SPECTRAL EVOLUTION OF LONG GAMMA-RAY BURST PROMPT EMISSION: ELECTROSTATIC ACCELERATION AND ADIABATIC EXPANSION

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ABSTRACT
Despite the great variation in the light curves of gamma-ray burst (GRB) prompt emission, their spectral energy distribution (SED) is generally curved and broadly peaked. In particular, their spectral evolution is well described by the hardness–intensity correlation during a single pulse decay phase, when the SED peak height $S_p$ decreases as its peak energy $E_p$ decreases. We propose an acceleration scenario, based on electrostatic acceleration, to interpret the $E_p$ distribution peak at $\sim 0.25$ MeV. We show that during the decay phase of individual pulses in the long GRB light curve, the adiabatic expansion losses likely dominate the synchrotron cooling effects. The energy loss as due to adiabatic expansion can also be used to describe the spectral evolution observed during their decay phase. The spectral evolution predicted by our scenario is consistent with that observed in single pulses of long BATSE GRBs.

Key words: acceleration of particles – gamma-ray burst: general – radiation mechanisms: non-thermal

1. INTRODUCTION
The acceleration mechanisms and the radiative processes underlying the prompt emission in long gamma-ray bursts (GRBs) are still unclear. Their large energies released on short timescales likely requires that the radiation is produced in a highly relativistic jet (e.g., Mészáros 2002).

We may consider that a GRB consists of fundamental units of emission, or pulses, in the light curve (e.g., Norris et al. 1996; Stern & Svensson 1996). The pulse structures generally show a sharp rise and a slower decay phase to the background flux threshold. However, GRBs exhibit a wide variety of light curves, both in shape and in duration, and the combination of many such pulses could create the observed diversity and complexity of light curves (Fishman et al. 1994).

GRB spectral energy distributions (SEDs) are generally curved and broadly peaked. They are usually well described by the Band function (Band et al. 1993) or, as shown more recently, by the simpler (and physically motivated) log-parabolic model (Massaro et al. 2010, hereinafter M10). Kaneko et al. (2006, 2008) investigated the time-resolved spectral behavior of the GRBs in the BATSE catalog (Paciesas et al. 1999) and showed that the distribution of their SED energy peaks, $E_p$, is symmetric around $\sim 0.25$ MeV (Goldstein et al. 2010).

As reported in the analysis of Ryde & Svensson (2002), the GRB spectral evolution during the decay phase of individual pulses can be described by the hardness–intensity correlation (HIC) between the time-resolved SED peak height, $S_p$ (defined as $nF_n$, and proportional to the total flux measured at $E_p$), and the peak energy, $E_p$, in the form of a power law: $S_p \propto E_p^{-\eta}$, where the distribution of the $\eta$ parameter peaks at value $\sim 1.7$ (Borgonovo & Ryde 2001).

Subsequently, Ryde & Petrosian (2002) showed that a power-law form (i.e., $S_p \propto E_p^{-\eta}$) can be reproduced through kinematic effects when applied to a spherical shell expanding at extreme relativistic velocity. The curvature of a relativistic shell would make the photons emitted off the line of sight delayed and affected by a varying Doppler boost as a result of the increasing angle at which the photons are emitted with respect to the observer. They show that these so called curvature effects, characterized by a timescale $\tau_{\text{ang}}$, display a similar trend to that of the HIC observed in the GRB spectral evolution, with the parameter $\eta = 2$ then expected. However, they also argued that an intrinsic correlation between these two spectral parameters in the GRB prompt emission could affect the observed HIC (see also Kocevski et al. 2003). These curvature effects are dependent on the radius $R$ of the emitting shell and are likely to be negligible if $R \lesssim 10^{13}$ cm.

Motivated by these observations, we propose an acceleration scenario to explain the observed $E_p$ distribution of individual pulses in long GRBs. We also show that losses for adiabatic expansion play an important role during the decay phase and could be more relevant than synchrotron radiative cooling. Finally, we argue that the observed spectral behavior of long pulses, during the GRB decay phase of the light curve, can be described taking into account the energy loss for adiabatic expansion.

For our analysis, we use cgs units and we assume a flat cosmology with $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.26$, and $\Omega_\Lambda = 0.74$ (Dunkley et al. 2009). Unless stated otherwise, primed quantities refer to the observer reference frame while unprimed quantities refer to the GRB frame.

2. ELECTROSTATIC ACCELERATION MECHANISM
We propose a particle acceleration scenario to explain the $E_p$ distribution around the observed value of $\sim 0.25$ MeV. We assume that the acceleration mechanisms occurring during the GRB prompt emission are a combination of systematic acceleration, responsible for the energy peak position of the accelerated particle energy distribution (PED), and stochastic acceleration, which accounts for the broadening of the PED around its peak (M10).

