The X-ray flux of the gamma-ray burst (GRB) afterglows monitored by the Swift satellite from January 2005 to July 2006 displays one to four phases of flux power-law decay. In chronological order, they are: the GRB tail, the ‘hump’, the standard decay and the post-jet-break decay. More than half of the GRB tails can be identified with the large-angle emission produced during the burst (but arriving later at observer). The remaining, slower GRB tails imply that the gamma-ray mechanism continues to radiate after the burst, as also suggested by the frequent occurrence of X-ray flares during the burst tail. The several GRB tails exhibiting a slow unbroken power-law decay until 100 ks must be attributed to the forward shock. In fact, the decay of most GRB tails is also consistent with that of the forward-shock emission from a narrow jet. The X-ray light-curve hump may be due to an increase of the kinetic energy per solid angle of the forward-shock region visible to the observer, caused by either the transfer of energy from ejecta to the forward shock or the emergence of the emission from an outflow seen from a location outside the jet opening. The decay following the X-ray light-curve hump is consistent with the emission from an adiabatic blast wave but, contrary to expectations, the light-curve decay index and spectral slope during this phase are not correlated. The X-ray light curves of two dozens X-ray afterglows that followed for more than a week do not exhibit a jet break, in contrast with the behaviour of pre-Swift optical afterglows, which displayed jet breaks at 0.5–2 days. Nevertheless, the X-ray light curves of several Swift afterglows show a second steepening break at 0.4–3 days that is consistent with the break expected for a jet when its edge becomes visible to the observer.

**Keywords:** relativistic shocks; non-thermal emission; gamma-ray bursts

1. Introduction

The X-ray, optical and radio emissions following a gamma-ray burst (GRB) arise in the interaction between the GRB ejecta and the circumburst medium, which leads to a forward shock energizing the ambient medium (the ‘external shock model’; e.g. Paczyński & Rhoads 1993; Mészáros & Rees 1997). This shock accelerates electrons (through first-order Fermi mechanism or the electric fields associated with the Weibel instability) to relativistic energies and generates magnetic fields. The afterglow emission is synchrotron; inverse Compton
scatterings may affect the electron radiative cooling and contribute to the early X-ray afterglow emission. The progressive deceleration of the forward shock, whose Lorentz factor $G \propto r^{-g}$ depends on the radial structure of the ambient medium and injection of energy into the blast wave, leads to the softening of the afterglow synchrotron spectrum. As this spectrum is a combination of power-laws, $F_\nu \propto \nu^{-\beta}$ with the spectral slope $\beta$ depending on the location of the observing frequency relative to the afterglow characteristic break frequencies, it follows that the afterglow light curve decays as a power-law, $F_\nu \propto t^{-\alpha}$, with the decay index $\alpha$ depending on $\beta$ and the evolution of the spectral break frequencies.

In its simplest form, the standard external (forward) shock model assumes a GRB outflow with a constant shock energy, a uniform kinetic energy per solid angle and constant microphysical parameters. The possibility of energy injection into the forward shock was proposed by Paczyński (1998) and Rees & Mészáros (1998). Its effect may have been observed for the first time in the rise of the optical emission of GRB afterglow 970508 at 1 day (Panaitescu et al. 1998). A non-uniform angular distribution of the ejecta kinetic energy per solid angle was proposed by Mészáros et al. (1998). The effect of ejecta collimation was treated by Rhoads (1999) and was seen for the first time in the optical light curve of GRB afterglow 990123 (Kulkarni et al. 1999). Since then, about a dozen other optical afterglows displayed a break at around 1 day (e.g. Zeh et al. 2006), which have been interpreted as evidence for GRB jets. As pointed out by Rossi et al. (2002), such light-curve breaks may also arise from structured outflows seen off-axis.

The BeppoSAX satellite (and other missions) has provided X-ray afterglow light curves starting at 8 h after the burst and evidence that, after the burst, there is a phase of fast decay (e.g. GRB 990510, Pian et al. 2001; GRB 010222, Zand et al. 2001). The continuous monitoring of X-ray afterglows achieved by the Swift mission has shown that this phase is present in most X-ray afterglows and has revealed a few other puzzling features: the existence of an intermediate-time phase of very slow decay, lasting up to hours after burst and ending with a steepening break that is generally not seen in the optical, and the existence of a long-lived X-ray emission with a power-law decay index comparable to that seen in the optical before the 1-day break, but lasting up to days or weeks.

