The late X-ray afterglow of gamma-ray bursts

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We have developed a functional fit which can be used to represent the entire temporal decay of the X-ray afterglow of gamma-ray bursts (GRBs). The fit delineates and parameterizes well-defined phases for the decay: the prompt emission; an initial steep decay; a shallow plateau phase; and finally, a powerlaw afterglow. For 20% of GRBs, the plateau phase is weak, or not seen, and the initial powerlaw decay becomes the final afterglow.

We compare the temporal decay parameters and X-ray spectral indices for 107 GRBs discovered by Swift with the expectations of the standard fireball model including a search for possible jet breaks. For approximately 50% of GRBs, the observed afterglow is in accord with the model, but for the rest the temporal and spectral properties are not as expected. We identify a few possible jet breaks, but there are many examples where such breaks are predicted but are absent. We also find that the start time of the final afterglow decay, $T_a$, is associated with the peak of the prompt $\gamma$-ray emission spectrum, $E_{\text{peak}}$, just as optical jet-break times, $t_j$, are associated with $E_{\text{peak}}$ in the Ghirlanda relation.

Keywords: gamma-ray bursts; black holes; X-ray; afterglow

1. Introduction

X-ray afterglows of gamma-ray bursts (GRBs) were first detected by the Beppo-SAX satellite (1996–2002) and the XMM-Newton observatory, but these observations started many hours after the initial burst. Multiwavelength observations of GRB030329 including X-rays (Hjorth et al. 2003; Tiengo et al. 2003; Stanek et al. 2003) and analysis of this bright afterglow and similar events (Harrison et al. 2001; Panaitescu & Kumar 2001, 2002, 2003; Willingale et al. 2004) established that afterglows were broadly consistent with the expected synchrotron spectrum and temporal evolution predicted by the standard fireball shock model of GRBs (Mészáros 2006 and references therein). Since its launch in November 2004, the Swift satellite (Gehrels et al. 2004) has provided a unique set of early-time X-ray light curves for GRBs. Combining data from the burst alert telescope (BAT) and the X-ray telescope (XRT) allows for a determination of the temporal and spectral properties of a burst from the initial trigger out to days or even weeks (e.g. Tagliaferri et al. 2005; Nousek et al. 2006; O’Brien et al. 2006).

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In this paper, we present analysis of data from 107 GRBs discovered by Swift. The properties of the early emission seen from these objects are discussed in a companion paper (O'Brien & Willingale 2007), but here we look at later times and the final X-ray afterglow. We combine data from the BAT and XRT on Swift using a technique described in O'Brien et al. (2006) but extended to provide a better description of the later-time emission. A functional fit as described by O'Brien et al. (2006) was used to provide robust estimates of the start time of the

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\begin{align*}
\text{Figure 1. Two examples of the fits to X-ray decay curves. (a) The most common type in which the second component dominates at late times. This example also includes a late temporal break. (b) A two component fit in which the second component forms a bump in the decay but the first, prompt, component decay dominates at late times.}
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\text{Figure 2. (a) The temporal decay index of the afterglow plotted versus the spectral decay index in the final afterglow decay. The lower band indicates the area expected to be occupied by a pre-jet break afterglow and the upper band the area post-jet break. GRBs which fall in the pre-jet break region are plotted as circular dots (black), those which fall above this near the post-jet break region are plotted as stars (red) and those below the pre-jet break band are plotted as squares (green). (b) Change in spectral index } \beta_{\text{ad}}-\beta_{\text{a}} \text{ versus the plateau spectral index } \beta_{\text{a}}.
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Figure 3. (a,b) Two X-ray decays in which a late temporal break consistent with a jet break is seen. (c–f) Four X-ray decays in which a predicted jet break is absent. $E_{\text{peak}}$ is listed in keV, $E_{\text{iso}}$ in $10^{52}$ ergs and $t_j$ in days. The shaded area indicates the expected range for $t_j$. Where $E_{\text{peak}} = 100$, not measured, $E_{\text{peak}}$ value was available and a range 50–150 keV was assumed.

