THE ANTICIPATED SUPERNova ASSOCIATED WITH GRB 090618

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ABSTRACT

We use the cannonball model of gamma-ray bursts (GRBs) and public data from the first day of observations of GRB 090618 to predict its X-ray and optical light curves until very late times, and, in particular, the emergence of a photometric and spectroscopic signature of an SN akin to SN1998bw in its optical afterglow with an anticipated peak brightness of magnitude $\sim 23.2$ in the R band around 2009 July 10, if extinction in the host galaxy can be neglected.

Key words: gamma rays: bursts – supernovae: general

1. INTRODUCTION

The relatively nearby bright gamma-ray burst (GRB) 090618 that was discovered by the Swift Burst Alert Telescope (BAT) on 2009 June 16 at 08:28:29 UT (Schady et al. 2009a) provides another good opportunity to investigate the association of long-duration GRBs with supernova (SN) explosions and to test theoretical models of long GRBs (e.g., Malesani 2009; Dado & Dar 2009). Two such models have been used extensively to analyze GRBs and their afterglows (AGs), the fireball (FB) model (for recent reviews see, e.g., Mészáros 2006; Zhang 2007), and the cannonball (CB) model (e.g., Dado et al. 2002, hereafter DDD2002; Dar & De Rújula 2004, hereafter DD2004; Dado et al. 2009a, 2009b, hereafter DDD2009a,b, and references therein). In this Letter, we use the CB model and early observations of the recent relatively nearby long GRB 090618 to predict the entire late-time behavior of its AG and the emergence of a photometric and spectroscopic signature of an SN akin to SN1998bw in its light curve. We show that the “master formulae” of the CB model (e.g., DDD2009a and references therein), which were derived in fair approximations from its underlying assumptions, describe correctly the reported X-ray and optical light curves of GRB 090618.

2. GRB 090618

At 08:28:29 UT, the Swift BAT triggered and located the bright long-duration GRB 090618 (Schady et al. 2009a) at redshift $z = 0.54$ (Cenko et al. 2009b). About 90% of the GRB energy measured by BAT was emitted within $T_90 = 113$ s (Baumgartner et al. 2009). The Swift X-ray telescope (XRT) began follow-up observations of its X-ray light curve (see Figure 1) 124 s after the BAT trigger and its UVO telescope detected its optical AG 129 s after trigger (Schady et al. 2009b). The burst was also detected by AGILE (Longo et al. 2009), Fermi GBM (McBreen et al. 2009), Suzaku WAM (Kono et al. 2009), KONUS-WIND, and KONUS-RF (Golenetskii et al. 2009). The burst light curve showed a smooth multipeak structure with four prominent peaks (one followed by three much brighter overlapping peaks) with a total duration of 160 s. Significant spectral evolution was observed during the burst. The spectrum at the maximum count rate, measured from $T+62.7$ to $T+64.0$ s, was well fitted (Golenetskii et al. 2009) in the 20 keV–2 MeV range by the Band function (Band et al. 1993) with a low-energy photon index $-0.99$ ($-0.06, +0.07$), a high-energy photon index $-2.29$ ($-0.5, +0.23$), and peak energy $E_p = 440 \pm 70$ keV, while the time-integrated spectrum had a low-energy photon index $-1.28 \pm 0.02$, a high-energy photon index $-2.66 (-0.2, +0.14)$, and a peak energy $E_p = 186 \pm 8$ keV. The isotropic equivalent energy in the 8–1000 keV band was $E_{iso} = 2.0 \times 10^{53}$ erg (standard cosmology).

The bright optical AG of GRB 090618 was first detected by the ROTSE III robotic telescope 23.9 s after the BAT trigger (Rujopakarn et al. 2009) and by the Palomar 60 inch telescope (Cenko et al. 2009a), the Katzman Automatic Imaging Telescope (Perley et al. 2009; Li et al. 2009), and the UVO Telescope aboard Swift (Schady et al. 2009a) within 2 minutes after trigger. Absorption features which were detected in its bright optical AG with the 3 m Shajn telescope at Lick observatory yielded a redshift of $z = 0.54$. Its optical AG was followed up by many telescopes and reported shortly after in GCN circulars (see Table 1). Its R-band light curve reported in these GCN circulars before 2009 June 27 is shown in Figure 2.

