The early X-ray afterglows of Gamma Ray Bursts

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Abstract. The X-ray light curves of hundreds of bursts are now available, thanks to the X-ray Telescope on board the Swift satellite, 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 XRT observations, with particular regard to the evolution of the X-ray light curves in the early phases. Unexpectedly, they 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 and it is still dominating the X-ray light curve well after the prompt phase, up to a few thousand of seconds. The real afterglow emission (external shock) is dominating the X-ray light curve only after the flatter phase ends. The flatter phase is probably the combination of late-prompt emission and afterglow emission. When the late-prompt emission ends the light curve steepens again. Some flare activity can still be detected during these later phases. Finally, even the late evolution of the XRT light curves is puzzling, in particular many of them do not show a “jet-break”. 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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INTRODUCTION

The first afterglow associated to a Gamma Ray Burst (GRB) has been detected in the X-ray band, thanks to BeppoSAX observations [1]. Optical and radio afterglows were soon discovered [2, 3]. These discoveries opened a new era in the studies of GRBs and their associated afterglows. First of all, they showed that GRBs are at cosmological distances and therefore they are the most powerful explosions in the Universe after the Big Bang. Thanks to the firm association of a GRB with a core-collapse SN in at least four cases, it is now generally believed that the progenitors of long-duration GRBs are massive stars, thus supporting the collapsar model (see recent review from [4] and references therein). While short-duration GRBs probably arise from the merger of two compact objects; this is based on 1) their position inside their host galaxies (HG), 2) the properties of the HG and 3) the properties of their light curves [5, 6, 7, 8, 9].

The studies in the pre-Swift era showed that the afterglows associated with GRBs are rapidly fading sources, with X-ray and optical light curves characterised by a power law decay $\propto t^{-\alpha}$ with $\alpha \approx 1.5$. Moreover, while most of the GRBs, if not all, had an associated X-ray afterglow only about 60% of them had also an optical afterglow,
FIGURE 1. Left panel: X-ray light curve of a typical GRB afterglows as observed with BeppoSAX. Note how the backward extrapolations of the afterglow light curves matched the flux of the burst itself. Therefore, we were expecting a smooth power law decay of the X-ray afterglow light curve since the first phases, gaining a few order of magnitude in source brightness. Right panel: on the contrary a very steep decay and then a flattening is detected in the early phases for the majority of the Swift GRBs (from [18]).

i.e. a good fraction of them were dark–GRBs (see [10] 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 [11]. 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 [12]; 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 [13]; 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 [14].

In the first two years of operation Swift has detected about 200 GRBs. Soon after detection the satellite autonomously determines if it can repoint the narrow field instruments to the burst location and, if possible, it usually slews to the source in less than 100-150 seconds. Therefore, we have now X-ray light curves of hundreds of bursts that cover a time interval from few tens of seconds up to weeks and months for some of the bursts. As expected, the most spectacular results have been obtained in the first few thousand seconds, i.e. in the gap not covered by the previous missions. In particular, the XRT observations have shown that the burst X-ray light curves in the early phases are much more complex than a simple backward extrapolation of the power law light curves observed few hours after the GRB explosion. Here we will outline the most relevant
results that have been obtained so far thanks to the XRT observations.

THE X-RAY LIGHT CURVES

The early phases

The X-ray observations obtained with BeppoSAX and other X-ray satellites before the advent of Swift showed that the X-ray afterglow light curves from > 6 hours after the explosion are well represented by a simple power law decay with a decay index of the order of $\alpha \approx 1.4$. The backward extrapolation of the afterglow X-ray flux matched that of the burst at the time of the explosion. Therefore with the Swift satellite we were expecting to gain orders of magnitude in brightness (see Fig. 1 left panel). Thanks to the much higher statistics we were then expecting to see, with higher signal to noise ratio (S/N), spectral lines that were previously seen in the X-ray spectra of some afterglows, although with a not very high S/N (e.g. [13, 16]).

