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Swift: Highlights on GRBs

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Abstract. Swift, with its rapid slewing and multiwavelength capability, is revolutionising the study of GRBs. The light curves of hundreds of bursts are now available on time scales from ∼ 1 minute up to weeks and, in some cases, months from the burst explosion. These data allow us to investigate the physics of the highly relativistic fireball outflow and its interaction with the circumburst environment. Here we review the main results of the Swift observations, that led to the discovery of very high redshift GRBs, up to z=6.29, of a SN in the act of exploding and of the afterglows of short-GRBs. The evolution of the X-ray light curves in the early phases are characterised by different slopes, with a very steep decay in the first few hundred of seconds, followed by a flatter decay and, a few thousand of seconds later, by a somewhat steeper decay. Often strong flare activity up to few hours after the burst explosion is also seen. These flares, most likely, are still related to the central engine activity, that last much longer than expected, still dominating the X-ray light curve well after the prompt phase, up to a few thousand of seconds. The late evolution of the X-ray light curves is also puzzling, many of them not showing a "jet-break". All this indicates that a clear understanding of the formation and evolution of the jet and of the afterglow emission is still lacking.

Key words. Gamma rays: gamma ray burst – X-ray: gamma ray burst Supernovae: general – Cosmology: young universe

1. Introduction

Gamma ray bursts (GRBs) are bright and short flashes that can come from any location in the sky (Klebesadel et al. 1973). Although for a few seconds they outshine the gamma-ray sky, they have been very enigmatic objects for decades. This is due to the fact that gamma-ray detectors provided their position with very loose accuracy (a few degrees). This together with their short duration and non-repeating nature, made almost impossible to study these objects in the other bands. Even their galactic or extragalactic nature has been unclear for decades. Essentially, only the properties of the prompt emission could be investigated. A big step forward in the study of these objects came with the BATSE experiment on board the Compton Gamma Ray Observatory (CGRO) satellite, that discovered more than 2600 GRBs in about nine years, showing that these objects are isotropic on the sky and that there are roughly two such explosions each day (Meegan et al. 1991). BATSE also showed that GRBs can be divided in two large groups, the long-GRBs, that usually last more than 2 seconds and have a softer gamma-ray spectrum and the short-GRBs that last less than 2 sec-

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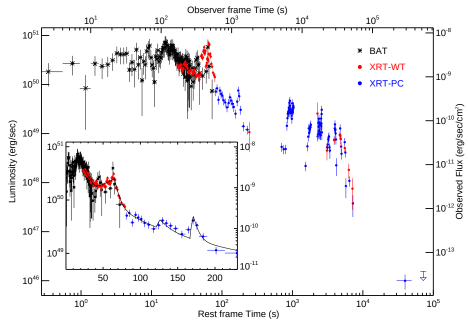

Fig. 1. The X-ray light curve of the very high redshift, z=6.29, GRB050904, note the continuous flare activity up to 10^4 s in the source rest frame (from Cusumano et al. 2007).

onds and have a harder spectrum (Kouveliotou et al. 1993). But the most important discoveries came with the Italian-Dutch satellite *Beppo*SAX that discovered the existence of X-ray afterglows associated to long-GRBs (Costa et al. 1997). The fast and good position accuracy provided by *Beppo*SAX on the X-ray afterglows allowed also the discovery of optical and radio afterglows (van Paradijs et al. 1997; Frail et al. 1997). Thanks to *Beppo*SAX, the cosmological nature of GRBs was finally established. It was also found that long GRB were associated with star forming regions and that at least some of them were clearly associated with very powerful core-collapse supernovae, or hypernovae (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004), strongly suggesting that the progenitors of long-GRBs are massive stars whose central core collapses to a black hole (collapsar model) (MacFadyen & Wosley 1999). Finally, decisive discoveries in the study of GRBs are now coming from the Swift satellite. Here we will outline the most relevant results that have been obtained so far with Swift.