3. THE CB MODEL

In the CB model (DDD2002, DD2004, DDD2009a, and references therein), long-duration GRBs and their AGs are produced by bipolar jets of highly relativistic CBs of ordinary matter which are ejected (Shaviv & Dar 1995; Dar & Plaga 1999) in core-collapse SN explosions akin to SN 1998bw (Galama et al. 1998). Their prompt MeV gamma-rays and hard X-rays are produced by the thermal electrons in the CBs’ plasma by inverse Compton scattering (ICS) of glory photons—photons emitted scattered into a cavity created by the wind/ejecta blown from the progenitor star long before the SN explosion. Slightly later when the CBs encounter the wind/ejecta, and afterwards when the CBs coast through the interstellar medium (ISM) behind it, the electrons of the ionized gas in front of them that are swept in and Fermi accelerated by the CBs’ turbulent magnetic fields emit synchrotron radiation (SR) which dominates the “prompt” optical emission and the broadband AG emission. ICS of the SR radiation by these electrons and the decay of $\pi^0$’s produced in collision between the swept-in wind and ISM protons and the ambient CB protons produces the “prompt” high-energy emission simultaneously with the optical emission. Within the CB model, the above radiation mechanisms with the burst environment suffice to provide a sufficiently accurate description of the observed emissions from GRBs at all times and all detected wavelengths.

3.1. The Optical Light Curve

In the CB model, the observed optical light has three origins: the ejected CBs, the SN explosion, and the host galaxy. The
optical light curve is the sum of their energy flux density:
\[
F_{\text{AG}}[\nu, t] = F_{\text{CB}}[\nu, t] + F_{\text{SN}}[\nu, t] + F_{\text{HG}}[\nu, t].
\]  
(1)

The contribution of the host galaxy, \(F_{\text{HG}}\), is usually extracted from very late time observations when the CB and SN contributions become negligible. In the case of GRB 090618, a faint object is visible in the Sloan Digital Sky Survey (SDSS) \(r\) and \(i\) frames at the position of the optical AG, likely its host galaxy. Compared to nearby SDSS stars, its \(r\) magnitude was estimated by Malesani (2009) to be \(22.7 \pm 0.3\).

The energy flux density of an SN-like SN1998bw with an energy flux density \(F_{\text{bw}}[\nu, t]\) at redshift \(z_{\text{bw}} = 0.0085\) (Galama et al. 1998) placed at a redshift \(z\) is given by (e.g., DDD2002)
\[
F_{\text{SN}}[\nu, t] = k \frac{D_L^2(z_{\text{bw}})}{D_L^2(z)} \frac{A_{\text{SN}}[\nu, z]}{A_{\text{BW}}[\nu, z_{\text{bw}}]} F_{\text{bw}}[k \nu, t/k],
\]  
(2)

where \(k = (1 + z)/(1 + z_{\text{bw}})\), \(A(\nu, z)\) is the attenuation of the observed SN light at frequency \(\nu\) arriving along the line of sight, and \(D_L(z)\) is the luminosity distance to redshift \(z\) (we use the standard cosmology with \(\Omega_M = 0.27, \Omega_\Lambda = 0.73\), and \(H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}\)).

In the CB model (DDD2009a,b and references therein), the AG emission begins when the CBs encounter the wind/ejecta of the progenitor star. It is dominated by SR from the electrons of the ionized wind and ISM in front of the CBs which are swept in and Fermi accelerated by the CBs’ turbulent magnetic fields which we assume to be in approximate energy equipartition with their energy.

