THE RAPID DECLINE OF THE PROMPT EMISSION IN GAMMA-RAY BURSTS

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ABSTRACT

Many gamma-ray bursts (GRBs) have been observed with the Burst Alert Telescope and X-Ray Telescope of the Swift satellite. The successive “pulses” of these GRBs end with a fast decline and a fast spectral softening, until they are overtaken by another pulse or the last pulse’s decline is overtaken by a less rapidly varying “afterglow.” The fast-decline phase has been attributed, in the currently explored standard fireball model of GRBs, to “high-latitude” synchrotron emission from a collision of two conical shells. This high-latitude emission does not explain the observed spectral softening. In contrast, the temporal behavior and the spectral evolution during the fast-decline phase agree with the predictions of the cannonball model for GRBs.

Subject headings: gamma rays: bursts — radiation mechanisms: nonthermal — X-rays: general

Online material: color figures

1. INTRODUCTION

Since the launch of the Swift spacecraft, precise data from its Burst Alert Telescope and X-Ray Telescope have been obtained on the spectral and temporal behavior of the X-ray emission in γ-ray bursts (GRBs) and X-ray flashes (XRFs). These data have already been used to test the most studied theories of long-duration GRBs and their afterglows (AGs), the fireball (FB) models (see, e.g., Piran 1999, 2000, 2005; Zhang & Mészáros 2004; Mészáros 2002, 2006; Zhang 2007; references therein) and the cannonball (CB) model (e.g., Dar & D’Rújula 2004, hereafter DD04; Dado et al. 2002, 2003, 2007, 2008, hereafter DDD02, DDD03, DDD07, and DDD08, respectively, and references therein).

The general behavior of the Swift X-ray light curves has been described as “canonical” (Nousek et al. 2006; O’Brien et al. 2006; Zhang et al. 2007) and is illustrated in Figures 1a, 1b, and 2a for XRF 060218, GRB 060904A, and GRB 061121. When measured early enough, the X-ray emission has peaks that coincide with the γ-ray peaks of the GRB. The prompt emission has a fast decline after the last detectable peak of the GRB. In most cases, the rapid decline ends within a couple of hundreds of seconds. Thereafter, it turns into a much flatter “plateau,” typically lasting thousands to tens of thousands of seconds. Finally, the X-ray light curve, within a time on the order of 1 day, steepens into a power-law decline that lasts until the X-ray AG becomes too dim to be detected. Often, there are also X-ray peaks during the fast-decline phase or even later, not coinciding with detectable γ-ray activity. There is a continuous transition of X-ray light curve shapes from the “canonical” ones to the those that are well described by a single-power-law decay (e.g., GRB 061126; see Fig. 2b).

Neither the general trend nor the frequently complex structure of the Swift X-ray data was correctly predicted by (or can be easily accommodated within) the standard FB models (for reviews of the pre-Swift standard FB model, see, e.g., Piran 1999, 2000, 2005; Zhang & Mészáros 2004; for recent comparisons with Swift data, see Kumar et al. 2007; Burrows & Racusin 2006; Kocevski & Butler 2008; Urrata et al. 2007; Zhang et al. 2007; Yonetoku et al. 2008; Liang et al. 2008).

The situation in the CB model (Dado et al. 2004, hereafter DDD04) is different. The model offers a good description, based on a specific synchrotron radiation mechanism, of the AGs of all “classical” GRBs (DDD02, DDD03) of known redshift and allows one to extract the relevant parameters of the CBs of GRBs and XRFs. The consequent predictions for the “prompt” γ-rays, based on an explicit inverse Compton scattering (ICS) mechanism, are simple and successful (DDD04). As shown in DDD07, DDD08, and references therein for “Swift-era” data, the CB model, with no modification, correctly predicts the temporal and spectral behavior of the prompt and AG phases.

