GRB 090510: A DISGUISED SHORT GAMMA-RAY BURST WITH THE HIGHEST LORENTZ FACTOR AND CIRCUMBURST MEDIUM

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ABSTRACT

GRB 090510, observed by both Fermi and AGILE satellites, is the first bright short-hard gamma-ray burst (GRB) with an emission from the keV up to the GeV energy range. Within the Fireshell model, we interpret the faint precursor in the light curve as the emission at the transparency of the expanding $e^+e^-$ plasma: the Proper-GRB. From the observed isotropic energy, we assume a total plasma energy $E_{\text{tot}}^{e^+e^-} = (1.10 \pm 0.06) \times 10^{53}$ erg and derive a Baryon load $B = (1.45 \pm 0.28) \times 10^{-3}$ and a Lorentz factor at transparency $\Gamma_0 = (6.7 \pm 1.6) \times 10^2$. The main emission $\sim 0.4$ s after the initial spike is interpreted as the extended afterglow, due to the interaction of the ultrarelativistic baryons with the CircumBurst Medium (CBM). Using the condition of fully radiative regime, we infer a CBM average spherically symmetric density of $\langle n_{\text{CBM}} \rangle = (1.85 \pm 0.14) \times 10^4$ particles cm$^{-3}$, one of the highest found in the Fireshell model. The value of the filling factor, $1.5 \times 10^{-10} \leq \mathcal{R} \leq 3.8 \times 10^{-8}$, leads to the estimate of filaments with densities $n_{\text{fil}} = n_{\text{CBM}}/\mathcal{R} \approx (10^5 - 10^6)$ particles cm$^{-3}$. The sub-MeV and the MeV emissions are well reproduced. When compared to the canonical GRBs with $\langle n_{\text{CBM}} \rangle \approx 1$ particles cm$^{-3}$ and to the disguised short GRBs with $\langle n_{\text{CBM}} \rangle \approx 10^{-3}$ particles cm$^{-3}$, the case of GRB 090510 leads to the existence of a new family of bursts exploding in an overdense galactic region with $\langle n_{\text{CBM}} \rangle \approx 10^5$ particles cm$^{-3}$. The joint effect of the high $\Gamma_0$ and the high density compresses in time and “inflates” in intensity the extended afterglow, making it appear as a short burst, which we here define as a “disguised short GRB by excess.” The determination of the above parameter values may represent an important step toward the explanation of the GeV emission.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB 090510)

Online-only material: color figures

1. INTRODUCTION

In their earliest classification of the 4BATSE catalog (Meegan 1997), all gamma-ray bursts (GRBs) were classified into short and long bursts depending on whether their $T_{90}$ duration is longer or shorter than 2 s (Klebesadel 1992; Desalay et al. 1992; Kouveliotou et al. 1993; Tavani 1998). In the meantime, short bursts have been shown to originate from a variety of astrophysical origins and not from a homogeneous class. In the Fireshell model (Ruffini et al. 2001a, 2001b, 2001c, 2010), the canonical GRB has two components: an emission occurring at the transparency of the optically thick expanding $e^+e^-$ plasma: the Proper-GRB. From the observed isotropic energy, we assume a total plasma energy $E_{\text{tot}}^{e^+e^-} = (1.10 \pm 0.06) \times 10^{53}$ erg and derive a Baryon load $B = (1.45 \pm 0.28) \times 10^{-3}$ and a Lorentz factor at transparency $\Gamma_0 = (6.7 \pm 1.6) \times 10^2$. The main emission $\sim 0.4$ s after the initial spike is interpreted as the extended afterglow, due to the interaction of the ultrarelativistic baryons with the CircumBurst Medium (CBM). Such an extended afterglow comprises the prompt emission as well as the late phase of the afterglow (Bianco & Ruffini 2005a, 2005b). The relative energy of these two components, for a given total energy of the plasma $E_{\text{tot}}^{e^+e^-}$, is uniquely a function of the baryon load $B = M_B c^2/E_{\text{tot}}^{e^+e^-}$, where $M_B$ is the total baryon mass (see Figure 1, left panel).

The genuine short GRBs (Ruffini et al. 2001b) are the bursts occurring for $B \leq 10^{-3}$. The first example of such systems has indeed been recently identified, originating in a binary neutron star merger (Muccino et al. 2013).