As proposed by Cavaliere & D’Elia (2002) for blazar jets, GRBs could be powered by the Blandford & Znajek (1977) mechanism for the extraction of rotational energy from a spinning black hole via the Poynting flux associated with the surrounding magnetosphere. In these magnetospheres, the electric fields parallel to magnetic fields can accelerate charged particles. They can arise, for example, as a result of magnetic field reconnection in current sheets or MHD jet instabilities (e.g., Litvinenko 1996; Medvedev & Loeb 1999).

The force-free condition $E \cdot B = 0$ governing these magnetospheres breaks down when the electric field $E \leq B$. In
particular, electric fields are electrodynamically screened out at distances that exceed the Debye length, \( d \), which for a pair plasma is defined as

\[
d = \frac{c}{\omega_p} = \left( \frac{\gamma m_e c^2}{4\pi e^2 n} \right)^{1/2} = 5.30 \times 10^5 \left( \frac{\gamma}{n} \right)^{1/2} \text{ cm},
\]

where \( \omega_p \) is the plasma frequency, \( \gamma \) is the electron Lorentz factor, \( m_e \) is the electron mass, \( e \) is its electric charge, \( c \) is the speed of light, \( B \) is the magnetic field, and \( n \) is the plasma density. Electric fields parallel to magnetic fields accelerate charged particles and consequently, the particle energy gain for each acceleration step can be written as

\[
\gamma m_e c^2 \simeq e B d.
\]

Substituting \( d \) from Equation (1), we obtain an expression for the Lorentz factor of the accelerated particle:

\[
\gamma = \frac{1}{4\pi m_e c^2} \left( \frac{B^2}{n} \right) = 9.77 \times 10^4 \left( \frac{B^2}{n} \right).
\]

We note that the above expression is similar to the assumption that the electron energy density \( u_e \sim n \gamma m_e c^2 \) is twice the magnetic energy density \( u_B = B^2/8\pi \), close to the equipartition condition.

With the above acceleration scenario, for an emitting region with particle density \( n \sim 5 \times 10^8 \text{ cm}^{-3} \), a magnetic field \( B \sim 10^4 \text{ G} \), and a beaming factor \( \delta \sim 100 \), all of which are typical values for GRB models (e.g., Zhang & Mészáros 2002), the synchrotron energy peak \( E_p^* \) is \( \sim 0.3 \text{ MeV} \), in agreement with the observed \( E_p^* \) distribution. We argue that the variance of the \( E_p^* \) distribution can be due to the dispersion of the other parameters and their intrinsic variations during the burst. The Poynting flux in the current sheet provides its luminosity, which can be estimated as \( L = cB^2/2\pi \cdot (l_c \cdot w) \), where \( w \) and \( l_c \) are the current sheet width and its length, respectively (Litvinenko 1999).

The typical observed isotropic luminosity of a GRB is \( L_{iso}^0 \sim 10^{52} \text{ erg s}^{-1} \) so the intrinsic equivalent value, rescaled for a beaming factor of 100, is \( L_{int}^0 = L_{iso}^0/\delta^4 \sim 10^{44} \text{ erg s}^{-1} \). Assuming \( l_c \sim w \sim 10^{13} \text{ cm} \), as derived from the GRB variability timescale i.e., \( \sim 0.1 \text{ s} \), the Poynting flux in a single current sheet is \( L \sim 10^{44} \text{ erg s}^{-1} \), the same order of magnitude of the GRB intrinsic luminosity.

3. PARTICLE ENERGY LOSSES

A simple scenario to describe single pulses in long GRB light curves assumes an impulsive heating of particles and a subsequent cooling and emission. The rise phase of pulses is attributed to particle acceleration energizing the emitting region while the decay phase reflects the particle energy losses. In the following, we show that adiabatic expansion is the main process responsible for the particle energy losses during the decay phase of single pulses. This is also supported by the fact that the synchrotron cooling time appears too short to account for the decay phase of GRB pulses. In addition, the observational evidence that GRB SEDs are curved (e.g., log parabolic) and not the superposition of two power laws (e.g., Band function) is a strong indication that stochastic acceleration occurs during the prompt emission (M10). This suggests that both systematic acceleration (e.g., due to electric fields) and stochastic acceleration mechanisms (e.g., due to turbulence) balance the synchrotron radiative losses.

We neglect the radiative losses from inverse Compton emission, since GRB prompt emission does not appear to be dominated by the high-energy \( \gamma \)-ray component (i.e., \( \gtrsim 10 \text{ MeV} \); Abdo et al. 2009).

