A Canonical High Energy Afterglow Emission Light Curve?

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Abstract

We present self consistent calculations of Synchrotron self Compton (SSC) radiation that takes place within the afterglow blast wave and External inverse Compton (EIC) radiation that takes place when flare photons (produced by an internal process) pass through the blast wave. We show that if our current interpretations of the Swift XRT data are correct, there should be a canonical high energy afterglow emission light curve. We expect that GRBs with a long term X-ray flattening or X-ray flares should show similar high energy features. The EIC emission, however, is long lasting and weak and might be outshined by the SSC emission of the forward shock. The high energy emission could be well detected by the soon to be launched GLAST satellite. Its detection could shed new light on the conditions within the emitting regions of GRBs.

Key words: Gamma Rays: bursts–ISM: jets and outflows–radiation mechanisms: nonthermal

1 Introduction

Very high energy emission provides us with another window on the condition within the emitting region in Gamma-ray Bursts (GRBs). Such a window is very important in view of the present confusion between different modifications to the standard afterglow model proposed to explain the recent observation of Swift. The upcoming high energy observatory GLAST is an ideal tool to detect such emission. Together with the Swift X-ray Telescope (XRT), it would provide a very wide band monitoring of the afterglow that might enable us to distinguish between the different models. We discuss here several predictions of current models for the expected high energy light curves and their relation to the X-ray afterglow.

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The dominant source of long lasting high energy GRB afterglow emission is SSC of the hot electrons in the forward external shock. At early stages of the afterglow when the cooling of most electrons is important, the luminosity of the SSC emission, $L_{\text{SSC}}$, is related to the luminosity of the synchrotron radiation, $L_{\text{syn}}$, as $L_{\text{SSC}} \sim Y L_{\text{syn}}$, where $Y$ is the Compton parameter. The X-ray luminosity $L_X$, is a small fraction of $L_{\text{syn}}$. We would like to use it as a proxy for the total luminosity and we define a factor $\epsilon_X \equiv L_X/L_{\text{syn}}$ so that $L_{\text{SSC}} \sim Y L_X/\epsilon_X$. A wide band SSC afterglow data and the X-ray data will have quite similar temporal behaviors, as long as $\epsilon_X$ does not vary significantly with time. Overall we expect, therefore, that $L_X$ and $L_{\text{SSC}}$ should be highly correlated. In other words, the GRBs with slowly decaying X-ray light curve should show similar high energy feature. This is confirmed by the more detailed analysis (Fan et al. 2007; Wei & Fan 2007) and by the numerical results, as shown in Fig. 1.

Energy injection and time increasing $\epsilon_e$, have been proposed to explain the slowly declining X-ray phase seen in many GRB afterglows. The resulting SSC light curves in both cases follow the X-ray. Although the SSC light curves are somewhat different the difference is probably too small to distinguish between the two modifications (Fan et al. 2007). However, the typical SSC frequency $\nu_m^{\text{SSC}} \propto \epsilon_e^4 E_k$, where $E_k$ is the total energy of the outflow. The strong $\epsilon_e$ dependence suggests a significant difference in the time evolution of the high energy spectrum between the two models.

3 Possible high energy emission associated with flares

X-ray flares during the afterglow have been detected by BeppoSAX (Piro et al. 2005) and confirmed by Swift to exist in a large fraction of the afterglows (Nousek et al. 2006; Zhang et al. 2006). Such flares should be accompanied by a high energy emission either because of SSC emission of the electrons powering the flares or because EIC upscattering that takes place when flare photons pass through a hot blast wave.

GeV flash. We consider first the direct SSC emission associated with X-ray flares. The typical frequency of the upscattered X-ray photons depends on the Lorentz factor of
the scattering electrons. The magnetic energy density \( B \) at a radius \( R_{\text{flare}} \) can be estimated as:

\[
B \sim 250 \text{ Gauss} \varepsilon^{1/2} L_{X,49}^{-1/2} R_{\text{flare},15}^{-1/2},
\]

where \( \varepsilon \equiv \epsilon_B/\epsilon_e \). For this value of the magnetic field the peak energy of the flare photons \( E_p \sim 0.2 \text{ keV} \) requires a typical random Lorentz factor of the emitting electrons:

\[
\gamma_e \sim 800 \varepsilon^{-1/4} L_{X,49}^{-1/4} R_{\text{flare},15}^{-1/4} (E_p/0.2 \text{ keV})^{1/2}.
\]

