Optical afterglows of gamma-ray bursts: peaks, plateaus and possibilities

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ABSTRACT
The optical light curves of gamma-ray burst (GRB) afterglows display either peaks or plateaus. We identify 16 afterglows of the former type, 17 of the latter and four with broad peaks, which could be of either type. The optical energy release of these two classes is similar and is correlated with the GRB output, the correlation being stronger for peaky afterglows, which suggests that the burst and afterglow emissions of peaky afterglows are from the same relativistic ejecta and that the optical emission of afterglows with plateaus arises more often from ejecta that did not produce the burst emission. Consequently, we propose that peaky optical afterglows are from impulsive ejecta releases and that plateau optical afterglows originate from long-lived engines, the break in the optical light curve (peak or plateau end) marking the onset of the entire outflow deceleration. In the peak luminosity–peak time plane, the distribution of peaky afterglows displays an edge with $L_p \propto t_p^{-3}$, which we attribute to variations (among afterglows) in the ambient medium density. The fluxes and epochs of optical plateau breaks follow an $L_b \propto t_b^{-1}$ anticorrelation. Sixty per cent of 25 afterglows that were well monitored in the optical and X-rays show light curves with comparable power-law decay indices and achromatic breaks. The other 40 per cent display three types of decoupled behaviours: (1) chromatic optical light-curve breaks (perhaps due to the peak of the synchrotron spectrum crossing the optical), (2) X-ray flux decays faster than in the optical (suggesting that the X-ray emission is from local inverse-Compton scattering) and (3) chromatic X-ray light-curve breaks (indicating that the X-ray emission is from external upscattering).

Key words: radiation mechanisms: non-thermal – shock waves.

1 INTRODUCTION
The prompt emission of gamma-ray bursts (GRBs) is thought to be produced by particles energized in internal shocks occurring in an unsteady outflow (Rees & Mészáros 1994; Ramirez-Ruiz & Fenimore 2000). The interaction of the GRB outflow with the circumburst medium generates shocks that accelerate energetic particles which, in turn, radiate the so-called afterglow emission (Mészáros & Rees 1997). The spectral, temporal and polarization properties of this afterglow are fundamental observational probes of the outflow interaction with the surrounding medium.

The X-ray afterglows observed by Swift display light curves with up to two inflection points or ‘breaks’ (e.g. Nousek et al. 2006; O’Brien et al. 2006; Zhang et al. 2006). A small number of afterglow light curves exhibit a single power-law decay for decades in time, while most display an initial phase of slow flux decay (a ‘plateau’) lasting for up to 1–10 ks after trigger, followed by a more rapid decline. While the decay is generally consistent with the expectations for synchrotron emission from an adiabatic forward shock energizing the circumburst medium, there are cases where the decay is slower than what is expected for that model (Willingale et al. 2007). These slower-than-expected decays can be due to an interval of energy injection that powers the blast wave. Some of the X-ray afterglows monitored for very long durations display a second light-curve break that could be a jet break (e.g. Panaitescu 2007; Racusin et al. 2010), although some of these breaks do not satisfy the expected closure relation between the flux decay index and the spectrum slope (Liang et al. 2008).

At gamma-ray energies, the prompt emission dominates the observed flux. In the X-rays, the fast-decaying tail of the prompt emission is also dominant up to hundreds of seconds after the trigger (e.g. Tagliaferri et al. 2005). This prominence of the prompt X-ray emission makes it difficult to detect the X-ray afterglow light-curve peak produced either when the blast wave begins to decelerate (i.e. when the reverse shock has crossed all the GRB ejecta) or when the peak of the synchrotron spectrum traverses the X-ray band. Prompt emission has also been detected at optical wavelengths (e.g. Akerlof et al. 1999; Vestrand et al. 2005; Racusin et al. 2008; Wozniak et al. 2009). However, in the optical, the prompt emission is usually less prominent, making it possible sometimes to detect the peak of the
optical afterglow (e.g. Molinari et al. 2007) even when the prompt component is present (e.g. Vestrand et al. 2006).

Panaitescu & Vestrand (2008) have studied the morphology of optical afterglow light curves and have identified two prominent classes: afterglows showing early peaks and afterglows showing extended plateaus. We have suggested that these two behaviours resulted from the observer being located initially outside the jet aperture (for peaked afterglows) and from outflows having a non-uniform angular distribution of the ejecta kinetic energy per solid angle (for afterglows with plateaus).

In this work, we expand our earlier study by adding new optical light curves that display peaks and plateaus and continue to investigate the possible reasons for the observed diversity of early optical light curves (Section 2). In particular, we explore another potential explanation: the onset of the blast-wave deceleration. In Section 3, we examine the correlation of optical and X-ray light curves and discuss the mechanisms that can account for the diverse optical and X-ray light-curve relative behaviours.