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2. Types of X-ray decay seen by Swift

Figure 1 illustrates the two forms of X-ray afterglow decay seen. Of the 107 decays fitted, 85 required two components in which the second component was dominant at the end of the observed light curve. In these cases, the decay index of the prompt phase, $\alpha_p$, was greater than $\alpha_a$, the final decay index of the afterglow. In a further six cases, two components were required but the second component appeared as a hump in the middle of the initial decay and the prompt component reappeared and dominated towards the end. The remaining 16 required only one component and did not exhibit a plateau phase in the afterglow. For 99 of the 107 GRBs, the latter stages of the light curve are well represented by the one or two component functional fit. However, in eight cases, there is clear evidence for an additional late temporal break. For these objects, two extra parameters were included in the fit, a final break at time $T_b$ and a decay index $\alpha_b$ for $t > T_b$. Figure 1a shows an example of this.

3. Coupling of $\alpha$ and $\beta$ in the afterglow decay

A coupling between the temporal decay index in the final afterglow, $\alpha_a$, and the spectral index in the final afterglow, $\beta_{ad}$, is predicted by the standard fireball model (Sari et al. 1998). As the source gets softer, $\beta$ increases, so the temporal decay index $\alpha$ increases because the spectrum is being red-shifted as the jet is slowed down by the circum-stellar medium (CSM) and after a jet break (Rhoads 1999; Frail et al. 2001) the peak of the observed synchrotron spectrum is also decaying with time (e.g. Panaitescu & Kumar 2002). The precise form of the relationship depends on the density profile of the surrounding CSM and whether the decay is observed before or after a jet break. Figure 2a shows the temporal decay index of the afterglow component, $\alpha_a$, versus $\beta_{ad}$, the spectral index in the final decay for those objects where the latest observed time, $t_{\text{max}} > T_a$, and for which we have a significant measurement of $\beta_{ad}$ at $t > T_a$. There is no correlation between $\alpha$ and $\beta$ and, if there is any trend at all, it is that some of the faster decays (large $\alpha$) occur for the smaller $\beta$ values. The lower band shown indicates the region for pre-jet break coupling predicted by the model, and the upper band the region expected to be occupied after any jet break has occurred. Of the 69 objects plotted, 37 lie below the expectations of the model in the bottom right of the plot. Therefore, for approximately 50% of GRBs, the spectral index of the afterglow is too large to produce the observed temporal decay index. This could be because there is significant energy injection such that the peak of the spectrum (or normalization) is boosted fast enough to counteract the drop expected from the change in red shift as the jet slows down. It was pointed out by Nousek et al. (2006) that the spectrum and decay of the plateau phase of several Swift GRBs were inconsistent with the expectations of the jet model and that energy injection during this phase was a possible explanation. The current analysis shows that the same is also true for many objects during the subsequent
decay phase, after the plateau. There is no correlation between the time at which the final decay starts and the position in the $\beta - \alpha$ plane. If energy injection is the explanation, it is occurring at late times, more than $10^5$ s, as well as much earlier times. Of the remaining approximately 50% of objects plotted on top of figure 2a, 23 lie within the pre-jet break band while nine lie above this close to or within the post-jet break region.

Figure 2b shows the change in spectral index from the plateau into the final decay, $\Delta \beta = \beta_{ad} - \beta_a$, plotted versus the plateau spectral index in the plateau, $\beta_a$. Here, there is a distinct trend. If $\beta_a < 1$, then $\Delta \beta < 0$ and the afterglow gets softer in the final decay. If $\beta_a > 1$, then $\Delta \beta < 0$ and the final decay is harder. The scatter of index $\beta_{ad}$ is smaller in the final decay being confined to the range 0.0–2.2 as indicated in figure 2a. One object, GRB060218, has an anomalously large final spectral index, $\beta_{ad} = 3$, but this GRB was very peculiar in many respects, in particular for having a significant thermal component in the X-ray spectrum (Campana et al. 2006). The trend in the change in spectral index from the plateau into the powerlaw decay is independent of the position in the $\beta - \alpha$ plane occupied by the final decay.

4. Do we observe jet breaks in X-rays?

For 64 of the 91 GRBs which required two functional components in the fit, the end of the plateau is visible, as is the case for the exemplar GRB shown at the top left of figure 1. In such cases, the plateau gets slowly steeper towards the end of the exponential plateau phase and eventually relaxes to a power law. There is often no definitive or sharp break but the time $T_a$ is a robust measure of where this transition occurs, taking into account all the data available. In some cases, it may be that any jet-break time associated with the edge of a putative jet becoming visible occurs at or before $T_a$. In such decays, we expect the subsequent afterglow to lie somewhere in the top left of the $\beta - \alpha$ plane shown in figure 2 and the seven candidates for such cases are shown as star symbols in this figure. The time $T_a$ for these GRBs is not a pure jet-break time since in all cases $T_a$ also marks the end of the plateau phase. However, $T_a$ is a reasonable estimate of where any jet break must have occurred.