The purpose of this work is to compare the X-ray decay indices and spectral slopes measured by Swift for several tens of GRB afterglows from January 2005 to July 2006, and to discuss the mechanisms that can accommodate them, for the various phases displayed by those afterglows. While it is possible that the same mechanism operates in most X-ray afterglows, X-ray observations alone cannot discriminate among those mechanisms and cannot identify a specific one. Simultaneous observations in other bands are needed for that.

### 2. Afterglow phases

A minority (approx. 10%) of Swift afterglows exhibit a single power-law decay from end of burst to 1 day. The decay is the slowest observed $\alpha_s \sim 1.5$, which may be a selection effect (given that such long-lived, but steeper, decays would fall below XRT’s detection capability). A quarter of the afterglows show a steeper decay $\alpha_{s1} > 1.75$ after the burst (this phase will be called ‘GRB tail’) followed by a break to a slower power-law fall-off ($0.5 < \alpha_{s2} < 1.25$) until after 100 ks. About
two-thirds of all the afterglows exhibit a fast-decaying GRB tail, followed by an even slower decay phase \((0 < \alpha_{x2} < 0.75)\) and then a break to a steeper fall-off \((0.75 < \alpha_{x3} < 1.75)\), creating a ‘hump’ in the X-ray light curve at 1–10 ks. From these three types of X-ray afterglows, one can surmise that the afterglow emission after the GRB tail is emission from a different mechanism or a different outflow compared with that of the burst, whose epoch of emergence determines the appearance of the afterglow light curve: the later this component appears, the ‘humpier’ the light curve is.

(a) The GRB tail

That the GRB emission observed by the BAT instrument joins smoothly with the GRB tail emission measured by XRT indicates that the GRB tail emission arises from the same mechanism as the burst. Figure 1 compares the decay indices and spectral slopes during this phase with the expectations from different
models. The correlation of $\alpha_{x1}$ and $\beta_{x1}$ is statistically significant and represents a natural consequence of any model in which, during the GRB tail, the spectral break frequencies of the synchrotron spectrum decrease.

One way to discriminate the possible models for this phase is the collimation of the GRB outflow. If the outflow opening, $\theta_0$, is larger than $\Gamma^{-1}$, the inverse of its Lorentz factor, then the spherical-forward shock (SPH) models shown in figure 1 can explain only the slowest 25% of GRB tails. For the rest, the steeper decay requires that the GRB emission mechanism switches off at the end of the burst. The steepest decay that can be obtained by a switch-off has an index $\alpha_{x1}=-2+\beta_{x1}$ because any faster cessation will be overlaid by the emission from the fluid moving at an angle $\theta$ (relative to the centre–observer direction) larger than $\Gamma^{-1}$.

The decay of this large-angle emission (LAE model; Kumar & Panaitescu 2000) is due to the photon arrival time increasing as $\theta^2$, while the relativistic Doppler boost decreases as $\theta^{-2}$. The latter also induces a dependence of $\alpha_{x1}$ on $\beta_{x1}$, as photons of a fixed observer frequency correspond to an increasingly larger co-moving frequency. The LAE model is consistent at the $1\sigma$ level with 40% of the GRB tails shown in figure 1 and consistent with 60% of afterglows at the $2\sigma$ level, where consistency between a model $\alpha_{model}=a\beta_x+b$ and an observed $\alpha_x$ at the $n\sigma$ level is defined by $\alpha_x-\alpha_{model}$ being within $n\sigma=n[\sigma(\alpha_x)^2+a^2\sigma(\beta_x)^2]^{1/2}$ of zero ($\sigma(\alpha_x)$ and $\sigma(\beta_x)$ are the measurement errors). Together, the SPH and LAE models can account for 80% of the GRB tails shown in figure 1. Most of the remaining cases lie between the expectations for these models, which clearly fail to account for only the four steepest decays shown in that figure.

