FLARES IN LONG AND SHORT GAMMA-RAY BURSTS

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ABSTRACT

The many similarities between the prompt emission pulses in gamma-ray bursts (GRBs) and X-ray flares during the fast decay and afterglow (AG) phases of GRBs suggest a common origin. In the cannonball (CB) model of GRBs, this common origin is mass accretion episodes of fall-back matter on a newly born compact object. The prompt emission pulses are produced by a bipolar jet of highly relativistic plasmoids (CBs) ejected in the early, major episodes of mass accretion. As the accretion material is consumed, one may expect the engine’s activity to weaken. X-ray flares ending the prompt emission and during the AG phase are produced in such delayed episodes of mass accretion. The common engine, environment, and radiation mechanisms (inverse Compton scattering and synchrotron radiation) produce their observed similarities. Flares in both long GRBs and short hard gamma-ray bursts (SHBs) can also be produced by bipolar ejections of CBs following a phase transition in compact objects due to loss of angular momentum and/or cooling. Optical flares, however, are mostly produced in collisions of CBs with massive stellar winds/ejecta or with density bumps along their path. In this paper, we show that the master formulae of the CB model of GRBs and SHBs, which reproduce very well their prompt emission pulses and their smooth AGs, seem to reproduce also very well the light curves and spectral evolution of the prominent X-ray and optical flares that are well sampled.

Key words: gamma-ray burst; general

Online-only material: color figures

1. INTRODUCTION

A flaring activity during the afterglow (AG) phase of a gamma-ray burst (GRB) was first observed in the late-time AG of GRB 970508 with the Narrow Field Instrument (NFI) aboard the BeppoSAX satellite in the X-ray band (Piro et al. 1998), and with ground based telescopes in the optical band (Pian et al. 1998; Galama et al. 1998a). It was interpreted in the framework of the fireball (FB) model of GRBs as a delayed burst from the central GRB engine (Piro et al. 1998). Alternatively, in the cannonball (CB) model of GRBs it was interpreted as a synchrotron radiation (SR) flare from an encounter of the highly relativistic jetted ejecta from an underlying supernova (SN) explosion with a density jump in the interstellar medium (ISM; Dado et al. 2002, 2004b). Late-time flares were later discovered in the broadband AG of several other GRBs that were localized by the BeppoSAX satellite, most notably in GRB 000301C at $t \sim 4$ days after burst (Berger et al. 2000; Sagar et al. 2000) where the flare was attributed to gravitational microlensing (Garnavich et al. 2000) and in GRB 030329 (Lipkin et al. 2004) where the flare was interpreted in the framework of the FB model as due to “refreshed shocks” generated by a late activity of the central engine (Granot et al. 2003). In the CB model, however, these flares were well reproduced by the emission of SR from encounters of the jetted ejecta from an underlying SN explosion in a star formation region with density jumps within or at the border of a super bubble created by the star formation region (Dado et al. 2002, 2004b).

Early-time X-ray flares ending the prompt emission phase were also detected by the wide field camera (WFC) aboard BeppoSAX in a few GRBs such as GRB 011121. In the FB model, they were attributed to the onset of the external shock in the circumburst material. In the CB model, they were interpreted as due to the last episodes of bipolar CB ejections from a shutting off central engine. Shortly after the launch of the Swift satellite in 2004 November, data collected with its X-ray telescope (XRT) showed that X-ray flares are quite common in all the phases of the emission from GRBs. In more than 50% of the GRBs observed with the Swift XRT, flares were observed at the end of the prompt emission and/or the early AG phase (Burrows et al. 2005, 2007; Falcone et al. 2007). In some cases, X-ray flares were observed also at very late times, of the order of several days after the prompt emission. Although the information on flares is much more sketchy compared to that on the prompt gamma-ray pulses, their spectral and temporal behaviors show clearly that the X-ray flares during the prompt $\gamma$-ray emission follow the pattern of the $\gamma$-ray pulses, suggesting they are the low energy part of these pulses. The X-ray flares ending the prompt emission and those superimposed on the early-time AG have a fast spectral evolution. Their peak intensities decrease with time, and their spectral and temporal behaviors are similar to those of the prompt X/$\gamma$-ray pulses, except that they are progressively softer and last longer. In most cases, their $\gamma$-ray emission probably is below the detection sensitivity of the Swift broad alert telescope (BAT). In some cases, their fluence in the XRT band exceeded that of the prompt emission in the BAT 15–150 keV band (Chincarini et al. 2008a, 2008b).

Late-time ($t \gtrsim 10^4$ s) X-ray flares, however, seem to exhibit temporal and spectral behaviors that are different from those of most of the early-time flares. Their power-law decline is more moderate, they are “achromatic” with a power-law spectrum almost identical to that of the late-time AG, and they show very little spectral evolution (see, e.g., the late-time broadband flares in GRBs 060614 (Mangano et al. 2007) and 081028 (Margutti et al. 2009), and the hardness ratio during late-time flares in Swift GRBs reported in the Swift-XRT light-curve repository, Evans et al. (2009)).

Flares in the X-ray light curve of Swift GRBs were studied phenomenologically by various observer groups (Burrows et al. 2005, 2007; Kocevski & Butler 2007; Butler & Kocevski 2007; Falcone et al. 2007; Chincarini et al. 2007a, 2007b, 2008a,
(Fan et al. 2006; Perna et al. 2006), but none of these proposed spectral behavior of the ICS pulses authors (Proga et al. 2005; King et al. 2005; Dai et al. 2006; Fan et al. 2006; Perna et al. 2006), but none of these proposed models was shown to actually derive the observed light curves and spectral evolution of either early-time or late-time flares from underlying physical assumptions.

Flares are a natural consequence of the CB model of GRBs, which was motivated by a GRB-microquasar analogy (Dado et al. 2002; Dar & De Rújula 2004). In the CB model, long-duration GRBs and their AGs are produced by bipolar jets of highly relativistic plasmoids of ordinary matter ejected in accretion episodes on the newly formed compact stellar object (Shaviv & Dar 1995; Dar 1998) in core-collapse SN explosions (Dar et al. 1992; Dar & Plaga 1999). It is hypothesized that an accretion disk or a torus is produced around the newly formed compact object, either by stellar material originally close to the surface of the imploding core and left behind by the explosion-generating outgoing shock, or by more distant stellar matter falling back after its passage (De Rújula 1987). As observed in microquasars (Mirabel & Rodríguez 1999), each time part of the accretion disk falls abruptly onto the compact object, two jets of CBs made of ordinary-matter plasma are emitted with large bulk-motion Lorentz factors in opposite directions along the rotation axis, wherefrom matter has already fallen back onto the compact object due to lack of rotational support. The entire radiation emitted from a GRB is produced by the interaction of the jet of CBs with the environment along its path, as illustrated in Figure 1. The prompt $\gamma$-ray and X-ray emission is dominated by inverse Compton scattering (ICS) of photons of the SN light filling the cavity produced by the pre-SN wind/ejecta blown from the progenitor star long before the GRB. The CBs' electrons Compton up-scatter this “glory” light into a narrow conical beam of $\gamma$ rays along the CBs' direction of motion. Each CB produces a single GRB pulse. An X-ray “flare” coincident in time with a prompt $\gamma$-ray pulse is simply its low-energy part. The natural explanation of flares ending the prompt emission and during the early-time AG is the same: ICS of glory photons by the electrons of CBs ejected in late accretion episodes of fall-back matter on the newly formed central object. Early-time X-ray flares without an accompanying detectable $\gamma$-ray emission are usually IC flares (ICFs) produced by CBs with relatively smaller Lorentz factors, due to weakening activity of the engine: as the accretion material is consumed, one may expect the “engine” to have a few progressively weakening dying pangs. Like the light curves of the prompt GRB pulses, the light curves of ICFs exhibit a rapid softening during their fast decline phase (see, e.g., the XRT hardness ratio reported for Swift GRBs in the Swift light curve repository; Evans et al. 2007, 2009).

In the CB model, each ICF is followed by the emission of SR flare (SRF) from the encounter of the CB with the wind/ejecta, which was blown from the progenitor star long before the GRB (see Figure 1). Because of time aberration in the observer frame, these SRFs appear to have only short lag times relative to the corresponding ICFs. Below their peak energy, the spectral behavior of the ICS pulses/flare is roughly $F_\nu \sim \nu^0$, while the SR emission from fast cooling electrons has typically $F_\nu \sim \nu^{-1.1}$. Thus, while the prompt keV–MeV pulses/flare are dominated by ICS of glory light, the “prompt” optical emission is dominated by SR. As the glory extends into the wind, often the SR emission begins before the ICS pulse/flare has ended.