The existence of disguised short GRBs, with baryon load $3 \times 10^{-4} \leq B \leq 10^{-2}$ (Bernardini et al. 2007, 2008), has also been proved. In this class the extended afterglow is indeed energetically predominant but results in a “deflated” emission, less intense than the P-GRB due to the low density of the CBM, $\langle n_{\text{CBM}} \rangle \approx 10^{-3}$ particles cm$^{-3}$, which is much lower than the canonical value $\langle n_{\text{CBM}} \rangle \approx 1$ particles cm$^{-3}$. The majority of the declared short bursts in the current literature appear to be disguised short GRBs (Bernardini et al. 2007, 2008; Caioto et al. 2009, 2010; de Barros et al. 2011).

In this paper we show a yet different kind of a disguised short GRB, GRB 090510, again, with $3 \times 10^{-4} \leq B \leq 10^{-2}$ and Lorentz factor $\Gamma_0 \approx 700$, occurring in a medium with $\langle n_{\text{CBM}} \rangle \approx 10^3$ particles cm$^{-3}$. We define, indeed, these GRBs as “disguised short burst by excess,” since their $\langle n_{\text{CBM}} \rangle$ is much larger than the canonical one. Correspondingly, we indicate the disguised short GRBs with a CBM density typical of the galactic halo environments, $\langle n_{\text{CBM}} \rangle \approx 10^3$ particles cm$^{-3}$, as “disguised short GRBs by defect” (see Figure 1, right panel).

The possibility of GRBs exploding in high density CBM has been already considered in the literature (Dai & Lu 1999; Lazzati et al. 1999; Piro et al. 2001; Wang et al. 2003; Prochaska et al. 2008; Izzo et al. 2012). In Dai & Lu (1999), Piro et al. (2001), and Wang et al. (2003), the high density has been inferred from the steepening in the afterglows, respectively, of GRB 990123 in the R band about $\sim 2.5$ days after the burst, of GRB 000926 in the R band after $\sim 2$ days, and of GRB 990705 in the H band after $\sim 1$ day, due to the transition to the nonrelativistic regime of the fireball. Lazzati et al. (1999) discuss the possibility that the detection of Fe lines in the afterglows of GRB 970508 and GRB 970828 could be due to recombination processes in extremely high densities during the X-ray afterglow. In Prochaska et al. (2008), the authors inferred dense environments, $n \gtrsim 10^5$ particles cm$^{-3}$, from a survey for Na absorption in GRB afterglow spectra. In particular, in Izzo et al. (2012) the Fireshell model has been applied in the analysis of GRB 970828, discussed also in Lazzati et al. (1999), inferring a dense environment with $\langle n_{\text{CBM}} \rangle = 3.4 \times 10^5$ particles cm$^{-3}$, consistent with the large column density environment in Yoshida...
et al. (2001). In the case of GRB 090510, the joint effect of the very dense CBM and the high Lorentz factor at the transparency, $\Gamma_{tr} \approx 700$, leads to an extended afterglow with $T_{00} < 2 s$ (see Figure 1, right panel). These high values of the CBM density $n_{CBM}$ and of the Lorentz factor $\Gamma_{tr}$ may represent an important step toward the explanation of the GeV emission.

The light curve of GRB 090510 is composed of two different episodes, 0.5 s apart. The first episode, from $T_0 - 0.064 s$ to $T_0 + 0.016 s$ (in the following denoted as $\Delta T_1$ time interval; $T_0$ indicates the trigger time), was not considered by Ackermann et al. (2010), Giuliani et al. (2010), and Guiriec et al. (2010) because of the small content of detected photons. Even though the statistical content of this first episode is very poor, in this paper we show its great relevance for theoretical analysis, since it can be identified with the P-GRB. The second episode can be interpreted as the extended afterglow. In the statistical analysis of the first episode, we have considered power-law (PL), black body (BB) plus PL, Band (Band et al. 1993), Comptonized (Compt), Band+BB, and Compt+BB models. Following the statistical analysis for nested models by Guiriec et al. (2010), models more complicated than the simplest Band and Compt are singled out (see the last column of Table 1). The direct statistical comparison between the BB+PL and PL models gives a significance level of 3% (see Table 1). This means that the BB+PL model improves the fit of the data of the first episode with respect to the PL model, which is excluded at the 97% confidence level. The simple Band model has an unconstrained $\alpha$ index and a large error on the energy peak $E_p$, as well as in the case of the Compt model, for which the total flux is underestimated with respect to the Band and BB+PL models. The quality of data does not allow us to favor the BB+PL model versus the Compt one from a purely statistical analysis. In order

