, prior to Swift, most afterglow data were collected hours after the burst so little was known about the origins of the short bursts or about the early emission behaviour of the high red-shift long bursts.

2. Observations with *Swift*

The Swift satellite (Gehrels et al. 2004) was specifically designed to study early GRB emissions and to detect the afterglows by automatically slewing to a GRB as soon as it had been detected on-board. Swift carries a sensitive coded mask Burst Alert Telescope (BAT) and finds new GRBs by detecting gamma ray emission in the 15-150 keV range. When BAT detects a new burst, subject to certain visibility constraints, Swift autonomously re-points to bring the GRB within the field of view of the X-ray Telescope and the UV/Optical Telescope. Observations with these instruments start very quickly after the initial burst detection from which precision location of the bursts, to arc-second accuracy, are usually obtained. Accordingly, Swift routinely provides prompt detections of GRBs and their afterglows and automatically transmits their locations and other information obtained from the three instruments via the TDRSS satellites and the Gamma-ray burst Coordinate Network (GCN) to observers and robotic telescopes around the world.

Swift was launched on November 20 2004 and has since been detecting GRBs at the predicted rate of 100 per year. At the time of the Erice meeting, 140 GRBs had been detected and, in most cases, the spacecraft was able to slew to the source within 5 minutes of the initial detection-often much more quickly. X-ray afterglows were detected on-board in virtually all of these promptly observed bursts, whereas optical/uv afterglows were detected on-board in only 30

Swift is locating many more high redshift ($z \gtrsim 2$) bursts than previous missions. Indeed, the majority of Swift GRB detections to date have been of the long burst variety, and studies of the early afterglows, previously inaccessible, have added to evidence supporting the view that long duration bursts are produced during the collapse of a massive star. Redshifts have now been measured for over 50 long bursts including the first GRB at very

high redshift ($z \geq 6$). (Cusumano et al., 2006, Haislip et al. 2006, Kawai et al. 2006.). These bursts are providing new ways to probe the high redshift universe (Lamb, 2007 and Ghirlanda, 2007) and Tanvir & Jakobsson, 2007, discuss conditions under which GRBs may be used as a tracer of the star formation rate in high redshift galaxies.

Swifts multi-wavelength measurements (gamma-ray to optical/uv) of the exceptional nearby burst GRB 060218 ($z = 0.033$) have provided a direct observation of the shock breakout in a supernova collapse (Blustin, 2007, Campana et al. 2006, Zhang et al. 2007), this observation adding to the small sample of previously observed nearby long GRBs associated with supernova collapse. More recently, Swift has found two bursts, GRB 060614 and GRB060505 for which no supernova association has been found down to deep limits (Watson et al, 2007 and references therein).

Swift also made the first X-ray afterglow localisation of a short burst and has since found several more along with two additional detections with HETE-2. (Gehrels, 2007, and references therein). Most Swift short bursts have X-ray afterglow detections and about half have host identifications and redshifts. Gehrels, (2007), and Barthelmy, et al. (2007) remark on the similarity of the emission of GRB 060614 with the peak luminosity and spectral lags seen in short bursts whilst its afterglow emissions are more characteristic of a low-redshift long bursts despite the non-detection of a coincident supernova to deep limits.

Various new features of GRB phenomenology, such as the soft tail in the spectra of short hard bursts; X-ray flares in the early afterglow indicating extended activity of the central engine in GRBs; GRBs associated with supernovae; GRBs with no supernovae; energetic supernovae with no GRBs; are all discoveries from the Swift era. All offer new challenges to current theoretical understanding. Many have been addressed in the papers in this volume.

3. Models, progenitors and jets

Woosley and Zhang (2007) remark on this diversity of burst phenomena and argue in favour of a single basic model for the central engine operating in a massive star but allowing for variable pre-supernova mass and different rotation and mass loss rates. Metallicity is a key factor affecting all three of these properties. The central engine must generate both a narrowly collimated, highly relativistic jet to make the GRB, and a wide angle, sub-relativistic outflow responsible for exploding the star and illuminating the supernova. As the two components may vary independently, it is possible

to produce a variety of jet energies and supernova luminosities. They go on to explore the production of low energy bursts and find a lower limit (1048 ergs/s) to the power that a jet requires in order to escape a massive star before that star either explodes or the core is accreted. Lower energy bursts may be particularly prevalent when the metallicity is high, i.e., in the nearby universe at low redshift. Conversely, Podsiadlowski (2007) discusses the potential of a variety of binary merger models to account for the diversity of long duration GRBs.

Pe'er et al (2007) suggest that thermal radiation may accompany the first stages of a GRB, to explain observed features in the prompt gamma emission which are inconsistent with the optically thin synchrotron emission more commonly associated with the fireball model. Lazzati et al. (2007) model hydrodynamic propagation of a relativistic jet through a massive star and find radiative phases in the jet propagation which could contribute to the GRB light curves. The scenario of jet evolution described in this work may also provide an explanation for the long dead-times between precursor and the main GRB emission seen occasionally with BAT and previously with BATSE bursts from CGRO.