In this paper, we confront the Swift observations with the predictions of the FB and CB models for the spectral evolution during the fast-decline phase of the prompt emission. In the FB model, this phase has been interpreted (e.g., Mészáros et al. 2006; Liang et al. 2006; O’Brien et al. 2006; Yamazaki et al. 2006) as the “curvature effect” or “high-latitude” emission of colliding shells (Fenimore et al. 1996; Kumar & Panaitescu 2000; Dermer 2004). Relative to photons centrally emitted on the line of sight to an on-axis observer, photons from off-axis latitudes arrive later and with smaller number density and energy. The consequent spectral behavior is entirely different from that observed (see, e.g., Zhang et al. 2007). In the CB model, the properties of the fast-decline phase are also predominantly “geometric.” A GRB’s γ-ray pulses and their sister X-ray flares are created by ICS of light in a “glory reservoir” bathing the circumburst material (DD04). This light becomes, in a very specific manner, less abundant and more radially directed with distance from the parent star. These simple facts result in a correct description of the temporal behavior and spectral evolution of GRBs before, during, and after the fast-decline phase.

In the CB model it is possible in principle to fit the spectral energy flux of a GRB in a given energy band, as a function of time, and determine the parameters partaking in a complete prediction of the spectrum at any time in the fitted interval. But the public Swift spectral data are limited to a “hardness ratio” between the count rates in the 1.5–10 and 0.3–1.5 keV bands (Evans et al. 2007). To convert these rates into more explicit spectral information, one must correct for instrumental efficiency, subtract the background, and correct for X-ray absorption in the host galaxy, in the intergalactic medium (IGM), and in our Galaxy. The unabsorbed spectra as functions of time are not generally available.

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However, the unabsorbed spectral energy flux in the X-ray band, parameterized as $F_{\nu} \propto \nu^{-\beta} t^{-\alpha}$, is available in the form of the fitted time-dependent power-law spectral index, $\beta(t)$, for a set of X-ray light curves measured with Swift’s X-Ray Telescope (Zhang et al. 2007). Such a parameterization is not a faithful description of an exponentially cut off power law, a Band function, or the spectrum predicted by the CB model, similar to the Band function for typical parameters (DD04). Moreover, to extract $\beta(t)$, the data from different time intervals are co-added, smoothing the time dependence of the effective fitted photon index. This can be seen by comparing the effective indices $\Gamma(t)$ in $dN_e/dE \propto E^{-\Gamma}$, reported at the UNLV GRB Group’s Web site, with the hardness ratios reported in the Swift light-curve repository.

3 And at the page maintained by the GRB group at the University of Nevada, Las Vegas, http://grb.physics.unlv.edu/~xrt/xrtweb/web/sum.html.

Fig. 1.— Comparisons between Swift XRT observations (Evans et al. 2007) and the CB model predictions. (a) The light curve of XRF 060218; (b) the light curve of GRB 060904A; (c) the hardness ratio of XRF 060218; (d) the hardness ratio of GRB 060904A. [See the electronic edition of the Journal for a color version of this figure.]
The spectral indices $\beta$ and $\Gamma$ are related by $\beta = \Gamma - 1$.

We do not have all the information needed for a decisive comparison between the CB model and the spectral behavior during the fast-decline phase of the prompt emission. But the variation with time of the hardness ratio and of the effective spectral index during the fast-decline phase are so spectacular and well correlated with the light curves that an approximate analysis suffices to prove our points. We demonstrate this for the hardness ratios of five Swift GRBs with well-sampled X-ray light curves during the fast-decline phase and for 14 other GRBs with extracted effective time-dependent spectral indices.

2. HIGH-LATITUDE EMISSION IN THE FIREBALL MODEL

In the FB model, GRB pulses are produced by synchrotron radiation (SR) emitted by shock-accelerated electrons, following collisions between conical shells ejected by a central engine (Rees & Mészáros 1994; see Zhang et al. 2007 for a detailed discussion). Consider a spherical shell, arbitrarily thin, that expands with a
Lorentz factor $\gamma = 1 / [1 - (v/c)^2]^{1/2}$. Assume that when two shells collide at a radius $R$, all points emit isotropically in their rest frame an arbitrarily short pulse of radiation. Let $t = 0$ be the time of arrival of the first photons on the line of sight to the center of the conical shell. Photons emitted from a shell polar angle $\theta$ arrive at $t = R(1 - \cos \theta)/c$. If the radiation has a power-law spectrum in the shell’s rest frame, $\nu^{-\beta}$, the spectral energy flux seen by the observer has the form $F_\nu \propto \nu^{-\beta-2/3}$, where $\beta = 1 / [1 - (v/c) \cos \theta]$ (Kumar & Panaitescu 2000). Thus, for $\gamma \gg 1$ the high-latitude emission from a shell collision obeys $F_\nu \propto \nu^{-2}\Delta t^2$ with $\Delta t = R(2\gamma /c)$. Note that the spectral behavior does not change during the temporal power-law decline. This is in contradiction with the observed rapid spectral softening.

