

# Evidence for chromatic X-ray light-curve breaks in Swift gamma-ray burst afterglows and their theoretical implications

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## ABSTRACT

The power-law decay of the X-ray emission of gamma-ray burst (GRB) afterglows 050319, 050401, 050607, 050713A, 050802 and 050922C exhibits a steepening at about 1–4 h after the burst which, surprisingly, is not accompanied by a break in the optical emission. If it is assumed that both the optical and X-ray afterglows arise from the same outflow then, in the framework of the standard forward shock model, the chromaticity of the X-ray light-curve breaks indicates that they do not arise solely from a mechanism related to the outflow dynamics (e.g. energy injection) or the angular distribution of the blast-wave kinetic energy (structured outflows or jets). The lack of a spectral evolution accompanying the X-ray light-curve break shows that these breaks do not arise from the passage of a spectral break (e.g. the cooling frequency) either. Under these circumstances, the decoupling of the X-ray and optical decays requires that the microphysical parameters for the electron and magnetic energies in the forward shock evolve in time, whether the X-ray afterglow is synchrotron or inverse-Compton emission. For a steady evolution of these parameters with the Lorentz factor of the forward shock and an X-ray light curve arising cessation of energy injection into the blast wave, the optical and X-ray properties of the above six Swift afterglows require a circumburst medium with a  $r^{-2}$  radial stratification, as expected for a massive star origin for long GRBs. Alternatively, the chromatic X-ray light-curve breaks may indicate that the optical and X-ray emissions arise from different outflows. Neither feature (evolution of microphysical parameters or the different origin of the optical and X-ray emissions) was clearly required by pre-Swift afterglows.