2. The Swift satellite

The Gamma Ray Burst (GRB) studies in the pre-Swift era showed that the afterglows associated with GRBs are rapidly fading sources and most of them, if not all, had an associated X-ray afterglow, while only about 60% of them had also an optical afterglow, i.e. a good fraction of them were dark–GRBs (see Zhang & Mészáros 2004 for a general discussion on GRBs and their afterglows). Therefore, it was clear that to properly study the GRBs, and in particular the associated afterglows, we needed a fast-reaction satellite capable of detecting GRBs and of performing immediate multiwavelength follow-up observations, in particular in the X-ray and optical bands. *Swift* is designed specifically to study GRBs and their afterglows in multiple wavebands. It was successfully launched on 2004 November 20, opening a new era in the study of GRBs (Gehrels et al. 2004). *Swift* has on board three instruments: a Burst Alert Telescope (BAT) that detects GRBs and determines their positions in the sky with an accuracy better than 4 arcmin in the band 15-150 keV (Barthelmy et al. 2005a); a X-Ray Telescope (XRT) that provides fast X-ray photometry and CCD spectroscopy in the 0.2-10 keV band with a positional accuracy better than 5 arcsec (Burrows et al. 2005); an UV-Optical Telescope (UVOT) capable of multifilter photometry with a sensitivity down to 24^{th} magnitude in white light and a 0.5 arcsec positional accuracy (Roming et al. 2005).

2.1. High-redshift GRBs

Swift is detecting about 100 GRBs per year. While essentially all Swift long burst have an X-ray afterglow, about 1/3 of them do not have an optical afterglow, despite prompt and deep searches. For a good fraction of them, the lack of an optical afterglow could be due either to dust extinction and/or high redshift. Indeed, the mean redshift of the GRBs sample detected so far by Swift is z $\sim$ 2.5 (this number changes somewhat while new burst are discovered, however it has always been between 2.3 and 2.8), significantly larger than that measured for pre-Swift events, providing a new possibility to study the young Universe. This was demonstrated by the most distant GRB050904 detected by swift at z=6.3 (see Fig. 1), whose emission was observable for several days (Tagliaferri et al. 2005a; Kawai et al. 2006; Cusumano et al. 2007). GRBs have the potential to probe the early Universe past the reionisation (z>6-7) epoch and up to the dark ages (i.e. when the light was absorbed by the neutral hydrogen), marking the moment of the first light in the Universe. The light from a GRB bears the imprint of the intervening matter, so that GRBs are also ideal probes of the high-redshift diffuse medium, and can be used to test the chemical enrichment in galaxies in the very young Universe. Therefore Swift GRBs are very promising for the study of the high redshift Universe. Given their origin in core-collapse SNe, long-GRBs are intrinsically tied to the cosmic star formation, and their sight lines directly probe the high-redshift star forming regions.

2.2. The GRB-SN connection

The SN-GRB connection has opened a fresh window on the study of massive star death in the local Universe, with GRB-SN being observable to z $\leq$ 0.5. Given that Swift is detecting GRBs on average at very high redshift, we have only a couple of Swift bursts that can be clearly associated to a SN. Still, Swift has significantly advanced our studies on the SN-GRB connection, in particular with the recent detections of two bursts: GRB060218 and GRB060614. GRB060218 was a nearby GRB (z=0.033), associated with a bright type Ic SN. Its X-ray spectrum shown a thermal component, that cooled steadily until its emission shifted into the optical/ultraviolet band (Campana et al. 2006; Pian et al. 2006; Soderberg et al. 2006). This has been recognised to be the break-out of a shock wave, driven by a relativistic shell, into the dense wind surrounding the progenitor, a massive Wolf-Rayet star. With this event, and for the first ever time, Swift has caught a SN in the act of exploding, directly observing the shock break-out. GRB060614 is another very nearby GRB (z=0.125) detected by Swift that exhibited opposite characteristics. It is important because, despite its proximity, it showed no sign of an associated SN, down to a limit at least 100 times fainter than the other SNe associated with GRBs (Della Valle et al. 2006; Fynbo et al. 2006). This opened a new paradigm for the association of GRBs with massive stellar collapse, demonstrating that some long GRBs may be associated with a very faint SN or be produced by different phenomena and leading to a detailed reanalysis of the original data, that finally questioned its membership of the class of long-GRBs: in fact, although the burst had a duration as long as ~ 100 s, its temporal lag and peak luminosity are typical of short-duration GRBs (Gehrels et al. 2006). All this led Zhang et al. (2007) to propose a new terminology, classifying the burst in “Type I” and “Type II”, instead of short and long. This new classification scheme would not be based just on the prompt properties, but on the properties both of the prompt, of the associated afterglow and of the host galaxy properties. We need now other examples to reach more firm conclusions.

