The Astrophysical Journal Letters, 755:L6 (4pp), 2012 August 10 doi:10.1088/2041-8205/755/1/L6

THE PHOTOSPHERIC RADIATION MODEL FOR THE PROMPT EMISSION OF GAMMA-RAY BURSTS: INTERPRETING FOUR OBSERVED CORRELATIONS

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Received 2012 May 6; accepted 2012 June 25; published 2012 July 20

ABSTRACT

We show that the empirical $E_{\rm p}$–L, Γ–L, $E_{\rm p}$–Γ, and $\bar{\eta}_\gamma$–$E_{\rm p}$ correlations (where L is the time-averaged luminosity of the prompt emission, $E_{\rm p}$ is the spectral peak energy, Γ is the bulk Lorentz factor, and $\bar{\eta}_\gamma$ is the emission efficiency of gamma-ray bursts, GRBs) are well consistent with the relations between the analogous parameters predicted in the photospheric radiation model of the prompt emission of GRBs. The time-resolved thermal radiation of GRB 090902B does follow the $E_{\rm p}$–L and Γ–L correlations. A reliable interpretation of the four correlations in alternative models is still lacking. These may point toward a photospheric origin of prompt emission of some GRBs.

Key word: gamma rays: general

Online-only material: color figure

1. INTRODUCTION

In the past 15 years, our understanding of gamma-ray bursts (GRBs) has been revolutionized. As usual, some aspects are understood better than others. For example, the detection of a bright supernova component in the afterglow of some nearby long GRBs establishes their collapsar origin and the late ($\sim 10^4$ s after the trigger of the burst) afterglow data support the external forward shock model (Piran 2004; Zhang & Mészáros 2004). Yet the physical origin of the prompt emission of GRBs is still not clear. The "leading" internal shock model is found to have difficulty explaining some observational facts, motivating people to develop internal magnetic energy dissipation models and the photosphere models (see Piran 2004; Zhang & Mészáros 2004 for reviews). It is rather hard to distinguish among these models reliably. It is widely speculated that the polarimetry of the prompt emission, for example, by the POlarimeters for Energetic Transients (POET; Hill et al. 2008) and by POLAR (Orsi 2011), may play key roles in the future. In this Letter, we show that some empirical correlations of the prompt emission properties may shed valuable light on the underlying physics and that the photospheric model is favored.

2. INTERPRETING THE FOUR OBSERVED CORRELATIONS IN THE PHOTOSPHERIC RADIATION MODEL

The tight correlation $E_{\rm p} \propto L^{0.5\pm0.1}$ was discovered by Wei & Gao (2003; see Figure 6 therein) and has then been confirmed by many researchers (e.g., Liang et al. 2004; Yonetoku et al. 2004; Ghirlanda et al. 2009; Zhang et al. 2012). Recently, a tight correlation $\Gamma \propto L^{0.3\pm0.002}$ was identified by Lü et al. (2012) and the correlation $\Gamma \propto E_{\rm p}^{0.78\pm0.18}$ was suggested by Ghirlanda et al. (2012). Very recently, Margutti et al. (2012) and Bernardini et al. (2012) discovered a tight correlation $E_\gamma/E_{\rm x} \propto E_{\rm p}^{0.66\pm0.16}$, where E_γ is the isotropic equivalent energy of the prompt emission and $E_{\rm x}$ is the total energy of the afterglow emission in the X-ray band. In the forward shock afterglow model, $E_{\rm x}$ is proportional to $E_{\rm k}$, the kinetic energy of the outflow (Piran 2004; Zhang & Mészáros 2004). Therefore, $E_\gamma/E_{\rm x}(\propto E_\gamma/E_{\rm k})$ is proportional to the GRB efficiency $\bar{\eta}_\gamma \equiv E_\gamma/(E_\gamma + E_{\rm k})$ as long as E_γ is considerably smaller than $E_{\rm k}$. Hence, one has $\bar{\eta}_\gamma \propto E_{\rm p}^{0.7}$. Some possible interpretations of the $E_{\rm p}$–L correlation can be found in the literature (e.g., Wei & Gao 2003; Rees & Mészáros 2005; Ghirlanda et al. 2012). In this Letter, we aim to interpret all the above four correlations together.[5] The starting point is the extensively discussed speculation that the prompt emission of GRBs is mainly from the photosphere, which suffers significant modification, and its spectrum is normally no longer thermal-like (e.g., Rees & Mészáros 2005; Ioka et al. 2007; Beloborodov 2010; Lazzati et al. 2011; Giannios 2012).