The initial expansion of the CBs and the slow-down of the leading ones by the circumburst matter may merge most of them into a single leading CB (Dar & De Rújula 2004; Dado et al. 2009a) during the AG phase. Its collimated beam of the prompt gamma rays ionizes the matter in front of it. The ions continuously impinging on a CB with a relative Lorentz factor $\gamma(t)$, where $\gamma(t)$ is the bulk motion Lorentz factor of the CB, generate within it an equipartition turbulent magnetic field. The intercepted electrons are isotropized and Fermi accelerated by these fields and emit isotropic SR in the CB’s rest frame, which is Doppler boosted and beamed relativistically into a narrow cone with a typical opening angle $\sim 1/\gamma(t)$ in the observer’s rest frame. Late SRFs are produced mainly when the CBs encounter winds or density bumps along their path first from the progenitor star and later in the ISM. The light curve of these flares depends on the unknown density profile of the encountered wind/density bump that cannot be predicted a priori. But, both the early-time and the late-time SRFs have a typical SR spectrum and a weak spectral evolution that are quite different from those of the accretion induced ICFs and can be used to identify their origin—late ejection episodes from the central engine or density bumps.

In the CB model, short hard bursts (SHBs) are also produced by bipolar jets of plasmoids ejected in mergers of compact objects in close binary systems such as neutron stars merger (Goodman et al. 1987) or in mass accretion episodes on compact objects in close binary systems, or in phase transitions in compact stars (neutron stars, hyper stars, and strange quark stars; Dado et al. 2009b). Bipolar ejections in late accretion episodes or phase transitions after cooling and loss of angular momentum probably produce the observed ICFs in SHBs, and SR radiation from encounters with winds/density bumps produces SRFs.

Flares were routinely included in the CB model description of the AGs of GRBs and SHBs (Dado et al. 2002, 2004a, 2004b, 2009a, 2009b). They were calculated from the master formulae of the model, which describe well the prompt ICS emission and the emission of SR at all times. It was shown that ICS explains successfully both the prompt keV–MeV pulses and the X-ray flares ending the prompt emission, while the SR emitted in the collision of the jet of CBs with the wind/ejecta from the progenitor star explains well the prompt optical flares measured with robotic telescopes in very bright GRBs (Dado et al. 2009a; Dado & Dar 2008). However, attention was focused there on the general properties of the prompt emission and the smooth AG, rather than on flares during the AG phase. Moreover, in many GRB AGs, flares are weak, or are blended, or are not well sampled, and their properties could neither be

![Figure 1](image-url). Schematic illustration, not in scale, of the typical environment encountered by a highly relativistic jet ejected in core collapse SN that escapes from the star formation region into the galactic halo.
inferred reliably from the AG light curve nor used reliably to test theoretical models. The situation concerning prominent X-ray flares observed by the Swift XRT is different. They are well resolved and their spectral properties are much better measured. In this paper, we focus our attention on GRB X-ray and optical light curves with prominent flares. In particular, we compare the CB model light curves and their spectral evolution with representatives set of X-ray and optical light curves measured with the Swift XRT, and with ground-based robotic telescopes and Swift UVOT in space, respectively, which have prominent flares that are well sampled. Such a comparison provides stringent tests of both the CB model and its interpretation of the origin of prompt emission pulses in GRBs, their AGs and the early- and late-time flares in their light curves. We show that the CB model correctly predicts their main observed properties, and reproduces well their entire light curves and show that the CB model correctly predicts their main observed properties, and reproduces well their entire light curves and spectral evolution with.

2. ICS FLARES

In this section, we summarize the master formula of the CB model for the pulse shape and spectral evolution of ICS pulses/flares (see Dado et al. 2009a, and references therein for their derivation). Let t denote the time in the observer frame after the beginning of a flare. The light curve of a flare, produced by the electrons in the CBs by ICS of thin bremsstrahlung photons filling the cavity formed by a wind blown by the progenitor star long before the GRB, is generally well approximated by (Dado et al. 2009a)

\[ E \frac{d^2N}{dt dE}(E, t) \approx A \frac{t^2/\Delta^2}{(1 + t^2/\Delta^2)^2} e^{-E/E_p(t)} \times e^{-E/E_p(0)} F(E t^2), \]

(1)

where A is a constant that depends on the CB’s baryon number, Lorentz and Doppler factors, and on the density along its trajectory, and the redshift and distance of the GRB, and \( E_p(t) \), the peak energy of \( E d^2N/dE dt \) at time t, is given roughly by

\[ E_p(t) \approx E_p(0) - \frac{t^2}{t^2 + t_p^2}. \]

(2)

with \( t_p \) being the time (after the beginning of the flare) when the ICS photon count rate reaches its peak value. For \( E \ll E_p \), it satisfies \( E_p(t_p) = E_p \) where \( E_p \) is the peak energy of the time-integrated spectrum of the flare. Thus, in the CB model, each ICS pulse in the GRB light curve is described by four parameters, \( A, \Delta(E), E_p(0), \) and the beginning time of the pulse when t is taken to be 0.

Equation (1) with \( E_p \) given by Equation (2) describes well the shape and the spectral evolution of GRB pulses and of early-time X-ray flares. In particular, it correctly describes their rapid spectral softening during their fast decline as demonstrated in Figures 2(c), (f), 3(b) and 7(d), and in Dado et al. (2008b) for many more cases.

If absorption in the CB is dominated by free–free transitions, then \( \Delta(E) \propto E^{-0.5} \), and for \( E \ll E_p \) the light curve of an ICF is approximately a function of \( E t^2 \) (the “\( E^2 \) law”), with a peak at \( t = \Delta t \), a FWHM \( \approx 2 \Delta t \) and a rise time from half peak value to peak value, \( RT \approx 0.30 \) FWHM independent of \( E \). Note that the approximate \( E t^2 \) law makes the fast decline sensitive only to the product \( E, t_p^2 \) and not to their individual values. This degeneracy in the pulse shape can be removed by inferring \( E_p \) from the broadband spectrum of the ICF.

The late-time decay of the energy flux of the prompt emission pulses and ICFs in an energy band \([E_1, E_2]\), which follows from Equation (1), is given approximately by

\[ \Gamma(E, t) \equiv d \log(d\nu/dE)/d \log E \text{ is given by } (\text{Dado et al. 2008b}) \]

\[ \Gamma(E, t) \approx \left[ \log \left( \frac{E}{E_p(t)} \right) \right]^{-1}. \]

Thus, for the Swift XRT light curves where \( E_1 = 0.3 \) keV and \( E_2 = 10 \) keV, as long as \( E_p(t) \gg E_2 \), the energy flux in an ICS pulse/flare decays like \( t^{-2} \) until it is taken over by the SR AG. When \( E_p(t) \gg E_1 \) but \( E_p(t) \lesssim E_2 \) the energy flux decays like \( t^{-4} \), and when \( E_p(t) \lesssim E_1 \) the energy flux decays like \( t^{-4} \frac{E^{1/2}}{E_{p(t)}^{1/2}} \).

For a single ICF beginning at \( t = 0 \), which is superimposed on a smooth SR AG, the effective photon spectral index \( \Gamma(E, t) \equiv d \log(d\nu/dE)/d \log E \text{ is given by } \) (Dado et al. 2008b)

\[ \Gamma(E, t) \approx \left[ 1 - \beta_\gamma + E/E_p(t) \right] \Theta(t - t_{AG}) + \frac{d \log(d\nu/dE)/d \log E}{\log(E/E_p(t))}. \]

(3)

where \( t_{AG} \) is the time when the SR AG takes over the ICS emission, \( \beta_\gamma \approx 0 \) for a glory with thin thermal bremsstrahlung spectrum, and \( \Gamma_{SR} \) is the best-fit photon spectral index of the smooth X-ray AG.

All the above properties are clear fingerprints of ICFs produced by highly relativistic CBs fired in mass accretion episodes on the newly formed compact central object. Moreover, the observations of X-ray flares indicate that their widths are proportional to their emission time \( t_f \) after the GRB trigger. In the CB model, this implies that their peak energy, equivalent isotropic gamma-ray energy, and peak luminosity decrease like \( E_p \propto t_f^{-1} \), \( E_{iso} \propto [(1 + z)/t_f]^2 \), and \( L_p \propto [(1 + z)/t_f]^3 \).

