SHORT HARD GAMMA-RAY BURSTS AND THEIR AFTERGLOWS

SHLOMO DADO1, ARNON DAR2, AND A. DE RÚJULA2,3
1 Physics Department and Space Research Institute, Technion, Haifa 32000, Israel; dado@phep3.technion.ac.il
2 Theory Unit, CERN, 1211 Geneva 23, Switzerland; arnon@physics.technion.ac.il, dar@cern.ch; Alvaro.Derujula@cern.ch
3 Physics Department, Boston University, USA

Received 2008 August 26; accepted 2008 October 30; published 2009 March 2

ABSTRACT

Long-duration gamma-ray bursts (GRBs) and X-ray flashes (XRFs) are produced by highly relativistic jets ejected in core-collapse supernova (SN) explosions. The origin of short hard gamma-ray bursts (SHBs) has not been established. They may be produced by highly relativistic jets ejected in various processes: mergers of compact stellar objects, large-mass accretion episodes onto compact stars in close binaries or onto intermediate-mass black holes in dense stellar regions, phase transition in compact stars. Natural environments of such events are the dense cores of globular clusters, super star clusters and young SN remnants. We have used the cannonball model of GRBs to analyze all Swift SHBs with a well-sampled X-ray afterglow. We show that their prompt gamma-ray emission can be explained by inverse Compton scattering (ICS) of the progenitor’s glory light and their extended soft emission component by either ICS of high-density radiation or synchrotron radiation (SR) in the high-density medium within the star cluster. The mechanism generating their afterglow is SR outside the cluster. No associated SN could be detected in the low luminosity nearby GRBs 060614 and 060505. We interpret them as SHBs seen relatively far off-axis.

Key words: gamma rays: bursts

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) have been traditionally classified as short hard bursts (SHBs) and long soft bursts. Their distribution as a function of duration is bimodal with a minimum around 2 s (Mazets et al. 1981; Norris et al. 1984; Kouveliotou et al. 1993). The γ-rays of short bursts are typically harder than those of long bursts; thus their acronym, SHBs, but their fluence, is much smaller. The SHBs consist of a single or a complex of peaks with a total duration of typically less than 2 s and peak widths that range between a few ms and a fraction of a second. The lag time between their emissions in soft and hard energy bands is much smaller than that in long GRBs and X-ray flashes (XRFs). We shall refer to the ensemble of long GRBs and XRFs as LGRBs.

A true breakthrough in the observations of SHBs came with the launch of Swift in 2004 November. Since its launch, Swift has detected over 30 SHBs with X-ray and ultraviolet-optical afterglows, and triggered follow-up ground-based observations that for most SHBs succeeded in identifying their host galaxy (HG) and measuring its redshift. Swift has also discovered that, in more than 25% of these cases, perhaps in all, the SHB was followed by an extended soft emission component (ESEC), a spectrally softer component lasting tens of seconds (for recent reviews, see Nakar 2007; Kann et al. 2008). The fluence of SHBs is typically much smaller than that of GRBs. The fluence of their ESEC is usually comparable with or smaller than that of the SHB. The ESECs end with a fast-decay phase, followed by an afterglow with a canonical time dependence (see Figures 1–4), similar to that observed in a large fraction of LGRBs (Nousek et al. 2006). LGRBs are located near the center of their hosts, which are all late-type galaxies (Covino et al. 2006). Contrariwise, SHBs have a heterogeneous population of hosts, and take place in both elliptical galaxies (e.g., SHBs 050709 and 050724, Gehrels et al. 2005; Berger et al. 2005) and spiral galaxies (e.g., SHB 051221A; Soderberg et al. 2006c).

Generally, the SHBs with an ESEC are centrally located, while those with no detectable ESEC are found at very large distances from their host’s center (Troja et al. 2008). There is also a clear trend of their afterglow to be fainter for larger offsets (Kann et al. 2008).

Observations indicate that LGRBs are mainly produced by core-collapse supernovae (SNe) of type Ib/c. A GRB–SN association was discussed long ago (Colgate 1968; Dar et al. 1992) but was dismissed by Woosley (1993), who suggested that only “failed supernovae” produce GRBs. Following the discovery by Galama et al. (1998) of SN1998bw in the error box of GRB980425, Wang & Wheeler (1998), Dar & Plaga (1999), and Dar & De Rújula (2000) suggested that perhaps most core-collapse SNe produce LGRBs. This was later advocated as an observed fact, based on a comprehensive analysis of optical afterglows within the cannonball (CB) model of LGRBs (Dado et al. 2002, 2003, hereafter DDD2002, DDD2003, respectively; Dar & De Rújula 2004, hereafter DDD2004, and references therein) and on empirical grounds by Zeh et al. (2004). General acceptance of the GRB–SN association waited until the spectroscopic discovery of an SN2003dh coincident with GRB030329 (Hjorth et al. 2003; Stanek et al. 2003) and additional discoveries of spectroscopically-proven GRB–SN associations such as GRB030213/SN2003lw (Malesani et al. 2003), GRB021211/SN2002lt (Della Valle et al. 2003), XRF060218/SN2006aj (Campana et al. 2006a; Pian et al. 2006; Mazzali et al. 2006), and XRF080109/SN2008D (Malesani et al. 2008; Modjaz et al. 2008).

In contrast, SHBs do not seem to be associated with any known type of SN (e.g., Hjorth et al. 2005b). The identity of their progenitors is not established, except that giant flares from soft gamma-ray repeaters (SGRs), which look like SHBs, may account for most of the observed SHBs in nearby (redshift z < 0.01) galaxies (Dar 2005a; Hurley et al. 2005). The extremely bright SHBs 051103 and 070201 observed by Konus-Wind could have been such events in the nearby galaxies M81/
M82 and M31 (Ofek et al. 2006, 2007; Frederiks et al. 2007). But hyperflares from SGRs cannot account for the bulk of the much more distant ones, ε ≳ 0.01, unless they are highly collimated or much more energetic but less frequent.

Although the observational data on cosmological SHBs and their afterglows did not pin down their progenitors, they do provide useful clues to their progenitors, production mechanism, and production sites. Their extremely short durations and large equivalent isotropic gamma-ray energies, and the absence of self-absorption features in their γ-ray spectra suggest that they are produced by highly relativistic jets ejected in violent processes involving compact stars (Shaviv & Dar 1995a), such as the following.

1. Neutron stars merger and neutron star—black hole merger in compact binaries (Blinnikov et al. 1984; Paczynski 1986; Goodman et al. 1987; Eichler et al. 1989).

2. Collapse of compact stars (neutron stars, hyper stars, quark stars) to a more compact star due to mass accretion, and/or loss of angular momentum and/or cooling by radiation (Dar 1998, 1999, 2006; Dar & De Rújula 2000).

3. Phase transition in compact stars, such as neutron stars, hyperstars, and quark stars (Dar 1999, 2006; Dar & De Rújula 2000).

4. Accretion episodes in microblazars (Dar 1998b, 1999) and on intermediate mass black holes in dense stellar regions.

The natural environment of these progenitors is superdense stellar regions such as collapsed cores of globular clusters (GCs) and young centrally condensed super star cluster (SSC) (Shaviv & Dar 1995b) whose stellar densities and total luminosities seem to be correlated with their distance from the center of their HG. If the ESEC is produced by inverse Compton scattering (ICS) of ambient light in GCs with a low-density interstellar medium (ISM) or by synchrotron radiation (SR) in SSCs with a very large ISM density, it may explain the observations that SHBs with an ESEC are centrally located, while those with no detectable ESEC are found at very large distances from their host’s center (Troja et al. 2008).

The spectra and pulse shapes of SHBs measured by the γ-ray telescopes on board satellites, except for being harder and shorter, are very similar to those measured by the same satellites in LGRBs (Nakar 2007; Kann et al. 2008). In particular, the X-ray light curves of SHBs, which were well sampled with the Swift Burst Alert Telescope (BAT) and X-ray Telescope (XRT), show the same canonical behavior seen in many LGRBs (Nousek et al. 2006; O’Brien et al. 2006): an early rapid temporal decay of the prompt emission during which the spectrum softens at a very fast rate. This rapid decay phase ends within a few hundred seconds when it is taken over by a plateau with a much harder power-law spectrum, typically lasting thousands to tens of thousands of seconds. Within a time of order of 1 day, the plateau steepens into a power-law decay, which lasts until the X-ray AG becomes too dim to be detected. Often, X-ray flares, not coinciding with any detectable γ-ray activity, are superimposed on the X-ray light curve during the fast-decaying phase and even later. These similarities with long GRBs suggest that the initial burst and the afterglow in both SHBs and LGRBs are produced by the same radiation mechanisms: ICS of glory light and SR from decelerating CBs.

The CB model has been successful in predicting/accommodating the observed properties of the prompt radiation of LGRBs (Dar & De Rújula 2004, hereafter DDD2004) and their afterglows (DDD2002; DDD2003; Dado et al. 2007b, 2008a, 2008b, 2008c, hereafter DDD2007b; DDD2008a; DDD2008b; DDD2008c, respectively). Because of the above similarities between LGRBs and SHBs, the CB model may also correctly reproduce the main observed properties of SHBs, after only simple adjustments. Indeed, in this paper we show that using only general properties of the putative SHB progenitors and their natural environments, the CB model with the same two basic radiation mechanisms, ICS of ambient light, which dominates the prompt emission, and SR, which dominates the afterglow emission, also provides a simple and successful description of the observed properties of SHBs and their afterglows. Moreover, we show that a few nearby LGRBs without a detectable SN, such as GRB 060614, which were interpreted as belonging to a new class of LGRBs (e.g., Gal-Yam et al. 2006b; Gehrels et al. 2006; Della Valle et al. 2006), can be interpreted as SHBs seen far off-axis.

No high-energy emission was detected so far from SHBs despite their proximity relative to LGRBs from which high-energy emission was detected by EGRET (Hurley et al. 1994; Dingus 2001; Gonzalez et al. 2003), HEGRA (Padilla et al. 1998), Milagrito (Atkins et al. 2000), AGILE (Giuliani et al. 2008), and the Large Area gamma-ray Telescope (LAT) aboard the Fermi Gamma Ray satellite that was launched on June 11 and is sensitive to high-energy photons with energy below 300 GeV (Bouvier et al. 2008). High-energy emission from SHBs, or the lack of, can provide useful constraints on SHB models. Such an emission from LGRBs and SHBs will be discussed in a separate paper (A. Dar & S. Dado 2009, in preparation).

2. SUMMARY OF THE UNDERLYING ASSUMPTIONS

2.1. The Progenitors of GRBs and their Environments

We have no novel suggestions regarding either the putative progenitors of cosmological SHBs or the ejection mechanism and the properties of their highly relativistic jets. As listed in Section 1, most conventionally, the progenitors may be the merger of a neutron star with another one or with a black hole, or large accretion episodes in microblazars (microquasars with their jets pointing accurately to us) or intermediate mass black holes. Accretion, cooling, or angular momentum loss may result in abrupt transitions of neutron stars to more compact objects (strange stars, quark stars, or stellar black holes). All these phenomena are natural candidates for SHB progenitors. The above putative progenitors meet the energy-budget requirements, even if the radiation of SHBs is not very highly collimated. The estimated merger rate of neutron stars is sufficient only if SHBs are not narrowly collimated. If they are, as in the CB model, some of the other mechanisms we cited must also be operative. Indeed, low-luminosity LGRBs detected by International Gamma-Ray Astrophysics Laboratory (INTEGRAL) led to the conclusion (Foley et al. 2008) that the rate of LGRBs with inferred low luminosity is ≳ 25% of that of Type Ib/c SNe.4 Since BATSE observed an SHB rate nearly 1/3 the rate of LGRBs, the rate of SHBs implied by the INTEGRAL observations must also be comparable with the rate of SNe of type Ib/c. Such a rate is a considerable fraction of the birth rate of neutron stars. It is much larger than the merger rate of neutron stars in close binaries. It favors other alternative sources of SHBs such as a phase transition in neutron stars or accretion episodes on stellar mass and intermediate mass, black holes.