To confront this problem, Liang et al. (2006) assumed that the high-latitude spectral index $\beta$ is time-dependent but that the temporal index still satisfies $\alpha(t) = 2 + \beta(t)$. Although structured-jet models (Mészáros et al. 1998; Zhang & Mészáros 2002; Rossi et al. 2002) may yield a time-varying $\beta$, there is no reason why it should depend on an angle defined by the position of the observer. Indeed, the relation $\alpha(t) = 2 + \beta(t)$ is badly violated in canonical light curves (Zhang et al. 2007). We conclude that the curvature effect in the currently explored FB models does not agree with the data.

3. THE CANNONBALL MODEL AND ITS PREDICTIONS

In the CB model (e.g., DD04 and references therein), GRBs and their AGs are produced by jets of highly relativistic “cannonballs” of ordinary matter (Shaviv & Dar 1995; Dar 1998; Dar & Plaga 1999). Long-duration GRBs originate from CBs ejected in core-collapse supernova explosions. The “engine” of short GRBs is much less well established; it could be the merger of compact objects—for example, neutron stars—or mass accretion episodes on compact objects in close binaries (e.g., microquasars), or even phase transitions of increasingly compact stars (neutron stars, hyperstars, or quark stars).

The pre-CB ejecta of the parent stars create “windy” environments of “circumburst” material. The early luminosity of the event (a core-collapse supernova for long GRBs) permeates this semitransparent material with a temporary constitutuency of scattered, non-radially directed photons: a glory of visible or UV light, with an approximately “thin bremsstrahlung” spectrum (DD04). The $\gamma$-rays of a single pulse of a GRB are produced as a CB coasts through the glory. The electrons enclosed in the CB boost the energy of the glory’s photons, by means of ICS, to $\gamma$-ray energies. The initial fast expansion of the CBs and the radially increasing transparency of the windy environment result in the exponential rise of a GRB pulse. As a CB proceeds, the distribution of the glory’s light becomes more radially directed and its density decreases. Consequently, the energy of the observed photons is continuously shifted to lower energies as their number plummets. These trends were observed in BATSE data (Grinlin et al. 2002; Connaughton et al. 2002; Ryde & Svensson 2002; DD04). During a GRB pulse, the spectrum softens and the peak energy decays with time as a power law. This is also the behavior of the X-ray softens of a GRB, which are either the low-energy tails of $\gamma$-ray pulses or fainter and softer signals with the same origin (DDD07). Typically, the fast decline of the prompt emission in the $\gamma$-ray and X-ray bands is taken over, within few minutes of the observer’s time, by the “afterglow”—synchrotron emission from swept-in electrons from the interstellar medium (ISM) spiraling in the CB’s enclosed magnetic field.

The above effects can be explicitly analyzed (DD04) and summarized to a good approximation in a “master formula” (DDD07) for the temporal shape and spectral evolution of the energy fluence of an ICS-generated $\gamma$-ray pulse (or X-ray flare):

$$F_\nu(t) \propto \frac{dE}{dt} N_i \propto \Theta(t - t_i)e^{-\Delta t_i/(t - t_i)}\left(1 - e^{-\Delta t_i/(t - t_i)}\right)N_i(E, t) \frac{dN_i(E, t)}{dE},$$

where $i$ denotes the $i$th pulse, produced by a CB launched at (observer’s) time $t_i$. In equation (1), the timescale is set by $\Delta t_i$, with $\gamma c \Delta t_i(1 + z)$ the radius of transparency of the glory, within which its photons are approximately isotropic. In $\Delta t_i$ time units, a pulse rises as $e^{-(-1/t_i) m}$, $m \sim 1 - 2$, and decreases as $1/t_i^n$, $n \sim 2$. Finally, $E dN_i/dE$ is the spectral function of the glory’s photons, upscattered by the CB’s electrons and discussed anon.

