X-Ray Afterglows
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Abstract.
We summarise the X-ray temporal and spectral variability properties of GRBs as observed using the Swift satellite. Despite much individual complexity, the flux and spectral variability can be reasonably well described by a combination of two components – which we denote as the prompt and the afterglow. The first, prompt component consists of the burst and its initial decay while the second, afterglow component fits the X-ray plateau phase and subsequent decline observed in the majority of GRBs. When strong spectral variability occurs it is associated with the prompt component while the X-ray plateau and later emission shows little if any spectral variability. We briefly compare the observations with some of the proposed models. Any model for the early or late emission must explain the differences in both temporal and spectral behaviour.

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INTRODUCTION

The Swift satellite [1] is discovering around 100 GRBs per year, the vast majority of which are detected with the X-ray Telescope (XRT) [2] following a trigger from the Burst Alert Telescope (BAT) [3]. The behaviour of the X-ray temporal and spectral data is complex. In the majority of bursts (~75%), the X-ray flux declines fairly rapidly, sometimes very rapidly, within the first few thousand seconds (observed time), before a shallower decay, or plateau, phase occurs which typically last a few tens of thousands of seconds but can last up to a day (e.g. [4, 5, 6, 7]). X-ray flares are also widely seen (~50% of GRBs), usually during the initial decay up to the start of the X-ray plateau. The flares have properties consistent with being due to an internal process [8, 9]. After the X-ray plateau, the flux decays at a rate fairly consistent with the predictions of standard pre-Swift GRB afterglow models [7]. This light curve behaviour is now often referred to as the “canonical X-ray light curve”. However, a significant number of GRBs decay in a more gradual, fairly uniform manner from the start (e.g. [13]).

X-RAY LIGHT CURVES

The X-ray light curves for 321 GRBs detected by the Swift XRT up until early June 2008 are shown in Figure 1. The sheer number of data points makes it difficult to pick out individual bursts(!), but a few bright ones can be identified, including the very bright burst GRB 080319B (the highest data from ~70s [14]) and GRB 060124 (the peaks at ~600 and 700s [15]). The data illustrate the dynamic range of the Swift XRT, covering approximately eight orders of magnitude in count rate compared to five in time. This illustrates in a simple way that GRBs decay at faster than t^{-1} on average, even allowing for the extended X-ray plateau phase. Comparing the observations at 100s to those at 1 day, the X-ray flux decays approximately as t^{-1.2}, but the path followed varies enormously. The initial range in XRT count rate (or X-ray flux) is over four decades, similar to the range in optical flux [10], although the detailed shape of the light curves are usually different between the optical and X-ray bands.

The diversity in observed X-ray light curves implies multiple emission processes contribute to the X-ray emission. Using a functional form with flux ~ t^{-a} v^{-b}, where alpha and beta are the temporal and spectral indices respectively, the diversity in the early X-ray decay and spectral indices is shown in Figure 2. These data describe the X-ray properties, excluding the effect of strong flares, during the initial X-ray decay. The initial X-ray decay may be due to high-latitude (curvature or off-axis) prompt emission [11] combined with gradually decaying afterglow emission produced by an external shock [12]. No single model, such as the predicted α = 2 + β from high-latitude emission, can explain the spread in indices seen in Figure 2.

Emission from an external shock may also explain the plateau phase, but with additional energy injection to explain the slow decay [5]. A fairly standard afterglow model without much, if any, energy injection may explain the entire
FIGURE 1. The *Swift* XRT light curves for 321 GRBs detected up until the early June 2008. The apparent vertical stripe pattern in the middle of the plot is due to orbit gaps.

FIGURE 2. The temporal (alpha) vs. spectral (beta) indices for the early X-ray light curves for GRBs observed by *Swift*.

X-ray decay (except flares) for those GRBs which show a fairly continuous slow decay from the earliest times and which have no plateau phase. A small subset of GRBs in Figure 2 have quite a soft X-ray spectrum yet a modest decay rate (small alpha and high beta). These are GRBs in which thermal emission may contribute significantly.