---

4 Such a fraction is larger by a factor ∼ 10^−10^ than that of previous estimates (e.g., Gal-Yam et al. 2006a; Soderberg et al. 2006b), which relied on the validity of uncertain fireball model relations.
The putative progenitors of SHBs are mostly located in the cores of GCs and the central region of SSCs. We shall assume that SHBs are produced in such an environment.

2.2. The Radiation Mechanisms

We shall assume that similar to LGRBs, the two dominant radiation mechanisms in SHBs are ICS and SR. ICS of glory light produced by a stellar companion or by an accretion disk, by electrons comoving with the CBs, dominates the prompt emission, while SR from the decelerating CBs in the ISM or the IGM dominates the afterglow emissions.

We shall also assume that ICS of ambient light in GCs of a low-density ISM or SR from the decelerating CBs in the high-density ISM of SSCs produces the ESEC.

2.3. The Glory Light

We contend that the prompt γ- and X-rays of an SHB’s pulse are made similar to those in LGRBs, that is, by ICS of glory light by the electrons contained within a CB. For LGRBs, the glory is formed by scattered and emitted radiations by the pre-SN wind/ejecta blown from the progenitor star, which was illuminated by light from the progenitor, the early flash of the SN explosion, and light from the jet itself. The burst environment of the putative progenitors of SHBs is probably complicated and can be estimated only very roughly. After ejection, the fast expanding CB probably propagates through a cavity produced by the ejecta/wind blown by the progenitor star, or by a close companion or from an accretion disk. The cavity contains a quasi-isotropic light from the companion star, the accretion disk and the jet itself, which illuminated the wind and was scattered/emitted by it.5 Outside a source of radius \( r_s \), the intensity of light roughly decreases like 1/(\( r^2 + r_s^2 \)). The kinetic temperature of the ionized wind is roughly proportional to the intensity of the photoionizing light. The photoionized wind emits a quasi-isotropic light that presumably has a thin thermal bremsstrahlung spectrum with a temperature that decreases with distance beyond a radius \( r_g \) like 1/r^2, where the wind becomes transparent (optical thickness \( \sim 1 \)) to glory photons. Unable to theoretically evaluate \( n_g(r) \), we will adopt a density of glory photons seen by a CB as that roughly given by \( n_g(r) \sim n_g(0) (r_g^2 + r^2)^{2/3} \), and treat \( r_g \) and \( n_g(0) \) as adjustable parameters to be directly determined from the data.

2.4. The Main Parameters

The launching of highly relativistic and narrowly collimated jets in mass accretion episodes, merger, or phase transitions is not sufficiently understood to predict the chaotic timing of CB emissions, nor the number, \( N_{CB} \), of dominant CBs in a particular jet, nor the baryon number, \( N_B \), nor the initial Lorentz factor, \( \gamma_0 \), of observable CBs. But once the typical values of these parameters are inferred from the data, all properties of LGRBs and SHBs can be understood in simple terms. This also requires a number of items of information independent of the model itself. They are the angle between a CB jet and the observer, the properties of the ambient light a CB encounters in its flight and of the density of the ISM or intergalactic medium (IGM), which CBs pierce through. Naturally, the cosmological redshift, \( z \), and the absorption or attenuation of light of various frequencies along the line of sight (LOS) play their usual roles, with the exception, in comparison with other models, that the LOS to a CB significantly moves (and hyperluminally) during the observation time. The standard cosmological model with \( \Omega = 1, \Omega_M = 0.27, \Omega_L = 0.73, \) and \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \), is assumed throughout this paper.

2.5. The Opening Angle of a Jet of CBs and the Typical Observers’ Angle

We hypothesize that a CB initially expands in its rest system at a speed comparable with the speed of sound in a relativistic plasma, \( v \equiv \beta_g c/\sqrt{3} \) with \( \beta_g \lesssim 1 \). A CB’s initial radius must be of the order of the size of the progenitor compact object or its accretion disk, and rapidly becomes negligible as the CB expands. Thus, a CB traces a cone in the space of an initial opening angle \( \theta_{\text{CB}} = \beta_g/\sqrt{3} \gamma_0 \). The characteristic opening angle of the emitted radiation is \( 1/\gamma_0 \), much larger than \( \theta_{\text{CB}} \), so that the jet opening is not a concept that plays a very major role. In the AG phase, the effect of the deceleration of CBs in the ISM becomes important, and the radiation is spread over an angle \( 1/\gamma(t) \).

In the CB model, the Doppler factor, \( \delta(t) \), relating times, energies, and fluxes in a CB’s rest system to those in the observer’s system plays a major role in the understanding of GRBs. Its form in terms of \( \theta \) and the time-dependent Lorentz factor, \( \gamma(t) \), of a CB, is

\[
\delta(t) = \frac{1}{\gamma(t)(1 - \beta(t) \cos \theta)} \approx \frac{2 \gamma(t)}{1 + [\gamma(t) \theta^2]^1/2},
\]

where the approximation is excellent for \( \gamma \gg 1 \) and \( \theta \ll 1 \). Doppler boosting and relativistic beaming enhances the observed energy flux from a CB by a factor \( \delta^2 \), making the observations of GRBs increasingly improbable to observe GRBs at angles \( \theta > 1/\gamma \). The angular phase space being \( d\Omega \propto \theta d\theta \), the most probable angle of observation is \( \approx 1/\gamma \).

3. THE PROMPT EMISSION

3.1. The Spectrum of ICS Pulses

During the short phase of γ-ray emission in a SHB, the Lorentz factor \( \gamma \) of a CB stays put at its initial value \( \gamma_0 \), for the deceleration induced by the collisions with the ISM has not yet had a significant effect. The electrons comoving with the CB scatter the photons of the glory around the progenitor, which have a thin thermal-bremsstrahlung spectrum,

\[
\frac{d\nu}{d\epsilon} \sim \left( \frac{\epsilon}{\epsilon_g} \right)^{-\beta_g} e^{-\epsilon/\epsilon_g},
\]

with a temperature that decreases with distance beyond \( r_g \) like, \( T_g(r) \sim T(0)(r_g^2/(r_g^2 + r^2)) \), with, \( T(0) \sim 1 \text{ eV} \), for a glory produced by stellar light, and \( \beta_g \sim 0 \) ( photon spectral index \( \Gamma = \beta_g + 1 \sim 1 \)). The observed energy of a glory photon, which suffered an ICS by an electron comoving with a CB at redshift \( z \), is then given by

\[
E = \frac{\gamma_0 \delta_0 \epsilon}{(1 + z)} (1 + \cos \theta_{\text{in}}),
\]

where \( \theta_{\text{in}} \) is the angle of incidence of the initial photon onto the CB in the SN rest system. For a quasi-spherical distribution of scattered light, \( \cos \theta_{\text{in}} \) in Equation (3) roughly averages to

---

5. The CB “catches” the wind’s scattered/re-emitted CB light long before it could have left the beaming cone (\( r/2c \gamma^2 \ll r/\gamma c \)).
zero. The predicted time-dependent spectrum of the GRB pulse produced by ICS of the glory photons is given by (DD2004):

$$\frac{d N_{\gamma}}{d E} \sim \left( \frac{E}{E_p(t)} \right)^{-\beta_g} e^{-E/E_{p}(t)} + b \left( 1 - e^{-E/E_{p}(t)} \right)$$

$$\times \left( \frac{E}{E_p(t)} \right)^{-p/2},$$

(4)

where

$$E_p(t) \approx E_p(0) \frac{t_p^2}{(t^2 + t_p^2)^{3/2}},$$

$$E_p(0) \approx \frac{\gamma_0 \delta_0}{1 + z} T(0),$$

(5)

with $t_p \approx (1+z)r_g/c \gamma_0 \delta_0$ being the peak time of $d N_{\gamma}/dt$ discussed in the following section.

The first term in Equation (4), with $\beta_g \sim 0$, is the result of Compton scattering by the bulk of the CB’s electrons, which are comoving with it. The second term in Equation (4) is induced by a very small fraction of “knocked-on” and Fermi-accelerated electrons, whose initial spectrum (before Compton and synchrotron cooling) is $d N_{\gamma}/d E \propto E^{-p}$, with $p \approx 2.2$. For $b = O(1)$, the energy spectrum predicted by the CB model, Equation (4), bears a striking resemblance to the Band function (Band et al. 1993) traditionally used to model the energy spectra of GRBs, but GRBs where the spectral measurements extend over a much wider energy range than those of BATSE and Swift/BAT are better fitted by Equation (4) (e.g., Wigger et al. 2008). For many Swift GRBs, the spectral observations do not extend to energies bigger than $E_p(0)$, or the value of $b$ in Equation (4) is relatively small, so that the first term of the equation provides a very good approximation. This term coincides with the “cutoff power-law” spectrum, which has also been recently used to model many GRB/SHB spectra. For $b \sim 0$ and $\beta_g \sim 0$, it yields a peak value of $E^2 d N/d E$ at $E_p(t)$ whose pulse-averaged value is

$$E_p \approx E_p(t_p) \approx 0.5 E_p(0) \approx 330 \frac{\gamma_0 \delta_0}{10^6} \frac{T(0)}{1 \text{ eV}} 1.5 \text{ keV}. \quad (6)$$

### 3.2. The Light Curve of the Prompt ICS Pulses

Let $t$ be the time after the launch of a CB in the rest frame of the progenitor. After its launch, the fast expanding CB propagates in the progenitor’s glory and wind on its way to the ISM. Its cross section increases, while both its density and opacity, as well as those of the wind, decrease. Approximating the CB geometry by a cylindrical slab of radius $R$ and neglecting the spread in arrival times of scattered glory photons in the CB that entered it simultaneously, the rate of scattered glory photons is given by

$$\frac{d N_{\gamma}}{d t} = e^{-\tau_w} n_{\gamma}(t) \sigma_T \left( 1 - e^{-\tau_w} \right).$$