3. THE SR LIGHT CURVE

In the CB model, the light curve in the observer frame of the SR emitted by a CB is given by the master formula (Dado et al. 2002, 2009a):

\[ F_\gamma(t) \propto n(t) \frac{R(t)^2 \gamma(t)^2 \delta(t) \delta_h^4}{v_h(t)} \times \left[ \frac{v}{v_h(t)} \right]^{-1/2} \left[ 1 + \frac{v}{v_h(t)} \right]^{(1-p)/2}, \]

(5)

where \( t = t \) the time after the ejection of the CB, \( R(t) \) is its radius, \( n \) is the density along its trajectory, \( A(v, t) \) is the attenuation of radiation along the line of sight to it, \( v_h(t) \) is the typical frequency in the observer frame of the SR emitted by the electrons that are swept into it at time \( t \) with a relative Lorentz factor \( \gamma(t) \),

\[ v_h(t) \propto \frac{n^{1/2} \gamma(t)^3 \delta(t)}{1 + z}, \]

(6)

and \( p \approx 2.2 \) is the spectral index of the Fermi accelerated electrons in it.
3.1. The Early-time SRFs

The SR radiation that is emitted from the encounter of a CB with the wind/ejecta of the progenitor star, with a density profile $n(r) \propto e^{-a/(r-r_w)}/(r-r_w)^2$ for $r > r_w$ and $n(r) = 0$ for $r < r_w$, follows from Equation (5) and is given approximately by Dado et al. (2009a):

$$F_{\nu} \propto \frac{e^{-a/t}}{t^{2+\beta}} f^{-\beta},$$

where $t = T - T_w$ with $T$ being the time after trigger and $T_w$ the time at the CB-wind encounter, $t_{\text{exp}}$ is the typical slow-down
time of the fast CB expansion, $\beta = \Gamma - 1$, and the exponent describes the decreasing attenuation of the emitted radiation when the CB penetrates the wind and/or the initial rise in the wind density due to an exponential cutoff of the wind ejection.

Note that for $t^2 \gg t_{\text{exp}}^2$ the asymptotic decline of an SRF is a simple power law (Dado et al. 2003),

$$F_\nu(t) \propto t^{-1} \nu^{-\Gamma+1}, \quad (8)$$

while that of an ICF is

$$F_\nu(t) \propto t^{-2} E^{-\beta_e} e^{-E/E_p(t)} \sim t^{-2} E^{-\beta_e} e^{-E (t^2+t_{\text{exp}}^2)/2E_p^2}. \quad (9)$$

Thus, ICFs and SRFs may be distinguished by their different tempo-spectral evolution.

In the X-ray band, early-time ICFs are usually much brighter than their following SRFs. But, due to their rapid late-time decay, occasionally the $\sim t^{-\Gamma}$ tail (Equation (8)) of the SRF, which follows an ICF, can be seen before the plateau/shallow decay phase of the early-time X-ray AG takes over (see, e.g., Figure 3 in Dado et al. 2009a).

The early-time SR has usually $\beta_{\text{OX}} \sim 0.75$ and $F_\nu$ that decreases strongly between the optical and the X-ray band. Consequently, although ICS dominates the prompt X-ray
emission, in the optical band SRFs are usually much brighter than their preceding ICFs, which typically have $\beta \sim 0$ around their peak time. Consequently, optical flares are usually SRFs. The evolution of the effective spectral index during an optical SRF that follows from Equation (5) has the simple form,

$$\beta \equiv \frac{d \log F[n]}{d \log \nu} = \frac{1/2 + (2\beta_X - 1/2) \nu}{\nu + \nu_b}.$$ \hspace{1cm} (10)

In early-time optical SRFs, $\nu_b$ that is initially below the optical band can cross above it as $n$ of the wind/ejecta increases and then cross back as the density decreases. Such a change in $\beta_O$, from $\beta_O \sim \beta_X$ toward $\beta_O \sim 1/2$ and back to $\beta_O \sim \beta_X$, has been observed in some early-time optical flares, e.g., in GRB 071031 (Kruhler et al. 2009).

### 3.2. The Late-time SR AG

When the merged CBs coast through the constant-density ISM, their SR in the X-ray band is well above the cooling frequency of the Fermi accelerated electrons and their unabsorbed ISM, their SR in the X-ray band is well above the cooling frequency of the Fermi accelerated electrons and their unabsorbed ISM.

$$F_{\nu,b} \propto \nu^{\gamma(t)} = \nu(t) \frac{\gamma_0}{\nu_0} \nu^{-\gamma(t)} \nu^{-\beta_X},$$ \hspace{1cm} (11)

where $\delta = 1/\gamma(t)$ and $\nu(t) = 1 + \delta^2 (t)$ to an excellent approximation. In the CB model, the canonical value of the spectral index well above the bend frequency $\nu_b$ has the value $\beta_X \approx 1.1$. For a CB of a baryon number $N_b$, a radius $R$ and an initial Lorentz factor $\gamma_0$, relativistic energy–momentum conservation yields the deceleration law of the CB in an ISM with a constant density $n$ (Dado et al. 2009a):

$$\gamma(t) = \frac{\gamma_0}{\nu_0} \left[1 \pm \frac{1}{\nu_0} \frac{1}{\nu_0} \frac{t}{\gamma_0} - \frac{\nu_0}{\nu_0} \nu^{-\beta_X} \right].$$ \hspace{1cm} (12)

with $t_0 = (1 + 7)N_b/8 c n \pi R^2 \nu_0^2$. As can be seen from Equation (12), $\gamma$ and $\delta$ change little as long as $t \ll t_b = [1 + \gamma_0^2 \theta^2] t_0$, and Equation (11) yields the "plateau" phase of "canonical AGs" (Nousek et al. 2006). For $t \gg t_b$, $\gamma$ and $\delta$ decrease like $t^{-1/3}$. The transition $\gamma_0 \rightarrow \gamma_0 (t/t_b)^{-1/3}$ around $t_b$ induces a bend, the so-called jet break, in the synchrotron AG from a plateau to an asymptotic power-law decay,

$$F_{\nu,b} \propto t^{-\beta_X - 1/2} \nu^{-\beta_X}. \hspace{1cm} (13)$$

Thus, the shape of the entire light curve of the SR AG from a CB that enters the constant density ISM depends only on three parameters, the product $\gamma_0 \theta$, the deceleration parameter $t_0$ (or the break time $t_b$) and the spectral index $\beta_X$. The post-break decline is given by the simple power law (Equation (13)) independent of the values of $\gamma_0 \theta$ and $t_b$. In cases where $t_b$ is earlier than the beginning of the XRT observations or is hidden under the prompt emission, the entire observed light curve of the AG has this asymptotic power-law behavior (Dado et al. 2008a).

### 3.3. Late-time SRFs

The light curve of late-time SRFs strongly depends on the density profile of the density bumps. For a wind-like density jump $n \propto e^{-a(r_r - r)}/(r_r - r)^2$ beyond $r = r_w$, the light curve is given by Equation (7). Such a density profile is expected for the boundaries of star formation regions where GRBs usually take place. At late times both the optical and the X-ray bands are above the bend frequency, $\beta_O \approx \beta_X$, and the asymptotic decline of the corresponding late-time SRF is given by

$$F_{\nu,[r]} \propto t^{-1/3} \nu^{-1/3},$$ \hspace{1cm} (14)

where $t = T - T_w$ is the observer time after the CB has reached $r_w$. At late times, the bend frequency is well below the optical band and remains so during the crossing of density bumps. Thus, no detectable spectral variation is expected in late-time SRFs.

### 3.4. Correlations

Because of the large bulk motion Lorentz factors of the jets of CBs, Doppler boosting, relativistic beaming, and time aberration yield strong dependence of their observed radiations on $\gamma$ and $\delta$. This dependence dominates the flare observables and can be used to correlate triplets of independent flare observables without knowing the exact values of $\gamma$ and $\delta$. Moreover, many independent observables depend on the same combinations of $\nu$ and $\gamma$, which results in pair correlations. Finally, due to selection effects, various observables strongly depend only on the Lorentz factor or on the Doppler factor, which also yields pair-correlations. These correlations between various radiations, between flare observables, and between flare and GRB observables are discussed in detail in Dado & Dar (2010).

### 4. CASE STUDIES

Although in the CB model early-time optical SRFs follow the X-ray ICFs, they have a different origin and a different tempo-spectral evolution. Thus, we shall compare separately the observational data on X-ray flares and optical flares and the CB model predictions.