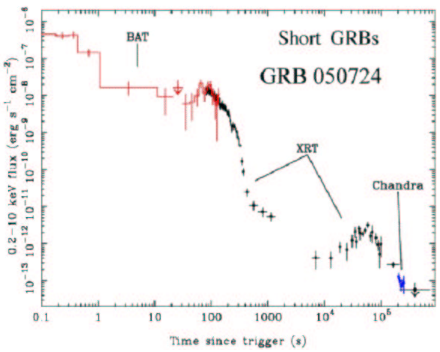

Fig. 2. The total X-ray light curve of the short GRB050724, from the prompt emission detected by BAT to the X-ray afterglow measured by XRT and later by Chandra. Note the second bump detected both by BAT and XRT around ~ 80 s after and the late flare activity detected by XRT a few ten thousand seconds after the trigger (from Barthelmy et al. 2005b).

2.3. The short GRBs

One of the most important breakthrough discovery of Swift is the detection of the X-ray afterglows of short-GRBs, that were not possible with *Beppo*SAX. Therefore their distance, energy scale and progenitors were unknown. The first discovery came with the detection of the

X-ray afterglow associated to GRB050509B (Gehrels et al. 2005). Contrary to that of the long GRB, this X-ray afterglow was very weak and associated to a bright nearby elliptical galaxy with no star formation activity, no optical afterglow was detected. This burst together with GRB050709 detected by HETE-II (Villasenor et al. 2005) and GRB050724 (Barthelmy et al. 2005b), detected again by Swift, led to a breakthrough in our understanding of these objects. The identification of X-ray, optical and radio counterparts of short GRBs allowed us to determine that they have total energies of $\sim 10^{48} - 10^{52}$ *ergs*, 2-3 orders of magnitude lower than those of long GRBs. Although their host galaxies can be quite different, ranging from very early to late types, they often lie at the outskirts of these galaxies, never associated with star forming regions. So far Swift has localised 20 short GRBs, about half have an optical afterglow and 6 a well-determined, but relatively low redshifts ($z \sim 0.2 - 0.4$). For some of the other short bursts there are indication that they could be at higher redshift ($z \sim 1 - 2$), but they are not conclusive. Their afterglows are weaker than those of long GRBs and imply relatively low ($n \sim 0.05$ cm^{-3}) or very low ($n \leq 10^{-5}$ cm^{-3}) density environments. This means that they are detected only for a few hours-days after the explosion, both in the X-ray and in the optical bands. Probably the most remarkable observation of an afterglow associated to a short burst is that one of GRB050724, that shows a rich temporal and spectral phenomenology in the X-ray band (Barthelmy et al. 2005b) (see Fig. 2). After the first short (0.25 s) bright peak, the BAT light curve shows an additional soft emission lasting for more than 100 s, while flare activity on late timescales is detected in the X-ray light curve of the afterglow. This is not easily explained by the standard coalescence model, implying more complex process around or from the nascent black-hole.