(7)

where $\tau_w$ is the opacity of the wind at the CB location, $\tau_{CB}$ is the effective opacity of the expanding CB encountered by a photon with energy $E' = (1 + z) E/\delta_0$, which begins crossing it at a time $t$, $\sigma_T(t)$ is the photoabsorption cross section at energy $E'$, and $\sigma_T$ is the Thomson cross section. At an early time, $r \approx c \gamma_0 \delta_0 t/(1 + z)$. Consequently, $n_{\gamma} \propto 1/(t^2 + \Delta t^2)$, where $\Delta t = (1+z)r_g/c \gamma_0 \delta_0$. Thus, the shape of an ICS pulse produced by a CB is given approximately by

$$\frac{d^2 N_{\gamma}}{d t \ d E} \propto e^{-\tau_w} n_{\gamma}(t) \pi R^2 \left[ 1 - e^{-R^2/R_w^2} \right]$$

$$\times \frac{d N_{\gamma}}{d E},$$

(8)

where $R_w$ is the radius of the CB at $t = t_w$, when $\tau_{CB} \approx 1$, that is, when it becomes transparent to the scattered radiation, and $E d N_{\gamma}/d E$ is given by Equation (4). The preburst wind from the progenitor system produces a density distribution,

$$n(r) = n_0 r_{0}^2 r^2/(1 + z)/c \gamma_0 \delta_0.$$ 

At sufficiently high energies, the opacity of the wind and the CBs are mainly due to Compton scattering and then, $\tau_{CB} \sim \sqrt{\sigma_T n_{\gamma}/\pi}$, where $\sigma_T$ is the Thomson cross section and $n_{\gamma}$ is the baryon number of the expanding CB. At low energies, their opacity is dominated by free–free (ff) absorption because the CBs and the wind along their trajectory are completely ionized. In the CB’s rest frame, the glory photons have typical energies, $E' \ll keV$. At such low energies, the opacity of CBs with a uniform density behaves like $\tau_{CB} \sim E'^{-3/2} \left( 1 - e^{-E'/(T)} \right) G(E') R^3$, where $G(E')$ is the quantum mechanical Gaunt factor that logarithmically depends on $E'$ (e.g., Lang 1999 and references therein). Thus, when the optical thickness of a CB is dominated by ff photoabsorption, its transparency radius increases with decreasing energy like

$$R_w \propto E^{-3/5} \left( E' \ll T' \right) \text{ and } \tau_{CB} \propto E^{-3/5} \left( E' \ll T' \right).$$

(9)

The initial rapid expansion of a CB slows down as it propagates through the wind and scatters its particles (DD2002; DD2004). If this expansion is roughly described by $R^2 \approx R_{CB}^2 (t^2 + t_{exp}^2)$, where $R_{CB}$ is the asymptotic radius of the CB and $t_{exp} \gg t_w$, then, Equation (8) can be approximated by

$$\frac{d^2 N_{\gamma}}{d t \ d E} \propto e^{-\Delta t^2/\sigma_T} \left( t^2 + \Delta t^2 \right) \frac{d N_{\gamma}}{d E},$$

(10)

For nearly transparent winds ($a \rightarrow 0$) and for $t_w \sim \Delta t$, Equation (9) has an approximate shape:

$$\frac{d^2 N_{\gamma}}{d t \ d E} \propto \Delta t^2 \frac{d N_{\gamma}}{d E},$$

(11)

which peaks around $t \sim \Delta t$. Except for very early times, this shape is almost undistinguishable from that of the “Master” formula of the CB model (DD2004):

$$\frac{d^2 N_{\gamma}}{d t \ d E} \propto e^{-\Delta t^2/\sigma_T} \left[ 1 - e^{-\Delta t^2/\sigma_T} \right] \frac{d N_{\gamma}}{d E},$$

(12)

which also took into account arrival time effects that depend on the geometry of the CB and the observer’s viewing angle, and was shown to well describe the prompt emission pulses of LGRBs (DD2004) and the rapid decay with a fast spectral softening of their prompt emission (DD2008a).

At the relatively low X-ray energies covered by Swift and, more so, at smaller ones, the first term on the rhs of Equation (4) usually dominates $E d N_{\gamma}/d E$. Consequently, the light curve generated by a sum of ICS pulses at a luminosity distance $D_L$ is generally well approximated by

$$\frac{d^2 N_{\gamma}}{d t \ d E} \approx \sum_i A_i \Theta(t_i - t_w) \left( t^2 - t_w^2 \right) \frac{d N_{\gamma}}{d E}.$$  

(12)
where the index “$i$” denotes the $i$th pulse produced by a CB launched at an observer time $t = t_i$, or, alternatively,

$$E \frac{d^2N}{dt \, dE} \approx \sum_i A_i \Theta[t - t_i] e^{-\Delta t^2/(t - t_i)^2} \left[1 - e^{-\Delta t^2/(t - t_i)^2}\right] \times e^{-E/E_{p,i}[t - t_i]},$$

(13)

where $E_{p,i}[t - t_i]$ is given by Equation (5) with $t$ being replaced by $t - t_i$ and

$$A_i \approx \frac{c \, n_o(\pi) \, \pi R^2_{CB} \, \gamma_0^3 (1 + z)}{4 \pi D_L^2}.$$  

(14)

Thus, in the CB model, each ICS pulse in the SHB light curve is effectively described by four parameters, $t_i$, $A_i$, $\Delta t_i$, and $E_{p,i}(0)$, which are best fitted to reproduce its observed light curve.

Setting $t_i = 0$, $E_{p}(t)$ has the approximate form $E_{p}(t) \approx E_p t^2_{\text{r}} / t^2$. Such an evolution has been observed in the time-resolved spectrum of well-isolated pulses (see, for instance, the insert in Figure 8 of Mangano et al. 2007), until the ICS emission is overtaken by the broadband synchrotron emission from the swept-in ISM electrons. Hence, the temporal behavior of the separate ICS peaks is given by

$$E \frac{d^2N}{dt \, dE} (E, t) \propto \frac{t^2 / \Delta t^2}{(1 + t^2 / \Delta t^2)^2} e^{-E t^2 / E_p t^2_{\text{r}}} \approx F\left(E t^2\right),$$

(15)

to which we shall refer as the “$E^2$ law.” A simple consequence of this law is that unabsorbed ICS peaks have approximately identical shapes at different energies when plotted as a function of $E t^2$.

A few other trivial but important consequences of Equation (15) for unabsorbed GRB peaks at $E \lesssim E_p$ are the following.

1. The peak time of a pulse is at

$$t_p = t_i + \Delta t_i.$$  

(16)

2. The FWHM of a pulse is

FWHM $\approx 2 \Delta t_i,$

(17)

and it extends from $t \approx t_i + 0.41 \Delta t_i$ to $t \approx t_i + 2.41 \Delta t_i$.

3. The rise time (RT) from the half peak value to the peak value satisfies

RT $\approx 0.30$ FWHM,

(18)

independent of energy. It agrees with the empirical relation that was inferred by Kocevski et al. (2003) from BATSE bright LGRBs, RT $\approx 0.32 \pm 0.06$ FWHM.

4. The FWHM increases with decreasing energy approximately like a power law:

FWHM($E$) $\sim E^{-0.5}$.

(19)

This relation is consistent with the empirical relation, FWHM($E$) $\propto E^{-0.42 \pm 0.08}$, satisfied by BATSE GRBs (Fenimore et al. 1995).

5. The onset time, $t_i$, of a pulse is simultaneous at all energies. But the peak times $t_p$ at different energies differ and the lower-energy ones “lag” behind the higher-energy ones:

$$t_p - t_i \propto E^{-0.5}.$$  

(20)

6. The time-averaged value of $E_p(t)$ for GRB peaks, which follows from Equation (5), satisfies

$$E_p = E_p(0)/2 = E_p(t_p).$$  

(21)

### 3.3. Effective Spectral Index and Hardness Ratio

The effective spectral index of unabsorbed ICS pulses in Equation (4) is given by (DDD2008a)

$$\Gamma_x[E, t - t_i] = -\frac{E}{d \log F_E \, dE} = 1 + \beta_x + \frac{E}{E_{p,i}[t - t_i]}.$$  

(22)

The hardness, defined as the ratio between the number of events in two energy bands, is generally reported, uncorrected for absorption, for the Swift 25–150 keV and 15–25 keV bands, respectively. It can be approximated by (DDD2008a)

$$HR_i(t) = B_i e^{-\Delta E / E_{p,i}[t - t_i]},$$  

(23)

where $\Delta E$ is an effective interval between the bands.

### 3.4. The Peak Energy of an SHB Pulse

For $b \sim 0$ and $\beta_x \sim 0$, Equation (4) yields a peak value of $E^2 \, dN / dE$ at $E = E_p(t)$.

1. Observers usually report $E_p(t)$ at the peak’s maximum or its averaged value in a chosen time interval. For the approximate pulse shape given by Equation (10), $E_p \approx 0.5 \, E_p(0)$ over the FWHM of a pulse.

For LGRBs, Equations (5) give a good description of the observations, for $\epsilon_g \approx 1$ eV, $\gamma_0 \sim 10^3$, and $\delta_0 \sim 10^3$, corresponding to the expected $\theta \sim 1 / \gamma_0$. As their name reflects, SHBs typically have a larger $E_p$ than LGRBs. One reason is model independent: SHBs are observed at smaller typical redshifts. In the CB model, according to Equations (5), larger values of $(1 + z) E_p$ may be due to a larger value of the typical $\epsilon_g$ and/or $\gamma_0$. The glory of LGRBs being the very early light of a core-collapse SN, there are observational reasons to adopt $\epsilon_g \approx 1$ eV. For SHBs, the ambient light may be the light of a companion star or of an accretion disk. In the first case, there is also a reason to adopt $\epsilon_g \approx 1$ eV, which we will use for the sake of definiteness. The typical Lorentz and Doppler factors leading to the average value of $(1 + z) E_p \sim 1000$ keV for the well-measured cases in the table of SHB properties of Kann et al. (2008) are

$$\gamma_0[\text{SHB}] \sim \delta_0[\text{SHB}] \sim 1400,$$

(24)

somewhat larger than the typical values, $\gamma_0 \sim \delta_0 \sim 10^3$, for LGRBs.

### 3.5. The Width and Time Lag of SHB Pulses

The peak time of $dN / dt$ for the pulse shape given by Equation (10) is around $t = \Delta t = t_{\text{r}}$, where

$$t_{\text{r}} \approx \frac{\sqrt{3} (1 + z)}{\delta_0 \beta_x} \frac{R_9}{c} \approx 23 \text{ ms} \times 10^3 \frac{1}{\beta_x \delta_0} (1 + z) \sqrt{\frac{N_9}{10^{48}}}. $$

(25)

The full width of $dN / dt$ at half-maximum is FWHM $\sim 2.38 t_{\text{r}}$, and its rise time from the half-maximum to the peak value is $t_{\text{rise}} \sim 0.59 t_{\text{r}}$ (FWHM $\sim 1.8 t_{\text{r}}$ and $t_{\text{rise}} \sim 0.7 t_{\text{r}}$ for the pulse shape used in Dado et al. 2004, hereafter DDD2004). The pulse shape is energy dependent because of the exponential factor in the pulse light curve:

$$E \frac{dN}{dE} \propto e^{-E/E_p(t)} \to e^{-2 \, E t^2 / E_p(0) \Delta t^2},$$

(26)

and the rise time, peak time, and FWHM of the ICS pulse are energy dependent and decrease with increasing energy. In the
CB model, this explains the observed time-lag effect in LGRB pulses, which decreases with increasing energy. As can be seen from Equation (26), the time lag is proportional to the width parameter, $\Delta t$, and decreases with increasing $E_p$, yielding a vanishingly small time lag in SHBs with a very small width and a large $E_p$. For $t^2 \gg \Delta t^2$, the pulse has a shape

$$E \frac{d^2N}{dt dE} \propto (E t^2)^{-\frac{1}{2}} e^{-2 E t^2/E_p(0) \Delta t^2} = F(E t^2).$$

(27)

This “$E t^2$” law is a test of ICS on a glory’s light that becomes more radially directed at increasing radii and times: $(1 + \cos \theta_{in}) \to r^2/2 \gamma^2 \sim \Delta t^2/2 t^2$ in Equation (10). For LGRBs and low energies, when the CB opacity is dominated by ff absorption, the law is also valid at early time. This law for LGRBs, in its form as a correlation between the FWHM by ff absorption, the law is also valid at early time. This law

for $L_{GRB}$, in its form as a correlation between the FWHM of collections of pulses and the energy interval at which they are measured (FWHM $\sim E^{-1/2}$) has been known for a long time (e.g., Ramirez-Ruiz & Fenimore 2000). For well-measured single-pulse XRFs, Equation (27) can be tested with precision, from X-ray to optical frequencies, both as an $(E, t)$ correlation and as a spectral form (DDD2007b). One example is XRF 060218, specifically discussed in De Rújula (2008). For SHBs, we do not have enough information to test Equation (27) and its underlying assumption that the source of the ambient light is localized close to, or around, the engine.