#### 4.1. X-ray Flares

In the CB model, the X-ray emission in GRBs, XRFs, and SHBs during the prompt emission phase is a sum of X-ray flares that are part of their prompt gamma-ray pulses. That has been shown repeatedly in CB model publications (see, e.g., Dado et al. 2009a, 2009b) and independently by many other authors. We have also shown that the fast decline phase of their prompt emission with its rapid spectral softening is just the tail of the last prompt emission pulses, because the exponential factor in Equation (1) suppresses very fast the relative contribution of the earlier pulses by the time the data sample the later pulses or flares. This is demonstrated in Figures 2(a)–(c) where we compare between the "canonical X-ray light curve" (Nousek et al. 2006) of GRB 060729 and the evolution of its spectral index as inferred by Zhang et al. (2007) and the CB model descriptions of these light curves. This has already been demonstrated in detail in Dado et al. (2008b, 2009a) for many other GRBs and XRFs. It is also the case for SHBs as shown in Figures 2(e) and (f) for SHB 050724 and in Dado et al. (2009b) for many other SHBs. GRBs with a non-canonical X-ray AG are simply GRBs where the emission of SR begins to dominate the X-ray light curve before the fast decline phase of the prompt emission. Such a case is shown in Figure 3(d) where we compare the XRT light curve of GRB 060418 and its CB model description. Many other cases are shown in Dado et al. (2008b, 2009a, 2009b).

In order to have a stringent test of the CB model interpretation of X-ray flares during the AG phase of GRBs, we have selected...
Figure 4. Comparison between the 0.3 and 10 KeV X-ray light curves of GRBs with prominent flares in their X-ray AG that were measured by the Swift XRT and reported in the Swift/XRT light curve repository http://www.swift.ac.uk/xrt_curves/ (Evans et al. 2009) and their CB model description with the parameters listed in Table 1. Top left (a): GRB 080506. Top right (b): zoom on the prominent X-ray flare in the early-time AG of GRB 080506. Middle left (c): GRB 080607. Middle right (d): zoom on the prominent X-ray flare in the early-time AG of GRB 080607. Bottom left (e): GRB 080810. Bottom right (f): zoom on the prominent X-ray flare in the early-time AG of GRB 080810.

(A color version of this figure is available in the online journal.)

a sample of 14 GRBs with X-ray light curves that are reported in the Swift/XRT GRB light curve repository (Evans et al. 2007, 2009) and have well-sampled prominent flares during their AG phase. This sample includes GRBs 050502B, 050916, 060526, 060929, 070704, 080506, 080607, 080810, 080906, 081102, 090417B, 090621A, 090709A, and the SHB 050724. For all these GRBs, we have fitted the entire XRT light curve with the master formulae of the CB model (see Figures 2–6). In
Figure 5. Comparison between the 0.3 and 10 KeV X-ray light curves of GRBs with prominent flares in their X-ray AG that were measured by the Swift XRT and reported in the Swift/XRT light curve repository (Evans et al. 2009) and their CB model description with the parameters listed in Table 1. Top left (a): GRB 080906. Top right (b): zoom on the prominent X-ray flare in the early-time AG of GRB 080906. Middle left (c): GRB 090417B. Middle right (d): zoom on the prominent X-ray flare in the early-time AG of GRB 090417B. Bottom left (e): GRB 090621A. Bottom right (f): zoom on the prominent X-ray flare in the early-time AG of GRB 090621A.

(A color version of this figure is available in the online journal.)

order to minimize the number of adjustable parameters in the theoretical light curves, we adopted the standard simplifying CB model assumptions (Dado et al. 2009a): the burst environment is a cavity full of thin bremsstrahlung optical photons (glory light) enclosed within a wind/ejecta that have a density profile $n \propto e^{-a_w(r-r_w)/(r-r_w)}$ beyond $r_w$ until the density is taken over by the constant density of the ISM. The CBs were taken to be well separated during the prompt emission phase and to be well represented by a single effective CB during the AG phase. The latest one or two observed pulses/flares in the prompt emission were assumed to dominate its fast decay. This fast ICF decay is overtaken by the tail of the SR emission from the encounter of the CBs with the wind/ejecta as given by Equation (7), or by the plateau phase of the SR AG emitted from the decelerating CB in the constant-density ISM. The smooth AG was calculated from Equations (11) and (12), using best-fit values of the normalization, $\gamma_0, \theta_0,$ and $p/2 = \beta_X$ within the error range reported for $\Gamma = \beta_X+1$ in the Swift X-ray repository (Evans et al. 2009).

Prominent X-ray flares during the AG with a rapid spectral softening during their decline phase were assumed to be ICS pulses/flares. Such flares were superimposed on the CB model
smooth SR AG. Flares with a constant hardness ratio similar to that of the smooth SR AG were assumed to be SRFs. They were generated by introducing density bumps with a windy profile into the master formula of the SR light curve (Dado et al. 2009a).

The fitted parameters of the CB model descriptions of the 14 X-ray light curves of the above GRBs are listed in Tables 1 and 2. When only the tail of the SRF was visible we used its parameter-free asymptotic form, Equation (8). Because of the use of simplifying assumptions, the values of the parameters may be effective values and not true values. Therefore, we refer to the CB model fits as “descriptions” rather than as best-fit predictions. In order to avoid repetitions and an excessively long section, we limit our detailed discussion to three representative cases, GRB 050502B representing long soft GRBs, SHB 050724 representing SHBs, and the recent peculiar GRB 090709A with a suspected 8 s periodicity in its prompt emission.

GRB 050502B was studied in detail by Falcone et al. (2006). The XRT began taking data 63 s after the BAT trigger and followed its X-ray light curve until 10.6 days after burst. The measured light curve in the 0.3–10 keV band is shown in Figure 2(a). Following an initial low-flux level, the XRT detected a giant X-ray flare, which began at 345 ± 30 s, reached a peak value around 770 s, with intensity more than 500 times larger than that of the underlying AG. The fluence of the flare, \((1.0 ± 0.05) × 10^{59} \text{ erg cm}^{-2}\) in the 0.2–10.0 keV energy band, exceeded that of the prompt emission measured with the Swift.
**Table 1**

| GRB/SHB     | $t_0$ (s) | $\alpha_0$ | $\beta_X = p/2$ | $\delta X = \Gamma_{\text{Swift}} - 1$ |
|------------|----------|------------|-----------------|-------------------------------------|
| GRB050502B| 674      | 0.73       | 0.96            | 0.945 (+0.077, −0.100)              |
| SHB050724  | 2178     | 0.74       | 0.90            | 0.915 (+0.14, −0.17)                |
| GRB050502A| 9545     | 1.19       | 1.10            | 0.966 (+0.051, −0.050)              |
| GRB050516  | 9402     | 1.04       | 1.12            | 1.21 (+0.27, −0.24)                 |
| GRB060418  | 123      | 1.73       | 1.05            | 0.96 (+0.15, −0.14)                 |
| GRB060526  | 4828     | 1.35       | 1.02            | 0.931 (+0.086, −0.084)              |
| GRB060729  | 32665    | 2.52       | 1.10            | 1.067 (+0.038, −0.037)              |
| GRB060929  | 5383     | 1.27       | 0.91            | 1.22 (+0.25, −0.25)                 |
| GRB061007  | 40       | 0.15       | 1.08            | 1.018 (+0.087, −0.083)              |
| GRB070704  | 5183     | 1.27       | 0.90            | 0.98 (+0.18, −0.33)                 |
| GRB071003  | 1214     | 1.94       | 1.08            | 0.984 (+0.107, −0.059)              |
| XRF071031  | 5451     | 2.56       | 0.74            | 0.86 (+0.14, −0.15)                 |
| GRB080319B| 86       | 0.14       | 1.08            | 1.03 (+0.064, −0.063)               |
| XRF080330  | 541      | 4.61       | 0.89            | 0.89 (+0.13, −0.12)                 |
| GRB080506  | 7801     | 1.76       | 0.91            | 0.990 (+0.122, −0.077)              |
| GRB080607  | 2904     | 0.55       | 0.91            | 1.102 (+0.098, −0.092)              |
| GRB080810  | 3452     | 0.63       | 1.25            | 1.156 (+0.099, −0.089)              |
| GRB080906  | 5790     | 0.90       | 0.96            | 1.049 (+0.069, −0.164)              |
| GRB081102  | 1891     | 0.47       | 0.92            | 0.921 (+0.079, −0.114)              |
| GRB081203A| 436      | 0.91       | 1.15            | 1.096 (+0.089, −0.081)              |
| GRB090102  | 348      | 0.80       | 0.95            | 0.858 (+0.078, −0.076)              |
| GRB090417B| 1259     | 0.63       | 1.04            | 1.09 (+0.11, −0.11)                 |
| GRB090618  | 1540     | 1.10       | 1.04            | 1.008 (+0.047, −0.046)              |
| GRB090621A| 1309     | 0.83       | 0.94            | 1.01 (+0.18, −0.18)                 |
| GRB090709A| 1098     | 0.51       | 1.08            | 1.081 (+0.076, −0.074)              |
| GRB090812  | 598      | 1.34       | 0.92            | 0.914 (+0.138, −0.089)              |
| GRB090929  | 5753     | 2.32       | 1.01            | 1.197 (+0.077, −0.070)              |

Notes. The CB model spectral index obtained from the temporal shape of the AG and that inferred from the measured XRT spectrum as reported in the Swift light curve repository (Evans et al. 2009) are compared in the last two columns.