The adiabatic expansion of the emitting region can be described by a self-similar model in which the temporal evolution of the radius and consequently the density can be expressed as

\[
R(t) = R_0 \left( \frac{t}{t_0} \right)^{-3q},
\]

where \( q \) is the expansion index and is positive (i.e., \( 0 < q \leq 1 \)), and \( t_0 \) is the reference time. The rate of expansion of the emitting region is defined by the relation

\[
\dot{R} = \frac{dR}{dt} = q \frac{R_0}{t_0} \left( \frac{t}{t_0} \right)^{-q-1},
\]

and the adiabatic expansion losses of a single particle can be written as

\[
\gamma_{ad} = \frac{d\gamma}{dt} = -\frac{\dot{R}}{R(t)} \gamma,
\]

for which the analytical solution is

\[
\gamma(t) = \gamma_0 \left( \frac{t}{t_0} \right)^{-q}.
\]

Assuming conservation of the magnetic flux, we can express the temporal evolution of its value as

\[
B(t) = B_0 \left( \frac{R_0}{R} \right)^2 = B_0 \left( \frac{t}{t_0} \right)^{-2q},
\]

where \( B_0 \) is the initial value at time \( t_0 \). We note that by replacing the relation for the magnetic flux conservation (Equation (8)) and for the temporal evolution of the particle density (Equation (1)) in Equation (3), we obtain the same temporal evolution for the particle energy as derived in Equation (7). Consequently, the assumption of the conservation of the magnetic flux is in agreement with the electrostatic acceleration scenario.

The ratio \( \rho \) between the energy losses due to synchrotron radiative cooling and adiabatic expansion is

\[
\rho = \frac{(dE/dt)_{syn}}{(dE/dt)_{ad}} = \frac{\sigma_T B_0^2 t_0}{6\pi q m_e c} \gamma \left( \frac{t}{t_0} \right)^{-4q},
\]

where \( B_0 \) is the magnetic field evaluated at the initial time \( t_0 \), and \( \sigma_T \) is the Thomson cross section.

By substituting Equation (3) into Equation (9), the ratio of energy losses \( \rho \) can also be written as

\[
\rho = 1.27 \times 10^{-5} \frac{B_0^2}{q} \left( \frac{t}{t_0} \right)^{1-5q}.
\]

We assume \( q > 1/5 \), as in the case of constant expansion rate (i.e., \( q = 1 \)) or expansion with constant energy (i.e., \( q = 2/5 \), Sedov phase condition). Then, for typical values of the prompt emission region, during their decay phase, \( B_0 \simeq 10^3 \text{ G} \) and \( n \simeq 10^7 \), the synchrotron radiative losses are dominated by those of the adiabatic expansion (i.e., \( \rho < 1 \)) after a time interval \( t_s \) of \( \sim 1 \text{ s} \). We also note that for a more compact source with \( B_0 \simeq 10^4 \text{ G} \) and \( n \simeq 10^8 \text{ cm}^{-3} \), \( t_s \) is \( \sim 10 \text{ s} \).
The curvature does not change. In our calculations, we set $B$ decay phase of $6\,s$. It is evident that the shape of the SED is preserved and $r$ assumption described in Section 3. Each SED is evaluated every $0.5\,s$ for a decay phase for an adiabatically expanding synchrotron shell based on the analysis of the $\log$-parabolic function (see M10). The shape of the light curve is given by dashed $\gamma_p$ and $S_p$ have temporal dependence:

$$E_p \propto \left(\frac{t}{t_0}\right)^{-q}, \quad S_p \propto \left(\frac{t}{t_0}\right)^{-6q}. \quad (11)$$

This gives the expected intrinsic relation between the two SED parameters $E_p$ and $S_p$, as a power law: $S_p \propto (E_p)^{3/2}$, independent of the value of the expansion index $q$. The relativistic corrections (due to the relativistic beaming or curvature effects, e.g., Ryde & Petrosian 2002) do not affect the intrinsic correlation between $E_p$ and $S_p$. Therefore, the expected observed power-law index is still $\sim 1.5$, and thus near the peak of the $n$ distribution estimated for the pulse decay phase of long GRBs. In addition, assuming that the size of the emitting region is $\sim 10^{15}\,cm$, the curvature effects are negligible, because their timescale is too short $\tau_{\text{ang}} \sim 10^{-2}\,s$ to explain the pulse decay in long GRBs. Thus, we describe that the decay phase in the GRB prompt emission has energy loss dominated by adiabatic expansion, assuming that the acceleration energy gain, via systematic and stochastic acceleration, balances the synchrotron radiative cooling.