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**Table 1**

| Interval | Model     | $kT$ (keV) | $\alpha$ | $\beta$ | $E_p$ (keV) | $\gamma$ | $F_{90} \times 10^{-6}$ (erg cm$^{-2}$ s$^{-1}$) | C-STAT/DOF | Significance |
|----------|-----------|------------|----------|---------|-------------|----------|---------------------------------------------|------------|-------------|
|          | PL        | ...        | ...      | ...     | ...         | ...      | $-1.22 \pm 0.06$                            | 9.2 $\pm 1.3$ | 195.41/195  |
|          | BB+PL     | 34.2 $\pm$ 7.5 | ...      | ...     | ...         | ...      | $-1.10 \pm 1.4$                            | 7.6 $\pm 1.3$ | 188.60/193  |
|          | Band      | ...        | ...      | $-1.44 \pm 0.11$ | ...      | 94 $\pm$ 74 | ...                                           | 7.4 $\pm 1.5$ | 187.11/193  |
| $\Delta T_1$ | Compt     | ...        | $-0.81 \pm 0.22$ | ...     | ...         | 990 $\pm$ 554 | ...                                           | 4.4 $\pm 1.6$ | 189.97/194  |
|          | Band+BB   | 24.3 $\pm$ 5.6 | ...      | $-1.76 \pm 0.62$ | ...      | unc         | ...                                           | 7.1 $\pm 2.0$ | 186.90/191  |
|          | Compt+BB  | 27.2 $\pm$ 6.7 | $-0.72 \pm 0.39$ | ...     | ...         | 2967 $\pm$ 1570 | ...                                           | 8.4 $\pm 2.3$ | 187.23/192  |
| $\Delta T_2$ | (a) Band+PL | ...        | $-0.70 \pm 0.10$ | ...      | $-3.13 \pm 0.97$ | ...      | $3941 \pm 346$                            | $-1.55 \pm 0.54$ | 43.6 $\pm 1.9$ | 207.78/236  |
| $\Delta T_2$ | (b) Band+PL | ...        | $-0.71 \pm 0.07$ | ...      | $-2.97 \pm 0.26$ | ...      | $4145 \pm 398$                            | $-1.62 \pm 0.05$ | 83.3 $\pm 6.8$ | 199.20/256  |

Notes. $\Delta T_1$ time interval: parameters of the best fits (Band+PL) in the energy ranges (a) 8–40,000 keV (GBM) and (b) 8 keV–30 GeV (GBM+LAT). In the last column of $\Delta T_1$, we list the significance levels from the comparison between nested models (BB+PL over PL, Band+BB over Band, and Compt+BB over Compt).

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**Figure 1.** Left panel: the energy emitted in the extended afterglow (green curve) and in the P-GRB (red curve) in units of $F_{90}^{tot}$ are plotted as functions of $B$. The values of $B$ of GRB 090510 (in blue) and of the genuinely short GRB 090227B (in black) are compared. Right panel: the 50 ms time-binned NaI-n6 light curve (green data) and the extended afterglow simulations corresponding to CBM average densities of a “disguised short GRB by excess” with $n_{CBM} = 10^3$ particles cm$^{-3}$ (red curve), of a canonical long GRB with $n_{CBM} = 1$ particle cm$^{-3}$ (blue curve), and of a “disguised short GRB by defect” with $n_{CBM} = 10^2$ particles cm$^{-3}$ (purple curve). For larger densities the extended afterglow compresses in time and “inflates” in intensity.
Figure 2. Upper panels: on the left, the 16 ms time-binned NaI-n6 light curve and, on the right, the NaI-n6+BGO-b1 νFν spectrum (best fit BB+PL) in the ΔT1 time interval. Lower panels: on the left, the 16 ms time-binned NaI-n6 light curve and, on the right, the NaI-n6+BGO-b1 νFν spectrum (best fit Band+PL) in the ΔT2 time interval.

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

to clarify such a fundamental issue, it is appropriate that future space missions with larger collecting area and X/γ-rays timing be flown in the near future (see, e.g., LOFT mission; Feroci et al. 2012). From our theoretical interpretation, the BB+PL, being equally probable as the Compt model, is adopted for its physical meaning and because it is not ruled out by the data.

The BB observed temperature is $kT_{\text{obs}} = (34.2 \pm 7.5)$ keV (see Figure 2, top right panel, and table below) and the total energy of the first episode is $E_1 = (2.28 \pm 0.39) \times 10^{51}$ erg.