**BAT in the 15–350 keV energy band.** After several hours, two weaker flares in the X-ray emission occurred consecutively beyond which the decay of the X-ray light curve became steeper. Except for the giant flare, the spectrum of the AG and the two late flares was well fit by a power law with a photon spectral index $\Gamma = 1.945$ (+0.077, −0.100) (Evans et al. 2007, 2009). The spectrum of the flare was well fit with a power law with an exponential cutoff; however, due to its non-detection by the BAT, its value could not be well determined from the spectrum measured only by the XRT. The photon spectral index of the giant flare before peak time was $\Gamma \approx 1$, much harder than that measured before and after the flare. During the fast decline phase of the flare, a rapid spectral softening took place and the spectral index increased rapidly to a value well above the constant value of the smooth AG.

CB model fits to the X-ray light curve of GRB 050502B and the evolution of its spectral index are shown in Figures 3(a) and (b). They show that the observed light curve and spectral evolution of the giant X-ray flare are well described by the master formula (Equation (1)) of the CB model for an ICF. As can be seen in Figures 3(a) and (b), the fast decay and spectral softening stopped simultaneously when the AG was taken over by the SR from the decelerating CB in an ISM of a constant density. The late-time SR AG is similar in shape to the smooth AG of long GRBs. Also the late-time flare superimposed on the canonical light curve is similar to those observed in many long GRBs. Its spectrum, which is similar to the smooth AG, suggests that it was produced by enhancement of the emitted SR when the CB encountered a density bump in its voyage through the host’s ISM. The Chandra data show that the canonical AG continued to decay after the flare with the same slope and the same spectral index, $\beta_X = 0.79 \pm 0.15$, as that of the AG before the SRs. As shown in Figure 2(e), the complete XRT light curve is well described by the CB model. Moreover, the CB model relation for the asymptotic decline of the smooth AG is well satisfied: the temporal behavior of the smooth AG was best fit with $p = 1.56$, implying an unabsorbed spectral index, $\beta_X = p/2 = 0.78$, in agreement with that inferred from the XRT and Chandra observations. The observed elliptical host galaxy of SHB 050724 was argued to provide strong support for a neutron star merger origin of this SHB. But it was pointed out that neutron star mergers do not produce the late accretion episodes needed to power a late central activity that could produce the large flare around 50 ks after burst (Grupe et al. 2006). In the CB model, a late flare with a typical SR spectrum and little spectral evolution is produced by density bumps along the CB trajectory in the ISM. Such flares neither rule out nor support any specific origin of the SHB.

**GRB 090709A** triggered the Swift BAT on 2009 July 9 at 07:58:34 UT (Morris et al. 2009). Its prompt emission light curve within 100 s after trigger appeared to show a quasi-

**SHB 050724** at redshift $z = 0.257$ was studied in detail by Campana et al. (2006), Grupe et al. (2006), and Malesani et al. (2007). The Swift BAT triggered on the burst at 12:34:09 UT on 2005 July 24. The burst had $T_0 = 3.0 \pm 1.0$ s, but most of the energy of the initial SHB was released in a hard spike with a duration of 0.25 s. The bulk of the burst energy was not emitted in the short initial spike but in an extended soft emission component that lasted $\sim 150$ s. Swift XRT began observing the AG 74 s after the BAT trigger. The Chandra X-ray Observatory performed two observations, 2 days and about 3 weeks after the burst. The complete X-ray light curve is shown in Figure 2(e). It has a rapid decay with a fast spectral softening ending with a sharp transition to a shallower decay with a much harder power-law spectrum, $\Gamma = 1.79 \pm 0.12$ (Swift repository; Evans et al. 2009). The AG steepens gradually into a late power-law decay. A large flare superimposed on the canonical light curve occurred around 50 ks after burst with a fluence of $\sim 7\%$ of that of the prompt burst. The flare has been detected also in the optical and NIR bands, e.g., Malesani et al. (2007). Spectral analysis of the XRT data (Campana et al. 2006) showed no evolution during the AG phase, including the large late flare. Spectral analysis of the Chandra observations from the fading tail of this flare confirmed this result (Grupe et al. 2006). The burst took place 2.5 kpc (in projection) from the center of an elliptical host galaxy (Malesani et al. 2007).
Table 2

The Parameters of the ICFs and SRFs Used in the CB Model Description of X-ray light curves of Swift GRBs

| GRB/SHB   | Flares     | $t_0$ (s) | $\Delta t$ (s) | $E_p$ (keV)/$a$ | $t_0$ (s) | $\Delta t$ (s) | $E_p$ (keV)/$a$ |
|-----------|------------|-----------|----------------|-----------------|-----------|----------------|----------------|
| GRB050502B | ICF,SRF    | 485.7     | 308.3          | 0.27 keV        | 13750     | 28950          | 6013 s          |
|           | SRF        | 58950     | 18911          | 0.13 keV        | 9.9       | 118            | 0.13 keV        |
| GRB060418 | ICF,ICF    | 60        | 12             | 0.13 keV        | 9.9       | 118            | 0.13 keV        |
|           | SRF,SRF    | 1.19      | 32.2           | 2.5 keV         | 653       | 3427           | 3645 s          |
| SHB050724 | ICF,ICF    | 1.58      | 114            | 1.08 keV        | 469       | 1422           | 1.32 keV        |
| GRB050916 | SRF,ICF    | 9757      | 49512          | 3.53 keV        | 17836     | 1335           | 91 keV          |
|           | ICF        | 9757      | 49512          | 3.53 keV        | 17836     | 1335           | 91 keV          |
| GRB060526 | SRF,ICF    | 280       | 25.7           | 60.2 keV        | 85        | 106            | 288 s           |
|           | SRF        | 233       | 42.5           | 0.15 keV        | 472       | 45             | 117 keV         |
| GRB070131 | ICF,ICF    | 84.8      | 46.2           | 13.2 keV        | 131       | 33.8           | 0.74 keV        |
|           | ICF,ICF    | 181.7     | 30.5           | 4.3 keV         | 228       | 40.6           | 14.63 keV       |
|           | ICF,ICF    | 328       | 176            | 7.4 keV         | 572       | 173.6          | 19.74 keV       |
|           | ICF        | 4251      | 1201           | 4.5 keV         |           |                |                |
| SRF,SRF   | 16743      | 5463      | 4.2            | 33241           | (53238)   |                |                |
|            |            |           |                |                 | < $a$     |                |                |
| GRB070704 | SRF,ICF    | (63)      | (0.35)         | (25 s)          | 472       | 45.2           | 117 keV         |
|           | SRF,ICF    | 130       | 36.7           | 14.4 keV        | 211       | 45             | 171 s           |
| GRB080506 | ICF,ICF    | 433       | (41)           | 159 keV         | 684       | (160)          | (156 keV)       |
|           | ICF,ICF    | 65.9      | 8.6            | 145 keV         | 113.9     | (15.4)         | (350 keV)       |
|           | ICF,ICF    | 222       | 332            | 0.6 s           | 652       | 1018           | 335 s           |
| SRF,SRF   | 79         | 10.8      | (0)            |                 |           |                |                |
| GRB080810 | ICF,SRF    | 74        | 16             | 25.5 keV        | 98.6      | 4.6            | 34 s            |
|           | ICF,SRF    | 196       | (14)           | (203 keV)       | 265       | 208            | (7.2 s)         |
| GRB080906 | SRF,SRF    | (49)      | (1)            | (477 s)         | 157       | 27.5           | 10.75 s         |
|           | SRF,ICF    | 490       | 8.58           | 200 s           | 836       | 78             | 145 keV         |
| GRB081102 | SRF,ICF    | 63        | 11             | 42.7 s          | 914       | 88             | 111 keV         |
| GRB090417B| SRF,ICF    | 336.2     | 203            | 82.6 s          | 1227.8    | 431            | 1.96 keV        |
| GRB090618 | ICF,SRF    | 65.9      | 12.9           |                 | (0)       | 884            | (0)             |
| GRB090621A| SRF,ICF    | 150.6     | 2.6 s          | 215             | 217.9     | 50.4           | 0.95 keV        |
| GRB090709A| ICF,SRF    | 70.3      | 20.61          | 2.38 keV        | 75.5      | 14.3           | 116 s           |
| SRF,ICF   | 165.8      | 110.2     | 149            | 324.6           | 37        | 187 s          |                |
| GRB091029 | ICF,ICF    | 0         | 38.8           | 9.8 keV         | 218.6     | 102.5          | 10.9 keV        |
| SRF       | 209360     | 245909    |                |                 |           |                |                |