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. [17]). But, for instance, the XRT data do not show the presence of spectral lines whatsoever in the X-ray spectra of GRB afterglows, neither in the first few thousand second, nor at later (hours-days) time scales. They do show the presence of a bright fading X-ray source. However, the source decay does not follow a smooth power law, rather it is usually characterised by a very steep early decay [18] (see Fig. 1 right panel), followed by a flatter decay and then a somewhat steeper decay [19] (see Fig. 2 left panel). Although this is the most common behaviour, in some of the Swift GRBs, the early X-ray flux follows the expected and more gradual power law decay (e.g. [21, 21]).

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 [22, 18, 19, 23, 24]. 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 [25, 23, 26] (see Fig. 2 right panel). The origin of the flatter part that follow the early steep decay, that is well represented by a power law with slope $0.5 \leq \alpha \leq 1$, 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 [23]. 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 [19, 27]. Not all bursts show the steeper+flatter parts, a significant minority of them show a more gradual decay with $\alpha \leq 1.5$. These are more 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.

The flares

When XRT detected the first flares in the X-ray light curve of GRB050406 and then of GRB050502B \cite{28,29,30}, this came as a full surprise (although X-ray flares were already detected by BeppoSAX in a couple of bursts, which were interpreted as due to the onset of the afterglow \cite{31}). We now know that X-ray flares are present in a good fraction of the XRT light curves (e.g. \cite{32}). Flares have been detected in all kinds of bursts: in X-ray flashes (XRF) \cite{29}, in long GRBs (e.g. \cite{30,33,34}), including the most distant one at redshift $z=6.29$ (see Fig. 3, left panel, \cite{35}) and in short GRBs \cite{8,9}. 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 thousand seconds (see Fig. 3). The ratio between their duration and peak time is very small, 0.1, with late flares having longer duration \cite{32}. They can be very energetic and in some cases can exceed the fluence of the prompt emission \cite{30}. 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 (see Fig. 3, right panel). 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.

Also the spectral properties of these flares differ from those of the underlying afterglow. For instance, their broad-band spectral energy distribution is clearly formed by distinct components. In particular, the optical-to-X-ray spectral index is often much harder...
FIGURE 3. Left panel: 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 [35]). Right panel: the X-ray light curve of GRB050713A, note the presence of various strong flares both during the steep and flatter decay phases. The underline X-ray light curve does not seem to be altered by these flares.

than both the optical and X-ray spectral indices alone. This implies a spectral discontinuity between the two bands, again suggesting a different origin for the two components [36]. The X-ray spectra of the afterglows are well fitted by a simple power law model plus absorption, with an energy spectral index of $\beta' \approx 1$. 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. 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. For a comprehensive analysis of the flare properties see references [32, 37, 38, 39].

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 [32].

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

In the standard fireball scenario (see [40] 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 [41]. 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 [42]. There seem to be also a tight correlation between this energy and the peak energy of the prompt spectrum [43].

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. 4 left panel). 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 [44]. In any case, from a systematic analysis of the XRT 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 [45]. 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 (for a discussion on this argument see also [46]). Moreover, by assuming the correlation between the prompt peak energy and the beaming corrected prompt energy derived for some GRB with a measured optical break [43], we can check if the absence of a jet-break in the X-ray light curve (see Fig. 4 right panel) is consistent with this correlation. The result is that many of the XRT afterglows are outliers of this correlation [47, 45] (however, note that the presence of these outliers is still argument of discussion, see [48]). If confirmed, this means that either this correlation somehow is valid only for breaks observed in the optical and not in the X-ray or that it is valid only for a subsample of GRBs whose properties have still to be defined or that it is not as tight as previously thought.

**CONCLUSIONS**

After more than two years of Swift operations, the data provided by the XRT allowed us to make breakthrough discoveries in various field of the GRB studies including the detection of the afterglows of short GRBs. We did not discuss this argument here, but for the first time we have been able to study in more details the properties of these elusive sources and to find and study their host galaxies with on ground follow-up [5, 8, 9, 7, 50, 51, 52, 53]. 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 1 minute after the burst trigger. In particular, in the X-ray band, thanks to XRT, we have hundreds of light curves spanning the range
FIGURE 4. Left panel: 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 [44]). Right panel: BAT and XRT light curve of GRB050416A. The solid line represents a double-broken power law model fit. Note the absence of any jet break up to about 60 days after the burst. This absence is not consistent with the empirical relations between the source rest-frame peak energy and the collimation-corrected energy of the burst (from [49]).

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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