The measured redshifts of SHBs are relatively small, averaging $(z) \sim 0.5$ compared with those of LGRBs; $(z) \sim 2$. The widths of their pulses have been studied in more detail than their rise times, and range from 5 to 300 ms, with a broad peak at 50 ms (Nakar 2007; Kann et al. 2008). These numbers correspond to full widths at quarter maximum, FWQM $\sim 3.5 t_r$, for the pulse shapes. The typical values $\gamma_0 = \delta_0 = 1400$, $z = 0.5$, and $\Delta t = 10$ ms in the observer’s frame correspond to $r_p = c \gamma(t) \delta(t) \Delta t/(1 + z) \approx 4 \times 10^{14}$ cm in the progenitor’s rest frame. Inverting Equation (25) and using $\gamma_0 = \delta_0 = 1400$, we obtain $N_p[SHBs] \sim 10^{48}$ for FWQM = 50 ms and $\beta_s = 1/3$, respectively. This is smaller than the typical $N_p[LRGBs] \sim 10^{50}$ by two orders of magnitude, probably because core-collapse SNe have much more available mass for potential CB-generating accretion than any of the putative SHB progenitors.

### 3.6. The Peak Luminosity and Isotropic Energy of SHBs

Let $L$ be the luminosity of the source (an accretion disk or a massive companion). For a transparent or semitransparent distribution of circumburst material, it is approximately the glory’s luminosity. The peak luminosity of a CB is at $t = t_r$, the time it becomes transparent, and it is given by (DDD2004)

$$(1 + z)^2 L_p = \frac{\delta_0^4 \beta_s^2 L}{9}.$$ 

(28)

In principle, Equation (28) could be used to estimate the typical $L$ of the ambient light of SHBs. However, the results for $L_p$ are often reported for binning times much larger than the peak rise times (e.g., Gehrels et al. 2006) and cannot be used to estimate $L$. For an SHB with $N_{CB}$ prominent pulses of similar properties, the isotropic-equivalent energy, $E_{iso}$, is (DDD2004)

$$E_{iso} = \frac{\delta_0^3}{6c} L \beta_s N_{CB} \sqrt{\frac{\sigma_f N_B}{4 \pi}} = (1.2 \times 10^{50} \text{erg}) N_{CB} \beta_s \times \left(\frac{\delta_0}{10^5}\right)^3 \frac{L}{10^{40} \text{erg s}^{-1}} \sqrt{N_B/10^{48}}.$$ 

(29)

The typical $E_{iso}$ of SHBs is a few $10^{50}$ ergs, with a wide spread between $10^{48}$ and $10^{52}$ erg (see, e.g., Kann et al. 2008). The typical values $\delta_0 = 1400$, $\beta_s = 1/3$, $N_{CB} = 3$, and $N_p = 10^{48}$ yield the estimate, $L \sim 10^{50}$ erg s$^{-1}$, which is quite normal for the putative progenitors of SHBs.

### 3.7. Correlations Between Prompt Emission Observables

The pronounced dependence of LGRB observables on the Doppler factor, which ranges over a broad domain, led to simple correlations between them (Dar & De Rújula 2000, hereafter DD2000; DDD2004; DDD2007a). Similar correlations between prompt emission observables are expected in SHBs if they are dominated by a single class of progenitors. But the scarcity of data and lack of statistics on SHBs with secured redshift do not yet allow conclusive tests of such correlations.

The simplest CB model correlations for single pulses are $\Delta t \propto E_p^{-1}$ and $E_{iso} \propto (1 + z)^2 L_p^{1/3}$. They are well satisfied for LGRBs (DD2004). For other pairs of observables, the predicted correlations are slightly more elaborate (DDD2007a). For instance, given that $(1 + z) E_p \propto \delta_0 \gamma_0$ and $E_{iso}$ large $\theta$ cases at the XRF limit of the LGRB distribution. For $\theta \lesssim 1/\gamma_0$, $(1 + z) E_p \propto \gamma_0^3$ and $E_{iso}$ large $\theta_0$ implying that $(1 + z) E_p \propto E_{iso}^{2/3}$. Since the observer’s angle continuously varies, XRFs and GRBs lie, in the $[1 + z] E_p$, $E_{iso}$ log–log plane, close to a line whose slope smoothly varies from 1/3 to 2/3 (DDD2007a), as shown in Figure 5. In Figure 5, we also show the limited observational information on the $[1 + z] E_p$, $E_{iso}$ correlation for SHBs. The results, like those for LGRBs, are fitted to a power law varying from a 1/3 to a 2/3 slope (DDD2007a):

$$\left(1 + z\right) E_p \approx E_p^0 \left(\frac{E_{iso}^0/E_0}{1/3} + \left(\frac{E_{iso}}{E_0}\right)^{2/3}\right).$$

(30)

with two parameters $E_p^0$ and $E_0$, respectively. They are almost equally well fitted by just the higher power. This is not surprising, for selection effects may imply that, so far, only the most energetic SHBs have been observed. SHBs viewed far off-axis, are wider, and should look like GRBs of low luminosity without an associates SN.

The correlations between $E_p$ and other prompt observables (peak luminosity, peak rise-time, lag time, and variability), which are satisfied for LGRBs (DDD2007a), are also very straightforward tests of the hypothesis of ICS for SHB produced by a single class of progenitors, but the data on SHBs are not precise enough to reach a conclusion at the moment.

### 4. THE SR AFTERGLOW

As a CB ploughs through the ISM, its radiation ionizes the gas in front of it. In its rest frame, the ionized ISM particles impinge on the CB with a Lorentz factor $\gamma$ and generate in it a turbulent magnetic field in equipartition with their energy density, $B \approx \sqrt{4 \pi n m_p c^2 \gamma}$. The swept-in electrons are Fermi accelerated by the CB’s turbulent magnetic field and emit SR. The SR, isotropic in the CB’s rest frame, has a characteristic frequency, $v_{ub}(t)$, the typical frequency radiated by the electrons that enter a CB at time $t$ with a relative Lorentz factor $\gamma(t)$. In the observer’s frame

$$v_{ub}(t) \approx \frac{v_0}{1 + z} \frac{[\gamma(t)]^3 \delta(t)}{10^{12}} \left[\frac{n}{10^{-3} \text{cm}^{-3}}\right]^{1/2} \text{Hz},$$

(31)
where \( v_0 \approx 8.5 \times 10^{15} \, \text{Hz} \approx 35 \, \text{eV} \). The spectral energy density of the SR from a single CB at a luminosity distance \( D_L \) is given by (DDD2003a)

\[
F_v \simeq \frac{\eta \pi R^2 n_m c^3 \gamma(t)^2 \delta(t)^4 A(v, t)}{4 \pi D_L^2 v_0(t)} \frac{p-2}{p-1} \left[ \frac{v}{v_0(t)} \right]^{-1/2} \left[ 1 + \frac{v}{v_0(t)} \right]^{-(p-1)/2},
\]

(32)

where \( p \approx 2.2 \) is the typical spectral index\(^6\) of the Fermi-accelerated electrons, \( \eta \approx 1 \) is the fraction of the impinging ISM electron energy that is synchrotron radiated by the CB, and \( A(v, t) \) is the attenuation of photons of the observed frequency \( v \) along the LOS through the CB, the HG, the IGM, and the Milky Way (MW):

\[
A(v, t) = e^{-(\tau_{\text{CB}} + \tau_{\text{HG}} + \tau_{\text{IGM}} + \tau_{\text{MW}})}.
\]

(33)

The opacity \( \tau_{\text{CB}} \) at very early times, during the fast-expansion phase of the CB, may strongly depend on time and frequency. The opacity of the circumburst medium \( \tau_{\text{CB}} \) at early times is affected by the SHB and could also be \( t \)- and \( v \)-dependent. The opacities \( \tau_{\text{CB}}, \tau_{\text{HG}}, \text{and } \tau_{\text{IGM}} \) should be functions of \( r \) and \( \nu \), respectively, for the LOS to the CBs varies during the AG observations, due to the hyperluminal motion of CBs. These and the dependence of the synchrotron AG on \( v_0(t) \) may generate complex chromatic behavior in the AGs (DDD2007b).

The Swift X-ray bands are above the characteristic frequency \( v_0 \) in Equation (31) at all times. It then follows from Equation (32) that the unabsorbed X-ray spectral energy density has the form

\[
F_\nu \propto R^2 n^{(p+2)/4} \gamma^{(3p-2)/2} \delta^{(p+6)/2} \nu^{-p/2} \nu^{-\nu/2} \theta^{-1/2} \gamma^{-3\Gamma-4} \delta^{\Gamma+2} \nu^{-\Gamma+1},
\]

(34)

where we have used the customary notation \( dN_\gamma/dE \approx E^{-\Gamma} \). The ISM density in GCs and in the surrounding medium, if they are far off the galactic center, may be low enough such that the optical band is also above the bend frequency \( v_0 \), and then the optical AG is also described by Equation (34) and the AG is achromatic all the way from the optical to the X-ray band with a spectral index \( \beta_{\text{OX}} \approx 1.1 \).

4.1. The Early-Time SR Afterglow

During its early-time emission, when both \( \gamma \) and \( \delta \) stay put at their initial values \( \gamma_0 \) and \( \delta_0 \), respectively, Equation (32) yields an early-time light curve \( F_\nu \propto e^{-\omega} R^2 n^{(1+\beta)/2} \nu^{-\beta} \). If the progenitor is embedded inside a GC or an SSC, which blows a constant wind into the ISM or IGM with a density profile \( n \propto 1/r^2 \sim 1/r^2 \), the early-time SR light curve as given by Equation (32) has the form

\[
F_\nu \propto e^{-\omega/(1+\beta)} \nu^{-\beta} \left[ 1 + \frac{v}{v_0} \right]^{-1/2} \left( 1 + \frac{v}{v_0} \right)^{-(p-1)/2},
\]

(35)

until the CB reaches the constant ISM or IGM density.

\(^6\) The normalization in Equation (31) is only correct for \( p > 2 \), otherwise the norm diverges. The cutoffs for the \( v \) distribution are time dependent, dictated by the acceleration and SR times of electrons and their “Larmor” limit. The discussion of these processes being complex (DD2003a, DD2006), we shall satisfy ourselves here with the statement that for \( p \leq 2 \), the AG’s normalization is not predicted.