We note that the PED in the form of a log-parabolic function is a good approximation for the solution of the kinetic equation for the particles when considering terms taking into account systematic and stochastic acceleration as well as including synchrotron radiative losses and adiabatic expansion (Kardashev 1962; Tramacere et al. 2009; Paggi et al. 2009; M10).

We calculate the synchrotron emission of an adiabatically expanding spherical region assuming an emitting PED with a log-parabolic shape: $N(\gamma) = N_0 (\gamma/\gamma_p)^{-2-\gamma} \log(\gamma/\gamma_p)$, where $\gamma_p$ (i.e., the peak of $\gamma^2 \cdot N(\gamma)$ is $(\gamma^2)^{1/2}$, $r$ is the PED curvature, and $n \propto N_0$ is the density (see M10). Then, as shown in Figure 1, the spectral curvature of the synchrotron PED is constant during the pulse decay phase.

We adopted the log-parabolic function (i.e., $F(E) = S_p/E^2(E/E_p)^{b \log(E/E_p)}$, see M10) to describe the time-resolved SED and to measure the spectral curvature $b$.

In Figure 2, we show that the examples of GRB 941026 and GRB 950818 do not show significant variation of their curvature $b$ during their pulse decay phases, in agreement with the scenario dominated by adiabatic expansion losses.

The detail of the spectral behavior observed during the decay phase (i.e., between 66 and 70 $s$) of GRB 950818 is also shown in Figure 3. The curvature is not drastically varying over the whole burst, in agreement with our scenario (Figure 1).

We also note the presence of small fluctuations in $b$, which appear to be anti-correlated with secondary peaks in the GRB light curve. As already pointed out by Vetere et al. (2007) from the analysis of the BeppoSAX WFC archive, the low-energy

![Figure 1](image1.png)  
![Figure 2](image2.png)
(i.e., 2–30 keV) GRB light curves are characterized by peaks superposed on a slowly evolving component. A more detailed analysis of these fluctuations will be presented in a forthcoming paper.

5. CONCLUSIONS

We propose an electrostatic acceleration scenario to interpret the $E_p$ distribution of GRB time-resolved SEDs. We show that taking into account adiabatic expansion losses it is possible to describe the spectral evolution during the decay phase of individual pulses in long GRBs. Our model assumes that the particle energy gain is due to both systematic and stochastic particle accelerations, while the particle energy losses are due to synchrotron emission and adiabatic expansion.

Describing the systematic acceleration in terms of electric field energy gain, we derive a simple relation for the expected particle Lorentz factor, $\gamma \sim 10^4–10^5$. Thus, for a typical GRB magnetic field of $\sim 10^4$ G, a plasma density of $\sim 10^8$ cm$^{-3}$, and a beaming factor $\sim 50–100$, the expected synchrotron peak energy $E_p'$ is $\sim 0.3$ MeV as found for the observed distribution (e.g., Kaneko et al. 2006). This may explain the non-uniform time-resolved $E_p$ distribution of the GRB SED peaking around a characteristic value.

Following the assumption that systematic and stochastic acceleration mechanisms balance the synchrotron radiative cooling, and the adiabatic expansion loss is the main process governing GRB spectral evolution during the decay phase of individual pulses, we derive that the expected intrinsic scaling relation between the height of the SED $S_p$ and its peak energy $E_p$ is $S_p \propto (E_p)^{3/2}$, which agrees with the observed HIC for single pulses in long GRBs.

Finally, on the basis of our assumptions, we note that the adiabatic losses do not change the shape of the SED during the prompt emission. We showed that this is consistent with the spectral behavior of the decay phase of single pulses during long GRB prompt emission as in the cases of GRB 941026 and 950818, for which we did not detect any large variation in the spectral curvature throughout the spectral evolution.

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ERRATUM: “SPECTRAL EVOLUTION OF LONG GAMMA-RAY BURST PROMPT EMISSION: ELECTROSTATIC ACCELERATION AND ADIABATIC EXPANSION” (2011, ApJL, 727, L1)

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Due to an error in the publishing process, the expression for the intrinsic equivalent value of the observed isotropic luminosity (given in the final paragraph of Section 2) contained a mistake. The correct expression is given below

\[ L_{\text{int}} = \frac{L'_{\text{iso}}}{\delta^4} \sim 10^{44} \ \text{erg s}^{-1}. \]

Also, the second-to-last paragraph of Section 3 (“In Figure 2, we show the time-resolved spectral analysis of the decay phases... with the observed spectral behavior.”) was misplaced from its intended placement as the fifth paragraph of Section 4 (preceding “We adopted the log-parabolic function... to measure the spectral curvature \( b \).”).