Notes. Values of parameters that are not well determined by a best fit are inserted within parentheses.

periodic variation with a period of $\sim 8$ s (Markwardt et al. 2009), which may have also seen in independent measurements of its light curve with Konus-Wind (Golenetskii et al. 2009), INTEGRAL (Gotz et al. 2009), and Suzaku (Ohno et al. 2009). The Swift XRT began its follow-up observations 68 s after the BAT trigger (Morris et al. 2009). However, analysis by Mirabal & Gotthelf (2009) of the XRT data during 79–469 s after the BAT trigger did not reveal any significant periodicity. From deep optical observations that did not detect its host galaxy, it was concluded that GRB 090709A took place either in the Milky Way or at a redshift between 8 and 10 (Castro-Tirado et al. 2009). The large redshift and the fluence of $9.1 \times 10^{-5}$ erg cm$^{-2}$ measured with Konus–Wind in the 20 keV–3 MeV energy range imply an isotropic equivalent gamma-ray energy between $8.6 \times 10^{54}$ and $1.1 \times 10^{55}$ erg cm$^{-2}$, which makes GRB 090709A more luminous than any GRB with known redshift.

Figures 6(e) and (f) present a comparison between the XRT light curve of GRB 090709A and its CB model description assuming it was an ordinary GRB. The early-time flare around $t = 90$ s probably is the X-ray part of the prompt emission pulse with a peak around 87 s in the Swift BAT light curve that is slightly delayed relative to the gamma-ray peak, as expected from the $E_t^2$ law of the CB model. Its fast decline and rapid softening are those expected from an ICF. They are taken over by SR around 150 s after the BAT trigger. The next three peaks probably are SR peaks as suggested by their shape and their hardness ratio that is roughly the same as that of the SR AG. The best-fit CB model light curve of the smooth AG yields $p = 2.16$, which, in the CB model, implies $\beta_X = 1.082$, in good agreement with the best-fit spectral index reported in the Swift repository (Evans et al. 2009), $\beta_X = (\Gamma - 1) = 1.081 (+0.076, -0.074)$. All together, GRB 090709A looks like a normal GRB with a normal early-time flaring activity that took place at a relatively very large redshift, and its X-ray light curve is well reproduced by the CB model.

4.2. Optical Flares

The CB model predictions for early-time and late-time flares in the optical light curves of GRBs are compared with observations for a representative set of GRBs in Figures 7–11. For all these GRBs, we show both their measured optical and X-ray light curves (if available) and their CB model descriptions with the parameters listed in Tables 1–5. Only in a very few bright GRBs was the prompt optical emission resolved into separate flares. Two such cases, GRB...
080319B (Wozniak et al. 2009) and GRB 071003 (Perley et al. 2008) are shown in Figures 7 and 8. In most GRBs and XRFs, the prompt optical emission that appears as a single extended flare, probably, is a sum of unresolved flares. Cases where the prompt optical flare was partially resolved into a sum of flares or where there is clear evidence for overlapping flares are, e.g., GRB 080330 (Guidorzi et al. 2009), XRF 071031 (Kruhler et al. 2009), GRB 061007 (Rykoff et al. 2009), which are shown in Figures 8 and 9. In most GRBs where the prompt optical emission was detected with robotic telescopes from the ground or from space (with the Swift/UVOT), the prompt emission appears like a single flare, probably as a result of either strongly overlapping flares, or insufficient temporal resolution due to low statistics, or because the prompt emission did consist of a single flare. Examples of GRBs with a “single” prompt optical flare are 990123 (Akerlof et al. 1999), 030418 (Rykoff et al. 2004), 050820A (Vestrand et al. 2006), 081203A (Kuin et al. 2009), and 091029 (LaCluyze et al. 2009), which are shown in Figures 9–11. Examples of bright GRBs with well-resolved late-time optical flares include GRB 030329 (Lipkin et al. 2004) and GRB 060206 (Wozniak et al. 2006) shown in Figure 11(f). However, in order not to inflate this paper, only GRB 080319B, XRF 071031, GRB 061007, and GRB 990123 are discussed here in detail.
Figure 8. Comparison between the observed early-time X-ray and optical light curves of XRFs and their CB model description. Unlike the X-ray flares, the early-time optical flares are barely resolvable to separate optical flares. XRF 080330—top left (a): the 0.3–10 keV XRT light curve. Top right (b): the optical (white) light curve. XRF 071031—middle left (c): the 0.3–10 keV XRT light curve. Middle right (d): zoom on the early-time XRT light curve. Bottom left (e): the early-time optical (white) light curve. Bottom right (f): evolution of the optical spectral index.

(A color version of this figure is available in the online journal.)

GRB 080319B at redshift $z = 0.937$, the brightest GRB observed so far, was simultaneously detected by the Swift-Burst Alert Telescope (BAT) and the Konus gamma-ray detector aboard the Wind satellite (Racusin et al. 2008; Golenetskii et al. 2008). The location of GRB 080319B was fortuitously only $10^\circ$ away from GRB 080319A, which was detected by Swift less than 30 minutes earlier, and allowed several wide field telescopes to detect the optical emission of GRB 080319B instantly. It started after the beginning of the prompt keV–MeV emission and it peaked 26 s after the Swift trigger at magnitude $V = 5.3$ (Racusin et al. 2008; Wozniak et al. 2009) visible to the naked eye. The extreme brightness of the burst and its gamma-ray, X-ray, and $UVOI R$ AGs led to a flurry of follow-up observations with a variety of space- and ground-based telescopes, which were summarized by Bloom et al. (2009), Racusin et al. (2008), and Wozniak et al. (2009). Its isotropic equivalent gamma-ray energy release was $E_{\text{iso}} \approx 1.3 \times 10^{54}$ erg, similar to that of GRB 990123. The fast spectral variation of its hard X-ray and gamma-ray emission was well parameterized with an exponentially cut-off power law with a cut-off energy that was strongly correlated with the peak structure of the light curve and a low-energy photon spectral index, $\Gamma \approx 1$, which
changed abruptly into $\Gamma \approx 2.1$ after the fast decay phase of the prompt emission. The optical and gamma-ray light curves during the explosion were not correlated (see, e.g., Figure 1 in Racusin et al. 2008): the onset of the optical emission lagged behind the gamma-ray emission by several seconds and decayed more slowly at the end of the prompt emission. The typical timescales of their temporal variability were entirely different. The extremely bright optical emission could not be reconciled with a single emission mechanism—extrapolating the gamma-ray spectrum to the optical band underestimates the optical flux by more than 4 orders of magnitude. Their spectra were also quite different. Contrary to FB model expectations, the X-ray and $UVO$ AG light curves were also chromatic, with no obvious “jet breaks” and with spectral and temporal power-law decays that did not satisfy the closure relations expected in the FB model (see, however, Bloom et al. 2009; Racusin et al. 2008; Wozniak et al. 2009; Kumar et al. 2008 for attempts to reconcile the observations with the FB model).