4.2. Jet Breaks, Missing Breaks, and Asymptotic Decay

As it ploughs through the ionized ISM, the CB gathers and scatters its constituent ions, mainly protons. These encounters are “collisionless” since, at about the time it becomes transparent to radiation, a CB also becomes “transparent” to hadronic interactions (DD2004). The scattered and re-emitted protons exert an inward pressure on the CB, countering its expansion. In the approximation of isotropic re-emission in the CB’s rest frame and a constant ISM density \( n \sim n_e \sim n_p \), one finds that within a minute or so of the observer’s time \( t \), typical SHB generating CBs of the baryon number \( N_B \sim 10^{48} \) reach an approximately constant “coasting” radius \( R \sim 10^{14} \, \text{cm} \), before they finally stop and blow up, after a journey of years of the observer’s time. During the coasting phase, and in a constant density ISM, \( \gamma(t) \) obeys (DDD2002a; DDD2006)

\[
\left( \frac{\gamma_0}{\gamma} \right)^{2} + 2 \frac{\gamma_0 \delta_0}{\gamma} \left( \frac{\gamma_0}{\gamma} \right)^{2} = 1 + 2 \frac{\gamma_0^{2}}{\gamma} \delta_0^{2} + \frac{t}{t_0},
\]

(36)

with

\[
t_0 = \frac{(1+z) \frac{N_B}{8 \pi c n \pi R^2 \gamma_0^2}}{c n}.
\]

(37)

As can be seen from Equations (36) and (37), \( \gamma(t, t_0, \theta, \nu_0) \) and, consequently also, \( \delta \) change little as long as \( t < t_b \), where

\[
t_b = (1300 \, \text{s}) \frac{[
u_0^{2}(\Gamma-2)]}{[1+z] \left[ \frac{\gamma_0}{10^3} \frac{n}{10^{-3} \, \text{cm}^{-3}} \right]^{2}} \times \left[ \frac{R}{10^{14} \, \text{cm}} \right]^{-2} \left[ \frac{N_B}{10^{48}} \right].
\]

(38)

and they approach a power-law decay, \( \delta \propto \gamma \sim t^{-1/4} \) for \( t > t_b \). The slow change in \( \gamma \) and \( \delta \) for \( t \lesssim t_b \) produces the “plateau” phase of canonical afterglows. Their asymptotic power-law decay for \( t \gg t_b \), when inserted in Equation (34), yields the asymptotic power-law decay (DDD2007b)

\[
F_\nu(t) \sim t^{\beta-1/2} \nu^{-\beta} \sim t^{-\Gamma+1/2} \nu^{-\Gamma+1},
\]

(39)

where \( \beta = \Gamma - 1 \equiv p/2 \approx 1.1 \). Equation (39) is valid as long as the ISM has an approximately constant density. The gradual transition (“break”) of the AG from the plateau phase to a power-law decay at \( t \approx t_b \) takes place when the CB has swept in a mass comparable with its initial mass. This CB model bend/gradual break is different from the achromatic break predicted by the conical Fireball model when the ejecta decelerate to a point when the observer begins to see the entire opening angle of a conical ejecta (Rhoads 1997, 1999).

Density variations complicate the simple shape of AGs and will not be discussed here, except for noting that for an ISM with an approximate \( 1/r^2 \) density profile, such as in a GC, or in a galactic halo with an isothermal sphere density profile, which CBs may reach late in their motion, or in a windy environment created around SSCs by their blowing winds, the predicted X-ray and optical AG has a simple power-law form:

\[
F_\nu(t) \sim t^{\beta-1/2} \nu^{-\beta} \sim t^{-\Gamma} \nu^{-\Gamma+1}.
\]

(40)

In ordinary LGRBs, \( t_b \) is usually larger than a few hundreds of seconds but, in intrinsically bright LGRBs, in particular in those that happen to take place in a dense ISM environment, the break in the X-ray AG may occur before the end of the prompt emission. Such breaks may be hidden under the much brighter
ICS emission and the only-power-law decaying tail of the AG is observed (DDD2008b). In SHBs, the low-density environment of GCs, in particular those with a large offset from the galactic center, yields relatively large $t_p$ values as can be seen from Table 2. For SHBs in young SSCs with a strong wind, the AG has the simple power-law decay given by Equation (40) with no jet break.

5. THE EXTENDED SOFT EMISSION COMPONENT

GCs are concentrations of $\sim 10^4–10^8$ stars in and around galaxies (e.g., the GC 037−B327 in M31 has a mass $M_{GC} = (3 \pm 0.5) \times 10^5 M_\odot$; Ma et al. 2006). They are the environment wherein a considerable fraction of low-mass X-ray binaries (compact stars accreting from a companion), millisecond pulsars (neutron stars having been spun up by accretion), and neutron star binaries are found including intermediate mass-accreting black holes at their center (e.g., Maccarone et al. 2007). Since these are some of the putative progenitors of SHBs, it is natural to test whether some features of these bursts, other than their distribution relative to the host–galaxy center (Troja et al. 2008; Kann et al. 2008), are also compatible with a GC location. GCs have typical core radii of $r_c \approx 1$ pc. Sometime, they have an intermediate mass black hole at their center. Relatively large GCs have a core-luminosity density of $O(10^5 \ L_\odot \ pc^{-3})$ and a total luminosity $L_{GC}$ of order $10^6 \ L_\odot \sim 4 \times 10^{39}$ erg s$^{-1}$.

The more recently discovered (Arp & Sandage 1985) SSCs are star concentrations similar to GCs in their sizes, but denser, more massive, and more active. A good fraction of SSCs may be gravitationally bound and constitute a proto-GC, thus the alternative denomination of young GCs. Many active hosts harbor SSCs, including interacting galaxies, starburst galaxies, and star-formation regions in normal spirals. Dust often obscures SSCs, which are not easy to see at optical frequencies, and have only recently been studied in detail with the Hubble Space Telescope (HST), mostly in the Antennae galaxies (Whitmore & Schweizer 1995), in M82 and in NGC 2533. The sizes of observed SSCs range from 1 to 6 pc, their masses from a few $10^2$ to $10^5 M_\odot$ and their luminosities from $10^{40}$ to $10^{42.5}$ erg s$^{-1}$, nearly $10^9 L_\odot$ (Melo et al. 2005 and references therein). Even at small redshifts, active SSCs are not a rare phenomenon; they must have been rather common in the past. Because of their enhanced stellar-evolution activity, SSCs are even more natural hosts than GCs for the putative progenitors of SHBs.

We shall argue that the extended soft component observed in a good fraction of SHBs is due to either ICS of the light of a SSC by the CBs crossing it, after they have left the close-by luminous environment generating the SHBs’ prompt peaks, or SR in young clusters with a very large ($n \sim 10^{-3}–10^2 \ cm^{-3}$) ISM density. This is supported by the typical duration and isotropic energy of ESECs, which are compatible with the said hypothesis. Concerning the ESEC spectrum, only spectral measurements can pin down the dominant mechanism: SR yields a typical time-independent spectral index $\Gamma \approx 2.2$, identical to that of the afterglow (except during early flares where there is a temporary hardening due to encounters with density bumps) as observed for most of the detected ESECs (see Table 1). However, a few ESECs exhibit a fast spectral softening from an initial $\Gamma \sim 1$ to $\Gamma > 2.2$ during the fast decline phase at the end of the ESEC, similar to that of the prompt emission in LGRBs. These are well explained by a dominant ICS component (see Figures 1(c), 2(f), and 4(c) and (d)). As we shall see, except for a few cases, the data are only sufficient to conclude that both ICS of cluster light and SR from the ISM electrons swept into the CBs while they pierce through the cluster ISM may have produced the ESEC in SHBs.

5.1. The Duration of an ESEC

For the measured average SHB redshift, $z \sim 0.5$, and with the typical values, $\delta_0 \gamma_0 \sim 1400$, the distance traveled by a CB in the typical $t_{ESEC} \sim 100$ s duration of an ESEC is $x \sim \gamma_0 \delta_0 \ c \ t_{ESEC}/(1 + z) \approx 1.2$ pc, coincident with the typical core radius of a GC or SSC. This straightforward understanding
of ESEC durations is independent of whether the mechanism generating the radiation is ICS or SR, provided the sources are CBs, moving relativistically, and not significantly decelerating in this short interval of the observer’s time.

5.2. The ICS Contribution to the ESEC

All the SHBs with ESECs (except perhaps 051210 with an unknown redshift) appear to reside in host galaxies. GCs and SSCs inside galaxies, probably when they are young, contain a considerable amount of gas and dust. Some may still be embedded in a molecular cloud. The light from the stars in such clusters is absorbed and re-emitted in the very far infrared. In a steady case, when the light of the stars is absorbed and re-emitted as a thermal radiation from the surface of the cluster core, $L \approx 4\pi \sigma R^2 T^4$. For $R \sim 1$ pc, and $L \sim 10^{40}$ erg s$^{-1}$, the temperature of the diffuse radiation in the cluster is typically $T_c \sim 0.003$ eV.

Figure 1. Comparisons between SHB observations and CB model predictions for (a) the 5 keV Swift XRT/Chandra light curve (Fox et al. 2005) and the R-band light curve (Watson et al. 2006) of SHB 050709. (b) The XRT/Chandra light curve of SHB 050724. (c) The evolution of the photon spectral index of GRB 050724 (data from Zhang et al. 2007). (d) The XRT light curve of SHB 051210. (e) The XRT light curve of SHB 051221A. (f) The XRT light curve of SHB 051227. (A color version of this figure is available in the online journal.)
As a CB moves through this microwave radiation of the host star cluster, its ICS produces a light curve, which traces the density of the radiation along the CB trajectory. This radiation is a sum of a smooth background radiation plus much harder light peaks from the passage near very luminous stars. For simplicity, consider the contribution to the ESEC light curve from ICS of background microwave radiation by a CB ejected near the center of an SSC. It is simply obtained by replacing the typical temperature $T_g$ and density $n_g(t)$ of the glory photons in the expression describing the prompt SHB with, respectively, the

![Graphs showing energy flux over time for different events.](image)
typical energy $\epsilon_c \sim T_c$ and the density $n_c(t)$ of the intracluster photons, where $n_c(0) = 3 L_\text{esc}/4\pi c \epsilon_c r_c^2$ and $L_\text{esc}$ is the SCC luminosity. The resulting spectrum is an exponentially cutoff power law with a typical cutoff energy $\approx$ peak energy, $E_p \sim 2$ keV (see Equations (4) and (5)).

The resulting ESEC light curve is given by Equations (10) and (4) with $\Delta t$ replaced by $\Delta t = r_c(1 + z)/c \gamma_0 \delta_0$. The isotropic-equivalent energy of the ESEC is then given by

$$E_{\text{iso}[ESEC]} \approx \sigma_t N_b N_{CB} \gamma_0 \delta_0^3 \frac{3 L_\text{esc}}{4 r_c} \sim \left(10^{59}\right)\text{erg}$$

$$\times \frac{N_b N_{CB} \rho c \gamma_0 \delta_0^3 L_\text{esc}}{10^{48}} \left(\frac{r_c}{1400}\right)^2 10^5 L_\odot.$$ 

(41)

The result of Equation (41) is of the observed order of magnitude, but has more sources of accumulated uncertainty and variability than other CB-model results.