2 POSSIBLE ORIGINS FOR LIGHT-CURVE PEAKS AND PLATEAUS

Fig. 1 shows the optical light curves, transformed to a fiducial redshift \( z = 2 \), for all afterglows with (1) known redshift and (2) sufficiently good optical coverage to allow a reliable identification of a light-curve peak or a plateau. A ‘peak’ is defined by a full width at half-maximum of less than a factor of 5 in time. A ‘plateau’ is defined by the optical flux displaying a systematic change of a factor of less than 3 over more than a decade in time, ending with a break and followed by a steeper decline. Only the above two criteria are used in selecting the sample listed in Table 1. With these selection criteria, we find 16 afterglows with optical light-curve peaks and 17 with plateaus. Four afterglows display a broader peak or a shorter-lived plateau than defined above; their peaks/plateaus are located in the \( F \sim t \) plane around the intersection of the fits to the two categories of afterglows.

Peaky afterglows display a strong anticorrelation of the peak flux \( F_p \) with the peak epoch \( t_p \) [linear correlation coefficient \( r(\log F_p, \log t_p) = -0.83 \), corresponding to a probability of obtaining a stronger correlation of \( 10^{-4.4} \) in the null hypothesis]. The afterglows with plateaus exhibit a weaker anticorrelation of the peak flux \( F_b \) with the plateau end epoch \( t_p \): \( r(\log F_b, \log t_p) = -0.49 \) (chance probability of 2.3 per cent). The strength of these correlations is reduced if the optical luminosity is scaled to the GRB output or the peak/plateau end epoch is scaled to the burst duration.

The power-law fits shown in Fig. 1 are obtained by minimizing \( \chi^2 = \sum (y_i - ax_i - c)^2/(a^2\sigma_{y,i}^2 + \sigma_{x,i}^2) \) between the linear fit \( y = ax + c \) and the measurement sets \((x_i, y_i)\), with the variables \( x_i \) and \( y_i \) being \( \log t_p \) and \( \log F_p, \log F_b \), respectively, and \( a \) being the uncertainty of each variable, in log space. The uncertainties arise mostly from our determination of the peak/plateau end locations and much less from the errors of reported afterglow photometry. The slopes shown in Fig. 1 are obtained assuming that the relative errors \( \epsilon_p = \sigma_p/F_{p,b} \) and \( \epsilon_b = \sigma_b/t_{p,b} \) in measuring the peak/plateau end flux and epoch are the same for both quantities (\( \epsilon_p = \epsilon_b \)) and for all afterglows (the slopes of the fits are independent of the assumed relative errors because the fits are done in log-log space); the uncertainties (given in parentheses) of these slopes are estimates obtained by varying \( \epsilon_p \) and \( \epsilon_b \) within plausible ranges.

We note that these anticorrelations (in particular, that for peack afterglows) are due, in part, to an observational limitation, as dimmer afterglows peaking at earlier times are more likely to be missed.

Fig. 1 shows mostly afterglows with a peak near the bright edge of the \( F_p - t_p \) distribution, and it is quite likely that future more rapid and deeper follow-ups of GRB afterglows will fill the bottom-left part of Fig. 1 (e.g. afterglow 080430 – Klotz et al. 2009). Thus, the correlations identified in Fig. 1 define, more precisely, the boundary of a ‘zone of avoidance’ in the top-right region of this figure.

The important question is what generates these boundaries? The \( F_b \propto t_p^{-1} \) anticorrelation for plateau breaks may only mean that, given the energetics of relativistic outflows produced by GRB progenitors, afterglows with an optical output larger than about \( 10^{50} \text{erg s}^{-1} \) are not produced. However, the much steeper \( F_p \propto t_p^{-3} \) dependence displayed by the edge of the \( F_p - t_p \) distribution appears more likely to arise from the mechanism which produces light-curve peaks; thus, this correlation should be used as a tool for investigating the possible light-curve peak mechanisms.
afterglows. This result should be tested in the future with a larger set of afterglows, as it may provide support to the ‘deceleration-onset’ hypothesis for the origin of afterglow light-curve peaks and plateaus. We note that Kann et al. (2010) have found a tentative correlation between the optical luminosity at 1 d (i.e. at a fixed time) and the GRB energy release for a larger sample of 76 afterglows. Liang et al. (2010) have also found a strong correlation of the peak luminosity or optical output with the GRB energy release for a set of 17 afterglows, five of their afterglows falling in our plateau sample. In comparison, the slopes of the log–log fits obtained by Liang et al. (2010): \( F_\nu \propto E_\gamma^{0.74 \pm 0.10} \) and \( E_\gamma \propto F_\nu^{0.74 \pm 0.10} \), are smaller than those shown in Fig. 2.

In the following subsections, we explore three scenarios for the generation of light-curve peaks and plateaus and assess their ability to generate the steep \( F_\nu \propto t_\nu^{-3} \) boundary exhibited by the peak afterglow population.

### 2.1 Passage of a spectral break

The passage of either the injection frequency \( \nu_i \), which is the peak frequency of the \( vF_\nu \) synchrotron spectrum, or the cooling frequency \( \nu_c \) through the observing band causes a break in the afterglow light curve.