**Key words:** radiation mechanisms: non-thermal – shock waves – ISM: jets and outflows – gamma-rays: bursts.

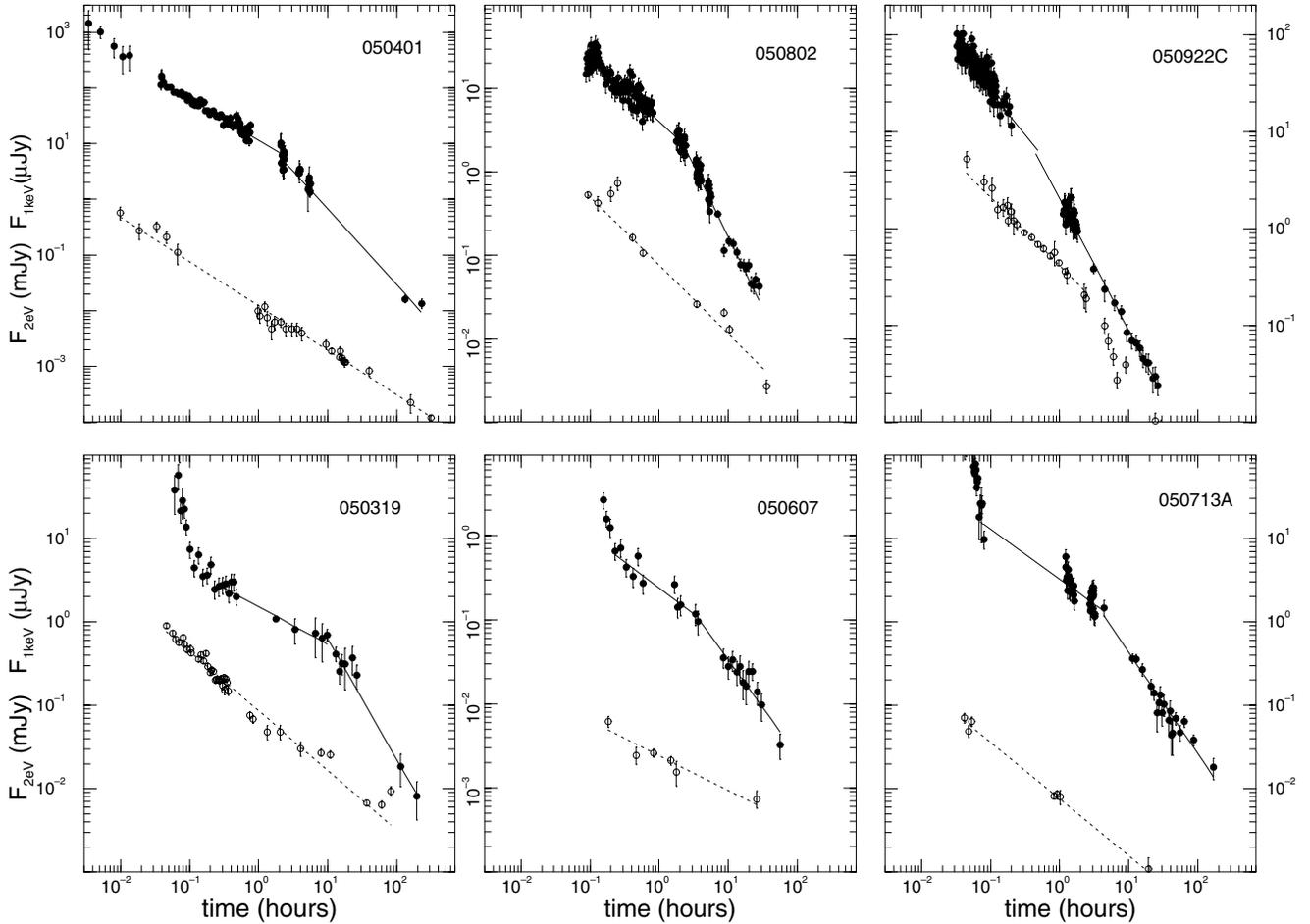
## 1 INTRODUCTION

The standard blast-wave model for gamma-ray burst (GRB) afterglows (e.g. Mészáros & Rees 1997), where the afterglow emission arises from the external shock which dissipates GRB ejecta kinetic energy, energizes the circumburst medium, accelerates relativistic electrons and generates magnetic fields, producing synchrotron emission, has been largely confirmed by the numerous X-ray, optical and radio afterglows discovered so far. Their light curves exhibited a power-law decay, as expected from the power-law decay of the shock Lorentz factor with observer time and the

power-law distribution with energy of shock-accelerated electrons (together, these two properties lead to synchrotron spectrum characteristics with a power-law temporal evolution). In general, the optical and X-ray light-curve decay indices were found consistent with the slope of the afterglow spectrum (e.g. Wijers, Rees & Mészáros 1997).

Further testing of the standard blast-wave model can be done by comparing the light-curve decays at different wavelengths. For instance, the light-curve breaks (i.e. steepening of power-law decay) arising from the dynamics or the collimation of the GRB outflow (Rhoads 1999) should be achromatic, occurring simultaneously at all frequencies. The lack of a sufficiently extended X-ray monitoring of pre-Swift afterglows prevented us to test if the breaks observed in the optical light curves of many GRB afterglows were achromatic,

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**Figure 1.** Light curves of six Swift GRB afterglows showing a chromatic X-ray break which is not seen in the optical at the same time. Optical data are shown with open symbols and are fit with a power-law decay (dotted lines). X-ray data shown with filled symbols are fit with a broken power law (solid lines). Optical measurements are from Woźniak et al. (2005), GCNs 3120 (T. Yoshioka), 3124/3140 (D. Sharpov) (050319); De Pasquale et al. (2006), Watson et al. (2006), Rykoff et al. (2005) (050401); GCNs 3531 & 3540 (J. Rhoads) (050607); Guetta et al. (2006) (050713A); GCNs 3739/3745 (K. McGowan), 3744 (E. Pavlenko), 3765 (V. Testa) (050802); GCNs 4012 (E. Rykoff), 4015 (P. Jakobsson), 4016 (E. Ofek), 4023 (D. Durig), 4026 (T. Henych), 4041 (S. Hunsberger), 4046 (S. Covino), 4048 (M. Andreev), 4040 (J. Fynbo), 4095 (W. Li) (050922C).

with the possible exceptions of GRBs 010222 and 030329. For the former, a single 10-d X-ray measurement (in't Zand et al. 2001) indicates the existence of a break in the X-ray light curve at  $\gtrsim 2$  d, which could have been simultaneous with the gradual optical break. For the latter, a break in the X-ray light curve at 0.5 d (Tiengo et al. 2003) is accompanied by a steepening of the optical light-curve decay (Lipkin et al. 2004), however the variability of the optical emission makes a jet-break identification difficult.

In the last year, the Swift satellite has monitored the X-ray emission of dozens of afterglows, and has shown that, after a rather shallow decay, the X-ray light curves exhibit a steepening at about 1–4 h after the burst. Because of their dimness, only a small fraction of these afterglows were followed in the optical. The only cases so far for an X-ray light-curve break possibly accompanied by an optical steepening are the GRB afterglows 050525A (Blustin et al. 2006) and 050801 (Rykoff et al. 2006). The X-ray light curve of the former appears more complex than just a broken power, with an uncertain break time, while the optical emission shows a brightening (Klotz et al. 2005) around the epoch of the X-ray break. The optical and X-ray breaks of the latter occur much earlier than for other afterglows, at only 4–5 min after the burst.