The ESEC after transparency time, for a spherical SSC, is a decreasing function of time from the beginning, if the progenitor is in the front hemisphere, and the CBs’ distance from the cluster’s center increases. Otherwise, the ESEC light curve first increases and then decreases with time. The data are consistent with these expectations, but so far insufficient to test them in detail.

5.3. The SR Contribution to the ESEC

Some young SSCs have a very large ISM density, $10^3 \lesssim n \lesssim 10^6\text{cm}^{-3}$. Consequently, the emission rate of SR radiation from CBs moving inside such SSCs, which is proportional to the ISM density (see Equation (32)), is very intense and relatively hard with a spectral index $\beta \approx 1/2$, because $\nu_0 \propto n^{1/2}$ (see Equation (31)) is well above the X-ray band. At early time, it is given by Equation (35) with $\beta \approx 1/2$. As soon as the CB escapes out of a dense core of an SSC, the density decreases fast like $1/r^2$, and the light curve decreases rapidly and becomes softer with its spectral index increasing to $\beta \approx 1.1$.

$$F_\nu \propto \frac{e^{-t/\tau} t^{1/2} \nu^{-1/2}}{t^2 + t_{\exp}^2} \rightarrow t^{-2.1} \nu^{-1.1}.$$  

(42)

Equation (42) is valid when the CBs encounter a very large density inside the SSC that the CBs reach their coasting radius, $R_{CB} \propto \frac{N_b^{1/3}}{n^{-1/3}} \gamma_0^{-2/3}$, well inside the SSC and $t_{\exp} \ll \Delta t_{\text{esc}}$.

6. COMPARISON BETWEEN SHB AFTERGLOWS AND THEIR CB MODEL DESCRIPTION

To date, Swift has detected over 30 SHBs, localized them through their $\gamma$, X-ray, and UVO emissions and followed them until they faded into the background, usually within less than a day or two. A few deep observations of the X-ray emission of several SHBs at later times were made with Chandra. Several additional SHBs were localized by the Inter-Planetary Network (IPN) to much larger error boxes and a couple more by High Energy Transient Explorer (HETE). Beside the Swift UVO observations, there have been many optical follow-up measurements of SHBs by ground-based optical telescopes including some of the largest ones. In order to demonstrate the success of the CB model to explain SHBs, we have limited the detailed comparison between theory and observations to all SHBs (15) whose X-ray and/or optical AG were well sampled. The a priori unknown parameters are the number of CBs, their ejection time, baryon number, Lorentz factor and viewing angle, and the distributions of the glory’s light and the ISM density along the CBs’ trajectory.

In more than 2/3 of the SHBs detected by Swift, no ESEC was detected and only in few SHBs, its light curve and spectrum were measured. Several SHBs have no measured redshift. So far, no absorption or emission lines were detected in the afterglow of SHBs due to their faintness (Stratta et al. 2007). Their redshifts listed in Table 1 were determined from their host galaxies or from the nearest bright galaxy or galaxy cluster if no galaxy or only extremely faint galaxies were found in their XRT error circles. But the lack of secured redshifts and well-measured ESECs does not prevent other critical tests of the CB model predictions, which are insensitive to the unknown redshift and the detailed behavior of the ESEC.

We have quite generally assumed an isothermal sphere density profile, $n \propto 1/(r^2 + r_c^2)$, for both the star clusters and galactic halos, with $r_c \sim O(1 \text{pc})$ for GCs and SCSs, and $r_c \sim O(10 \text{kpc})$ for galactic halos, until being taken over by a constant-density ISM or IGM, respectively. This density profile also describes the wind density profile outside young SSCs or SN remnants, created by the strong winds from SSCs or the progenitor star of core-collapse SNe, respectively.

Because of the short duration of SHBs and the fast initial expansion of the CBs, we have assumed that by the time they have escaped from the globular SSC, they have merged into a single CB. This dramatically reduces the number of fitted parameters without affecting the quality of the fits. Flares during the fast decay phase of the ESEC or the afterglow phase due to late CB ejections are superimposed on the smooth light curve. To demonstrate that the CB model correctly describes all of the observed features of the Swift X-ray observations, it suffices to include in the fits only the latest observed pulses or flares during the ESEC. This is because the last exponential factor in Equation (26) very fast suppresses the relative contribution of earlier pulses by the time the data sample the later pulses or flares.

The X-ray light curves reported in the Swift/XRT GRB light-curve repository (Evans et al. 2007) were fitted with use of Equation (10) for ICS pulses and Equation (32) for their synchrotron contribution, with an early-time behavior as given by Equation (35).

Below, we summarize the observations and CB model description of all the SHBs with a well-sampled X-ray light curve, reported in the Swift/XRT GRB light-curve repository (Evans et al. 2007) and/or the optical light curve. The CB model predictions are based on Equation (10) for the prompt emission and the fast decay phase, on Equation (22) for the evolution of the spectral index during the decay of the prompt emission or Equation (23) for the hardness ratio, and on Equation (32) for the SR afterglow. The hardness ratio during the SR-dominated phase was fitted by a constant. The best-fit parameters used in their CB model description are reported in Table 2. The CB model fit parameters of the flares (subscript f) superimposed on the smooth XRT and/or optical light curves are also reported in the table. Due to their faintness, in most cases, the AGs of SHBs are not well measured beyond the plateau phase. This does not allow a reliable estimate of $p$ or the density profile from the late temporal decay of the AG. In such cases, we have fixed $p$ to have its canonical theoretical value, $p = 2.2$, and indicated that by (2.2) in Table 2.
7. CASE STUDIES

7.1. SHB 050709

Observations. This SHB, which was localized by HETE (Villasenor et al. 2005), was relatively very faint ($E_{iso} \sim 2.4 \times 10^{48}$ erg). It had a multispiked peak with $T_90 = 70 \pm 10$ ms in the 30–400 keV band, $T_90 = 220 \pm 50$ ms in the 2–25 keV band, and showed a fast hard to soft spectral evolution with $E_p \sim 86 \pm 16$ keV and a photon spectral index $\Gamma = 0.82 \pm 0.13$. A soft extended emission component was detected 24 s after the burst with $T_90 = 130 \pm 7$ s, $\Gamma = 1.98 \pm 0.18$, and a fluence much larger than that of the short burst, unlike what is seen in the giant flares of SGRs. It was the first SHB for which an optical AG was discovered and was used to localize it in a star-forming dwarf galaxy at redshift $z = 0.16$ (Hjorth et al. 2005a; Fox et al. 2005; Covino et al. 2006) at a projected distance of $\sim 3.8$ kpc from its center. Its X-ray AG that was detected by Swift and Chandra (Fox et al. 2005) and its optical light curve as measured by Watson et al. (2006) are shown in Figure 1(a). The optical data do not shed light on a possible late-time flare suggested by the last two data points of Chandra (Fox et al. 2005).

Interpretation. The short burst shows all the properties expected from ICS of glory light by a jet of CBs with a relatively small baryon number emitted by the source. The spectral index of the ESEC, $\gamma = 1.98 \pm 0.18$, the lack of spectral evolution during the ESEC, and the duration of the ESEC are consistent with those expected from SR ($\Gamma \sim 2.1$) of CB propagating in a $r_c \sim 1$ pc core of a GC and $t \sim (1+z)r_c/c \gamma_0, \delta_0 \sim 120$ s. The optical afterglow is well explained by a CB propagating out of the dwarf galaxy with an isothermal sphere density distribution $n \propto 1/(r^2 + r_c^2)^{3/2}$, as demonstrated in Figure 1(a). The 5 keV SR afterglow was calculated using the parameters of the optical light curve, assuming the theoretically expected spectral index, $\beta = 1.1$. No attempt was made to fit the the last two data points with a SR flare whose light curve, in the CB model, depends on four adjustable parameters.

7.2. SHB 050724

Observations. This burst at redshift $z = 0.257$ was studied in detail in Campana et al. (2006b), Grupe et al. (2006), and Malesani et al. (2007). The BAT on board Swift triggered on the burst at 12:34:09 UT on 2005 July 24. The burst had $T_90 = 3.0 \pm 1.0$ 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 ESEC with $\Gamma = 2.5 \pm 0.2$, which lasted $\sim 150$ s. Swift’s XRT began observing the afterglow 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 1(b). It has the canonical shape observed in long GRBs, namely a rapid decay with a fast spectral softening ending with a sharp transition to a plateau phase with a much harder power-law spectrum, $\Gamma = 1.79 \pm 0.12$, as shown in Figure 1(c). The AG gradually steepens 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 also been detected in the optical and NIR bands (e.g., Malesani et al. 2007). Spectral analysis of the XRT data (Campana et al. 2006b) showed no evolution during the afterglow 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 HG (Malesani et al. 2007).

Interpretation. The CB model X-ray light curve of SHB 050724 and its spectral index “light curve” are shown in Figures 1(b) and (c), respectively. The early-time emission is described by ICS of the progenitor’s glory light and the ESEC by ICS of the light of the core of the assumed SSC or a GC environment. The fast decay of the X-ray light curve and the rapid spectral softening took place when the CB moved away from the quasi-isotropic light distribution in the dense stellar environment of the progenitor into the ISM of its elliptical HG. As can be seen in Figures 1(b) and (c), this 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. As expected, apart from normalization, the late-time SR afterglow is similar in shape to the SR afterglow of LGRBs. Also, the late flare superimposed on the canonical light curve is similar to those observed in many LGRBs. 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 shown in Figure 1(b), the complete XRT light curve is well fitted by the CB model. Moreover, the CB model relation $\alpha = \beta_X + 1/2 = p/2$ is well satisfied. The temporal behavior of the canonical AG was best fitted with $p = 1.56$, implying an unabsorbed spectral index, $\beta_X = p/2 = 0.78$, and an asymptotic power-law decay with a power-law index, $\alpha = \beta_X + 1/2 = 1.28$, in agreement with those observed.

The elliptical HG 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 in the standard folklore to power a late central activity, which 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.

7.3. SHB 051210

Observations. This was a faint two-spiked SHB localized by Swift. It had $T_90 = 1.27 \pm 0.05$ s and no soft extended emission was detected (La Parola et al. 2006). The BAT spectrum was fitted with a power law with a photon spectral index $\Gamma = 1.1 \pm 0.3$. The XRT started observation 79 s after the BAT trigger. It detected a rapidly decreasing light curve, shown in Figure 1(d), with a small flare superimposed around 134 s. A possible HG was discovered within the XRT error circle (Bloom et al. 2008), but no emission or absorption lines were detected. No optical afterglow was detected.

Interpretation. The spectrum of the burst is consistent with ICS of glory light ($\Gamma \sim 1$ for $E \ll E_p$). The fast declining XRT light curve was fitted as the tail of an ICS flare. The data are insufficient for a critical test of the CB model interpretation.