**Cooling frequency.** The afterglow spectrum has a shallow break at the characteristic synchrotron frequency \( \nu_c \) of the electrons whose radiative cooling time-scale equals the dynamical time-scale, across which the spectrum \( F_\nu \propto \nu^{-\beta} \) softens by \( \delta \beta = 1/2 \) if \( \nu < \nu_c \) and by \( \delta \beta = 5/6 \) if \( \nu > \nu_c \). In the forward-shock model, \( \nu_c \) evolves slowly (\( \nu_c \propto t^{-1/2} \) for a homogeneous medium and \( \nu_c \propto t^{i/2} \) for a wind). Consequently, the passage of \( \nu_c \) yields a weak steepening of the power-law flux \( F_\nu \propto t^{-\delta \beta} \) by \( \delta \beta = \delta \beta [\log \nu_c/\log t] = 1/4 \) or \( 5/12 \) for \( \nu_c > \nu \) and \( \nu < \nu_c \) respectively, which is less than the break seen at the peak and plateau ends of optical afterglows.

**Injection frequency.** If \( \nu < \nu_i \), the \( vF_\nu \) peak frequency \( \nu_i \) is a stronger spectral break, from \( F_\nu \propto \nu^{i/3} \) to \( F_\nu \propto \nu^{-\beta} \) with \( \beta \simeq 1 \). For \( \nu < \nu_i \), the afterglow spectrum has a weaker break at \( \nu_c \), from \( F_\nu \propto t^{-i/2} \) to \( F_\nu \propto t^{-\beta} \). The passage of \( \nu_i \) through the optical yields a stronger light-curve break than \( \nu_c \), because the evolution of \( \nu_i \) is faster: \( \nu_i \propto t^{-3/2} \). For \( \nu < \nu_i \), the light-curve decay steepening at the \( \nu_c \) crossing is \( \delta \beta = \delta \beta [\log \nu_c/\log t] = (3/2) \) and could account for an optical light-curve peak, provided that the medium is homogeneous. For \( \nu > \nu_i \), \( \delta \beta = 1.5 (\beta - \frac{1}{2}) \simeq 1.5 \), and the \( \nu_c \) crossing could produce only a plateau end. As a simple test of this scenario, the optical light-curve break produced by the passage of \( \nu_i \) must be accompanied by a significant spectral softening of the afterglow optical spectrum.

However, the passage of \( \nu_i \) cannot be the explanation for all optical light-curve peaks or plateau ends shown in Fig. 1 because (1) peaky afterglows rise with an index \( \alpha \simeq (-3, -2) \), i.e. they rise faster than can be accommodated by \( \nu_i \), being above optical, and (2) variations in the afterglow parameters \( E_\gamma \) and \( \nu_e \), which determine both the synchrotron peak flux \( F_i \) at \( \nu_i (F_i \propto E_{\gamma e}^{1/2} \) for a homogeneous medium and \( F_i \propto E_{\gamma e}^{1/2} \nu_\gamma^{-3/2} \) for a wind) and the epoch when \( \nu_i \propto E_{\gamma e}^{1/2} \nu_\gamma^{i/2} \) crosses the optical, lead to positive \( F_\nu \propto t_\nu^{-3} \) correlations, in contrast, anticorrelations are observed.

### 2.2 Misaligned jets

A misaligned jet yields an achromatic light-curve peak when the jet has decelerated enough for the observer’s direction (at angle \( \theta_o \) from the jet direction of motion) to enter the cone of opening 1/\( \Gamma \).
into which the jet emission is relativistically beamed, \( \Gamma \) being the jet Lorentz factor.

Possible failure. This scenario can account for the fast rise of peaky optical afterglows, but has difficulty in explaining the slope of the \( F_p - t_p \) anticorrelation shown in Fig. 1, if this relation arises from jets having various orientations \( \theta_0 \) relative to the observer. In this framework, special relativity effects lead to a received flux \( F_\nu \propto (2\Gamma / (\Gamma^2 \theta_0^2 + 1))^{\beta_1 + 1} \); hence, the afterlight-curves peak (when \( \Gamma \theta_0 = 1 \)), we have \( F_\nu \propto \theta_0^{-\beta_1} \). Rhoads (1999) has shown that the jet lateral spreading is dynamically significant when \( \Gamma \theta_0 = 1 \); it leads to an exponential jet deceleration \( \Gamma \propto e^{-kr} \), and \( t_p \propto r_o \theta_0^2 \), where \( r_o \) is the radius at which \( \Gamma = \theta_0^{-1} \), after which the jet radius increases only logarithmically with the observer time. Thus \( t_p \propto \theta_0^3 \), which together with \( F_\nu \propto \theta_0^{-\beta_1} \) leads to \( F_p \propto t_p^{-0.5} \).

Then, the observed anticorrelation slope of about \(-3\) requires an optical spectral slope \( \beta_o = 3 \), which is much softer than what is measured typically (\( \beta_o \approx 1 \)), albeit at times after the optical peak.