**X-RAY SPECTRAL VARIABILITY**

In earlier work [6,7] we found that the X-ray light curve can be described well using two generic components each consisting of an exponential followed by a power-law decay. The two components, hereafter called prompt (p) and afterglow (a) dominate at different times. The first component (p) usually dominates until close to the end of the initial steep decline while the second (a) dominates during the plateau and final decay with an additional late, break, possibly a jet-break, in some cases [7]. We proposed that the p component is the decaying prompt emission while the a component is emission from the external shock including any energy injection.
Constraining what physical process dominates when requires additional information which we can obtain from the observed X-ray spectral variability. Here we derive spectral information in the form of time-dependent power-law photon indices ($\beta + 1$) by using the best-fit late-time absorption column (including Galactic and intrinsic absorption) combined with hardness ratio data calculated from the observed counts in the soft (0.3–1.5 keV) and hard (1.5–10.0 keV) bands [16]. We include X-ray counts detected when the XRT was in Windowed Timing (WT) and Photon Counting (PC) modes. The count-rate and hardness-ratio data are available at [http://www.swift.ac.uk/xrt_curves/](http://www.swift.ac.uk/xrt_curves/). Example temporal and spectral light curves for GRB 060729 [17] are shown in Figure 3.

A wide range of spectral variability is observed among the GRB population, but some general trends can be identified which correlate with the behaviour of the flux light curves. GRBs with steep early decays tend to get spectrally softer initially before getting harder and more constant during the X-ray plateau phase and beyond. Other GRBs show relatively little spectral variability, particularly those with gradual temporal decays from the start. The analysis is complicated in those GRBs with strong X-rays flares as the spectrum tends to get harder during the flares. Similar conclusions were reached by [18, 19], but here we have extended the spectral analysis to fit across the entire temporal range so we can compare the initial decay and plateau phase in detail.

Other than during strong flares, where the X-ray spectrum initially hardens and then softens, those GRBs where strong spectral variability occurs show spectral softening during the initial decline. In this short paper we concentrate on those GRBs whose spectra soften initially, do not have strong flares and which have well determined plateau phases. GRB 060729 is a good example of a GRB which shows early spectral softening. It has a longer than average X-ray
plateau. As can be seen in Figure 3, the spectrum is actually significantly harder at the start of the plateau compared to the end of the initial decay, a common pattern in these GRBs, arguing against a single emission component being responsible for both phases.

To try and model the spectral variability we adapt our previous models for the temporal behaviour [6, 7] but now allow two components (prompt and afterglow) to vary both in relative strength and spectral shape as power-law functions of time. Thus, for the prompt component the flux varies as $t^{-\alpha_p}$ while the photon index varies as $t^{-\alpha_h}$. The exact spectral shape of the later (afterglow) component is not well constrained initially as the emission is dominated by the prompt component until close to the end of the initial decay. For simplicity we assume the afterglow component starts to rise when the prompt component starts to decay. Adopting a constant flux or spectral shape initially would not significantly alter the results. The model predicts that the photon index evolution illustrated in Figure 3 is created by the combination of a rapidly softening component followed by the emergence of a harder plateau component.

The relation between $\alpha_h$ and $\alpha_p$ is shown in Figure 4 for those GRBs with particularly well determined values. A correlation exists such that GRBs with the fastest spectral variability also show the most rapid decline in flux. The most natural explanation is that a spectral break passes through the band, quite rapidly, causing a spectral softening and decline in flux (see also [19]). The rapidity of the spectral evolution is, however, difficult to understand. In addition, a single power law usually provides a good fit to the X-ray data. This also limits the possibility of additional spectral components, such as thermal emission, explaining the spectral variability.