We then analyzed the second episode in the time interval from $T_0 + 0.400$ s to $T_0 + 1.024$ s (in the following ΔT2). The best fit in the energy range 8 keV–40 MeV is Band+PL (Ackermann et al. 2010) or alternatively Compt+PL (Giuliani et al. 2010; Guiriec et al. 2010). The results are shown in Figure 2 and in Table 1. Including the LAT data, the spectrum is again best fitted by Band+PL (see the last row in Table 1), with the PL observed up to 30 GeV (Ackermann et al. 2010). The total energy is $E_2 = (1.08 \pm 0.06) \times 10^{53}$ erg.

3. GRB 090510: THEORETICAL INTERPRETATION

In the Fireshell model (Ruffini et al. 2001a, 2001b, 2001c) GRBs originate from an optically thick $e^+e^-$ plasma created by vacuum polarization processes in the gravitational collapse to a black hole (Damour & Ruffini 1975; Ruffini et al. 2010). The dynamics of such an expanding plasma in the optically thick phase is described by its total energy $E_{\text{tot}}^{e^+e^-}$ and by the amount of the engulfed baryons $B$. Spherical symmetry of the system is assumed. The canonical GRB light curve is then characterized by a first emission due to the transparency of the $e^+e^-$-photon-baryon plasma, the P-GRB, followed by a multi-wavelength emission, the extended afterglow, due to the collisions, in a fully radiative regime, between the accelerated baryons and the CBM. The radius at which the transparency occurs, $r_{\text{tr}}$, the theoretical temperature blueshifted toward the observer $kT_{\text{blue}}$, and the Lorentz factor $\Gamma_{\text{tr}}$, and the amount of the energy emitted in the P-GRB are functions of $E_{\text{tot}}^{e^+e^-}$ and $B$ (Ruffini et al. 2001b, 2009).

The structures observed in the extended afterglow of a GRB are described by two quantities associated with the environment: the CBM density profile $n_{\text{CBM}}$, which determines the temporal behavior of the light curve, and the filling factor $R = A_{\text{eff}} / A_{\text{vis}}$, where $A_{\text{eff}}$ is the effective emitting area of the Fireshell and $A_{\text{vis}}$ is its total visible area (Ruffini et al. 2002, 2005). This second parameter takes into account the inhomogeneities in the CBM and its filamentary structure (Ruffini et al. 2004). The density of each filament is simply defined as $n_{\text{fil}} = n_{\text{CBM}} / R$.

We identified the first episode, where the thermal component is not statistically excluded, with the P-GRB. Then we started the simulation using our numerical code (for details, see, e.g., Ruffini et al. 2007). The input parameters are $E_{\text{tot}}^{e^+e^-}$, constrained to the isotropic energy of the burst, $E_{\text{iso}} = (1.10 \pm 0.06) \times 10^{53}$ erg, and the baryon load $B = (1.45 \pm 0.28) \times 10^{-3}$, 

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determined by matching the theoretically simulated energy $E_{\text{tr}}$ and temperature $kT_{\text{th}} = kT_{\text{blue}}/(1 + z)$ of the P-GRB with the ones observed in the faint pulse, $E_1$ and $kT_{\text{obs}}$. The results of our simulation are the following:

$$\Gamma_0 = (6.7 \pm 1.6) \times 10^2, \quad \Gamma_1 = (6.51 \pm 0.92) \times 10^{13} \text{ cm},$$
$$E_{\text{tr}} = (2.94 \pm 0.50)\% E_{e^+ e^-}^\text{iso}, \quad kT_{\text{th}} = (34.2 \pm 7.5) \text{ keV}.$$  

(1)

The theoretically predicted P-GRB energy slightly differs from the observed $E_1 = (2.28 \pm 0.39) \times 10^{53} \text{ erg} = (2.08 \pm 0.35)\% E_{\text{iso}}$, since emission below the threshold is expected between the small precursor and the main emission. (see light curves in Figure 2), thus the value of $E_1$ is certainly underestimated.