First, we discuss the simplest scenario, in which the luminosity, spectral peak energy, and efficiency of the emission roughly resemble $L_{\rm b}$, $T_{\rm b}$, and $Y_{\rm b}$, where $L_{\rm b}$, $T_{\rm b}$, and $Y_{\rm b}$ are the luminosity, temperature, and efficiency of the photospheric radiation, and $Y_{\rm b}$ and $L_{\rm b}$ are related to the total luminosity L_0 as $Y_{\rm b} = L_{\rm b}/L_0$. In such a scenario, if there are valid correlations among $L_{\rm b}$, $T_{\rm b}$, Γ, and $Y_{\rm b}$, so will there be valid correlations among L, $E_{\rm p}$, Γ, and $\bar{\eta}_\gamma$. For a relativistic baryonic fireball, the acceleration and the subsequent photospheric radiation have been initially investigated by Piran et al. (1993) and by Mészáros et al. (1993). Following these approaches, Fan & Wei (2011) have recently derived the expressions of the initial radius of the accelerated outflow (i.e., R_0) and the final Lorentz factor of the outflow (i.e., Γ)

$$R_0 \propto L_{\rm b}^{1/2} Y_{\rm b}^{3/2} T_b^{-2}, \tag{1}$$

$$\Gamma \propto \left(Y_{\rm b}^{-1} - 4/3\right)^{1/4} L_{\rm b}^{1/8} T_{\rm b}^{1/2}, \tag{2}$$

respectively. For $Y_{\rm b} \ll 1$ (actually even for $Y_{\rm b} = 0.5$, the difference between $(Y_{\rm b}^{-1} - 4/3)^{1/4}$ and $Y_{\rm b}^{-1/4}$ is only by a factor of 1.3), Equation (2) reduces to the form obtained by Pe'er et al. (2007), i.e.,

$$\Gamma \propto Y_{\rm b}^{-1/4} L_{\rm b}^{1/8} T_{\rm b}^{1/2}. \tag{3}$$

As shown in Lü et al. (2012), for the outflow launched via the annihilation of neutrino pairs emitting from a hyper-accreting

[5] Two other highly relevant correlations are the $E_{\rm p}$–$E_{\gamma,\rm iso}$ correlation (Amati et al. 2002) as well as the $E_{\gamma,\rm iso}$–Γ correlation (Liang et al. 2010), where $E_{\gamma,\rm iso}$ is the isotropic energy of the prompt γ-rays. Both of them are interpretable if one takes the duration of the bursts to be roughly constant.

disk, the dimensionless entropy of the initial outflow is related to the total luminosity as $\eta \propto L_0^{k}$ ($k \sim 7/27$ is derived if the poorly understood collimation process is ignored (Lü et al. 2012). In the following derivation we regard k as a "free parameter"). The final Lorentz factor of the accelerated outflow is related to the initial dimensionless entropy as $\Gamma \approx 4(1-4Y_{\rm b}/3)\eta/3$. As long as the thermal radiation is not extremely efficient (say, $Y_{\rm b} \leqslant 0.25$),[6] we approximately have

$$\Gamma \propto L_{\rm b}^{k} Y_{\rm b}^{-k}. \tag{4}$$

Combining Equation (1) with Equation (3), we have

$$\Gamma \propto L_{\rm b}^{1/4} R_0^{-1/4} Y_{\rm b}^{1/8}. \tag{5}$$

Substituting this relation into Equation (4), we have

$$Y_{\rm b} \propto L_{\rm b}^{\frac{8k-2}{1+8k}} R_0^{\frac{2}{1+8k}}. \tag{6}$$

Hence Equations (4) and (1) give

$$\Gamma \propto L_{\rm b}^{\frac{3k}{1+8k}} R_0^{-\frac{2k}{1+8k}}, \tag{7}$$

and

$$T_{\rm b} \propto L_{\rm b}^{\frac{32k-5}{4(1+8k)}} R_0^{\frac{1-4k}{1+8k}}, \tag{8}$$

respectively. Finally we have

$$\Gamma \propto T_{\rm b}^{\frac{12k}{32k-5}} R_0^{-\frac{2k}{(32k-5)}}. \tag{9}$$

So far we have shown that some correlations should be present.