The glory has a thin thermal bremsstrahlung spectrum: $dN_e/dE \sim (\epsilon_e/e_0)^{1-\alpha_e} e^{-\epsilon_e/\epsilon_0}$, with a typical (pseudo-) temperature $e_0 \sim 1$ eV and index $\alpha_e \sim 1$. During the $\gamma$-ray phase of a GRB, the Lorentz factor $\gamma$ of a CB stays put at its initial value, for the deceleration induced by the collisions with the ISM has not yet had a significant effect (DDDD02, DDDD07). Let $\theta$ be the observer’s angle relative to the direction of motion of a CB and let the corresponding Doppler factor be $\delta = 1 / [\gamma (1 - (v/c) \cos \theta)]$. Let $\theta_c$ be the angle of incidence of the initial photon onto the CB, in the parent star’s rest frame. The energy of an observed photon, Compton-scattered in the glory by an electron comoving with the CB at redshift $z$, is given by $E = \gamma \delta e(1 + \cos \theta_t)/(1 + z)$. The predicted GRB prompt spectrum is

$$E \frac{dN_e}{dE} \sim \left(\frac{E}{T}\right)^{1-\alpha_e} e^{-E/T} + b(1 - e^{-E/T}) \left(\frac{E}{T}\right)^{-\eta/2}$$

(DDD04). The first term, with $\alpha_e \sim 1$, is the result of Compton scattering by the bulk of the CB’s electrons, which are comoving with it. The second term in equation (2) is induced by a very small fraction of “knocked on” and Fermi-accelerated electrons, whose initial spectrum (before Compton and synchrotron cooling) is $dN/dE \propto E^{-\jmath}$, with $\jmath \approx 2.2$. Finally, $T$ is the effective (pseudo-) temperature of the GRB’s photons:

$$T \equiv 4 \gamma \delta e(1 + \cos \theta_t)/[3(1 + z)].$$

For a semitransparent glory, $<\cos \theta_t>$ would be somewhat smaller than zero.

For $b = O(1)$, the energy spectrum predicted by the CB model (eq. [2]) bears a striking resemblance to the Band function (Band et al. 1993) traditionally used to model the energy spectra of GRBs. For many Swift GRBs, the spectral observations do not extend to energies much higher than $T$, or the value of $b$ in equation (2) is relatively small, so that the first term of the equation provides a very good approximation. This term coincides with the “cut-off power law” spectrum recently used to model GRB spectra. It yields a “peak energy” (the maximum of $E^2 dN/dE$ at the beginning of a pulse) $E_p = (2 - \alpha_e)T \approx T$ for $\alpha_e \sim 1$. At later times, the CB is sampling the glory at distances for which its light is becoming increasingly radial, $1 + \cos \theta_t \rightarrow 1/r^2 \sim 1/t^2$ in equation (3). The value of $E_p(t)$ consequently decreases as

$$E_p(t) \approx E_p(t_0) \left[1 - \frac{t - t_i}{\sqrt{\Delta t_i^2 + (t - t_i)^2}}\right].$$

(4)
The light curve generated by a sum of pulses is well approximated (DDD07) by
\[ F_E \approx \sum_i A_i \Theta(t-t_i) e^{-|\Delta t/(t-t_i)|^{\gamma}} \left(1 - e^{-|\Delta t/(t-t_i)|^{\gamma}}\right) \]
\[ \times \left[\frac{E}{E_\nu(t)}\right]^{1-\alpha} e^{-E/E_\nu(t)} \]
until ICS is overtaken by SR.

In X-rays, the distinction between a prompt and an afterglow period can be made precise: they correspond to the successive dominance of the two radiation mechanisms, ICS and SR. The actual form of the SR-dominated AG spectral energy flux, \( F_\nu \), we have discussed very often (DDD07, DDD08, and references therein). Suffice it to recall that (for cases such as those we discuss here, whose AGs can be well fitted with a single dominant or average CB) the shape of the observed \( F_\nu \), corrected for absorption, is determined by \( \gamma_\nu \theta \), and its timescale is determined by a...
1.1 (DDD08).

/C20 peak energy evolved from 54 keV to low 50 keV (Campana et al. 2006; Liang et al. 2006). The prompt 300 s, beginning 159 s after trigger, with most of the emission be-
t 0.18 for an unabsorbed flux with \( \beta = 1.1 \).