Figure 9. Comparison between observed and CB model description of light curves. GRB 990123—top left (a): comparison between the 20 and 50 keV BATSE light curve (Briggs et al. 1999) and its CB model description, Equation (1), in terms of nine ICS peaks + a constant background of 3850 counts s$^{-1}$. Top right (b): comparison between the V-band light curve of GRB 990123 and its CB model description assuming a single CB moving in circumstellar density profile $\propto 1/r^2$ overtaken by a constant ISM density around an observer time $t = 1000$ s. The prompt flare was not resolved into separate flares. GRB 061007—middle left (c): the 0.3–10 keV XRT light curve. Middle right (d): the optical light curve with evidence for at least two early-time overlapping flares. Bottom left (e): the optical (white) light curve of GRB 030418. Bottom right (f): the $R$-band light curve of GRB 090102 with evidence for a tail of a prompt optical flare.

(A color version of this figure is available in the online journal.)
The prompt $\gamma$-ray and hard X-ray emission in GRB 080319B is composed of many narrow peaks (see Figure 1 in Racusin et al. 2008), most of which are not well resolved. Its 0.3–10 keV X-ray light curve measured with the Swift XRT (Racusin et al. 2008) and its CB model description assuming a constant ISM density until around $t \sim 4 \times 10^5$ s, presumably when the CB escaped the star formation region into the halo of the host galaxy, are shown in Figure 7(a). The best-fit parameters are listed in Table 1. The late-time temporal decay of the X-ray AG is well described by a power law with $\alpha_X = 1.54 \pm 0.04$, except around 40 ks, where the light curve is poorly sampled. This value of $\alpha_X$ satisfies well the CB model closure relation $\alpha_X = \beta_X + 1/2 = 1.53 \pm 0.064$. As expected for GRBs with large measured $E_p$, $E_{iso}$, and $L_p$ (Dado et al. 2008b), no AG break was observed in the XRT light curve before $6 \times 10^5$ s. The wiggling of the measured light curve around a power-law decay is probably due to variations in the ISM density along the CB trajectory, which we have not tried to parameterize. A late-time SRF with a typical late-time decay $\sim (t - t_f)^{-2.1}$ probably was observed around $6 \times 10^5$ s.

In Figure 7(b), we compare the measured $R$-band (and $V$ band renormalized to the $R$ band) light curve of GRB 080319B...
(Racusin et al. 2008) and its CB model description assuming that the initially expanding three CBs merged into a single CB by the end of the prompt ICS emission of gamma-rays and hard X-rays around 300 s (observer time), which decelerates in roughly a constant density ISM. The AG parameters are listed in Table 3. The “missing jet break” probably is hidden under the prompt emission. Shown also is the contribution to the R-band AG from an SN akin to SN1998bw (Galama et al. 1998b) displaced to the GRB site.

The early-time optical emission that was resolved into three prominent peaks and its CB model description in terms of three SR peaks, each one described by Equation (7) with the parameters listed in Table 3, are compared in Figure 7(c). The decay of the prompt emission can also be reproduced assuming a single CB crossing three wind shells, which were ejected by the progenitor star long before its SN explosion, rather than three CBs crossing a continuous pre-SN wind blown by the SN progenitor.

In Figure 7(d), the observed evolution of the spectral index in the 15–150 keV band during the prompt emission and the AG (Racusin et al. 2008) are compared with that predicted by the CB model. The predicted sharp transition from the prompt emission, which is dominated by ICS of thin bremsstrahlung ($\Gamma \approx 1$), to SR ($\Gamma_x \approx 2.1$), which dominates the emission...
The observed...

\index{late-time power-law decay}

\curve repository; \cite{Evans2009} is dominated by bright up from the ground in automated observations by GROND.

Their parameters are listed in Table 2. As shown in Figures 8(c) and (d) the CB model describes well the very complex XRT light curve. The parameters used in the CB model description are listed in Table 3. Comparison between the optical spectral index light curve that was inferred by \cite{Kruhler2009} and the CB model prediction as given by Equation (10) is shown in Figure 8(f).

\textbf{Table 3}

The Parameters Used in the CB Model Description of Unresolved Prompt Emission SRFs in the Optical Light Curves of Swift GRBs

| GRB     | Flare | \( t_0 \) (s) | \( a \) (s) | \( t_{\text{exp}} \) (s) | \( \beta \) |
|---------|-------|---------------|-------------|--------------------------|-----------|
| GRB090123 | SRF    | 22           | \(< 10\)   | 1.67 \( \pm 0.50\)       |           |
| GRB030418 | SRF    | 200          | 4097       | \(< a \) \( \pm 0.56\)    |           |
| GRB050820A | SRF    | 109          | 479        | \(< a \) \( \pm 0.60\)    |           |
| GRB061007 | SRF    | 15.8         | 90.37      | \(< a \) \( \pm 0.60\)    |           |
| GRB081230A | SRF   | 0            | 316        | 368 \( \pm 0.90\)        |           |
| GRB090102 | SRF    | 1.65         | 0.13       | 2.16 \( \pm 0.53\)       |           |
| GRB090618 | SRF    | 118          | \(< 0\)    | 61 \( \pm 0.51\)         |           |

(Kruhler et al. 2009) with good temporal resolution, which began 225 s after burst and lasted nearly 7 hr. The white light curve obtained by adding the various optical bands, in order to increase sensitivity, shows a broad peak with clearly deviations from a power-law rise and decay. Figure 8(e) shows the CB model description of this light curve in terms of strongly overlapping four SRFs following their preceding ICFs in the X-ray light curve. The parameters used in the CB model description are listed in Table 3. Comparison between the optical spectral index light curve that was inferred by Kruhler et al. (2009) and the CB model prediction as given by Equation (10) is shown in Figure 8(f).

\textbf{Table 4}

CB Model Parameters of the ICS \( \gamma \) Peaks in GRB 990123

| Peak | \( t_0 \) (s) | \( D_r \) (s) | \( E_y \) (keV) | \( A \) (counts s\(^{-1}\)) |
|------|---------------|--------------|----------------|-----------------|
| 1    | \(-5.57\)     | 15.4         | 300             | \(4.00 \times 10^3\) |
| 2    | 19.42         | 4.28         | 1450            | \(3.95 \times 10^4\) |
| 3    | 29.88         | 0.87         | 500             | \(6.74 \times 10^4\) |
| 4    | 32.95         | 5.43         | 800             | \(2.75 \times 10^4\) |
| 5    | 43.67         | 4.99         | 500             | \(1.11 \times 10^4\) |
| 6    | 52.77         | 4.30         | 450             | \(1.05 \times 10^4\) |
| 7    | 61.09         | 4.10         | 450             | \(1.21 \times 10^4\) |
| 8    | 70.35         | 5.63         | 600             | \(1.69 \times 10^4\) |
| 9    | 85.50         | 1.86         | 600             | \(6.64 \times 10^4\) |

once the CBs encounter the progenitor’s wind/ejecta, is clearly observed.

\textbf{XRF 071031} was studied in detail by Kruhler et al. (2009). The \textit{Swift}/XRT began follow-up observations of XRF 071031 103 s after the burst. The early XRT light curve (XRT light curve repository; \cite{Evans2009}) is dominated by bright flares at around 120 s, 150 s, 200 s, 250 s, and 450 s. The late X-ray data exhibit re-brightenings at 5.5 ks, 20 ks, and 55 ks superimposed on a smooth AG. The complete XRT light curve was reproduced with the CB model, assuming seven early-time ICFs plus two late-time SRFs superimposed on a smooth SR AG. Their parameters are listed in Table 2. As shown in Figures 8(c) and (d) the CB model describes well the very complex XRT light curve (\(x^2/dof = 431/426\)). The values of the photon spectral index of the late-time AG, \(\Gamma_x = 1.86 \pm (0.14, -0.15)\), and the index of the late-time power-law decay, \(\alpha_x = 1.4 \pm 0.1\), which were inferred from the \textit{Swift}/XRT observations (\textit{Swift} XRT light curve repository; \cite{Evans2009}), satisfy well the CB model closure relation, \(\alpha_x = \Gamma_x - 1/2\).

The emission in the optical band was detected and followed up from the ground in automated observations by GROND (Kruhler et al. 2009) with good temporal resolution, which began 225 s after burst and lasted nearly 7 hr. The white light curve obtained by adding the various optical bands, in order to increase sensitivity, shows a broad peak with clearly deviations from a power-law rise and decay. Figure 8(e) shows the CB model description of this light curve in terms of strongly overlapping four SRFs following their preceding ICFs in the X-ray light curve. The parameters used in the CB model description are listed in Table 3. Comparison between the optical spectral index light curve that was inferred by Kruhler et al. (2009) and the CB model prediction as given by Equation (10) is shown in Figure 8(f).