In the current scenario, $E_{\rm p}, L$, and $\bar{\eta}_\gamma$ largely resembles $T_{\rm b}, L_{\rm b}$, and $Y_{\rm b}$, respectively. So if we take $k \sim 0.34$, the expected relations are

$$\Gamma \propto E_{\rm p}^{0.7} R_0^{-0.11}, \quad \Gamma \propto L^{0.27} R_0^{-0.18},$$
$$E_{\rm p} \propto L^{0.4} R_0^{-0.1}, \quad \bar{\eta}_\gamma \propto E_{\rm p}^{0.5} R_0^{0.5}, \tag{10}$$

respectively, which are nicely in agreement with the four correlations summarized in the first paragraph of this section and the only requirement is that R_0 depends on L insensitively. Interestingly, the required $k \sim 0.34$ is close to that ($k \sim 7/27$) found in a simple analytical approach (Lü et al. 2012). Actually, when adopting Equations (18) and (16) of Fan & Wei (2011), we have $\Gamma \approx 400(L/10^{52}\ {\rm erg\ s^{-1}})^{1/4}(Y_{\rm b}/0.2)^{1/8}(R_0/10^8\ {\rm cm})^{-1/4}$ and $E_{\rm p} \approx 260\,{\rm keV}(L/10^{52}\,{\rm erg\,s^{-1}})^{1/4}(Y_{\rm b}/0.2)^{3/8}(R_0/10^8\,{\rm cm})^{-1/2}$, and the coefficients are consistent with those reported in the literature, as long as R_0 is in order of 10^8 cm. These together with the plots in Figure 1 illustrate that the correlations found in the literature (including the normalization) are indeed interpretable within the photosphere model.

Second, we adopt the so-called generic dissipative photospheric model developed by Giannios (2012), in which it is shown that at the radius $R_{\rm eq}$ (see Equation (5) therein), where radiation and electrons drop out of equilibrium, the spectral peak of the prompt emission forms[7] and the Lorentz factor can be expressed as (see Equation (9) therein)

$$\Gamma \propto E_{\rm p}^{3/5} \bar{\eta}_\gamma^{-1/5} L^{1/10} f_\pm^{1/5} (\eta/\Gamma)^{-1/5}, \tag{11}$$

where $f_\pm$ is the number of electron+positron pairs per proton and is expected to be moderate. The acceleration calculation yields $R_{\rm eq} \propto \Gamma R_0 \bar{\eta}_\gamma^{-3/2}$ (e.g., Piran et al. 1993; Fan & Wei 2011), with which we have[8]

$$\Gamma \propto L^{1/4} \bar{\eta}_\gamma^{1/4} R_0^{-3/10} f_\pm^{1/5} (\eta/\Gamma)^{-1/5}. \tag{12}$$