In the ICS-dominated phase, the shape of the flux determines the number of flares one ought to fit, one in Figure 1a, for in-
stance. If one uses equation (5) with \( \alpha = 1 \), each pulse is fitted with four parameters: \( t_i, \Delta t_i, E_{p}(t_i), \) and \( A_i \). For the rapid-decline phase, it suffices to consider the main or the latest few flares, since the last factor in equation (5) suppresses the relative contribution of earlier flares by the time the data are sampling the later ones. Once the parameters are fixed, the HR is determined by the quo-
tient of the integrals \( \int \frac{dE}{E} A(E) dN/E dE \) in the two Swift X-ray energy bands. This rosy picture is clouded by two facts: the data for the integrated flux in the 0.3–10 keV interval are very insen-
sitive to the values of \( E_{p}(t_i) \), which the fit consequently returns with very large errors, and we do not know \( A(E) \).

We studied numerically the HR of a pulse given by equation (5), in the large interval 0 < \( t - t_i \) < 10\( \Delta t_i \), for an exaggerated range of \( E_d \) in \( A(E) \approx \exp \left(-E_d(E)^2/2\right) \). We find that

\[
HR(t_i) = B e^{-\Delta E/E_{p}(t_i)} [1-(t-t_i)/\sqrt{\Delta t_i^2+(t-t_i)^2}]^{-1} \tag{6}
\]

is a fair approximation, with \( \Delta E \) an effective interval between the bands in the HR. More explicitly, if \( B \) and \( \Delta E/E_{p}(t_i) \) are fitted, the approximation is good to a few percent for a typical \( E_{p}(t_i) \) > 200 keV, deteriorating to \(-40\%\) for an extreme and atypical \( E_{p}(t_i) \) = 30 keV. We shall consequently fit \( B \) and \( \Delta E/E_{p}(t_i) \) in comparing theory and data for the HR. For times at which the late-time tail of a single pulse dominates, the HR satisfies

\[
HR(t) \to B e^{-\Delta E/E_{p}(t_i) [2(t-t_i)/\Delta t_i]^2} \tag{7}
\]

with precision increasing with \( t \).

4. HARDNESS RATIOS: CASE STUDIES

The Burst Alert Telescope (BAT) on Swift has detected nearly 250 GRBs or XRFs whose X-ray emission was followed with its X-Ray Telescope (XRT) from ~70 s after trigger until it faded away. Being incapable of discussing all these observations, we first study five cases, which we view as representative and which have well-sampled X-ray fluxes and HRs during the fast decline and the ensuing AG phase. They are the “clean” single-peak XRF 060218; GRB 060904A, with four X-ray flares during the fast-decline phase; the simpler two-flare GRB 061121; the duller GRB 061126, for which the XRT observations began late; and the bright GRB 061007, with an approximately single-power-

\[
\text{TABLE 1}
\]

| Parameter | 060218 | 060904A | 061121 | 061126 | 061007 |
|-----------|--------|---------|--------|--------|--------|
| \( t_1 \) (s) | -1080 | 41.08 | 52.48 | ... | ... |
| \( \Delta t_1 \) (s) | 1977 | 16.02 | 12.44 | ... | ... |
| \( \Delta E/E_{p}(t_i) \) | 0.19 | 0.0452 | 0.061 | ... | ... |
| \( t_2 \) (s) | ... | 252.8 | 96.88 | ... | ... |
| \( \Delta t_2 \) (s) | ... | 27.75 | 18.80 | ... | ... |
| \( \Delta E/E_{p}(t_2) \) | ... | 0.0177 | 0.0014 | ... | ... |
| \( t_3 \) (s) | ... | 629.7 | ... | ... | ... |
| \( \Delta t_3 \) (s) | ... | 44.0 | ... | ... | ... |
| \( \Delta t_4 \) (s) | ... | 703.4 | ... | ... | ... |
| \( \Delta t_5 \) (s) | ... | 740.3 | ... | ... | ... |
| \( \gamma \theta \) | 4.28 | 1.25 | 1.42 | 1.12 | 1.0 \( \leq 1 \) |
| \( r \) | 2.26 | 2.20 | 2.20 | 1.92 | 2.26 |

GRB 060904A.—BAT detected a weak emission of \( \gamma \)-rays for about a minute, with several small peaks before the main burst, also seen by the Konus-Wind and Suzaku satellites (Yonetoku et al. 2008). The XRT followed the fast decline of the main burst and saw three additional flares, as shown in Figure 1b. A rapid spectral softening was observed during both the prompt tail phase and the decline phase of the X-ray flares (see Fig. 1d). Because of a second GRB (060904B) that was detected just 1.5 hr later, Swift slewed away from GRB 060904A, so there are no data for a couple of hours until the XRT returned to follow its fading afterglow. After correcting for absorption (Yonetoku et al. 2008), the photon spectral index during the AG phase is found to be \( \Gamma = 2.1 \pm 0.1 \).