In the following analysis, we focus our attention on the main emission. Since in $\Delta T_2$ no evidence of a thermal component has been found (see Figure 2, bottom right panel, and table below), we have interpreted this emission as the extended afterglow. Using the above values of $E_{e^+ e^-}^\text{iso}$ and $B$, we have simulated the light curve of the extended afterglow by defining the radial number density distribution of the CBM (assuming spherically symmetrically distributed clouds) and the value of the filling factor $R$, following a trial and error procedure to reproduce the pulses observed in the light curve and the corresponding spectrum. The errors on the densities and the filling factors are obtained by varying them within the observational errors; typically the errors are about 10% of the value. The average value is indeed very high, $\langle n_{\text{CBM}} \rangle = (1.85 \pm 0.14) \times 10^{10}$ particles cm$^{-3}$, assuming spherically distributed clouds (see Figure 3, top plot). Basically this high average density is due to the second and the third brightest spikes of the light curve (see Figure 3, middle panel), where the density of the clouds is $\sim 2 \times 10^8$ particles cm$^{-3}$ (see Table 2, second column). The filling factor assumes values $1.5 \times 10^{-10} \lesssim R \lesssim 3.8 \times 10^{-8}$ (see Table 2, third column). Correspondingly, the values of the densities of the filaments $n_{\text{fil}}$ are estimated (see Table 2, fourth column). In Figure 3, we show also the simulated extended afterglow light curve from the NaI-n6 detector (middle panel) and the corresponding spectrum of the early $\sim 0.4$ s of the emission (bottom panel) in the energy range 8 keV–40 MeV, using the spectral model described in Ruffini et al. (2004) and Patricelli et al. (2012). The last part of the simulation requires a more detailed three-dimensional code to take into account the distribution of the CBM.

4. CONCLUSIONS

We list our conclusions as follows.

1. The simulated spectrum of the extended afterglow in the time interval $\Delta T_2$, considered in the analysis by Ackermann et al. (2010), is in excellent agreement with the one in Figure 2 in the sub-MeV and MeV region. The baryon load $B = (1.45 \pm 0.28) \times 10^{-3}$ used in this simulation has been determined from analysis of the first episode, which has been identified with the P-GRB. The current quality of the data does not allow us to properly distinguish between BB+PL and Compt spectral models. From our theoretical interpretation, the BB+PL model was adopted, since it is not ruled out by the data. Such a fundamental issue will be further clarified by future space missions with larger collecting area and X-/γ-ray timing, as, e.g., the LOFT mission (Feroci et al. 2012).

2. We have stressed a key difference between the Fireshell and the Fireball approaches. In the Fireshell model, the extended afterglow encompasses the prompt emission and the afterglow of the traditional Fireball model. The density of the CBM is inferred from the prompt emission by assuming fully radiative condition emission in an optically thin regime (Ruffini et al. 2002, 2004, 2005) and a precise spectrum in the comoving frame is assumed (Patricelli et al. 2012) and convoluted over the equitemporal Surfaces (Bianco & Ruffini 2005a, 2005b). In the Fireball model, the density is instead estimated from the afterglow emission by analyzing emission or absorption.
lines in the X-ray spectra (see, e.g., Lazzati et al. 1999; Prochaska et al. 2008), or by observing steepening or breaks of the optical afterglow light curves (see, e.g., Dai & Lu 1999; Piro et al. 2001; Wang et al. 2003). From the fully radiative condition, we have found that GRB 090510 occurs in an overdense medium with an average value of $\langle n_{\text{CBM}} \rangle \approx 10^2$ particles cm$^{-3}$ (for spherically symmetrically distributed clouds). This high CBM density and the small value of the filling factor, $1.5 \times 10^{-10} \leq R \leq 3.8 \times 10^{-8}$, leads to local overdense CBM clouds, in the form of filaments, bubbles, and clumps, with a range of densities $n_{\text{fil}} = n_{\text{CBM}}/R \approx (10^0-10^{15})$ particles cm$^{-3}$.

3. The joint effect of the high value of the Lorentz factor, $\Gamma_{\text{tr}} = (6.7 \pm 1.6) \times 10^2$, and the high density compresses the emission of the extended afterglow in time. Therefore its light curve is shortened in time and “inflated” in intensity with respect to the canonical one for disguised short bursts (see Figure 1, right panel), making it apparently closer to the genuine short class of GRBs (Muccino et al. 2013). It is interesting to note that in this GRB, with an abnormally high value of the CBM density, the extended afterglow does not fulfill the Amati relation (Amati 2006).

4. From the values of $n_{\text{fil}}$, we obtain a range of grammages of $\rho_{\text{fil}} = (10^{-2}-10^4)$ g cm$^{-2}$, where $\rho_{\text{fil}}$ is the mass of the hydrogen atom and $\Delta r$ is the size of the cloud inferred from our simulation (see Figure 3 and the first column in Table 2). This high value of the grammage may be relevant in the explanation of the observed GeV emission as originating in the collisions between ultra-high energy protons, with the bulk Lorentz factor of $\Gamma_{\text{tr}} = (6.7 \pm 1.6) \times 10^2$, and the CBM.

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