If the outflow opening (or the opening of the emitting region), $\theta_0$, is smaller than $\Gamma^{-1}$, then there is no large-angle emission and the GRB tail decay reflects the intrinsic switch-off of the burst emission. That switch-off could be the progressive dimming of the forward-shock emission from a narrow jet. The decay rate expected for a jet undergoing lateral spreading is consistent with 60% of the bursts shown in figure 1 at the $1\sigma$ level and with 85% at $2\sigma$, this model clearly failing to explain only the three slowest decays shown in figure 1. Taking into account that the Lorentz factor $\Gamma$ of a spherical, decelerating blast wave of isotropic-equivalent energy $E=10^{53}E_{53}$ ergs, interacting with a WR stellar wind is $\Gamma=60E_{53}[(z+1)/3.5]^{1/4}(t/100\ s)^{-1/4}$, it follows that the JET model for the GRB tail requires a very narrow jet, of half-angle $\theta_0\leq1^\circ$.

A different way of separating the above models for the GRB tail is the absence/presence of a significant forward-shock emission at the end of the burst. The GRB tail is the LAE emission if the forward-shock contribution is dimmer. The LAE model relies on the fast dimming of the intrinsic burst emission that would be expected in the internal shock model (Rees & Mészáros 1994) after the cessation of internal shocks and when the fast cooling of electrons brings their characteristic synchrotron frequency below the observing range. As can be seen in figure 1, the LAE model can explain the GRB tails with a faster decay. The observation of slower-decaying tails implies that, sometimes, the burst emission does not switch-off sufficiently fast to reveal the large-angle emission. In the internal shock model, this means that such shocks continue to occur during the GRB tail (that GRB tails often exhibit flares, whose short time-scale is inconsistent with a forward-shock origin, supports the idea that internal shocks can occur after the GRB phase). However, the six afterglows in the current sample with a long-lived (up to 100 ks), slowly decaying, unbroken power-law GRB tail show that, at least in a few cases, the
forward-shock emission is bright at the end of the burst. In fact, all the GRB tail
decays shown in figure 1 can be explained with the forward-shock emission: the
slower decaying tails can be attributed to a spherical outflow, the faster ones to a jet.
If so, the continuity of the burst and tail emissions indicates that the prompt GRB
emission arises also from the forward shock or, else, the flux produced by the GRB
mechanism at the end of the burst should match that of the forward shock at the
same time, as is the case with the electromagnetic model proposed by Lyutikov &

(b) The slow-decay (hump)

If the GRB and its tail arise from the forward shock, then the slower-decay phase following the tail, which many times is a hump in the X-ray light curve, may have the same origin as the burst. The forward shock emission depends on the outflow dynamics (determined by the blast wave energy and collimation and medium density) and radiation parameters (two microphysical parameters quantifying the electron and magnetic field energies). It follows that the decay of the forward-shock emission depends on the evolution of the kinetic energy (per solid angle), $E$, of the visible outflow, the ambient medium stratification and the possible evolution of the microphysical parameters. The last possibility finds support in the chromatic X-ray light-curve breaks observed at the end of the hump (Panaitescu et al. 2006), as these breaks are not usually seen in the optical.

Figure 2. Decay index versus spectral slope during the slow-decay phase following the GRB tail for 55 Swift afterglows. Two-thirds of afterglows decay slower than expected for the SPH model (the standard adiabatic blast wave model with constant microphysical parameters). One-third of afterglows are consistent with the SPH1 model, requiring that the cooling frequency is a X-ray and an electron distribution with energy harder than $dN_e/d\gamma \propto \gamma^{-2}$. Thick lines labelled ‘1b’ and ‘2b’ are for the forward-shock emission from a spherical outflow interacting with a wind *before* deceleration sets in: $a=\beta$ for cooling above X-ray and $a=\beta-1$ for cooling below X-ray.
Leaving aside this complication and considering the two possibilities of a wind-like medium with a $r^{-2}$ stratification (as expected within a few parsecs around a massive stellar GRB progenitor) or a homogeneous medium (if the star’s wind is weak enough that a high-pressure circumstellar medium confines the freely expanding wind to less than 0.1 pc), the hump decay is determined then by how $E$ changes with time. The necessity of $E$ increasing in time is illustrated in figure 2, which shows that, for an adiabatic forward shock, the slowest decay (obtained for a spherical outflow) is too fast to explain this afterglow phase.