GRB 061121.—The \( \gamma \)-ray burst started with a bright precursor that lasted 10 s. Then, 50 s later, there was a much brighter burst of \( \gamma \)-rays. Swift had already turned the XRT when the second \( \gamma \)-ray flare occurred, and the X-ray emission was measured during the actual event and its subsequent rapid decline, as shown in Figure 2a. After the rapid decline, the photon spectral index, corrected for absorption, was \( \Gamma = 2.05 \pm 0.15 \) (Page et al. 2007).
GRB 061126.—This very long burst had four main overlapping peaks, the last one ending \( \sim 25 \) s after trigger, but low-level emission was detected until \( \sim 200 \) s later. The RHESSI satellite also detected this burst and also saw \( \gamma \)-ray emission for \( \sim 25 \) s. The XRT detected the X-ray emission only long after the prompt emission had faded. These late data are shown in Figure 2b. The photon spectral index after correcting for absorption (Perley et al. 2008) is \( \Gamma = 2.00 \pm 0.07 \) and is time-independent, suggesting that the entire XRT light curve is that of the synchrotron afterglow of GRB 061126.

GRB 061007.—This long, bright burst lasted \( 75 \pm 5 \) s. Its light curve shows three large peaks, and a smaller peak starting at \( 75 \) s, rising to a maximum at \( 79 \) s and declining with a very long and fast decay. The XRT began follow-up observations \( 80 \) s after trigger. The \( 0.3-10 \) keV light curve (Fig. 3a) shows a single–power-law decline with a slope of \( 1.6 \pm 0.1 \). In the CB model, this is the tail
of a canonical AG whose “plateau” ended before the XRT began its observations. The predicted photon spectral index (DD08), $\Gamma = \alpha + 0.5 = 2.10 \pm 0.10$, is consistent with the best-fit spectral index, $\Gamma = 2.03 \pm 0.10$, shown in Figure 3d.

4.1. Hardness Ratios: CB Model Results

In the CB model, the SR-dominated X-ray afterglow, if corrected for absorption, has a time-independent photon spectral index $\Gamma \sim 2.1$ and a constant hardness ratio. This expectation is consistent, within the observational errors, with the Swift data in all the cases we considered, with the possible exception of XRF 060218, whose complex situation regarding absorption corrections we have reviewed. The spectral behavior is much more complex during the prompt emission.

Since XRF 060218 is a single-flare event, its light curve and the evolution of its HR, shown in Figures 1a and 1c, are simple. The agreement between the model expectations and the XRT observations is satisfactory. The CB model parameters are specified...
in Table 1. Multiple-flare events such as GRB 060904A and, to a lesser extent, GRB 061121 require multiparameter fits; the fitted peaks and their relevant parameters are also specified in Table 1. The way the HRs of these bursts predictably follow the ups and downs of the flux is quite impressive: compare Figure 1b with 1d and Figure 2a with 2c. For GRBs 061126 (Figs. 2b, 2c, and 3b) and 061007 (Figs. 3a, 3c, and 3d), the available data cover only the SR-dominated X-ray AG, where, as expected, the hardness ratio is constant. Note in Figure 2b that although the late-time behavior of the flux has the shape predicted by the CB model, the measured points lie systematically above the prediction. Such a discrepancy might result from decreasing X-ray absorption along the line of sight to the AG source. The fluxes reported in the Swift XRT repository (Evans et al. 2007) assume a constant absorption during the entire measurement. In the CB model, the jet of cannonballs moves hundreds of parsecs during the observations, and the absorption may decrease with time as the jet approaches the halo of the host galaxy.