4. Afterglows

Swift has filled the temporal gap between the prompt emission and the afterglow that earlier missions were generally unable to probe. O'Brien & Willingale (2007) have shown that light curves combined from BAT and XRT show an essentially smooth transition between the non-thermal prompt X-ray emission and the decaying X-ray afterglow. They and others (Piran & Fan, 2007, Panaitescu, 2007, Burrows et al. 2007 and references therein) agree on the generic nature of early GRB light curves, as illustrated in Figure 1, with the proviso that not all phases in the afterglow evolution shown in the figure are present in all bursts thus suggesting that several different dissipation processes may be involved.

When present as the dominant feature, the initial steep decay is usually attributed to large angle high latitude emission produced from internal shocks; when the slower unbroken power law decay is dominant this is attributed to forward shock emission from a narrow jet. Most bursts appear to exhibit a combination of both features. About half of the afterglows have X-ray flares superimposed on the broken power law curve, as illustrated in Fig. 1, (Burrows et al, 2007) also indicative of continuing activity within the central engine for extended periods after the initial outburst. Piran & Fan, 2007, Panaitescu, 2007, and others have discussed added complexity

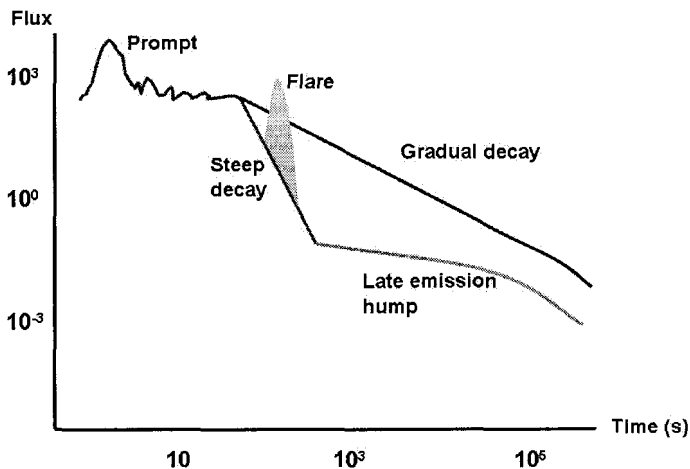


Fig. 1. A schematic view of the early GRB X-ray light curve. Following the prompt emission, which typically lasts a few 10s of seconds, the decay tends to follow one of two paths: (i) a steep decay, during which the flux can fall by several orders of magnitude, followed by a shallower, late emission hump starting at 10^3 s; or (ii) a more gradual decay. Either decay path can end with a break at $>10^4$ s to a steeper decay. X-ray flares can occur during either decay path, most prominently during the first hour. (O'Brien & Willingale, 2007)

to afterglow models needed to fully understand these new features.

Optical afterglows have been monitored on-board Swift with the UVOT telescope (Mason et al, 2007) as well as with ground based telescopes (e.g. Antonelli et al, 2007). Results indicate considerably more complexity in many bursts than would be expected from the standard fireball model and varying degrees of correspondence between the X-ray and optical light curves. In this respect GRB 050525A may be an exception as it exhibits an achromatic jet break at 104s, although, even in this case, the decay indices are shallow compared with what might be expected from the standard model (Zhang et al, 2007, and references therein). Afterglow behaviour from other bursts is not so easily interpreted and the absence of jet breaks in the X-ray afterglow, when present in the optical remains to be understood.

Radio monitoring of GRB afterglows, enable the evolution of GRB explosions to be monitored long after the X-ray and optical afterglows have faded. GRB 030329 is still visible at radio wavelengths 1100 days after the burst trigger (van der Horst et al., 2007) and continuing monitoring is re-

vealing structural evolution of the burst with and indicating transition from a collimated relativistic outflow to spherical non-relativistic outflow during this period.

5. Short-hard gamma-ray bursts

Swift's discovery of the first afterglows from short-hard Gamma-ray bursts is being followed by a systematic study of short bursts through X-ray, optical and radio afterglow measurements of multiple short bursts. (Fox & Roming, 2007, Barthelmy, 2007, Levan, 2007, Zane, 2007, and references therein). Their distance scale ($z < 0.1$) and energetics ($E > 10^{48}$ erg) are now established, and they have been revealed definitively as a cosmological phenomenon. The short bursts have been found among old stellar populations in elliptical galaxies, galaxy clusters and the outskirts of younger galaxies and the absence of associated supernovae appear to rule out an origin in the deaths of massive stars. This is in contrast to the now accepted view of the origins of long-duration gamma-ray bursts (GRBs), whose host galaxies, redshifts, and associated supernovae are all consistent with the collapsar-supernova model.

The effect of these discoveries has been to strongly favour the compact-object merger model for short bursts. The observed properties point to coalescence of a compact-object binary, either neutron star-neutron star or neutron star-black hole (King, 2007) and enabling the prospects for gravitational-wave detection to be re-assessed (Hough, 2007).

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