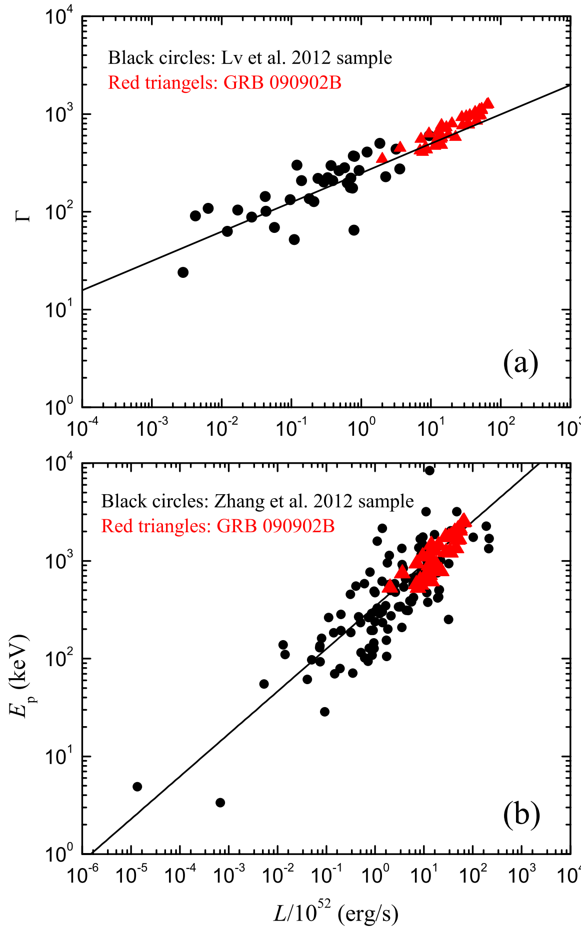

Figure 1. (a) Γ–L diagram for the bursts discussed in Lü et al. (2012; excluding those with a Γ in dispute, for example GRB 090510 and GRB 090328A) and for the time-resolved thermal radiation of GRB 090902B. The solid line is the best-fit $\Gamma \approx 249(L/10^{52}\,{\rm erg\,s^{-1}})^{0.3}$ obtained in Lü et al. (2012). (b) $E_{\rm p}$–L diagram for the bursts investigated in Zhang et al. (2012) and for the time-resolved thermal radiation of GRB 090902B (please note that we have taken $E_{\rm p} = 3.92(1+z)T_{\rm b,obs}$, where $T_{\rm b,obs}$ is the observed temperature). The solid line is the best-fit $E_{\rm p} \approx 302\,{\rm keV}(L/10^{52}\,{\rm erg\,s^{-1}})^{0.4}$ found in Zhang et al. (2012).

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

[6] The GRB efficiency of some bursts is quite high if one takes the energy injection model to account for the early shallowly decaying X-ray afterglow data. Such kinds of models however are usually found to be unable to interpret the simultaneous optical afterglow data, as first pointed out by Fan & Piran (2006). The modeling of the late ($t > 10^4$ s) better-understood afterglow data suggests a typical GRB efficiency of ∼10%–20% (e.g., Fan & Piran 2006).

[7] The "generic" dissipative photospheric model is different from the simplest photosphere model in two main aspects. One is that the electron–positron pairs delaying photosphere have been taken into account. The other is that the peak energy of the emerging spectrum traces the temperature of the outflow at $R_{\rm eq}$ (the optical depth is about tens, see Equation (6) of Giannios 2012) rather than that at the photospheric radius.

[8] Numerically one gets $\Gamma \approx 120(L/10^{52}\,{\rm erg\,s^{-1}})^{1/4}(\bar{\eta}_\gamma/0.2)^{1/4}(R_0/10^8\,{\rm cm})^{-3/10}(f_\pm/5)^{1/5}(\eta/\Gamma)^{-1/5}$ and then $E_{\rm p} \approx 160\,{\rm keV}(L/10^{52}\,{\rm erg\,s^{-1}})^{1/4}(\bar{\eta}_\gamma/0.2)^{3/4}(R_0/10^8\,{\rm cm})^{-1/2}$. These coefficients are comparable with that of the observed correlations as long as $R_0 \sim 10^7$ cm.

With the relation $\eta \propto L^{k}\bar{\eta}_{\gamma}^{-k}$, Equations (11) and (12) give

$$E_{\rm p} \propto L^{\frac{(10k-1)}{6}}\bar{\eta}_{\gamma}^{\frac{(1-5k)}{3}} f_{\pm}^{-1/3}(\eta/\Gamma)^{-4/3} \tag{13}$$

and

$$\bar{\eta}_{\gamma} \propto L^{\frac{(4k-1)}{4k+1}} R_0^{\frac{6}{5(4k+1)}} f_{\pm}^{\frac{-4}{5(4k+1)}} (\eta/\Gamma)^{\frac{-16}{5(4k+1)}}, \tag{14}$$

respectively. Substituting Equation (14) into Equations (12) and (13), we have

$$\Gamma \propto L^{\frac{2k}{4k+1}} R_0^{-\frac{6k}{5(1+4k)}} f_{\pm}^{\frac{4k}{5(4k+1)}} (\eta/\Gamma)^{-\frac{4k+5}{5(4k+1)}} \tag{15}$$

and

$$E_{\rm p} \propto L^{\frac{8k-1}{2(4k+1)}} R_0^{\frac{2(1-5k)}{5(4k+1)}} f_{\pm}^{-\frac{3}{5(4k+1)}} (\eta/\Gamma)^{-\frac{12}{5(4k+1)}}, \tag{16}$$

respectively. As long as the radiation efficiency is not very efficient (say $\bar{\eta}_{\gamma} < 0.25$), one can take $\eta/\Gamma \sim 1$ (Piran et al. 1993; Mészáros et al. 1993). For $k \sim 0.34$ we have

$$\Gamma \propto L^{0.29},\ E_{\rm p} \propto L^{0.37},\ \Gamma \propto E_{\rm p}^{0.78},\ \bar{\eta}_{\gamma} \propto E_{\rm p}^{0.4},$$

which are roughly consistent with the correlations summarized at the beginning of this section.