Fig. 6d

Fig. 6c

Fig. 6b

Fig. 6a

Fig. 6c – Same as Fig. 4, but for (a) GRB 050814, (b) GRB 050724, (c) GRB 050717, and (d) GRB 050716. [See the electronic edition of the Journal for a color version of this figure.]
5. CB MODEL RESULTS FOR THE EFFECTIVE SPECTRAL INDEX

The spectral index, $\Gamma(t) = \beta(t) + 1$, of many GRBs, extracted from an empirical power-law parameterization, $F_{\nu} \propto \nu^{-\beta(t)-\alpha}$, is reported by the UNLV GRB Group and discussed in more detail for a selected set of bright GRBs by Zhang et al. (2007). As reported in § 1, these results on $\Gamma(t)$ may themselves be a rough description of rapidly varying spectra potentially having an exponential energy dependence, as in equation (5). Yet, we may define an effective index by means of the logarithmic derivative of the prompt ICS spectrum. For a single pulse in equation (5),

$$\Gamma_{\text{eff}}(E, t-t_1) = -E \frac{d \log F_E}{dE} \bigg|_{E=E_0} = \alpha_g + \frac{\dot{E}}{E_p(t-t_1)}, \quad (8)$$

where $\dot{E}$ is an effective constant energy, $t$ is the time after trigger, and $\alpha_g \approx 1$ is defined in equation (2). For the synchrotron afterglow, the CB model predicts a power-law spectrum with roughly a constant photon index $k_{SR}$ and a late-time temporal power-law decline with a power-law index

$$\alpha = k_{SR} - \frac{1}{2} \quad (9)$$

(DDD08).

In the data analysis at the UNLV group’s site, for lack of sufficiently large statistics, different time intervals were co-added, smoothing the time dependence of the fitted spectral index. For an “effective index” study of the results of this data analysis, a single-pulse approximation is adequate for the description of a GRB’s $\Gamma(t)$ at the end of the prompt phase and during the fast decline. In this approximation, for a pulse starting at $t = t_1$, followed by an SR-dominated afterglow, the rough CB model prediction is

$$\Gamma_{\text{eff}} \sim \left[1 + \frac{\dot{E}}{E_p(t)}\right] \Theta(t_{AG} - t) \Theta(t - t_1) + k_{SR} \Theta(t - t_{AG}), \quad (10)$$

where $t_{AG}$ is the time at which the SR “afterglow” takes over the ICS “prompt” emission. The assumed rather abrupt transition from the ICS-dominated first term in equation (10) to the second, SR-dominated term is justified by equations (4) and (5). Indeed, the late decline of the ICS-dominated term is exponential in the square of the time.

In Figures 4–6, we compare equation (10) with the results for $\Gamma(t)$ for 12 GRBs from the UNLV Web Site for which the measurements are good. The figures show how the extracted $\Gamma(t)$ reflects the expected very abrupt transition. Our simple description of the observations in terms of three parameters $\{t_1, E_p(t), t\Delta t\}$, listed in Table 2 is satisfactory. Also listed in Table 2 are the values of $k_{SR}$ and the values of $\alpha + \frac{1}{2}$ from our CB model fits to the synchrotron radiation afterglow. They are in fair agreement with equation (9).

6. APPROXIMATE RESULTS FOR MORE GRBs

Other authors have analyzed many more GRBs than we have in this paper. Zhang et al. (2007), for instance, confronting the failure of the high-latitude emission of the FB model to explain the rapid softening of the tail of the prompt emission in 16 “clean tail” bright GRBs, proposed an empirical parameterization of the X-ray light curve during this phase. Its spectral evolution can be rewritten as a time-dependent, exponentially cut off, power law:

$$F_E \propto \left[\frac{E}{E_p(t)}\right]^{1-\alpha} e^{-E/E_p(t)}, \quad E_c(t) = E_c(t_1) \left(\frac{t-t_1}{t_1}\right)^{-k}. \quad (11)$$

For $t > t_1$, this is the evolution predicted by the CB model (DDD04), provided one identifies $E(t_1) = E_p(t_1)$. Indeed, $E(t) \approx E_p(t_1)$ for $t - t_1 \ll \Delta t$, while for $t - t_1 \gg \Delta t$, $E(t) \approx E_p(t_1)[(t-t_1)/\Delta t]^{-k/2}$, with $k = 2$; see equations (4) and (7). These limiting behaviors may be interpolated by the empirical parameterization of Zhang et al. (2007), in their chosen narrow range of $t_1$, with a constant $k \leq 2$ (they find $1 \leq k \leq 1.6$). These authors also discarded GRBs without a rapid spectral softening during the fast decline. These seem to us to be cases whose spectral evolution is poorly measured or cases, such as GRBs 061126 and 061007, whose “fast-decline phase” is not the end of the prompt emission but the late decline of a canonical AG whose plateau phase ended before the beginning of the XRT observations (DDD08).