All this indicates that short GRB have different progenitors, different intrinsic properties and different surrounding densities, than the long ones. The tight upper limits on any associated SN rule against models involving core-collapse SN explosions. Most likely short-

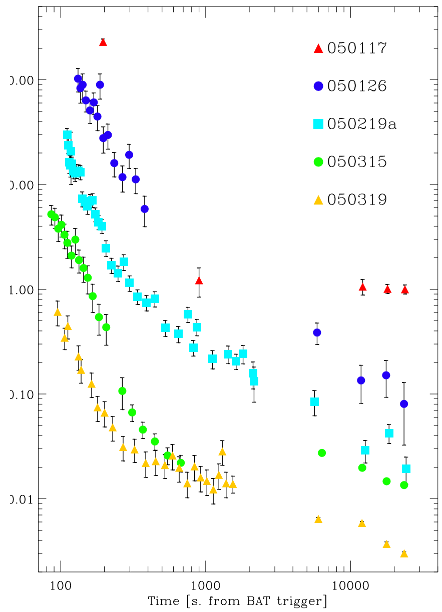

Fig. 3. X-ray light curve of GRB afterglows as observed by Swift-XRT. Note the very steep decay and then the flattening detected in the early phases for the majority of the Swift GRBs (from Tagliaferri et al. 2005b).

bursts are due to the merging of a double neutron star binary system. In these systems, the delay between binary formation and merging is in the range 0.1-1 Gyr. Therefore, before the merging takes place these systems could have moved away from the star-forming regions and perhaps even from the galaxy in which they formed. This could explain why in some cases we are not able to identify the host galaxy. Clearly, statistically more significant samples are now required to make further progress.

3. The X-ray afterglows early phases

The X-ray observations obtained with *Beppo*SAX and other X-ray satellites before the advent of Swift showed that the X-ray afterglow light curves from $\gtrsim 6$ hours after the explosion are well represented by a simple power law decay with a decay index of the order of $\alpha \sim 1.4$. However, as often is the case when a new observing window became available, the XRT data presented us with expected but also unexpected results. The XRT confirmed that essentially all long GRBs are accompanied by a X-ray afterglow, there are only a couple of them that have been fastly repointed by Swift and do not have an associated X-ray afterglow (e.g. Page et al. 2006). However, the source decay does not follow the expected smooth power law behaviour, rather it is usually characterised by a very steep early decay (Tagliaferri et al. 2005b) (see Fig. 3), followed by a flatter decay and then a somewhat steeper decay (Nousek et al. 2006).

Do we have an explanation for what we are observing? The most likely explanation for the steep early decay is that this is still due to the prompt emission. Thanks to the fast reaction of the Swift satellite often we are able to detect the prompt emission also with the XRT telescope and the steep decay that we are observing is probably due to the “high-latitude emission” effect: when the prompt emission from the jet stops, we will still observe the emission coming from the parts of the jet that are off the line of sight (Kumar & Painatescu 2000; Tagliaferri et al. 2005b). This interpretation is supported by the fact that the prompt BAT light curve converted in the XRT band joins smoothly with that one seen by XRT for almost all of the Swift GRBs (Barthelmy et al. 2005c; O’Brien et al. 2006; Vaughan et al. 2006) (see Fig. 4). The origin of the flatter part that follow the early steep decay, that is well represented by a power law with slope $0.5 \lesssim \alpha \lesssim 1$, is more controversial. The total fluence that is emitted during this phase is comparable to, but it does not exceed that one of the prompt phase (O’Brien et al. 2006). It is probably a mixture of afterglow emission (the forward shock) plus a continuous energy injection from the central engine that refreshes the forward shock. When this energy injection stops, the light curve steepens again to the usual power law decay already observed in the pre-Swift era (Nousek et al. 2006). Not all bursts show the steeper+flatter parts, a significant minority of them show a more gradual decay with $\alpha \lesssim 1.5$ (e.g. Campana et al. 2005). These are more

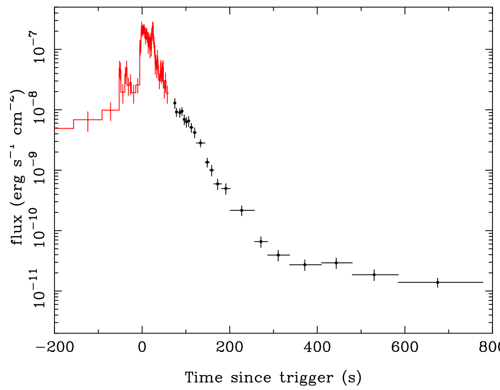

Fig. 4. This figure shows the prompt BAT light curve converted into the XRT X-ray band and the subsequent X-ray light curve as seen by XRT. Note how the two light curves match perfectly, strongly supporting the idea that the steep X-ray emission seen by XRT is an extension of the fading prompt emission (from Vaughan et al. 2006).

consistent with the classical afterglow interpretation in which the X-ray emission is simply due to the external shock. The flatter part is not seen either because in these cases the continuous activity from the internal engine is not present, or because the afterglow component is much brighter and it dominates over the internal contribution.