There are two reasons for a non-constant kinetic energy per solid angle $E$ in that part of the blast wave which is visible to the observer. An increase of $E$ will result before all the GRB ejecta start to undergo the deceleration caused by the interaction with the circumburst medium. Another possibility is a structured outflow where $E$ varies with direction.

\textbf{c) The standard decay}

If the slow decay of the hump emission is attributed to an increase in the kinetic energy per solid angle within the visible region, then it would be natural to attribute the steepening of the X-ray light-curve decay observed at the end of the hump (approx. 10 ks) to $E$ becoming constant. That corresponds to a cessation of energy injection or to having observed the core of an outflow seen off-axis.
Allowing for any location of the cooling frequency relative to the X-ray and any of the two possible stratifications of the circumburst medium renders the SPH model (an outflow of constant kinetic energy per solid angle and whose Lorentz factor is still sufficiently large that the outflow boundary is not yet visible to the observer) consistent with 75% of the decays of the afterglows with a hump and 60% of the decays of afterglows without a steepening break until 100 ks. At the 2σ level, the SPH models shown in figure 3 are consistent with 100 and 90% of the two types of afterglows, respectively. That the slow-decay afterglows without a hump exhibit decays which are somewhat slower than expected for an adiabatic forward shock suggests that there is a slow and long-lived energy injection into the shock for this class of afterglows.

We note that, despite the correlation between \( \alpha \) and \( \beta \) expected for any variant of the SPH model, the observed decay indices and spectral slope do not display such a correlation, \( r(\alpha_{x3}, \beta_{x3}) = -0.26 \pm 0.15 \). If the adiabatic forward-shock model is correct, then this lack of a correlation must be attributed to the scatter in \( \alpha_{x3} \) for the same \( \beta_{x3} \) caused by X-rays being either below or above the cooling frequency and, perhaps, by the circumburst medium having both possible radial structures. We note that, even if the afterglows without a steepening break until 100 ks (shown with green symbols in figure 3) are excluded (as it is possible that energy injection is a long-lived process in these afterglows and yields decays slower than expected in the standard model) and only those afterglows with

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Figure 4. Decay index versus spectral slope for nine Swift afterglows whose X-ray light curves exhibit a second steepening after 40 ks and which can be interpreted as a jet break. Most of these possible post-jet-break decays are also consistent with the SPHb2 model (wind-like medium, cooling frequency above X-ray), i.e. the SPH model which yields the fastest decay, but such an interpretation of the latest afterglow decay would require a departure from the standard SPH model to explain the slower pre-break decay.
a hump (blue symbols) are retained (assuming that their steepenings indicate the cessation of energy injection), there is no correlation between the observed $\alpha_{x,3}$ and $\beta_{x,3}$.

\begin{itemize}
\item[(d)] The jet break
\end{itemize}

In contrast to the pre-Swift optical afterglows monitored, most of the Swift X-ray afterglows monitored well after 1 day do not exhibit a break at 1 day. The standard decay phase of 25 X-ray afterglows extends after 5 days, with eight afterglows lasting longer than 10 days and three afterglows displaying a $t^{-1}$ fall-off until after 20 days. The X-ray light curves of seven Swift afterglows show a second steepening break at 0.4–3.5 days to a $t^{-2}$ or faster decay, which can be interpreted as arising from the jet edge becoming visible to the observer and the jet starting to expand laterally. For two other Swift afterglows, only one steepening break is observed at 0.1–0.2 days, but it is followed by a steep decay that can be interpreted as a jet break. The JET1 model (cooling below X-ray) is consistent at 1\sigma with five of these nine afterglows and consistent with eight of them within 2\sigma (figure 4). For all these eight afterglows, the pre-jet-break decay index is consistent with the SPH1 model, i.e. the standard jet model can explain the Swift X-ray light-curve breaks. Further testing of this model requires optical monitoring: if the standard jet model is indeed correct, then (i) the optical light curve should exhibit a break at the same time as in the X-ray (jet breaks are achromatic) and (ii) the optical and X-ray pre-break decay indices should not differ by more than a quarter.

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References