Both long and short GRBs follow the $E_{\rm p}$–L correlation (Ghirlanda et al. 2009; Zhang et al. 2012) and the $\bar{\eta}_{\gamma}$–$E_{\rm p}$ correlation (Margutti et al. 2012; Bernardini et al. 2012). When taking the peak time of the GeV emission of the short GRB 090510 as the deceleration time of the forward shock, we found that the inferred bulk Lorentz factor also follows the Γ–L correlation. These suggest that the photospheric origin of the prompt emission may also apply to some short bursts.

3. DISCUSSION

Prominent thermal radiation components have been identified in GRB 090902B, a very bright burst at redshift $z = 1.822$ (Abdo et al. 2009; Pandey et al. 2010; Ryde et al. 2010; Zhang et al. 2011; Liu & Wang 2011; Barniol Duran & Kumar 2011; Pe'er et al. 2012). For example, Zhang et al. (2011) divided the whole data set of GRB 090902B into several time bins and showed that the spectrum in each bin can be nicely fitted by a thermal component plus a power-law spectral component. By applying the same technique, we redo the analysis using *Fermi*/GBM data and the newest *Fermi*/LAT PASS7 data. The thermal (blackbody) and non-thermal (power-law) spectral parameters and fluxes are derived in each time bin. Following Pe'er et al. (2007) and Fan & Wei (2011) and assuming a constant thermal radiation efficiency of ∼20%, the bulk Lorentz factors of the outflow shells can be evaluated in a straightforward manner. We plot the inferred Γ together with the simultaneous luminosity in the Γ–L diagram presented by Lü et al. (2012). As shown in Figure 1(a), these two sets of data are in agreement with each other. For most bursts discussed in Lü et al. (2012), the measurement of Γ was based on the modeling of the afterglow light curve(s). The physics involved in such a kind of estimation is completely different from that for GRB 090902B. The agreement between these two sets of data thus not only supports our hypothesis of a photospheric origin of the prompt emission but also validates the robustness of both methods of evaluating Γ. In Figure 1(b) we plot the time-resolved spectral peak energy versus the simultaneous luminosity of GRB 090902B in the $E_{\rm p}$–L diagram presented by Zhang et al. (2012). Again, a nice agreement between these two sets of data is present, in support of the photospheric origin of the prompt emission of some GRBs.

Finally, we would like to point out that all these correlations have not been reasonably interpreted in either the internal shock models or the internal magnetic energy dissipation models (the outflow is magnetic). In the standard internal shock model, one has $E_{\rm p} \propto L^{1/2}\Gamma^{-2}$ (e.g., Zhang et al. 2002; Dai & Lu 2002; Fan & Wei 2005) and we expect no evident positive correlation between $E_{\rm p}$ and the luminosity after taking into account the correlation $\Gamma \propto L^{0.3}$, which is at odds with the data. It is also straightforward to show that the correlation $\Gamma \propto L^{0.3}$ predicts an extremely low internal shock efficiency unless the slow material shell has a width much wider than that of the fast shell (i.e., the duration to eject the slow shell needs to be a factor of $\sim(\Gamma_{\rm f}/\Gamma_{\rm s})^{3.4}$ that of the duration needed to eject the fast shell, where $\Gamma_{\rm f}$ and $\Gamma_{\rm s}$ are the bulk Lorentz factor of the fast and slow shells, respectively). For a magnetic outflow, it was recognized by Lü et al. (2012) that an interpretation of the Γ–L correlation is not yet available, let alone an interpretation of the other correlations. All these facts strongly favor the suggestion that the dominant component of the prompt emission of some GRBs may be tightly relevant to the photospheric radiation process, though much work on getting a spectrum that nicely matches the data is still needed (P. Veres et al. 2012, in preparation).

We thank B. Zhang, D. Giannios, R. Margutti, and M. G. Bernardini for helpful communications and the referee for insightful comments. This work was supported in part by the National Natural Science of China under grants 10973041, 10921063, 11073057, and 11163003, and by the National Basic Research Program of China under grant 2009CB824800. Y.-Z.F. is also supported by the 100 Talents program of the Chinese Academy of Sciences.

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