Surprisingly, as shown in Fig. 1, the optical light curves of other GRB afterglows do not exhibit a steepening at the epoch of the X-ray break, as noted also for GRBs 050319 and 050401 by Fan & Piran (2006). Summarizing their temporal properties, the X-ray light-curve decays steepen from  $F_x \propto t^{-0.8 \pm 0.2}$  to  $F_x \propto t^{-1.4 \pm 0.2}$  at  $t_b = 1\text{--}4$  h, however the optical light curves, which start 1–2 decades before  $t_b$ , maintain a  $F_o \propto t^{-0.6 \pm 0.2}$  decay after  $t_b$ . The evidence for the X-ray break chromaticity is weak for GRBs 050607 and 050713A (lower panel of Fig. 1), for which there is only one post-break optical measurement (possibly contaminated by the host galaxy emission) but is rather compelling for GRBs 050401, 050802 and 050922C (upper panel of Fig. 1). In particular, no optical light-curve break is seen for the GRB afterglow 050401 for 2.5 decades in time after  $t_b$  (Watson et al. 2006). Only the optical emission of the GRB afterglow 0509022C exhibits a steepening, but at  $10 t_b$ .

The purpose of this article is to investigate the conditions required for the external shock to produce such a chromatic X-ray light-curve break. The afterglow emission is described by

$$F_\nu(t) \propto \nu^{-\beta} t^{-\alpha}, \quad (1)$$

as expected in the standard blast-wave model for GRB afterglows (e.g. Paczyński & Rhoads 1993; Mészáros & Rees 1997; Sari,

**Table 1.** X-ray and optical properties for the afterglows of Fig. 1.

GRB	$\alpha_{x1}$ (i)	$t_b$ (ii)	$\alpha_{x2}$ (iii)	$\beta_x$ (iv)	Refs.	$\alpha_o$ (v)	$t_o/t_b$ (vi)	$s$ (vii)	$e$ (viii)	$b$ (ix)	$i$ (x)
050319	$0.54 \pm 0.04$	7.5	$1.14 \pm 0.20$	$0.75 \pm 0.05$	(1)	$0.71 \pm 0.02$	0.006–10	$2.28 \pm 0.04$	3.8	5.4	−3.6
050401	$0.65 \pm 0.02$	1.2	$1.39 \pm 0.05$	$1.00 \pm 0.13$	(2, 3)	$0.80 \pm 0.03$	0.01–250	$2.17 \pm 0.08$	5.6	5.5	−1.7
050607	$0.61 \pm 0.11$	3.3	$1.12 \pm 0.07$	$1.15 \pm 0.11$	(4)	$0.41 \pm 0.10$	0.05–7	$1.87 \pm 0.08$	3.6	4.5	0.0
050713A	$1.02 \pm 0.07$	4.4	$1.45 \pm 0.06$	$1.07 \pm 0.04$	(5)	$0.68 \pm 0.05$	0.008–4	$2.06 \pm 0.04$	1.9	5.8	−1.4
050802	$0.64 \pm 0.10$	1.7	$1.66 \pm 0.06$	$0.91 \pm 0.19$	(6)	$0.82 \pm 0.03$	0.06–20	$2.24 \pm 0.13$	7.2	7.6	−4.1
050922C	$0.80 \pm 0.10$	0.3	$1.19 \pm 0.02$	$1.10 \pm 0.09$	(6)	$0.71 \pm 0.05$	0.1–10	$2.06 \pm 0.06$	2.4	4.2	−0.3

(i) Pre-break X-ray decay index; (ii) epoch of X-ray light-curve break, in hours; (iii) post-break X-ray decay index; (iv) slope of X-ray spectrum; (v) optical decay index (same before and after  $t_b$ ); (vi) time range of optical power-law decay relative to the X-ray break epoch; (vii)–(x) parameters for the medium structure (equation 7) and evolution of blast-wave energy and microphysical parameters (equation 6). References for (i)–(iv): (1) Cusumano et al. (2006), (2) Watson et al. (2006), (3) De Pasquale et al. (2006), (4) Nousek et al. (2006), (5) Morris et al. (2006) and (6) O’Brien et al. (2006).

Narayan & Piran 1998), with ‘o’ and ‘x’ for the subscript ‘ $\nu$ ’ designating optical and X-ray quantities, respectively. Additionally, the pre- and post-break X-ray light-curve decay indices are denoted by  $\alpha_{x1}$  and  $\alpha_{x2}$ .