Caveats. The real \( F_p - t_p \) anticorrelation could be less steep, perhaps only \( F_p \propto t_p^{-2} \), and consistent with the misaligned-jet model expectation for a \( \beta_o = 1 \) optical spectrum, for the following two reasons. First, there is an observational bias against peaks occurring earlier than those shown in Fig. 1. Afterglows peaking at an earlier time must exist, as shown by those afterglows which display a decay from their first measurement. Secondly, the sample of peaky afterglows shown in Fig. 1 may be contaminated with early optical emission that does not arise from the afterglow of the blast wave, but from the prompt emission mechanism (the GRB). Indeed, three of the brighter peaks shown in Fig. 1 are coincident with a GRB pulse. In these cases, the true afterglow flux of the earlier light-curve peaks is lower than what is measured.

Contrived feature. Misaligned jets can also account for plateau afterglows if the ejecta kinetic energy per solid angle is not uniform within the jet opening. This is the model proposed by Panaitescu & Vestrand (2008) to explain the diversity of optical afterglow light curves. An unattractive aspect of this explanation is its contrived requirement of another jet producing the GRB emission, as the prompt emission from the misaligned optical jet is not relativistically beamed towards the observer.

2.3 Onset of deceleration

2.3.1 Peaky afterglows: impulsive ejecta release

For an impulsive ejecta release and a narrow distribution of the ejecta Lorentz factor after the burst phase, the forward-shock synchrotron emission light curve prior to the onset of deceleration displays a rise similar to that measured for peaky afterglows and a decay rate compatible with the observations after the onset of deceleration. Also, the onset of deceleration can yield an \( F_p - t_p \) anticorrelation similar to that observed for peaky afterglows, if that correlation arises from variations of the ambient density among afterglows, as shown below.

(1) Homogeneous medium. There are two cases where a decaying light curve is obtained after the deceleration time-scale \( t_d \propto (E/n \Gamma_0^3)^{1/3} \) (which is the light-curve peak time):

(i) \( F_{E_p} \propto \eta_p^{-1/2} \)

(ii) \( F_{E_p} \propto \eta_p^{-1/6} \)

In case (i), different ambient medium densities among afterglows yield \( F_0 \propto t_p^{-\beta_0} \), hence, an optical spectral slope \( \beta_o = 1 \) is required to account for the observed anticorrelation, while the various initial Lorentz factors of afterglows lead to \( F_0 \propto t_p^{-1.5} \), for which the measured anticorrelation requires a too soft optical spectrum, with slope \( \beta_o = 2 \).

In case (ii), differences in \( n \) or \( \Gamma_0 \) among afterglows induce the same anticorrelation: \( F_0 \propto t_p^{-3(\beta_o - 1)/2} \), which requires a rather soft optical spectrum with slope \( \beta_o = 7/3 \) to account for the observed \( F_p \propto t_p^{-3} \).

Thus, there is one scenario:

\( v_1 < v_\nu < v_e, \beta_o = 1, \) various medium densities,

which can account for the measured \( F_p - t_p \) anticorrelation displayed by peaky afterglows. Owing to the weak dependence of the deceleration time-scale on the external density, \( F_p \propto n^{1/3} \) for \( \beta_o = 1 \), the 1.5-dec in the peak time shown in Fig. 1 requires that the ambient density varies by 4–5 dex.

(2) Wind-like medium. In this case, \( t_d \propto E/(A \Gamma_0^3) \), where \( A \propto (dM/dv)/v_e \) is the wind density parameter, which depends on the

\[ T_{\text{GRB}} = 1.5 \times 10^{14} \text{ yr} \]

\[ T_{\text{GRB}} > 10^{11} \text{ yr} \]

\[ T_{\text{GRB}} > 10^{12} \text{ yr} \]

\[ T_{\text{GRB}} > 10^{13} \text{ yr} \]

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\[ T_{\text{GRB}} > 10^{15} \text{ yr} \]
massive star (GRB progenitor) mass-loss rate $dM/dt$ and the wind terminal velocity $v_o$. The cases yielding a decaying light curve after the onset of deceleration are as follows.

(i) $F_{\nu_1 < \nu < \nu_0} \propto E^{-\alpha} A^{(3+1)/2} \Gamma_0^{(3+1)/2}$.

(ii) $F_{\nu_0 < \nu < \nu_0} \propto E^{-\alpha} A^{(3+1)/2} \Gamma_0^{(3+1)/2}$.

In case (i), diversity in $A$ leads to $F_\nu \propto \nu^{(3+1)/2}$, which requires $\beta_o = 4/3$, while various $\Gamma_0$ among afterglows lead to $F_\nu \propto \nu^{(3+1)/2}$, which is the observed $F_\nu \propto \nu^3$ for $\beta_o = 5/3$.

In case (ii), the result is the same as for a homogeneous medium: $F_\nu \propto \nu^{(3+1)/2}$ for either the $A$ or the $\Gamma_0$-induced correlation.

Therefore, the deceleration-onset model accounts for the $F_\nu-t_p$ anticorrelation in the best way if $v_i < v_0 < v_c$, $\beta_o = 4/3$, various wind densities; hence $F_\nu \propto A^3$, and the wind density parameter $A$ should vary by 1.5 dex among afterglows.