7.4. SHB 051221A

Observations. This burst was discussed in detail in Soderberg et al. (2006a) and Burrows et al. (2006). It was an intense, multispike burst localized by Swift. The burst was also detected
by Konus-Wind, Suzaku, INTEGRAL, and RHESSI and its late afterglow by Chandra. The burst had $T_90 = 1.4 \pm 0.2$ s, $\Gamma = 0.92 \pm 0.13$, and showed no signs of extended emission. The Swift/XRT observations of its X-ray light curve began 88 s after the Swift/BAT trigger. Its late-time X-ray emission was also detected by Chandra. The measured X-ray light curve (Figure 1(e)) of SHB 051221A shows the canonical behavior of X-ray light curves of LGRBs (Nousek et al. 2006) with an asymptotic decay index $\Gamma \approx 2$. Its afterglow was also detected in the NIR and optical bands, and was localized near the center ($\sim 1$ kpc in projection) in a star-forming galaxy with $z = 0.546$.

**Interpretation.** The prompt SHB was produced by ICS of glory light as evident from its spectral index $\Gamma \sim 1$. The XRT light curve is well fitted by the SR tail of prompt flares taken over by the canonical SR afterglow emitted by a CB moving in a constant density ISM of the HG, as shown in Figure 1(e). Its late afterglow with $\alpha = 1.6 \pm 0.05$ and that with $\Gamma = 1.97 \pm 0.13$ are consistent within errors with the CB model prediction, $\alpha = \Gamma - 1/2$. The wiggling of the light curve around the smooth theoretical line can be due to density variations along its trajectory, as was observed in afterglows of many LGRBs.

**7.5. SHB 051227.**

**Observations.** This was a multi-peaked burst with a bright X-ray afterglow localized by Swift (Barbier et al. 2005). It was initially thought to be LGRB, since it has $T_{90} = 8.0 \pm 0.2$ s (Hullinger et al. 2005), but a spectral analysis that showed a negligible spectral lag and a broad softer bump between 30 and 50 s was claimed to indicate an SHB (e.g., Kann et al. 2008). An exceedingly faint optical afterglow was discovered within the XRT error circle (Malesani et al. 2005a, 2005b) with the Very Large Telescope (VLT) and also detected by Gemini.

**Interpretation.** The prompt burst is consistent with ICS of glory light ($\Gamma \sim 0.91 \pm 0.28$). The XRT light curve is consistent with an SR tail of a prompt emission taken over by a canonical SR afterglow, as shown in Figure 1(f). The XRT does not shed light on whether this GRB was or was not an SHB. Due to a gap in the data between 400 s and 4000 s, the theoretical shape and the values of the SR afterglow parameters are uncertain.

**7.6. SHB(?) 060121**

**Observations:** This intermediate-duration GRB was discussed in detail in Donaghy et al. (2006), de Ugarte Postigo et al. (2006), and Levan et al. (2006). It was localized by HETE-2. It consisted of two peaks with $T_{90} = 1.60 \pm 0.07$ s at high energies, which were followed by a faint soft emission for several hundreds of seconds. It was also detected by Konus-Wind, Suzaku, and RHESSI. Follow-up observations by Swift began 3 hr after the burst. Its XRT light curve is shown in Figure 1(f). Its faint optical afterglow was discovered by Malesani et al. (2006a), which led to the discovery of its extremely faint HG (Levan et al. 2006). The burst outshined its HG (by a factor of greater than 100). A photometric redshift for this event placed it at a most probable redshift of $z = 4.6$, with a less probable $z = 1.7$. In either case, GRB 060121 could be the farthestmost short GRB detected to date with an isotropic-equivalent energy release in gamma rays comparable with that of LGRBs.

**Interpretation.** Its intermediate duration and its unusual large redshift $Z = 4.7$, relatively small $E_p \approx 120$ keV, large equivalent isotropic gamma-ray energy, $E_{iso} \approx 2.2 \times 10^{53}$ erg (or $E_{iso} \approx 4.3 \times 10^{53}$ erg for $z = 1.7$), vicinity ($\sim 2$ kpc) to the center of the HG, and its bright optical afterglow suggest that GRB 060121 may have been an ordinary LGRB, and was wrongly classified as SHB. In Figure 2(a), we show that the CB model fit to its late AG, which, although satisfactory, does not shed light on its true identity.

**7.7. SHB 060313**

**Observations:** This unusual burst was reported and discussed in detail in Roming et al. (2006). It was detected by Swift, Konus-Wind, and INTEGRAL. It was a very intense burst, with many short spikes, each with FWHM smaller than 20 ms, with $T_{90} = 0.7 \pm 0.1$ s. It had a very unusual average initial photon index, $\Gamma = -0.33\pm(0.29, +0.25)$, below the spectral peak during the initial 0.192 s of the burst (Golenetskii et al. 2006). It had the highest fluence and the highest observed peak energy of all SHBs observed by Swift. No extended soft emission was detected. Swift XRT detected its X-ray afterglow 79 s after the BAT trigger and measured its light curve until 200 ks (Figure 2(b)) with a late afterglow photon index of $\Gamma = 1.96 \pm 0.09$. The XRT light curve shows flaring activity superimposed on a canonical light curve during the first 1000 s after burst. The optical afterglow of SHB 060121 was detected and followed by the Swift UVOT and by the VLT following its localization by the Swift UVOT. A very faint HG was detected at the afterglow position by Berger et al. (2006a).

**Interpretation.** The unusual early light curve and spectrum of SHB 060313 suggest an unusual progenitor and environment of this unusual SHB. In the framework of the CB model, the large number of short pulses requires a progenitor, which fires many small CBs like a shot gun (R. Plaga 2008, private communication) or a machine gun, rather than a cannon. The unusual hard spectrum could be produced by ICS of self-absorbed radiation produced inside the CBs. In contrast to the usual prompt emission, the afterglow is not unusual, and can be well explained as SR radiation from a CB propagating in a constant density ISM of the HG, as shown in Figure 2(b).

**7.8. SHB 060801**

**Observations:** This SHB was detected and localized by Swift (Racusin et al. 2006a) and was also detected by Suzaku. It had $T_{90} = 0.5 \pm 0.1$ s. It consisted of two pulses, which peaked 60 ms and $\sim 100$ ms after their beginning (Sato et al. 2006). No extended soft emission was detected. The XRT began taking data 63 s after the BAT trigger (Racusin et al. 2006b). The 0.3–10 keV X-ray light curve shows a plateau from 73 s until 115 s after the BAT trigger, which turns into an exponential decay. The X-ray emission was not detected after 1000 s. Follow-up optical observations did not detect an optical afterglow. A single galaxy lying within the XRT error box at redshift $z = 1.1304$ was suggested as its HG, making SHB 060801 the most distant SHB with a secured redshift.

**Interpretation.** The prompt emission pulses are well explained by ICS of a thin bremsstrahlung glory of two CBs. The extended soft emission at redshift 1.13 was too dim to be detected by BAT, but its ending and decay probably are the emission detected and followed with the XRT, respectively. In the CB model, it is well described by ICS of the GC’s light when the CBs leave their dense core and move into the surrounding ISM, as shown in Figure 2(c).

**7.9. SHB 061006**

**Observations.** The Swift observations of this burst are reported in Schady et al. 2006. This burst began with an intense...
double spike, which lasted 0.5 s. The SHB was also detected by RHESSI, Konus-Wind, and Suzaku (Hurley et al. 2006). It was followed by an extended soft emission with $T_{90} = 130 \pm 10$ s. The XRT began follow-up observations at 143 s after the burst. The XRT light curve (Figure 2(d)) initially decayed with a slope of $\alpha = 2.5 \pm 0.3$, followed by a shallow slope beginning at 300 s with a spectral index $\Gamma = 1.7 \pm 0.3$. VLT observations (Malesani et al. 2006a) found a faint source that was subsequently found to fade, revealing a star-forming HG (Malesani et al. 2006b; Berger et al. 2006b) at redshift $z = 0.4377$. The burst location is about 8 kpc from the galactic center.

**Interpretation.** In the CB model, the prompt pulses can be explained by ICS of glory light of the SHB progenitor. The extended soft emission could be produced by SR from the CBs while they were crossing the SSC where the SHB took place. As shown in Figure 2(d), the initial decay of the XRT light curve can be explained by SR emission from the CBs while it was crossing the SSC wind, whereas the shallow decaying AG is the afterglow emitted when the CBs propagate in the ISM surrounding the SSC.

7.10. SHB 070714B

**Observations.** The *Swift* observations of this SHB are given in detail in Racusin et al. (2007). The SHB was a very bright multispeaked event lasting about 3 s, which was followed by soft extended emission that lasted 64 ± 5 s. *Swift*/XRT began follow-up observations 61 s after trigger. A joint *Swift*/Suzaku spectral analysis yielded a hard spectrum and a high peak energy (Ohno et al. 2007). The photon spectral index integrated over the SHB was $\Gamma = 0.99 \pm 0.08$. The 0.3–10 keV light curve (Figure 2) showed the canonical behavior observed in LGRBs, namely a steep decay with superimposed flares taken over around 400 s by an afterglow that gradually bends over into an asymptotic power-law decay with $\alpha \sim 1.6$. The fast decay of the soft extended emission was accompanied by a rapid spectral softening (Figure 2(i)) until the plateau phase took over. The photon spectral index during the AG phase was $\Gamma = 1.95 \pm 0.15$ (Zhang et al. 2007). An optical afterglow was discovered 10 min after the GRB by the Liverpool Telescope (Melandri et al. 2007), which led to the discovery of an HG at a redshift $z = 0.92$ (Graham et al. 2008).

**Interpretation.** The initial fast decay and rapid spectral evolution of the early-time X-ray light curve of SHB 070714B are well reproduced by the CB model (Figures 2(e) and (f), respectively). The data beyond 400 s show a considerable flaring activity. This makes quite uncertain the CB model best-fitted parameters of the smooth SR afterglow component, reported in Table 2.

7.11. SHB 070724A

**Observations.** This short burst was a faint single-spiked GRB with $T_{90} = 0.40 \pm 0.04$ s localized by *Swift* with no detected ESEC (Ziaeepour et al. 2007). *Swift* XRT began its observations of the burst X-ray afterglow 72.1 s after trigger and followed its rapid decay and two superimposed X-ray flares peaking around 127 s and 200 s, respectively. The fast decay of the AG turned into a shallow decay around 400 s, which steepened around 40 ks. A faint source at redshift $z = 0.457$ within the XRT error circle was suggested as a possible star-forming HG. Deep imaging and image subtraction did not reveal an optical afterglow. An analysis of the BAT data yielded $E_p \sim 41$ keV and a photon index of $\Gamma = 2.2$.

**Interpretation.** The CB model fit to the XRT light curve is shown in Figure 3(a). The light curve is well fitted by two ICS pulses taken over by an SR afterglow from a CB moving in a constant low-density ISM. The relatively large value, $\gamma \theta$, indicates nearly a “far off-axis” SHB consistent with its relatively small $E_{\text{iso}}$ and $E_p$ and a large pulse width compared with those of ordinary SHBs.

7.12. SHB 071227A

**Observations.** This short burst was detected and localized by *Swift* (Sakamoto et al. 2007; Sato et al. 2006). It was also observed by Suzaku and Konus-Wind. The SHB was a multipeaked structure with a duration of about 1.5 s and a time-averaged power-law spectrum with a photon spectral index $\Gamma = 1.2 \pm 0.2$. The *Swift* XRT began observing GRB 071227 79.5 s after the BAT trigger. The XRT light curve shows the canonical behavior: soft flares superimposed on a decaying light curve that changes to a fast decay with a spectral softening, until it is taken over by a plateau/shallow decay around 1000 s.