## 2 MODEL INTERPRETATION

The lack of an optical light-curve break contemporaneous with that seen in the X-ray shows that the X-ray light-curve breaks do not arise from the outflow collimation (a jet) or angular structure (where the ejecta kinetic energy is a function of direction). For this reason, we consider only the case of a uniform outflow which is sufficiently relativistic that its boundaries are not yet visible to the observer.

### 2.1 Cooling frequency crossing the X-ray

The possibility that the X-ray light-curve break is caused by the passage of a spectral break through the X-rays is largely excluded by the lack of a significant spectral evolution (Cusumano et al. 2006; De Pasquale et al. 2006; Morris et al. 2006; Nousek et al. 2006), a fact also pointed out by Fan & Piran (2006) for the X-ray afterglows 050319 and 050401. In contrast, if the cooling break frequency,  $\nu_c$  (which is the frequency at which the electrons whose cooling time-scale is equal to the dynamical time-scale radiate), had crossed the X-ray band, then the X-ray continuum should have softened by  $\Delta\beta_x = 0.5$  for a homogeneous circumburst medium (for which  $\nu_c \propto t^{-1/2}$ ) or hardened by  $\Delta\beta_x = -0.5$  for a wind-like medium (for which  $\nu_c \propto t^{1/2}$ ).

Should the above spectral evolution be measured across  $t_b$  in other X-ray afterglows, the passage of  $\nu_c$  through X-ray domain would lead to a break of the X-ray light curve with the following properties:

$$\text{(homogeneous medium)} \quad \alpha_{x1} = \alpha_o, \quad \alpha_{x2} = \alpha_o + 1/4, \quad (2)$$

$$\text{(wind medium)} \quad \alpha_{x1} = \alpha_o - 1/4, \quad \alpha_{x2} = \alpha_o, \quad (3)$$

if the electron radiative cooling is synchrotron dominated (i.e. Compton parameter  $Y < 1$ ). In this case, the magnitude of the X-ray light-curve break is  $\Delta\alpha_x \equiv \alpha_{x2} - \alpha_{x1} = 1/4$ , i.e. smaller than that observed for most (if not all) Swift afterglows.

If inverse-Compton (iC) scattering dominated the electron cooling ( $Y > 1$ ) then, for a homogeneous medium, the cooling frequency would decrease more slowly or can even increase, which leads to an even smaller X-ray break magnitude:  $\Delta\alpha_x < 1/4$  (Panaitescu & Kumar 2001). A stronger X-ray break is produced by a wind-like medium, where an iC-dominated electron cooling accelerates the increase in time of  $\nu_c$ , leading to  $1/4 < \Delta\alpha_x \leq 5/4$  (Panaitescu & Kumar 2001). However, in this case, the optical and post-break

X-ray decay indices should be equal ( $\alpha_{x2} = \alpha_o$ ), in contradiction with what is observed for all afterglows in Table 1.

Therefore, the passage of the cooling frequency through the X-ray as a reason for the X-ray light-curve breaks shown in Fig. 1 is incompatible not only with the lack of an X-ray spectral evolution but also with the measured optical and X-ray decay indices.

### 2.2 Synchrotron emission in the X-ray

In a model where both the optical and X-ray emissions arise from the same afterglow synchrotron component, the optical and X-ray light curves can have different behaviours if the cooling frequency lies between the optical and X-ray. Then, one can determine its evolution from the optical and X-ray decay indices. In the external shock model, the optical and X-ray afterglow fluxes are related by

$$F_x = F_o \left( \frac{\nu_o}{\nu_c} \right)^{\beta_o} \left( \frac{\nu_c}{\nu_x} \right)^{\beta_x}. \quad (4)$$

It follows that  $\nu_c$  must have the following evolution:

$$\frac{d \ln \nu_c}{d \ln t} = \frac{\alpha_o - \alpha_x}{\beta_x - \beta_o} = 2(\alpha_o - \alpha_x), \quad (5)$$

where  $\beta_x = \beta_o + 1/2$  (for  $\nu_o < \nu_c < \nu_x$ ) was used.

For the afterglows of Table 1,  $\alpha_{x2} - \alpha_o \in (0.4, 0.9)$ , implying a post-break decrease of the cooling frequency,  $\nu_c \propto t^{-1.3 \pm 0.5}$ , which is much faster than that expected in the standard forward shock model. In this model, for constant microphysical parameters and no energy injection in the blast wave, the steepest decrease is obtained for a homogeneous medium and synchrotron-dominated electron cooling:  $\nu_c \propto t^{-1/2}$ . Energy injection in the forward shock by means of some GRB ejecta catching-up with it leads to a faster decrease of  $\nu_c$  but cannot by itself produce a chromatic X-ray light-curve break because it alters the afterglow flux below the cooling frequency as well. Instead, the fast decrease of  $\nu_c$  suggests that the fraction of the post-shock energy in magnetic fields,  $\epsilon_B$ , is evolving. Because the afterglow emission also depends on the fraction  $\epsilon_i$  of the post-shock energy that is imparted to electrons, we also allow it to be time dependent.