In stark contrast to the initial decline, during the plateau phase, and subsequently, little or no spectral variability is observed. In Figure 5 we show the photon-index temporal-decay rate during the plateau vs. the photon index at the end of the plateau. The stars show those GRBs for which the data are consistent with no spectral evolution in the plateau and final decay. The range in spectral decay indices is much smaller during the plateau than during the initial decay ($\sim 0.2$ compared to $\sim 1$). Any model put forward to explain the plateau has to explain this lack of strong spectral evolution. One possible process is the external shock, which would require energy injection as noted above for the plateau phase. In some GRBs the final decay itself is quite slow so exactly when energy injection ends is unclear [7].

**IS THE X-RAY PLATEAU DUE TO DUST SCATTERING?**

As an example of using spectral variability to test proposed models, we have examined the case of an X-ray dust echo origin for the X-ray plateau. An extended shell of dust in the GRB host galaxy, between the GRB and observer, would scatter prompt X-rays into the line of sight. Due to light travel-time effects, these scattered photons would be observed later and hence could explain the X-ray plateau and subsequent decay (but not a jet break) seen in many GRBs [20]. This model, however, also predicts strong spectral evolution across the plateau as the scattering optical depth has an
FIGURE 5. The relation between the temporal decay of the photon index (or spectral index) during the X-ray plateau and the photon index at the end of the plateau.

angular dependence which is a function of energy.

Recently we have compared the predictions of the dust scattering model with both the temporal and spectral light curves of GRBs [21]. While we confirm that the temporal behaviour of the X-ray emission can be very well reproduced, the predicted spectral variability is not seen. This is illustrated in Figure 6 where we show the X-ray light curves for GRB 060729 in two different energy bands. The X-ray plateau begins and ends at the same time for each band, whereas the dust echo model predicts the high-energy plateau should end more than an order of magnitude earlier in time.

DISCUSSION AND CONCLUSIONS

The temporal and spectral variability of the GRBs observed using the Swift satellite is intriguing. All GRBs show a decaying light curve, such that by the time a day has passed the X-ray flux has typically declined by around five orders of magnitude. The exact decay path, however, varies enormously. The initial decline occurs at different rates among GRBs and they display different strength X-ray plateaus. The X-ray plateau is not observed in a significant minority of GRBs which rather decay gradually throughout. The large majority of X-ray flares occur before the plateau phase dominates, although some are seen at later times.

In GRBs where strong X-ray spectral variability is seen, there is a correlation between the flux and spectral temporal decay indices. This is at odds with the simplest expectation of the high-latitude emission model and may be due to the rapid passage of a spectral break through the X-ray band. The spectrum hardens at the start of the plateau followed by relatively little variability, strongly supporting the idea of a separate origin for the plateau and final decay. A potential candidate explanation for the plateau and final decay is emission from an external shock with energy injection — essentially an afterglow component [5, 7]. Allowing for evolution in the spectral energy distribution, this may also explain the contrasting behaviour of the optical and X-ray emission in which most of the optical emission, except (prompt) flares, may be connected to the second (afterglow) X-ray component (e.g. [22, 23]).

Those GRBs which show a fairly uniform flux decay have no evidence for strong spectral variability, implying their X-ray emission is dominated by a single process. This may also be the same process — the external shock — as for the plateau and final decay in the majority of GRBs, but with a much less dominant, if any, contribution from energy injection. What is as yet unclear is why these GRBs are distinct from those with a strong plateau phase.

Recently it has been proposed [24] that fallback of the stellar envelope and accretion could explain the shape of the early X-ray light curve rather than a significant contribution from an external shock, particularly in those GRBs with significant plateaus. It is not obvious why such a model would produce the observed spectral evolution, particularly during the transition from the initial decay to the plateau or such a constant spectral shape during the plateau, nor
FIGURE 6. The X-ray light curve of GRB 060729 shown in two energy bands: 0.3–1.5 keV (circles) and 1.5–10 keV (triangles). The dust scattering model predicts the higher energy plateau should have ended an order of magnitude earlier in time than that of the softer band, which is clearly not the case.

explain the relation with the optical emission, but a more detailed comparison is required.

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