The SR, isotropic in the CB’s rest frame, has a characteristic frequency, \(v_b(t)\), the typical frequency radiated by the electrons that enter a CB at time \(t\) with a relative Lorentz factor \(\gamma(t)\), and spiral around its equipartition magnetic field (with the incident protons). In the observer’s frame
\[
v_b(t) \simeq \frac{v_0}{1 + z} \left[ \frac{\gamma(t)^3 \delta(t)}{10^{12}} \right] \left[ \frac{n}{10^{-2} \text{ cm}^{-3}} \right]^{1/2} \text{Hz}, \]
(3)

where \(v_0 \simeq 3.85 \times 10^{16} \text{ Hz} \simeq 160 \text{ eV}\) and \(\delta(t)\) is the Doppler factor of the CB. The spectral energy density of the SR from a single CB at a luminosity distance \(D_L\) is given by (DDD2009a)
\[
F_{\text{CB}}[\nu, t] \simeq \frac{\pi R^2 n m_e c^3 \gamma(t)^2 \delta(t)^3 A(\nu, t)}{4 \pi D_L^2 v_b(t)} \times \frac{p - 2}{p - 1} \left[ \frac{\nu}{v_b(t)} \right]^{-1/2} \left[ 1 + \frac{\nu}{v_b(t)} \right]^{-\left(p - 1/2\right)},
\]  
(4)

where \(p \sim 2.2\) is the typical spectral index of the Fermi accelerated electrons and \(A(\nu, t)\) is the attenuation of photons of observed frequency \(\nu\) along the line of sight through the CB,
the host galaxy (HG), the intergalactic medium (IGM), and the Milky Way (MW):

\[ A(v, t) = \exp[-\tau_v(CB) - \tau_v(HG) - \tau_v(IGM) - \tau_v(MW)]. \]  

(5)

The opacity \( \tau_v(CB) \) 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 \( (\tau_v(HG) \) at early times) is affected by the GRB and could also be \( t \) and \( v \)-dependent. The opacities \( \tau_v(HG) \) and \( \tau_v(IGM) \) should be functions of \( t \) and \( v \), for the line of sight to the CBs varies during the AG observations, due to the hyperluminal motion of CBs.

3.2. The Early-time SR

At early time, before the CB has swept a mass comparable to its rest mass, both \( \gamma \) and \( \delta \) stay put at their initial values \( \gamma_0 \) and \( \delta_0 \). Then, Equation (4) yields an early-time SR light curve, \( F_{SR}(v, t) \propto e^{-\tau_v(R) R^2 n^{(1+\gamma)/2} v^{-\beta}} \). Since \( r \propto t \), a CB ejected into a windy density profile, \( n \propto 1/r^2 \), created by the mass ejection from the progenitor star prior to its SN explosion, emits SR with an early-time light curve

\[ F_{SR}(v, t) \propto e^{-\rho(t) t^{1-\beta}} \times t^{-\delta(v,t)} v^{-\gamma} \rightarrow t^{-(1+\beta)} v^{-\gamma}. \]  

(6)

For a CB ejected at time \( t_b \), the time \( t \) must be replaced by \( t - t_b \), the time after ejection. In the \( \gamma \)-ray and X-ray bands, the SR emission from a CB is usually hidden under the prompt keV–MeV ICS emission. But, in many GRBs, the asymptotic exponential decline of the energy flux density of the prompt keV–MeV ICS emission is taken over by the slower power-law decay, \( F_{SR}(v, t) \propto t^{-\Gamma_v} v^{-\epsilon} \), with \( \Gamma_v = \beta X + 1 \approx 2.1 \) of the synchrotron emission in the wind \( \sim 1/r^2 \) circumburst density before the CB reach the constant ISM density and the AG enters a plateau phase (see examples, e.g., in DDD2009a). Note that the “prompt” optical emission that is dominated by SR, decays initially like \( F_{SR}(v, t) \propto t^{-1.5} v^{-0.5} \) since the spectral index of the unabsorbed SR emission at frequencies well below the bend frequency is \( \beta_0 \approx 0.5 \). As the wind density decreases with distance, the bend frequency may cross the optical band while the CB is still in the wind, yielding a steeper decay, \( F_{SR}(v, t) \rightarrow t^{-2.1} v^{-1.1} \).