2.3.2 Unifying picture

An extended release of ejecta, or one where the ejecta have a range of initial Lorentz factors after the burst, can lead to a gradual injection of energy into the blast wave because, in both scenarios, there will be some ejecta inner to the decelerating blast wave, which catch up with the forward shock. In these scenarios, the forward-shock emission could be constant or slowly decaying, followed by a steep decay when the energy injected stops being dynamically important. The correlation between the plateau flux and break epoch $F_\nu \propto t_0^{-1}$ shown in Fig. 1 suggests a (very roughly) constant optical output among afterglows.

Therefore, the unifying picture for the peaky and plateau optical afterglows shown in Fig. 1 is that they all arise from the onset of the blast-wave deceleration, the former being identified with an impulsive ejecta release where all ejecta have the same Lorentz factor after the burst phase and the latter being attributed to energy injection in the forward shock due to an extended ejecta release, a wide distribution of the ejecta initial Lorentz factor or both.

In the next section, we compare the optical and X-ray light curves of the two classes of optical afterglows identified, to search for differences in the correlation of the optical and X-ray flux histories and to identify the models that can account for the diversity of optical versus X-ray light-curve behaviours.

3 OPTICAL AND X-RAY AFTERRGLOWS

3.1 Expectations

In the forward-shock model, the flux power-law decay indices at optical and X-ray frequencies are equal if there is no spectral break between these two domains. If $v_o < v_c < v_i$, then the differences of the decay indices are $\alpha_x = \alpha_o = 1/4$ (the X-ray flux decays faster than the optical flux) for a homogeneous medium and $\alpha_x - \alpha_o = -1/4$ (the optical flux falls off faster than the X-ray’s) for a wind-like medium.

Three caveats to the above results are worth mentioning.

The first is that these results stand when the electron radiative cooling is synchrotron-dominated. If it is due mainly to inverse-Compton losses, then the fastest possible evolutions of the cooling break are $v_c \propto t^{1/2}$ (thus $\alpha_x - \alpha_o = -1/4$) for a homogeneous medium and $v_c \propto t^{3/2}$ (hence $\alpha_x - \alpha_o = -5/4$) for a wind-like medium, but the required conditions for this case to occur are unlikely to be maintained over a long time.

The second caveat is that a slowly decreasing or constant optical flux also results for $v_o < v_i$. In this case, an optical light-curve plateau is obtained if

1. $v_c < v_o < v_i$ and the medium is homogeneous, for which $\alpha_o = 1/4$ and the optical spectral slope is $\beta_o = 1/2$;
2. $v_o < v_c < v_i$ and the medium is a wind, for which $\alpha_o = 2/3$ and $\beta_o = -1/3$;
3. $v_c < v_i < v_o$ and the medium is a wind, for which $\alpha_o = 0$ and $\beta_o = -1/3$.

We note that a rising afterglow optical spectrum has never been observed (to the best of our knowledge); hence, only case (1) above may be relevant.

The third caveat is that if energy is added to the forward shock, then the evolution of the cooling frequency is ‘accelerated’ and the difference between the optical and X-ray flux decay indices is larger.

If the increase of the blast-wave kinetic energy is described by $E \propto t^2$, then $v_c \propto t^{(3+1)/2}$ and $\alpha_x - \alpha_o = (e + 1)/4$ for a homogeneous medium. For a wind-like medium, $v_c \propto t^{(3+1)/2}$ and $\alpha_x - \alpha_o = -(e + 1)/4$.

Using the above expectations for the forward-shock model, we define coupled optical and X-ray light curves for which $|\alpha_x - \alpha_o|$ is zero, 1/4 or slightly larger than 1/4, and define decoupled light curves for which $|\alpha_x - \alpha_o|$ is substantially larger than 1/4.

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The first is that these results stand when the electron radiative cooling is synchrotron-dominated. If it is due mainly to inverse-Compton losses, then the fastest possible evolutions of the cooling break are $v_c \propto t^{1/2}$ (thus $\alpha_x - \alpha_o = -1/4$) for a homogeneous medium and $v_c \propto t^{3/2}$ (hence $\alpha_x - \alpha_o = -5/4$) for a wind-like medium, but the required conditions for this case to occur are unlikely to be maintained over a long time.
Figure 3. Optical (red symbols) and X-ray (blue symbols) light curves of afterglows with optical peaks and coupled optical and X-ray light curves. To illustrate that the two frequencies’ light curves follow each other, we also show the optical light curve shifted to overlap the X-ray light curve. The X-ray light curves do not exhibit a peak at the same time with the optical because the optical peaks occur early, when the X-ray emission is still dominated by the decaying contribution from the prompt (burst) mechanism. Vertical lines indicate the first X-ray measurement, after which the prompt mechanism contribution is negligible and the X-ray flux is from the afterglow.