3.1. The flares

When XRT detected the first flares in the X-ray light curve of GRB050406 and then of GRB050502B (Burrows et al. 2005b; Romano et al. 2006; Falcone et al. 2006), this came as a full surprise (although X-ray flares were already detected by *Beppo*SAX in a couple of bursts, which were interpreted as due to the onset of the afterglow (Piro et al. 2005). We now know that X-ray flares are present in a good fraction of the XRT light curves (e.g. (Chincarini et al. 2007)). Flares have been detected in all kinds of bursts: in X-ray flashes (XRF) (Romano et al. 2006), in long GRBs, including the most distant one at redshift z=6.29 (see Fig. 1) and in short GRBs (see Fig. 2). These flares are usually found in the early phases up to a few thousand of seconds, but in some cases they are also found at $> 10^4$ s (see Fig. 1,2). The ratio between their duration and peak time is very small, ~ 0.1, with late flares having longer duration (Chincarini et al. 2007). They can be very energetic and in some cases can exceed the fluence of the prompt emission (Falcone et al. 2006). The fact that in the X-ray light curve of the same GRB there are more than one flare argues against the interpretation that the flares correspond to the onset of the afterglow. Moreover, they do not seem to alter the underlying afterglow light curve that after the flare follows the same power law decay as before the flare. Therefore, since the beginning it was clear that these flares were correlated to the central engine activities and not to the process responsible for the afterglow emission.

The X-ray spectra of the afterglows are well fitted by a simple power law model plus absorption, with an energy spectral index of $\beta \simeq 1$. While the flares spectra are usually harder and, for the strongest ones that have better statistics, more complex models, such as a Band function or a cutoff power law, are needed. Spectral evolution during flares is common, with the emission softening as the flare evolves, again a behaviour similar to that seen during the prompt phase (Falcone et al. 2006, 2007; Kocevski et al. 2007). Given this similarities between the prompt and the flares properties, one would expect that X-ray flares are more common in those bursts with a prompt characterised by many pulses. But there seems to be no correlation between the number of pulses detected in the prompt phase and the number of X-ray flares detected by XRT. However, the distribution of the intensity ratio of consecutive BAT prompt pulses and that one of consecutive XRT flares is the same, another piece of evidence that prompt pulses and X-ray flares have a common origin. Although various models have been proposed to explain the presence of these X-ray flares, all these properties indicates that they are related to the central engine activities and that they are due to the internal shocks, rather than the external shocks (Chincarini et al. 2007).

3.2. The late X-ray light curve: any evidence for a jet break?

In the standard fireball scenario (see (Mészáros 2002) and references therein) the afterglow emission is due to the deceleration of the expanding fireball by the surrounding medium (external shock). If the expanding fireball is collimated in a jet, then we expect to see an achromatic break in the power law decay at the time when the full jet opening angle becomes visible to the observer (Rhoads 1999). The evaluation of the beaming factor is very important in order to determine the total energy emitted by the burst, in fact if we assume isotropic radiation this energy can range up to 10^{54} ergs. A value that is difficult to explain, unless a beaming correction is applied. Breaks were detected a few days after the explosion in the optical and radio light curves of burst detected before the Swift advent. If interpreted as jet-breaks, then the correct total energy emitted in the gamma band by the prompt clusters around 10^{51} ergs (Frail et al. 2001). There seem to be also a tight correlation between this energy and and the peak energy of the prompt spectrum (Ghirlanda et al. 2004).