3.3. The Plateau, the Break, and the Late-time Decay

During the coasting phase of a CB in a constant-density ISM, the behavior of its SR light curve as given by Equation (4) is dominated by the time dependence of its Lorentz factor \( \gamma(t) \). From energy-momentum conservation, it follows that

\[ \gamma(t) = \frac{\gamma_0}{[\sqrt{(1 + \theta^2 \gamma_0^2)^2 + t/t_0 - \theta^2 \gamma_0^2}]^{1/2}}, \]  

with

\[ t_0 = \frac{(1 + z) N_n}{8 c n \pi R^2 \gamma_0^3}. \]  

(8)

This deceleration law is for the case in which the ISM particles re-emitted fast by the CB are a small fraction of the flux of the intercepted ones. As can be seen from Equation (7), \( \gamma \) and \( \delta \) change little as long as \( t < t_0 = [1 + \gamma_0^2 \theta^2] t_0 \) which results in the shallow decline/plateau phase of the AG. In terms of typical

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Flare & \( t_b \) (s) & \( \Delta t \) (s) & \( E_p(0) \) (keV) & \( A \) (erg cm\(^{-2}\) s\(^{-1}\)) \\
\hline
ICF & 40.3 & 65.92 & 12.90 & \( 3.2 \times 10^{-5} \) \hline
SRF (tail) & 61.44 & 118 & 0.17 \times 10^{-2} & 0.505/1.04 \hline
AG & 0.71 & 1310 & 1.04 & \hline
\end{tabular}
\caption{The Parameters of the Last Major ICF, SRF, and the AG used in the CB Model Description of X-ray and R-band Light Curves of Swift GRB 090618}
\end{table}

CB-model values of \( \gamma_0, R, N_n, \) and \( n \),

\[ t_b = (1300) \left[ 1 + \gamma_0^2 \theta^2 \right]^{1/2} (1 + z) \left[ \frac{\gamma_0}{10^3} \right]^{-3} \left[ \frac{n}{10^{-2} \text{cm}^{-3}} \right] \times \left[ \frac{R}{10^{14} \text{cm}} \right]^{-2} \left[ \frac{N_n}{10^{50}} \right] \]  

(9)

For \( t \gg t_b \), \( \gamma \) and \( \delta \) decrease like \( t^{-1/4} \). The transition \( \gamma(t) \approx \gamma_0 \rightarrow \gamma \approx \gamma_0 (t/t_0)^{-1/4} \) induces a bend (the so-called “jet break”) in the synchrotron AG from a plateau to an asymptotic power-law decay,

\[ F_{SR}(v, t) \propto t^{-p/2-1/2} v^{-\beta_0} \rightarrow t^{-\beta_0-1/2} v^{-\beta_0} \rightarrow t^{-1/2} v^{-1/4}, \]  

(10)

with a power law in time steeper by half a unit than that in frequency. This jet break is different from the break in the AG predicted by Rhoads (1997) for conical jets (for more details see DDD2008a).