\[ \alpha_o = \frac{1}{4} \begin{cases} 3p - 3 - (p + 3)e \nu_i^{(\text{opt})} < \nu_o < \nu_i^{(\text{opt})} \\ 3p - 2 - (p + 2)e \nu_i^{(\text{opt})} < \nu_o \end{cases} \]

while for the inverse Compton (X-ray)

\[ \alpha_x = \frac{1}{8} \begin{cases} 9p - 11 - (3p + 7)e \nu_x^{(\text{ic})} < \nu_x < \nu_x^{(\text{ic})} \\ 9p - 10 - (3p + 2)e \nu_x^{(\text{ic})} < \nu_x \end{cases} \]

For a wind-like medium

\[ \alpha_o = \frac{1}{4} \begin{cases} 3p - 1 - (p + 1)e \nu_i^{(\text{opt})} < \nu_o < \nu_i^{(\text{opt})} \\ 3p - 2 - (p + 2)e \nu_i^{(\text{opt})} < \nu_o \end{cases} \]

\[ \alpha_x = \begin{cases} p - (p - 1)e/2 \nu_x^{(\text{ic})} < \nu_x < \nu_x^{(\text{ic})} \\ p - 1 - pe/2 \nu_x^{(\text{ic})} < \nu_x \end{cases} \]

When there is no energy injection, the previous equations (1) to (4) give the flux decay index by setting \( e = 0 \).

With the above results, it can be shown that the synchrotron self-Compton (SSC) model can explain the decoupled light curves of the following afterglows:

(i) 080129 – \( \nu_o < \nu_i^{(\text{opt})}, \nu_x < \nu_i^{(\text{ic})}, p \simeq 1.6, e \simeq 1.0 \);
(ii) 090423 – \( \nu_o < \nu_i^{(\text{opt})}, \nu_x < \nu_i^{(\text{ic})}, p \simeq 2.2, e \simeq 2.4 \) (but here the resulting rise and decay are slightly faster than what is measured);
(iii) 090510 – \( \nu_o < \nu_i^{(\text{opt})}, \nu_x < \nu_i^{(\text{ic})}, p \simeq 1.6, e \simeq 1.0 \);
(iv) 050730 and 090418 (Fig. 5), we cannot find a set of parameters \((p, e)\) to accommodate their decoupled optical and X-ray decays within the SSC model with energy injection cessation at the light-curve break epoch (model is overconstrained, with two free parameters and three to four observational constraints), which suggests that energy injection continues after the break (but with a different power-law exponent \( e \)).

3.4 Decoupled light curves with chromatic breaks

**Chromatic optical light-curve breaks.** They are observed for the plateau afterglows 080804 and 080928 (Fig. 6) and may originate from the peak \( \nu_i \) of the synchrotron spectrum crossing the optical. In this scenario, the optical and X-ray light curves should be coupled after the break. A simple test for the origin of the optical light-curve break in the passage of \( \nu_i \) is the softening of the optical spectrum across the break epoch.

**Chromatic X-ray light-curve breaks.** Such breaks are observed for the peaky afterglows 060606 and 061121 (Fig. 5) and for the plateau afterglow 060605 (Fig. 6). They suggest that the optical and
X-ray emissions either (i) arise from different radiation processes or (ii) have a different origin. The former scenario is an unlikely explanation because, in this case, the X-ray light-curve break can be produced only by a spectral break crossing the observing band, which is in contradiction to the general lack of an X-ray spectral evolution observed to occur simultaneously with a chromatic light-curve break (e.g. Nousek et al. 2006). The latter scenario is motivated by the fact that if the X-ray and optical afterglow emissions had the same origin, then a light-curve break arising from a change in the blast-wave dynamics should also be present in the optical light curve.

Reprocessing of the lower frequency forward-shock emission through upscattering by another part of the outflow can yield X-ray light curves that are decoupled from the optical provided (i) the scattering outflow has an optical thickness (well below unity) sufficiently large to account for the measured X-ray flux and (ii) the scattering outflow moves at a higher Lorentz factor than the forward shock, to boost the shock’s emission to higher frequency and to yield a flux larger than that coming directly from the forward shock (Panaitescu 2008).

A simple expectation for the bulk-scattering model is that chromatic X-ray light-curve breaks should be seen more often for
afterglows with optical plateaus than for peaky afterglows. That is so if, as proposed here, afterglows with plateaus arise from an incoming outflow that adds energy to the blast wave, and upscatters the forward-shock emission. In contrast, if afterglows with peaks arise from impulsive ejecta releases, then an outflow inner to the forward shock should not exist for them.

Contrary to this expectation, only one plateau afterglow (060605) displays a chromatic X-ray light-curve break whereas two peaky afterglows (060607 and 061121) have such a feature. Taken at face value, the deceleration-onset model for peaky and plateau afterglows is in contradiction to this low-number ‘statistics’ and, evidently, a larger number of optical and X-ray afterglows should be studied before drawing a reliable conclusion. Nevertheless, we note that an outflow inner to the blast wave may also exist for peaky afterglows and, while that outflow might carry too little energy to modify the forward-shock dynamics and yield an optical light-curve plateau instead of a peak, the upscattered emission from the incoming outflow could still overshadow the direct forward-shock emission and produce a chromatic X-ray light-curve plateau.