If these breaks are really due to a jet, then they should be seen simultaneously also in the X-ray band. Before the advent of Swift the observations in the X-ray band were limited and there were only few measurements. Now thanks to XRT we have many detailed X-ray light curves and the picture is not so clear any more. First of all as we have seen, in the early phases there can be more than one break, but none of them seems to be due to a jet-break. Rather they are probably due to the activity of the internal engine, as we have seen previously. Moreover, for some of these bursts we have also the early optical data and the breaks are not seen in the optical, therefore they are not achromatic (see Fig. 5). This behaviour can be explained either by assuming an evolution of the microphysical parameters for the electron and magnetic energies in the forward shock or by assuming that the X-ray and optical emission arise from different components (Panaitescu et al. 2006). In any case, from a systematic analysis of the XRT

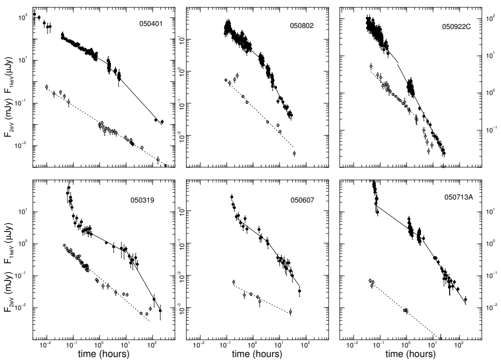

Fig. 5. The X-ray and optical light curves of six Swift GRB afterglows that show a chromatic X-ray break not seen in the optical (from Panaitescu et al. 2006).

light curves of 107 GRBs, 72 afterglow breaks are found, but of these only 12 are consistent with being jet-breaks and only 4 are not related to the early flat phase (Willingale et al. 2007). In other words there are only 4 breaks that are good candidates for being jet breaks. Therefore, contrary to the earlier expectations, jet-breaks seem to be the exception and not the rule in the X-ray light curves of GRB afterglows. This has implications also on the correlation between the prompt peak energy and the beaming corrected prompt energy (Ghirlanda et al. 2004). In fact, either this correlation somehow is valid only for breaks observed in the optical and not in the X-ray or it is valid only for a subsample of GRBs whose properties have still to be defined and it is not as tight as previously thought.

4. Conclusions

After more than 2.5 years of Swift operations, the data provided by the satellite allowed us to make break-through discoveries in various field of the GRB studies including the detection of the afterglows of short GRBs, the detection of a SN in the act of exploding and the possible identification of a new sub-class of GRBs. The detection of very high redshift GRBs, possibly up to the reionisation era, is opening a new window in the study of the young Universe. As for the high redshift quasar, we can use them to illuminate the intervening matter, testing the chemical enrichment of their high redshift host galaxies and of the other intervening clouds. But, unlike the quasar, they do not suffer of the "proximity effect" and they quickly fade away, giving us the possibility to study the environment unperturbed by their presence.

Thanks to the Swift fast repointing and its instrumentation capabilities, we have now the fast localisation of GRB with an accuracy of few arcsec, which allows us to immediately start ground-based observations. Uniform multiwavelength light curves of the afterglows are available starting from $\sim$ 1 minute after the burst trigger. In particular, we have hundreds of X-ray light curves spanning the range from few tens of seconds up to weeks and months after the explosion. These data allow us to investigate the physics of the highly relativistic fireball outflow and its interaction with the circumburst environment.

Unexpectedly, these X-ray light curves are characterised by different slopes in the early phases and often by the presence of strong flare activity up to few hours after the burst explosion. The picture that is consolidating is that the central engine activity lasts much longer than expected and it is still dominating the X-ray light curve well after the prompt phase, up to a few thousand of seconds. The external shock, the real afterglow, takes over the emission only after the end of the flatter phase, although some flare activity can be still detected during these later phases. Finally, even the evolution of the XRT light curve at the later phases is providing more questions than solutions. In particular, the lack of a "jet-break" in many of these light curves is puzzling. There are various possibilities to explain these observations (e.g.time evolution of the microphysical parameters, structured jet). However, a clear understanding of the formation and evolution of the jet and of the afterglow emission is still lacking.

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