4. THE X-RAY LIGHT CURVE OF THE AFTERGLOW OF GRB 090618

The X-ray light curve of GRB 090618 (Evans et al. 2009) shows the canonical behavior predicted by the CB model (e.g., DDD2002; DDD2009a) and displayed by many Swift GRBs (e.g., Nousek et al. 2006). This behavior is well reproduced \((x^2/1311 \text{ dof} = 1.08)\) by the CB model as shown in Figure 1. The fast decline phase with a rapid spectral softening is that predicted for ICS of glory light (e.g., Dado et al. 2008a, 2008b; DDD2009a): \( F_{ICS}(v, t) \propto t^{-1} v^{-\Gamma_v}, \) where \( t \) and \( t_p \) are measured relative to the beginning of the last large prompt emission episode (we used the best-fit values listed in Table 2). The sharp transition around 300 s to a shallow decline phase with a constant hardness ratio is produced when the synchrotron AG as given by Equation (4) takes over. The shape of the SR AG of GRB 090618 was reproduced with three best-fitted parameters, \( \gamma_0 \theta = 1.10 \) and \( t_0 = 312 \) s which yield \( t_p = 1540 \) s and \( p = 2.08 \). This best-fit value of \( p \) satisfies well the CB model relation, \( p = 2\Gamma_v - 2 = 2.02 \pm 0.10 \), where the photon spectral index \( \Gamma = 2.008 \pm 0.047 = 0.0464 \) is that reported in the Swift XRT light curve repository (Evans et al. 2009). The “jet break” takes place when the jet of CBs gathers a mass times gamma comparable to its rest mass (DDD2002; DDD2008b; DDD2009a) as given by Equations (8) and (9). The post-break power-law decay of the AG is well described (DDD2008b) by Equation (10).

5. THE OPTICAL AG OF GRB 090618 AND EMERGENCE OF AN UNDERLYING SN?

The late-time optical AG can be estimated by extrapolating the post-break power-law decay to the time of the anticipated
emergence of an SN signature akin to that of SN1998bw at the burst location. However, unlike the X-ray light curve which was inferred from a continuous follow-up measurements with the same telescope (Swift XRT), the optical light curve of GRB 090618 constructed from reported measurements in GCNs with different telescopes at different times, locations, atmospheric and seeing conditions, calibrations, and spatial resolutions. In particular, the detection of the SN signature depends on a precise subtraction of the host galaxy contribution to the observed light curve. In view of all that we preferred to best fit the early-time observational data on the optical AG which were reported in the GCNs listed in Table 1 and to use the CB model with the parameters determined from the X-ray AG and the early-time observational data (Table 1) on the optical AG of GRB 090618 to predict the late-time R-band light curve of the optical transient. A host galaxy contribution of \( r = 22.7 \pm 0.3 \) (Malesani 2009) was subtracted from the last two data points, and the anticipated SN1998bw-like contribution at the host location was dimmed by the Galactic extinction along the line of sight corresponding to \( E(B-V) = 0.09 \). The results of this exercise are presented in Figure 2.

Although the very early optical emission does not directly affect the late-time behavior of the AG, we have also fitted the very early (prompt) optical emission in a windy environment as given by Equation (6), for completeness and in order to demonstrate the validity of the CB model. The fit to the two prompt emission peaks was obtained with \( \beta_O = 0.50, t_1 = 25.1 \text{ s}, a = 1.47 \text{ s}, t_{\text{exp}} = 19.4 \text{ s} \) for the first peak and \( t_1 = 52.4 \text{ s}, a = 98 \text{ s}, t_{\text{exp}} = 40.3 \text{ s} \) for the second. The scarcity of data points during the rise part of the peaks allows for other equally good fits.

A careful subtraction of the host galaxy contribution from the optical light curve of GRB 090618 measured with large telescopes of good spatial resolution should have shown already (on 2009 June 29) spectroscopic and photometric evidence for an underlying SN if its brightness is similar to that of SN1998bw. As of today, the R-band light curve should show a plateau with a very small rise toward a shallow maximum around July 10, when an SN akin to SN1998bw with only little extinction in the host galaxy will reach its peak brightness of magnitude \( \sim 23.2 \) in the R band. The detailed data on the broadband AG of GRB 090618, which is less bright than that of GRB 030329, can still provide another useful test of the long-duration GRB–SN association and of GRB models.

Note added in proof. As shown in Figures 1 and 2, all the published data on the late X-ray and optical AG light curves of GRB 090618 were correctly predicted by the CB model from the first day observations. As of today, 2009 September 17, no observational data on the optical light curve around July 10 and beyond nor the emergence or absence of an underlying SN akin to SN1998bw at the burst location were reported.