Given that the afterglow light curves are power laws in observer time, evolution of the microphysical parameters and blast-wave kinetic energy  $E$  (allowing for energy injection) must also be power laws in  $t$ . The latter implies that the blast-wave Lorentz factor  $\Gamma$  is also a power law in time, hence  $E$ ,  $\epsilon_B$  and  $\epsilon_i$  must evolve as power laws of  $\Gamma$ :

$$E(>\Gamma) \propto \Gamma^{-e}, \quad \epsilon_B \propto \Gamma^{-b}, \quad \epsilon_i \propto \Gamma^{-i}, \quad (6)$$

where  $E(>\Gamma)$  denotes the energy of all ejecta with Lorentz factor larger than a given  $\Gamma$  which have caught-up with the forward shock. For a decelerating blast wave, the increase of its kinetic energy is equivalent to  $e > 0$ . We also allow for a power-law stratification of the ambient medium

$$n(r) \propto r^{-s} \quad (s < 3) \quad (7)$$

to be determined from the optical and X-ray afterglow properties. The condition  $s < 3$  ensures that the blast wave is decelerated, for any  $e > 0$ .

The synchrotron optical ( $\nu_o < \nu_c$ ) and X-ray ( $\nu_c < \nu_x$ ) light curves can be inferred from the decay indices given in Panaitescu & Kumar (2004) by using

$$\frac{d \ln \Gamma}{d \ln t} = -\frac{3-s}{e+8-2s} \quad (8)$$

which follows from assuming an adiabatic blast wave,  $\Gamma^2 M \propto E$ , where  $M \propto r^{3-s}$  is the mass of the swept-up medium, and from the relation between the blast-wave radius and photon arrival time,  $R \propto \Gamma^2 t$ . The results are

$$\alpha_o = \frac{s}{8-2s} + \frac{3p-3}{4} - \frac{3-s}{e+8-2s} \times \left[ \left( \frac{p+3}{4} - \frac{s}{8-2s} \right) e + (p-1)i + \frac{p+1}{4}b \right], \quad (9)$$

$$\alpha_x = \frac{3p-2}{4} - \frac{3-s}{e+8-2s} \left[ \frac{p+2}{4}e + (p-1)i + \frac{p-2}{4}b \right], \quad (10)$$

where  $p = 2\beta_x$  is the exponent of the power-law electron distribution with energy in the forward shock

$$\frac{dN}{d\gamma}(\gamma > \gamma_i) \propto \gamma^{-p}, \quad (11)$$

$\gamma_i$  being the typical (comoving) Lorentz factor of the shock-accelerated electrons.

We do not consider a scenario where the evolutions of the microphysical parameters change at  $t_b$  to yield an X-ray light-curve break because such a scenario is very contrived: those changes in the evolution of  $\epsilon_i$  and  $\epsilon_B$  would have to ‘conspire’ to leave the optical power-law light curve unaffected. A more natural scenario is that where the evolution of the microphysical parameters with the blast-wave Lorentz factor is steady (i.e. constant  $i$  and  $b$  in equation 6), and the X-ray light-curve break is caused by a change in the evolution of  $\Gamma$ . The latter could be due to (i) the blast wave encountering the termination shock of the burst progenitor’s wind or (ii) cessation of energy injection into the blast wave.

In the former scenario, the termination shock marks the transition between the freely expanding wind of a massive star and the homogenized shocked wind. Substituting  $s = 2$  at  $t < t_b$  and  $s = 0$  at  $t > t_b$  in equation (10), one can find the parameter  $e$  for the energy injection. However, for all the afterglows listed in Table 1, we obtain an unphysical result:  $e < 0$ , therefore this scenario does not work.

In the second scenario, the cessation of energy injection implies a lower cut-off to the Lorentz factor of the incoming ejecta. From equation (9), it can be shown that the condition that the optical decay index remains unchanged when  $e(t < t_b) > 0$  switches to  $e(t > t_b) = 0$  leads to

$$(p-1)i + \frac{p+1}{4}b = 2(p+3) - \frac{s}{2}(p+5). \quad (12)$$

There is no obvious reason for the evolution of the microphysical parameters with the blast-wave Lorentz factor to ‘know’ about the structure of the ambient medium, hence this scenario remains contrived. The above condition also shows why the standard forward shock model with energy injection cannot explain the chromaticity of the X-ray light-curve break: for  $i = b = 0$  (i.e. constant microphysical parameters), the resulting medium structural parameter,  $s = 4(p+3)/(p+5)$ , leads to an optical decay index  $\alpha_o = 2\beta_x$  which, for the X-ray spectral slopes given in Table 1, is much steeper than observed.