**Interpretation.** The CB model fit to the XRT light curve is shown in Figure 3(c). The light curve and spectral evolution are well fitted by ICS of a GC light of a CB moving away from the GC into a constant low-density ISM where the AG is dominated by SR emission. However, the data after the fast decay phase are scarce and constrain only weakly the CB model parameters of the SR afterglow.

7.13. SHB 080123

**Observations.** This short burst was detected and localized by *Swift*. The *Swift* observations of this burst are reported in detail in Ukwatta et al. (2008) and Copete et al. (2008). Its light curve shows two well-separated peaks. The first started at 0.3 s and is no wider than 64 msec. The second peak started at 0.6 s with a FRED-like shape and a duration of 256 ms. Its soft extended emission lasted 120 s after the prompt hard emission of the short GRB and included soft flares (Copete et al. 2008). The XRT observations started 108 s after the BAT trigger. The XRT light curve (Figure 3(d)) shows the canonical behavior: a fast decay with a rapid spectral softening, which was taken over by a plateau/shallow decay around 500 s with a typical photon index of $\Gamma = 2.1 \pm 0.2$.

**Interpretation.** The fast decay of the XRT early-time light curve and its rapid spectral softening (not shown here) are well fitted by ICS of light from a GC/SSC. It is being taken over around 500 s by a plateau/shallow decay with a typical photon index of $\Gamma = 2.1 \pm 0.2$, which is well fitted by SR emission from a CB deceleration in a medium of low constant density (Figure 3(d)). The scarce data on the late afterglow constrain only weakly the CB model parameters of the SR afterglow.

7.14. SHB 080503

**Observations.** This short burst was detected and localized by *Swift*. The *Swift* observations of this burst are reported in detail in Mao et al. (2008). Its light curve (Figure 3(e)) shows an initial spike starting at 0.1 s after the BAT trigger with a fast rise to a peak at 0.2 s, and then a roughly exponential decay down to background at 0.7 s. It had an extended soft emission, which started at about 10 s, rose with two peaks at 26 s and 37 s, respectively, and then fell to background levels at 220 s. The *Swift* XRT began observing SHB 080503 81 s after the BAT trigger. The XRT light curve showed an exponential
decay with a gradual spectral softening from $\Gamma \sim 1$ at the beginning of the XRT observations to $\Gamma \sim 3$ around 500 s. The X-ray AG (Figure 3(e)) decreased below the Swift detection sensitivity around 1000 s after the burst, but was detected later between 4.29 and 4.66 days after the burst by Chandra (Butler et al. 2008). A rising optical afterglow was detected on the second night after trigger by Perley et al. (2008a) with Gemini-North. Continuous monitoring of this optical counterpart on consecutive nights (Bloom et al. 2008; Perley et al. 2008b) found no further rebrightening and its fading (Figure 3(f)). The OT was not detected with HST 9.2 days after the BAT trigger (Perley et al. 2008c).
Figure 4. Comparisons between observations and CB model predictions. (a) The X-ray light curve of SHB 060614 (Evans et al. 2007). (b) The R-band light curve of SHB 060614 (Della Valle et al. 2006). (c) The photon spectral index light curve of SHB 060614 (Zhang et al. 2007). (d) The peak energy evolution during the fast decay of the ESEC in SHB 060614.

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

Interpretation. The exponential decay of the XRT light curve at the end of the ESEC is well described by ICS of a CB emerging from the dense stellar core of a SSC of a typical core radius $r_c \sim 1$ pc, as shown in Figure 3(e). This is supported by the rapid spectral softening/decreasing hardness ratio during this decay. The decay is stretched over $t > 900$ s, probably because of a relatively large redshift and a very low surrounding density, which results in a very faint X-ray synchrotron afterglow and a delayed take-over time. The low extra cluster density yields a prolonged expansion time of the CB, $t_{\text{exp}} \approx 7553$, in Equation (42) and an initially rising SR afterglow (Figure 3(f)). The asymptotic decay of the optical AG is well described by $F_\nu \propto t^{-(1+\beta)}$ (Figure 3(f)) with $\beta = \beta_X \approx 1.1$, typical of a SR emitted by a CB moving in the wind of a young SSC (a proto-GC). An SSC environment of the SHB is supported by the general properties of its ESEC.

7.15. GRB 060614.

Observations. This puzzling GRB was discussed in detail in Gehrels et al. (2006); Gal-Yam et al. (2006b); Cobb et al. (2006); Mangano et al. (2007); and Della Valle et al. (2006). Swift-BAT triggered on GRB 060614 on 2006 June 14 at 12:43:48 UT. The BAT light curve showed a 5 s series of short hard peaks followed by a fainter, softer, and highly-variable extended prompt emission with $T_{90} \sim 102$ s. Konus-Wind was also triggered by GRB 060614, about 4 s after the BAT trigger. For the initial group of short hard peaks, it measured $E_p \sim 300$ keV. The XRT and UVO aboard Swift started observation 97 s after the BAT trigger, which continued up to 51 days after burst. The X-ray light curve showed the canonical behavior observed in many LGRBs and in practically all SHBs, that is, initial fast decay with a rapid spectral softening that is taken over by a plateau that later bends into an asymptotic power-law decay. The AG bend/break started around 30 ks and the asymptotic temporal decay had a power-law index $\alpha = 2.1 \pm 0.07$. The burst was located at the outskirts of a faint star-forming galaxy at redshift $z = 0.125$. Very deep searches (Gal-Yam et al. 2006a, 2006b; Mangano et al. 2008) did not discover an associated SN.

Interpretation. The initial short peaks of GRB 060614, the lack of an associate SN akin to those discovered in ordinary LGRBs, the strict limits on lag times in its early short pulses, its extended soft emission (well fitted by a power-law spectrum with a photon index $\Gamma = 2.13 \pm 0.05$), and its low isotropic energy $(2.5 \pm 0.7) \times 10^{51}$ erg; Mangano et al. 2008) are typical of SHBs. However, the long $T_{90} \sim 5$ s of its initial complex of short pulses, its $(1 + z) E_p \sim 440 (\sim 281, +923)$ keV, and its location
Figure 5. Comparison between the observed correlation \([E_p, E_{iso}]\) in LGRBs and SHBs and the CB model expectations for LGRBs (DDD2007a) and SHBs as given by Equation (30).

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

inside a star-forming galaxy are typical of LGRBs. Various solutions of these apparent contradicting pieces of evidence were suggested. Gal-Yam et al. (2006a, 2006b) and Gehrels et al. (2006) suggested that GRB 060614 (and GRB 060505) belongs to a new class of long GRBs. Dado et al. (2008c) suggested that its location in the nearby HG could be a chance coincidence. DDD2008a, and DDD2008b suggested that GRB 060614 could be produced by an extremely faint core-collapse SN or by a “failed SN”—the original collapsar model (Woosley 1993).

Our CB-model analysis indicates that GRB 060614 probably was a very hard and energetic SHB in a very bright SSC, which was viewed far off-axis (\(\gamma \theta \approx 3.08\)). Its relatively large viewing angle yielded a relatively small Doppler factor \(\delta\), which stretched the observed durations of its prompt emission pulses and its ESEC relative to those of ordinary SHBs, and decreased their peak emission energy, equivalent isotropic energy, and peak luminosity.

In Figure 4(a), we present the CB model fit to the canonical X-ray light curve of GRB 060614. The decay of the ESEC is very well described by ICS of the light of a SSC as the CB leaves the cluster and enters the ISM. In Figure 4(b), we compare the measured \(R\)-band light curve (Della Valle et al. 2006 and references therein) and its CB model prediction obtained with the parameters of the X-ray afterglow. A contribution, \(F_v = 3 \mu Jy\), from the HG was added to the SR afterglow light curve. In Figures 4(c) and (d), we compare the observed evolution of the XRT hardness ratio and of \(E_p(t)\) during the fast decay phase of the ESEC and the CB model predictions. The agreement between theory and observations is quite satisfactory.

The XRT data on the decay of the prompt ICS emission extended only up to 480 s. The CB model estimates that it was taken over by SR only around 950 s. The second orbit XRT data began only at 4.5 ks after the BAT trigger but clearly show a stretched plateau until 30 ks when it begins to bend into an asymptotic power-law temporal decay. The plateau phase and the late decay of the X-ray afterglow are those expected for an SR afterglow from CB decelerating in an isothermal sphere density profile, \(n \propto 1/(r^2 + r_s^2)^{3}\), namely \(F_v \propto r^{-(1+\beta_X)} \nu^{-\beta_X}\) with \(\beta_X \approx 1.1\). Such a density profile is encountered by CBs, which move from inside the HG into its halo. The CB model best-fit value, \(\gamma_0 \theta = 3.08\), is typical of XRFs, which, in the CB model, are interpreted as far off-axis GRBs (e.g., DD2004, DDD2004). The corresponding value, \(\delta = 2\gamma/(1 + \gamma^2 \theta^2) \approx \gamma/5\), yields \(E_{iso}\) and \(L_p\), which are, respectively, \(\sim 125\) and 625 times smaller than when they are measured at a typical viewing angle, \(\theta \approx 1/\gamma_0\).

8. SUMMARY AND MAIN CONCLUSIONS

We have demonstrated that the entire observational data on SHBs can be explained by the assumption that SHBs are produced by highly relativistic jets ejected in processes involving compact stars, such as mergers of compact stellar objects, large-mass accretion episodes onto compact stars in close binaries or onto intermediate-mass black holes in dense stellar regions, and phase transition of compact stars. Natural environments of such events are the dense cores of GCs or SSCs and young SN remnants. We have demonstrated that the CB model of GRBs can reproduce the main observed properties of their prompt emission, ESEC, and afterglows. In particular, we have used the CB model to fit the XRT light curve of all Swift SHBs with a well-sampled X-ray afterglow. We have shown that their prompt gamma-ray emission is well described by ICS of the progenitor’s glory light, their ESEC by ICS of light of the host star cluster or by SR in the high-density interstellar medium of SSC, and their afterglow by SR outside the cluster.

We have also demonstrated that nearby GRBs of low-luminosity short end of the duration distribution of LGRBs and without an associated SN, such as GRBs 060614 and 060505, may be SHBs viewed far off-axis. The BATSE observations on board CGRO indicated that nearly \(\sim 25\%\) of all GRBs are SHBs. The evidence from INTEGRAL that the rate of LGRBs is comparable with that of SNe of type Ib/c, which are a significant fraction of all core-collapse SNe, implies that the production rate of SHBs is also large and comparable with the birth rate of neutron stars. Hence, the neutron star merger, which has a rate much smaller than the birth rate of neutron stars, cannot be the main source of SHBs. A high rate of SHBs (most of which are beamed away from us), comparable with that of SNe Ib/c, suggests that phase transition in neutron stars or mass-accretion episodes onto stellar and intermediate mass black holes are more probable sources of SHBs.

A.D. would like to thank the Theory Division of CERN for its hospitality during this work. Useful comments and suggestions by an anonymous referee are gratefully acknowledged.

REFERENCES

Arp, H., & Sandage, A. 1985, AJ, 90, 1163
Atkins, R., et al. 2000, ApJ, 533, L119
Band, D., et al. 1993, ApJ, 413, 281
Barbier, R. L., et al. 2005, GCN Circ., 4397
Berger, E., et al. 2005, Nature, 438, 988