### 3.5 X-ray to optical flux ratio

Fig. 7 shows the distributions of the optical-to-X-ray spectral slope $\beta_{ox} = -\log(F_x/F_o)\log(\nu_x/\nu_o)$ for afterglows with coupled (same decays, without breaks or with achromatic breaks) and decoupled (different decays or with chromatic breaks) optical and X-ray light curves. The simple result shown in Fig. 7 is that the afterglows with decoupled light curves are, on average, brighter in the X-ray relative to the optical (smaller slope $\beta_{ox}$) than the afterglows with coupled light curves. Quantitatively, the difference between the average slopes $\bar{\beta}_{ox}$ of the two categories of afterglows is $\delta\bar{\beta}_{ox} = 0.24 \pm 0.32$, which means that the X-ray to optical flux ratio of decoupled afterglows is, on average, $(\nu_x/\nu_o)^{0.24} = 4.4$ times larger than for the afterglows with coupled light curves.

A similar conclusion is reached if the measured X-ray flux is normalised to that estimated from the optical flux, obtained by assuming that the afterglow spectrum is a pure power law. Here, we define $y = \log(F_x^{(obs)}/F_x^{(extr)})$ with $F_x^{(extr)} = F_o^{(obs)}(\nu_o/\nu_x)^{\beta_o}$, where $\beta_o$ is the intrinsic power-law slope of the optical spectrum. As $\beta_o$ is hard to determine accurately (owing primarily to the unknown reddening by dust in the host galaxy), we use the value required within the forward-shock model by the measured power-law optical flux decay $F_o^{(obs)} \propto t^{-\alpha_o}$, with $\alpha_o$ measured after the optical plateau (i.e. when the blast wave is adiabatic): $\beta_o = (2/3)\alpha_o + c$.

The constant $c$ depends on the location of the optical relative to the cooling frequency $\nu_c$ of the forward-shock synchrotron emission spectrum and, for $\nu_o < \nu_c$, also on the radial stratification of the ambient medium. The major assumption made here is that the constant $c$ is the same for all afterglows. For instance, if the ambient medium is homogeneous and if $\nu_o < \nu_c$ (for which $c = 0$), we find...
that $\bar{\gamma} = 0.22 \pm 0.54$ for afterglows with coupled light curves and $\bar{\gamma} = 0.64 \pm 0.51$ for afterglows with decoupled light curves, the difference between the average values being $\delta \bar{\gamma} = 0.42 \pm 0.74$. This indicates that the X-ray flux of decoupled afterglows is, on average, $10^{35} = 2.6$ times brighter than that of coupled afterglows. We note that $\bar{\gamma}$ depends on the constant $c$, but $\delta \bar{\gamma}$ does not; hence, this conclusion is independent of the assumed optical spectral regime and medium stratification.

That the afterglows with decoupled light curves have a higher X-ray to optical flux ratio indicates that there is a mechanism which operates mostly/only in decoupled afterglows and which yields more X-ray emission than the underlying synchrotron flux from the forward shock. This mechanism could be local inverse-Compton scattering or external upscattering (bulk and/or inverse Compton).

Alternatively, the higher X-ray brightness of decoupled afterglows could be explained if there were a process that reduces the optical emission of coupled afterglows. Given that the media involved in GRB afterglows are optically thin to electron scattering, that reduction of the optical flux should be due to dust extinction in the host galaxy. However, there is no obvious reason for which afterglows with coupled light curves should undergo more dust extinction than decoupled afterglows.

We note that the optical luminosity distributions of afterglows with coupled and decoupled light curves are consistent with being drawn from the same parent distribution, a conclusion which also holds for the X-ray luminosities of these two classes. For all afterglows moved at the same redshift $z = 2$, we find that the average optical flux (in mJy) at a fixed time (10 ks) is $\langle \log F_{\nu} \rangle_{c} = -1.03 \pm 0.61$ for coupled afterglows and $\langle \log F_{\nu} \rangle_{d} = -1.35 \pm 0.62$ for decoupled afterglows. For the $z = 2$ X-ray flux (in mJy), $\langle \log F_{\nu} \rangle_{c} = 0.02 \pm 0.60$ and $\langle \log F_{\nu} \rangle_{d} = 0.15 \pm 0.77$. Thus, decoupled afterglows are on average only slightly dimmer (by factor of 2.0) in the optical and only slightly brighter (by a factor of 1.3) in the X-ray than coupled afterglows, the difference between the two types of afterglows becoming clearer in the distributions of the X-ray to optical flux ratio.

\section{Conclusions}

Based on the appearance of their light curves, we identify two types of optical afterglows, with light-curve peaks and with plateaus (Fig. 1). In the plateau end luminosity–epoch plane, plateau afterglows show an $F_{\nu} \propto t_{\nu}^{-1}$ anticorrelation that might suggest a universal afterglow optical output. However, the optical energy release during the plateau, shown in Fig. 2, has a substantial spread.