Substituting equation (12) in (9), the optical decay index requires a circumburst medium with

$$s = 4 \frac{\alpha_o + 3}{p + 5}. \quad (13)$$

As shown in Table 1, the optical decay index  $\alpha_o$  and X-ray spectral slope  $\beta_x$  of the six afterglows with chromatic X-ray breaks require a circumburst medium with a wind-like stratification. For  $s \simeq 2$  and  $p = 2\beta_x \simeq 2.0$ , equation (12), which is the condition for the lack of an optical break, becomes

$$\frac{1}{3}i + \frac{1}{4}b = 1. \quad (14)$$

The energy injection parameter  $e$  is determined by the steepening of the X-ray light-curve decay. From equation (10), we obtain

$$e = \frac{(8-2s)(\alpha_{x2} - \alpha_{x1})}{\alpha_{x1} + 2 - 0.25s(p+2)}. \quad (15)$$

Finally, the parameters  $i$  and  $b$  can be determined from the decays of the optical and post-break X-ray light curves. Transforming to observer time with the aid of equation (8), the average evolutions given in Table 1 are

$$t < t_b : \Gamma \propto t^{-0.12 \pm 0.04}, \quad \epsilon_B \propto t^{0.6 \pm 0.2}, \quad \epsilon_i \propto t^{-0.2 \pm 0.1} \quad (16)$$

$$t > t_b : \Gamma \propto t^{-0.24 \pm 0.02}, \quad \epsilon_B \propto t^{1.3 \pm 0.2}, \quad \epsilon_i \propto t^{-0.4 \pm 0.4} \quad (17)$$

and  $E \propto t^{0.4 \pm 0.1}$  before the X-ray break epoch.

### 2.3 Inverse-Compton emission in the X-ray

If the circumburst medium is sufficiently dense then iC emission can outshine synchrotron in the X-rays. Alternatively, the synchrotron spectrum could have a cut-off below the X-ray, as the shock-accelerated electrons may not acquire sufficient energy (Li & Waxman 2006). We consider here the case where the optical afterglow is synchrotron emission and the X-ray afterglow arises from iC scattering.

The iC continuum has spectral breaks at the frequencies  $\gamma_i^2 \nu_i$  and  $\gamma_c^2 \nu_c$ , where  $\nu_i$  is the frequency at which the  $\gamma_i$  electrons radiate and  $\gamma_c$  is the Lorentz factor of the electrons which cool radiatively on a time-scale equal to the dynamical time-scale (i.e. they radiate at the cooling frequency  $\nu_c$ ). In the standard model for the forward shock emission (e.g. Sari et al. 1998; Panaitescu & Kumar 2001), it can be shown that the decay indices of the iC light curves are

$$\alpha_x = \frac{(18-5s)p + c_1(s)}{16-4s} - \frac{3-s}{e+8-2s} \times \left[ \frac{(6-s)p + c_2(s)}{16-4s} e + c_3(p)i + c_4(p)b \right], \quad (18)$$

where

$$c_1 = 11s - 22, \quad c_2 = 14 - 9s, \quad c_3 = 2p - 2, \quad c_4 = \frac{p+1}{4} \quad (19)$$

for  $\gamma_i^2 v_i < v_x < \gamma_c^2 v_c$  (in which case  $p = 2\beta_x + 1$ ) and

$$c_1 = 6s - 20, \quad c_2 = 4 - 2s, \quad c_3 = 2p - 2, \quad c_4 = \frac{p - 6}{4} \quad (20)$$

for  $v_x > \max\{\gamma_i^2 v_i, \gamma_c^2 v_c\}$  (in which case  $p = 2\beta_x$ ). Synchrotron-dominated electron cooling ( $Y < 1$ ) was assumed for the latter expressions of  $c_3$  and  $c_4$ ; if iC dominates ( $Y > 1$ ) then  $c_3 = (2p - 3)$  and  $c_4 = (p - 2)/4$ .