7. CONCLUSIONS

The spectrum of the γ-ray peaks and X-ray flares of a GRB or an XRF is predicted in the CB model: it is the spectrum of the “glory’s” light, Compton-boosted by the electrons in a CB (DDD04). The time evolution of the spectrum traces the voyage of the CB through this “target” light. Although the model predicts the spectrum and its evolution at all frequencies and times, we have focused on the very rapid decline of the flux at the end of a pulse and the equally swift spectral softening. Their interpretation is simple: the glory’s “target” light is light scattered by the circumburst matter, and its spectrum is exponentially cut off. Its number density, and the flux of a pulse, decrease roughly as $1/r^2 \propto 1/t^2$. Simultaneously, the target light is becoming more radial, so that the characteristic energy of the upscattered radiation also decreases as $1/r^2$. These simple facts, explicitly reflected in the predicted “master formula” (eqs. [4] and [5]), result in an excellent description of the observations.

Lacking access to detailed spectral analyses, we have used Swift data on hardness ratios, uncorrected for X-ray absorption (Evans et al. 2007), as well as the effective spectral index of the unabsorbed spectrum reported by the UNLV GRB Group. We have demonstrated that the spectral time dependences snugly trace their expected correlation with the corresponding flux variations. This test of the CB model validates it once again. Yet, carefully time-resolved absorption corrections would allow even more conclusive tests. Time-resolved corrections are important, because in

**Table 2**

| GRB        | $\Gamma_{SR}$ | $\alpha + \frac{1}{2}$ |
|------------|---------------|------------------------|
| 061126.....| 1.93 ± 0.12   | 1.95                   |
| 061007.....| 2.10 ± 0.20   | 2.13                   |
| 070129.....| 2.28 ± 0.22   | 2.14                   |
| 061222A....| 2.15 ± 0.08   | 2.15                   |
| 061121.....| 1.99 ± 0.13   | 2.10                   |
| 061110A....| 1.80          |                        |
| 060814.....| 2.20 ± 0.10   | 2.16                   |
| 060729.....| 2.10 ± 0.10   | 2.10                   |
| 060510B....| 2.14 ± 0.15   |                        |
| 060211A....| 2.03 ± 0.12   | 2.04                   |
| 050814.....| 1.91 ± 0.09   | 1.93                   |
| 050724.....| 1.88 ± 0.16   | 1.86                   |
| 050717.....| 1.85 ± 0.12   | 1.84                   |
| 050716.....| 1.97 ± 0.11   | 1.88                   |

Notes.—The values of $\Gamma_{SR}$ are from the Swift public data at http://grb.physics.unlv.edu/~xrt/xrtweb/websum.html. The values of $\alpha + \frac{1}{2}$ are from our CB model fits to the synchrotron radiation afterglow. In the model, the two last columns ought to be equal (see eq. [9]).
the CB model the line of sight to the hyperluminal CBs changes significantly during the long afterglow phase (see, e.g., DD04), sweeping different regions of the host galaxy and the IGM. The changing absorption may induce flickering of the observed X-ray light curve and X-ray spectrum. In fact, the scintillation-like behavior in many X-ray light curves and spectra (see Figs. 1–3), if not instrumental, may be due to the motion of the CBs in the host galaxy. This motion may also explain (S. Dado et al. 2008, in preparation) the reported time dependence of the equivalent widths of intergalactic absorption systems detected in the afterglow of GRB 060206 (Hao et al. 2007; but see also Thöne et al. 2007).

At least for GRBs or XRFs with a “canonical” light curve, the transition in time from a rapidly falling X-ray decline to a much less steep plateau—accompanied by the simultaneous and even more pronounced change in the spectrum that we have studied—reflects one of the most discontinuous transitions seen in astrophysical data. In the CB model this transition is not attributed to the continued activity of a steadily energizing engine, but to the passage from one to another dominant radiation mechanism: inverse Compton scattering versus synchrotron radiation. The transition is so fast because the late decline of the ICS contribution in equations (4) and (5) is exponential in time, a consequence of the exponential cutoff (in energy) of the thin bremsstrahlung spectrum of the upscattered light (DD04).

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