In the peak luminosity–peak epoch plane, the distribution of peaky afterglows displays an $F_{\nu} \propto t_{\nu}^{-1}$ bright edge, with earlier and/or dimmer peaks being missed. We speculate that this steep dependence seen at the bright edge arises from the mechanism that generates optical light-curve peaks, and we have discussed/investigated three such possible mechanisms.

One is that optical observations are made below the synchrotron spectrum peak $\nu_{\nu}$, which can also yield light-curve plateaus. This mechanism is easily invalidated by the fact that $\nu_{\nu}$ crossing the optical should lead to a positive correlation of the peak/plateau end flux with the epoch, contrary to the observed anticorrelations.

In our previous study (Panaitescu & Vestrud 2008), we have attributed peaky afterglows to the observer being slightly outside the jet initial aperture and plateau afterglows to outflows endowed with an angular structure and an off-axis observer location. For a typical optical afterglow spectrum ($F_{\nu} \propto \nu^{i}$), variations in the observer offset angle induce an $F_{\nu} \propto t_{\nu}^{-1}$ anticorrelation that is less steep than what is measured. However, there are two observational selection effects that could make the slope of the observed anticorrelation appear steeper. The first is that rapidly slewing telescopes capable of observing during the first few minutes after a GRB are typically less sensitive than those observing the afterglow at later stages. This means that faint and early peaks (which would be in the bottom-left corner of Fig. 1) have been missed. The second factor that could make the sample of early peaks appear brighter is contamination from the prompt mechanism. A more troubling issue with this model is the required and contrived double-jet structure of the ejecta, with one jet moving towards the observer and producing the burst emission and another slightly offset jet producing the afterglow emission and becoming visible after it has decelerated enough.

Here, we propose another model to unify peaky and plateau afterglows, in which the two classes are related to the duration of the central engine, the light-curve peak and plateau break corresponding to the end of energy injection in the blast wave and to the onset of its deceleration. In this model, plateau afterglows are associated with an extended production of ejecta or with an impulsive one but with a range of ejecta initial Lorentz factors, such that energy injection...
in the forward shock can last up to 100 ks, while peaky afterglows are associated with an impulsive release of ejecta that have a narrow distribution of the Lorentz factor.\footnote{If the burst emission arises from internal shocks, then the narrow distribution of ejecta Lorentz factors should occur only after the burst phase, as otherwise the internal shocks will have a very low dissipation efficiency, and the GRBs of peaky afterglows should be much dimmer than those of afterglows with plateaus. This is in contradiction to the GRB energies shown in Fig. 2.}

We find that the exponent of the $F_o - t_p$ correlation is set by the slope of the afterglow optical spectrum ($F_o \propto \nu^{-\beta_o}$). This slope is very rarely measured at the early times when the optical peaks occur; at later times, $\beta_o \in (0.7, 1)$ for most of the peaky afterglows shown in Fig. 1. The hardest optical spectrum for which variations in the afterglow parameters that set the deceleration/peak time-scale yield the observed $F_p \propto t_p^{-3}$ correlation is $\beta_o = 1$, obtained for a homogeneous ambient density. Then, the observed range of optical peak fluxes (or peak epochs) requires the external density to vary by 4–5 dex among the afterglows shown in Fig. 1.

This model for the dichotomy of optical light curves has a straightforward implication. For peaky afterglows arising from impulsive ejecta releases, it is quite likely that all the afterglow ejecta participated in the production of the burst emission. As some optical plateaus may arise from a long-lived central engine, it is possible that most of the afterglow ejecta did not produce the short-lived GRB emission. Thus, the optical output of afterglows with plateaus is expected to be less correlated with the burst energy than for peaky afterglows. This indeed seems to be the case (Fig. 2).

We have compared the optical and X-ray light curves of peaky and plateau afterglows and have found that, for 15 of the 25 afterglows with good coverage, the light curves at these two frequencies are well coupled, having the same power-law decay indices and achromatic breaks. For the other 10, we propose the following scenarios to explain their decoupled light curves.

1. If the external medium is sufficiently dense, then local (inverse-Compton) scattering may overshine the synchrotron emission from the forward shock in the X-rays. This SsC model can account for the decoupled X-ray and optical flux decays of GRB afterglows 080129, 090423 and 090510, but has difficulties in accounting for the light curves of afterglows 050730 and 090418. In this scenario, the X-ray (inverse-Compton) afterglow flux is expected to decrease faster than the optical (synchrotron) flux.

2. If the synchrotron spectrum peak passes through the observing band, then a chromatic light-curve break will result, which is more likely to be observed at optical frequencies, as for afterglows 080804 and 080928. In this scenario, the chromatic light-curve break should be accompanied by a strong spectral softening.

3. If a sufficiently relativistic and pair-rich outflow exists behind the forward shock, then bulk-scattering of the forward-shock emission by this incoming outflow may overshine the direct emission from the forward shock and yield a chromatic X-ray light-curve break, as observed for GRB afterglows 060605, 060607 and 061121. In this model, the bulk-scattered emission mirrors the radial distribution of the Lorentz factor and/or optical thickness of the scattering outflow; hence, the light curves of the scattered (X-ray) and direct (optical) emissions are naturally decoupled.

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