Aside from the above two possible locations of the X-ray domain relative to the iC spectral breaks, the cooling frequency could be either above or below the optical range (the optical light-curve decay index being given by equations 9 and 10, respectively), which yields four possible combinations to be considered. Just as for the case where the X-ray afterglow was attributed to the synchrotron emission, we obtain an unphysical solution ( $e < 0$ ) if the X-ray light-curve break is attributed to the blast wave encountering the wind termination shock. For the scenario where this break arises from cessation of energy injection,  $e > 0$  solutions exist only for  $v > \max\{\gamma_i^2 v_i, \gamma_c^2 v_c\}$  and, for three afterglows, only if the cooling frequency is higher than optical frequencies (in this case, the lack of an optical light-curve break leads to equation 12). The magnitude of the X-ray light-curve break determines the energy injection parameter  $e$  and the result is the same as when the X-ray afterglow was assumed to be synchrotron emission (equation 15). However, the evolution of the microphysical parameters with the blast-wave Lorentz is weaker now because the decay indices of the iC light curves have a stronger dependence on  $\epsilon_i$  and  $\epsilon_B$ .

### 3 DISCUSSION

The lack of an optical light-curve break contemporaneous with the steepening of the power-law decay observed at 1–4 h in the X-ray light curves of several Swift afterglows (Fig. 1) is a puzzling new feature. It does not originate from the outflow collimation (such breaks should be chromatic) nor from the passage of a spectral break through the X-ray (such light-curve breaks should be accompanied by a spectral evolution). If the optical and X-ray afterglows are the same synchrotron forward-shock emission then the only possibility left is that the chromatic X-ray light-curve breaks are caused by the evolution of a spectral break  $\nu_b$  located between the optical and X-ray. That evolution could be determined from the optical and X-ray decay indices and spectral slopes (equation 5). However, the optical intrinsic spectral slope may be difficult to measure because of dust extinction in the host galaxy, as is the case of GRB 050401 (Watson et al. 2006).

For the GRB afterglow 050401, whose optical emission has been monitored well after the X-ray light-curve break, the required post-break evolution of  $\nu_b$  is barely compatible with the lack of a break in the optical light curve until 10 d: in the most favourable situation, where  $\nu_b$  was just above the X-Ray Telescope's (XRT) 0.3-keV threshold at  $t_b = 1.2$  h, the  $\nu_b(t > t_b) \propto t^{-1.25}$  required by the post-break X-ray decay implies that this spectral break should cross the  $R$  band at 8 d. Over the four decades in time during which the optical afterglow of GRB 050401 exhibits an unbroken power-law decay, the energy of the electrons radiating in the optical increases by a factor of 30, for a homogeneous circumburst medium (100 for a wind-like medium). Moreover, over four decades in time, the ratio of the energy of the optical-emitting electrons to that of the peak of the electron distribution increases by a factor of  $10^3$ . These facts suggest that the spectral break at  $\nu_b$  is not associated with a break in the distribution with energy of the shock-accelerated electrons,

as in this case it would be difficult to understand why  $\nu_b$  remains above the optical over a  $10^4$ -fold increase in time.

If the spectral break  $\nu_b$  is the cooling frequency ( $\nu_c$ ) then its evolution required by the decay indices listed in Table 1 is  $\nu_c(t > t_b) \propto t^{-0.8}$  or faster, exceeding the fastest decay expected for the cooling frequency in the standard blast-wave model:  $\nu_c \propto t^{-1/2}$ , for a homogeneous circumburst medium (for a wind-like medium,  $\nu_c$  should increase at least as fast as  $t^{1/2}$ ). This shows that evolving microphysical parameters for the electron energy and magnetic field are required to explain the chromatic X-ray light-curve breaks. This feature of the forward shock model was not previously required by the analysis of the broad-band emission of pre-Swift afterglows.

Attributing the X-ray light-curve break to a sudden change in the evolution of the microphysical parameters seems ad hoc and contrived because their evolution would have to be such that a break in the optical light curve is not produced. A less contrived scenario is that the microphysical parameters have a steady evolution with the blast-wave Lorentz factor and that the X-ray light-curve break arises from cessation of energy injection in the forward shock (as previously proposed by Nousek et al. 2006; Panaitescu et al. 2006; Zhang et al. 2006). Then, the lack of an optical light-curve break simultaneous with that seen in the X-rays requires that the evolution of the microphysical parameters satisfies equation (14), whether the X-ray emission is synchrotron or iC.