With this Lorentz factor the expected SSC emission peaks at

\[
\nu_{\text{ssc}} \sim 0.3 \text{ GeV} \varepsilon^{-1/2} L_{X,49}^{-1/2} R_{\text{flare},15}^{-1/2} (E_p/0.2 \text{ keV})^2.
\]

The total fluence of the SSC emission of the flare shock is comparable to that of the X-ray emission, typically \( 10^{-7} \sim 10^{-6} \text{ erg cm}^{-2} \). In a late internal shock with \( R_{\text{flare}} \sim 10^{15} \text{ cm} \) (Fan & Wei 2005), a GeV flash accompanying the X-ray flare is possible (Wei et al. 2006, however see Wang et al. 2006). In an external shock, a GeV-TeV flash is predicted (see also Galli & Piro 2007).

**Extended EIC emission.** A second source of high energy emission arises when X-ray flare photons that are produced by internal energy dissipation are be inverse Compton upscattered by the external shock’s hot electrons. A central ingredient of this scenario is that in the rest frame of the blast wave, the seed photons are highly beamed. We take care of this effect, following the analysis of Aharonian & Atoyan (1981).

If the EIC emission duration is comparable to that of the X-ray flare, the EIC luminosity can be estimated by

\[
L_{\text{EIC}} \sim 10^{49} \text{ erg s}^{-1} \epsilon_{e,-1} E_{k,53} t_3^{-1} . \tag{2}
\]

In the rest frame of the shocked material, the EIC emission peaks at \( \theta_{\text{sc}} = \pi \) and it vanishes for small scattering angles. This effect lowers the high energy flux significantly in two ways. First, a fraction of the total energy is emitted out of our line of sight and thus the received power is depressed (relative to the isotropic seed photon case). Second, the strongest emission is from \( \theta \sim 1/\Gamma \) (Fan & Piran 2006). Thus, the high energy EIC emission will be delayed by

\[
T_p \sim (4 - k) t_f , \tag{3}
\]

after the flare (emitted at \( t_f \)). As \( T_p \) is much longer than \( \Delta T \), the duration of the soft X-ray flare the EIC high energy flux would be low:

\[
L_{\text{EIC}} \sim \frac{L_{\text{eln}}}{(T_p/\Delta T)}. \tag{4}
\]

A comparison of the EIC high energy component with the SSC emission from the forward shock may render the EIC high energy component undetectable. At the time of the flare, 100-1000sec after the burst, the forward shock emission peaks in far-UV to soft X-ray band. The corresponding SSC a luminosity of the forward shock around \( t_f \) is \( L_{\text{SSC}} \sim L_{\text{eln}} Y/(1 + Y) \). This is significantly larger than \( L_{\text{EIC}} \) and the wide EIC flare would be undetectable (cf. Wang et al. 2006).

In special cases the EIC component might still be detectable. This hap-
pens for bursts having a weak SSC emission and in which the forward shock electrons are in slow cooling (before the X-ray flare phase). The energy of these electrons will be lost mainly in the EIC process and in this case the EIC luminosity will be enhanced. If the EIC emission dominates over the SSC emission, the high energy light curve will flatten, as shown in Fig. 2. Such a flattening could also arise by energy injection or due to an increasing $\varepsilon_e$. However, as shown in last section, in these two scenarios, the X-ray and the high energy emission behaviors are quite similar and flattening should be apparent also in the X-ray signal. The EIC emission should, on the other hand show an X-ray flare preceding high energy emission and not accompanying flat X-ray light curve.

A numerical example illustrating the possible EIC emission following the X-ray flare in GRB 050502B is shown in Fig. 2.

4 Summary and Discussion

We have shown that if the current interpretation of the Swift XRT data (the upper panel of Fig. 3) is correct there should be a canonical high energy afterglow light curve (see the lower panel of Fig. 3 for illustration). A detection of such a high energy component will enable us to test current models of GRBs and their afterglow. A high energy component that follows the lower energy light curve will confirm that the low energy component is Synchrotron. If the lower component is produced via Inverse Compton the Klein-Nishina suppression will prevent a second upscattering. A detailed comparison of the high energy and the low energy light curves, in particular during the shallow decline phase, might even enable us to distinguish between different modifications of the standard afterglow model.
is because for the two most widely considered models, the energy injection and time increasing $\epsilon_e$, the time evolution of the high energy spectra are very different. A long lasting high energy component that follows a low energy flare would prove the internal origin of this flare and the EIC model for the origin of the high energy emission. The upcoming high energy observatory GLAST can thus play a key role in exploring the GRB afterglow physics.

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