As mentioned above, seven decays required a late break to fit the data as illustrated in figure 1a. Just three of these objects, GRB050814, GRB060105 and GRB060607A, lie in the top left of the $\beta - \alpha$ plane and are good candidates for jet breaks. For two of these, we have a red shift and so we can estimate the range of any expected jet-break time, $t_j$, using the Ghirlanda relation (Ghirlanda et al. 2004). The X-ray decay curves for these GRBs are shown at the top of figure 3 with the expected range of jet-break times shown as a shaded band. Following Sato et al. (in press), we can adopt the opposite approach and look for X-ray decays in which a predicted jet break is absent. Apart from GRB050401, GRB0416A and GRB050525A already considered by Sato et al. (in press), there are four other X-ray decays monitored by Swift which come under this category and these are shown in the bottom of figure 3. Each decay was followed for at least a factor of 100 times longer than $T_a$ without any indication of a break in the temporal decay index. For those GRBs for which we have not measured $E_{\text{peak}}$, a range of 100–200 keV was assumed and a value of 100 keV is given in figure 3. In
summary, out of 71 afterglow breaks identified by the fitting procedure, only 10 are followed by an afterglow which is consistent with post-jet break conditions and only three of these are isolated breaks independent of the end of the plateau phase. The remaining 62 have slow X-ray decays (low $\alpha$) and/or soft X-ray spectra (high $\beta$). Seven decays have extended coverage in which a jet break predicted using the Ghirlanda relation is absent.

If we can identify jet-break times, $t_j$, and we have a red shift for the GRB, then we can use the formulation of Sari et al. (1999) and estimate of the jet angle $\theta_j$ and hence the collimation-corrected energy $E_g$ from the isotropic energy $E_{iso}$. For calculation of $E_\gamma$ values considered below, we have assumed the product of the CSM density and energy conversion efficiency to be $n\eta_\gamma=0.6$ (or equivalently $n=3 \text{ cm}^{-3}$ and $\eta_\gamma=0.2$). We have also assumed a cosmology with $H_0=71 \text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Lambda=0.27$ and $\Omega=0.73$ and calculated $E_{iso}$ over an energy band of 1–10 000 keV in the rest frame applying a $k$-band correction independently for the BAT and XRT data.

There are 14 GRBs for which we have a $T_a$ value, a red shift and a measurement of the peak energy of the $\gamma$-ray spectrum, $E_{peak}$. For these objects, we can construct a Ghirlanda-type correlation between the peak energy in the rest frame $E_{peak}(z+1)$ and the collimated beam energy $E_\gamma$ calculated assuming $t_j=T_a$. This is shown alongside the conventional Ghirlanda relation in figure 4. The X-ray measurements show a similar behaviour, not as statistically significant as the optical version but with approximately the same gradient and an offset in $E_\gamma$ by a factor of approximately 26. For these cases, the X-ray break times, $T_a$, are a factor of approximately 90 less than pre-Swift optical break times. It appears that $T_a$ extracted from X-ray decays in the present analysis has properties related to $t_j$ derived from optical data. Whether this apparent connection is purely statistical in nature or has some deeper significance remains to be seen but it is not unreasonable to suppose that the

![Figure 4. The Ghirlanda relation. The open circles and solid line show the original correlation (Ghirlanda et al. 2004). The points with error bars are Swift GRBs for which values of $E_\gamma$ were derived assuming $t_j=T_a$. The symbols plotted are the same as in figure 2. The dashed line is a fit to the Swift sample assuming the gradient is fixed at 0.706, the best-fit value from Ghirlanda et al. (2004). The lower limits of energy shown were derived using the latest observed time as $t_j$ for GRBs with lasting afterglow decays which show no break (four of which are illustrated in figure 3).](http://rsta.royalsocietypublishing.org/)

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end of the plateau phase, $T_a$, does depend on the total energy in the jet and/or the collimation angle of the jet. The seven lower limits to $E_g$ plotted to the right of the Ghirlanda relation on figure 4 were calculated using the latest observed time as $t_j$ for those afterglows with extended coverage but without any indication of a jet break. We conclude that a significant number of jet breaks that should be seen in X-rays, according to the Ghirlanda relation, are not present.

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References