\textbf{Table 5}

The Parameters Used in the CB Model Description of Unresolved Prompt Emission SRFs in the Optical Light Curves of Swift GRBs

| GRB | Flare | \( t_0 \) (s) | \( a \) (s) | \( t_{\text{exp}} \) (s) | \( \beta \) |
|-----|-------|---------------|-------------|--------------------------|-----------|
| GRB090123 | SRF    | 22           | \(< 10\)   | 1.67 \( \pm 0.50\)       |           |
| GRB030418 | SRF    | 200          | 4097       | \(< a \) \( \pm 0.56\)    |           |
| GRB050820A | SRF   | 109          | 479        | \(< a \) \( \pm 0.60\)    |           |
| GRB061007 | SRF    | 15.8         | 90.37      | \(< a \) \( \pm 0.60\)    |           |
| GRB081230A | SRF   | 0            | 316        | 368 \( \pm 0.90\)        |           |
| GRB090102 | SRF    | 1.65         | 0.13       | 2.16 \( \pm 0.53\)       |           |
| GRB090618 | SRF    | 118          | \(< 0\)    | 61 \( \pm 0.51\)         |           |
Instruments (Briggs et al. 1999). It was also detected and localized by the Gamma-ray Burst Monitor (GBM) aboard the BeppoSAX satellite (Maiorano et al. 2005). The light curves of the prompt emission in the keV–MeV range showed a complex structure of at least 9 pulses/flares (see Figure 9(a)). The prompt optical emission that was detected by the Robotic Optical Transient Search Experiment (ROTSE) at Los Alamos 22 s after the onset of the burst, brightened and peaked at magnitude \( V \sim 9 \), about 50 s after the GRB onset, and decayed rapidly with time (Akerlof et al. 1999). The prompt optical flare was not resolved into separate flares. It was followed in the \( UVONIR \) bands with large ground-based telescopes (Castro-Tirado et al. 1999; Galama et al. 1999; Kulkarni et al. 1999; Fruchter et al. 1999; Holland et al. 2000) and with the Hubble Space Telescope until it faded to a magnitude \( V = 27.7 \pm 0.15 \), 2 months after burst (Fruchter et al. 2000). The broadband \( \gamma \)-ray, X-ray, \( UV \) and \( NIR \) light curves of GRB 990123 were re-analyzed recently within the synchrotron FB model by Corsi et al. (2005).

Essentially, they found that the spectral and temporal properties of the prompt optical emission are uncorrelated to the \( \gamma \)- and X-ray emission, implying different physical origins, that the optical and X-ray AG light curves are chromatic contrary to expectations, and that their spectral and temporal power-law decays do not satisfy the closure relations of the FB model.

In Figure 9(a), we compare the BATSE multi-peak light curve of GRB 990123 in the 20–50 keV channel (Briggs et al. 1999) and its CB model description. The count rate in the 20–50 keV energy band was calculated from the integral \( \int F_\nu dE/E \) using Equation (1) with the best-fit parameters, which are listed in Table 4 for the nine peaks suggested by the multichannel BATSE data and by the BeppoSAX data (Maiorano et al. 2005). As shown in Figure 9(a), the shape of the peaks and the entire light curve are well reproduced by Equation (1). The 2–10 keV light curve of the X-ray AG of GRB 990123 that was measured with BeppoSAX (Maiorano et al. 2005) for \( t < 2.5 \) days (not shown here) was best fit by the CB model with \( p = 1.79 \), implying \( \beta_X = 0.90 \), consistent with \( \beta_X = 0.94 \pm 0.12 \) that was inferred by Maiorano et al. (2005) from their data. The observed temporal power-law decay index of the late-time X-ray AG, \( \alpha_X = 1.46 \pm 0.04 \) (Maiorano et al. 2005), also obeys the CB model relation, \( \alpha_X = \beta_X + 1/2 = 1.44 \pm 0.13 \).

In Figure 9(b), we compare the observations of the optical light curve of GRB 990123 from onset (Akerlof et al. 1999) until late-time (Castro-Tirado et al. 1999; Galama et al. 1999; Kulkarni et al. 1999; Fruchter et al. 1999; Holland et al. 2000), normalized to the \( V \) band, and its CB model description as given by Equation (11) with the AG parameters \( \gamma \theta = 0.24 \), \( t_0 = 2250 \) s, and \( p = 1.79 \). Due to a gap in the data between 500 s and 15,000 s, the expected transition from a circumstellar density profile \( \propto 1/r^2 \) to a constant ISM density was not well determined. However, the gradual bending (“jet break”) of the optical AG to an asymptotic power-law decay, \( F_\nu \propto t^{-\beta_0 -1/2} v^{-\beta_0} \), is well reproduced with the expected late-time spectral index \( \beta_0 \sim \beta_X \sim 1.1 \).

5. SUMMARY AND CONCLUSIONS

In the CB model, GRBs, XRFs, and SHBs and their AGs are produced by the interaction of bipolar jets of highly relativistic plasmoids (CBs) of ordinary matter, which are ejected in mass accretion episodes on a newly formed compact stellar object, with the radiation and matter that they encounter along their path. As observed in microquasars, each time part of the accretion disk falls abruptly onto the compact object, two jets of ordinary-matter plasma with large bulk-motion Lorentz factors are emitted in opposite directions along the rotation axis, wherefrom matter has already fallen back onto the compact object due to lack of rotational support. The prompt \( \gamma \)-ray and X-ray emission is dominated by ICS of photons of the glory—a quasi-isotropic optical light emitted by the SN and scattered by the wind/ejecta blown from the progenitor star long before the GRB. The CBs’ electrons Compton up-scatter the glory photons into a narrow conical beam of \( \gamma \) rays along the CBs’ direction of motion. An X-ray “flare” coincident in time with a prompt \( \gamma \)-ray pulse is simply its low-energy part. The early-time X-ray flares without a detectable accompanying \( \gamma \)-ray emission are usually ICFs produced by CBs with relatively smaller Lorentz factors due to a weakening activity of the central engine: as the accretion material is consumed, the “engine” has a few progressively weakening dying pangs. The light curves of ICFs, like those of the prompt emission pulses, exhibit a rapid softening during their fast decline phase. Roughly, the light curves are a function of the product \( E_I t^2 \) and not of the individual values of the photon energy \( E \) and the time \( t \) after the beginning of the flare. The peak energy, isotropic equivalent energy, and peak luminosity of the ICFs are correlated like those of the prompt GRB pulses.

In the CB model, each ICF is followed by SRF from the encounter of the CB with the wind/ejecta that was blown from the progenitor star long before the GRB. Because of time aberration, in the observer frame, these SRFs lag after their preceding ICFs by a short time of the order of the ICS pulse duration. Optical flares are usually much wider than their corresponding gamma/X-ray pulses and overlap, which makes it difficult to associate the early-time optical flares with their preceding gamma/X-ray pulses/flares and measure their lag time. Only in single-pulse GRBs that are bright enough to be detected with robotic telescopes and/or Swift UVOT and in very bright GRBs, such as 080319B and 071031, where the optical flares were partially resolved with robotic telescopes, could the predicted association between early-time optical flares following gamma/X-ray pulses/flares be tested.

Often the fast decay of an X-ray ICF is taken over by SR of X-rays from the CB encounter with the wind enclosing the glory light before it disappears under the plateau/shallow decay phase of the AG (see, e.g., Figures 3(a)–(c) in Dado et al. 2009a).

Late-time flares are usually SRFs produced by CB encounters with the bumpy boundary of the star formation region, or with density bumps within this region where the GRB took place. Their exact profile is not known a priori but a wind-like profile seems to be a good working hypothesis.

Unlike the empirical parameterizations (such as Band function (Band et al. 1993), cut-off power-law, Beuermann function (Beuermann et al. 1999), broken power-law, segmented power-law, etc.) used in most of the published standard analyses of GRB light curves, which have never been properly derived from underlying physical assumptions, the master formulae of the CB model were derived in fair approximations from its underlying physical assumptions. As shown in this paper, the light curves and spectral evolution of X-ray flares and optical flares in GRBs, XRFs, and SHBs are well described by the master formulae of the CB model of GRBs. So far, no new assumptions or modifications of these formulae were needed when applied to well-sampled flares in the GRB light curves. Probably, in the future, when much more refined data and better sampled light curves of GRBs and their AGs will become available, the CB
model with its current simplifying assumptions, which were introduced in order to avoid “over parameterization” and make it predictive and falsifiable, will have to be refined in order to reproduce such data with sufficient accuracy.

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