In this scenario, to accommodate the optical and X-ray properties of the six GRB afterglows considered here requires that the stratification of the circumburst medium (Table 1) is that of a stellar wind,  $n \propto r^{-2}$ , as expected from a massive star progenitor for long GRBs (e.g. Woosley 1993). However, such an ambient medium was not found to be consistent in all cases with the jet break observed in optical light curves. For instance, the sharp optical breaks of GRB afterglows 990510, 000301C and 011211 are better modelled with a homogeneous external medium, whether the break is attributed to seeing the jet boundary or the bright core of a structured outflow seen off-axis (Panaitescu 2005). In a wind-like medium, the slower deceleration of the blast wave leads to a more gradual steepening of the power-law decay of the afterglow emission (Kumar & Panaitescu 2000), as was observed in many, but not all, pre-Swift afterglows with optical light-curve breaks. The identification of one or the other kind of circumburst medium may have to do with the location of the termination shock of the stellar free wind. For the innermost locations of this shock (at less than  $10^{18}$  cm), the boundary of a narrow jet may become visible after the jet has crossed the shock and entered the quasi-homogeneous shell of shocked wind, while for outer locations the jet break occurs in the free-wind region. The lack of a jet-break signature in the six Swift afterglows analysed here can be explained if their outflows are not tightly collimated. Furthermore, as discussed above, the chromaticity of their X-ray light-curve breaks indicates that the afterglow emission occurred in the freely expanding stellar wind.

A difficulty with the above model is that there is no evident reason for which evolution of the microphysical parameters should satisfy equation (14). In the absence of a physical reason for this, an alternative conclusion would be that, at least in some afterglows, the optical and X-ray emissions arise from different outflows. However, such a conclusion is not supported by pre-Swift afterglow observations. For example, the optical and X-ray emissions of the 12 afterglows modelled numerically by Panaitescu (2005) can be explained with a single outflow. The optical and X-ray continua shown in figures 10 and 11 of Nardini et al. (2006) also suggest that, in many cases, they could be the same afterglow spectral component, although such a test is complicated by the likely presence of the cooling break between

the optical and X-ray and by the possible dimming and reddening of the optical emission by dust in the host galaxy.

Further work, both theoretical and observational, is needed to verify if afterglows such as those discussed here are indeed weakly collimated outflows interacting with a wind environment and leading to shocks with evolving microphysical parameters or if the optical and X-ray afterglow emissions are produced by different regions of the GRB outflow.

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#### REFERENCES

- Blustin A. et al., 2006, *ApJ*, 637, 901  
 Cusumano G. et al., 2006, *ApJ*, in press (astro-ph/0509689)  
 De Pasquale M. et al., 2006, *MNRAS*, 365, 1031  
 Fan Y., Piran T., 2006, *MNRAS*, in press (astro-ph/0601054)  
 Guetta D. et al., 2006, preprint (astro-ph/0602387)  
 in't Zand J. et al., 2001, *ApJ*, 559, 710  
 Klotz A. et al., 2005, *A&A*, 439, L35  
 Kumar P., Panaitescu A., 2000, *ApJ*, 541, L9  
 Li Z., Waxman E., 2006, *ApJ*, submitted (astro-ph/0603427)  
 Lipkin Y. et al., 2004, *ApJ*, 606, 381  
 Mészáros P., Rees M. J., 1997, *ApJ*, 613, 477  
 Morris D. et al., 2006, *ApJ*, submitted (astro-ph/0602490)  
 Nardini M. et al., 2006, *A&A*, in press (astro-ph/0508447)  
 Nousek J. et al., 2006, *ApJ*, in press (astro-ph/0508332)  
 O'Brien P. et al., 2006, *ApJ*, submitted (astro-ph/0601125)  
 Paczyński B., Rhoads J., 1993, *ApJ*, 418, L5  
 Panaitescu A., 2005, *MNRAS*, 363, 1409  
 Panaitescu A., Kumar P., 2001, *ApJ*, 554, 667  
 Panaitescu A., Kumar P., 2004, *MNRAS*, 350, 213  
 Panaitescu A. et al., 2006, *MNRAS*, 366, 1357  
 Rhoads J., 1999, *ApJ*, 525, 737  
 Rykoff E. et al., 2005, *ApJ*, 631, L121  
 Rykoff E. et al., 2006, *ApJ*, 638, L5  
 Sari R., Narayan R., Piran T., 1998, *ApJ*, 497, L17  
 Tiengo A. et al., 2003, *A&A*, 409, 983  
 Watson D. et al., 2006, *ApJ*, submitted (astro-ph/0510368)  
 Wijers R., Rees M., Mészáros P., 1997, *MNRAS*, 288, L51  
 Woosley S., 1993, *ApJ*, 405, 273  
 Woźniak P. et al., 2005, *ApJ*, 627, L13  
 Zhang B. et al., 2006, *ApJ*, in press (astro-ph/0508321)

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