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 (∼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 many researchers (e.g., Liang et al. 2004; Yonetoku et al. 2004; 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 \( L_b \), \( T_b \), and \( Y_b \), where \( L_b \), \( T_b \), and \( Y_b \) are the luminosity, temperature, and efficiency of the photospheric radiation, and \( Y_b \) and \( L_b \) are related to the total luminosity \( L_0 \) as

\[ Y_b = L_b / L_0 \]

In such a scenario, if there are valid correlations among \( L_b \), \( T_b \), \( \Gamma \), and \( Y_b \), so will there be valid correlations among \( L_0 \), \( E_p \), \( \Gamma \), and \( \eta_p \). 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., \( \Gamma \))

\[ R_0 \propto L_b^{1/2} Y_b^{3/2} T_b^{-2} \]

\[ \Gamma \propto (Y_b^{-1} - 4/3)^{1/4} L_b^{1/8} Y_b^{1/2} \]

respectively. For \( Y_b \ll 1 \) (actually even for \( Y_b = 0.5 \), the difference between \( (Y_b^{-1} - 4/3)^{1/4} \) and \( Y_b^{-1/4} \) is only by a factor of 1.3), Equation (2) reduces to the form obtained by Rees & Mészáros (1992), i.e.,

\[ \Gamma \propto Y_b^{-1/4} L_b^{1/8} T_b^{1/2} \]

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

The tight correlation \( E_p \propto L^{0.5 \pm 0.1} \) 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 \( \Gamma \propto E_p^{0.78 \pm 0.02} \) was identified by Lü et al. (2012) and the correlation \( \Gamma \propto E_p^{0.78 \pm 0.18} \) was suggested by Ghirlanda et al. (2012). Very recently, Margutti et al. (2012) and Bernardini et al. (2012) discovered a tight correlation \( E_p / E_{\gamma} \propto E_p^{0.9 \pm 0.18} \), where \( E_{\gamma} \) is the isotropic equivalent energy of the prompt emission and \( E_b \) is the total energy of the afterglow emission in the X-ray band. In the forward shock afterglow, \( E_p \) is proportional to \( E_b \), the kinetic energy of the outflow (Piran 2004; Zhang & Mészáros 2004). Therefore, \( E_{\gamma} / E_b \propto (E_{\gamma} / E_b) \) is proportional to the GRB efficiency \( \eta_{\gamma} = E_{\gamma} / (E_{\gamma} + E_b) \) as long as \( E_{\gamma} \) is considerably smaller than \( E_b \). Hence, one has \( \eta_{\gamma} \propto E_p^{0.7} \). Some possible interpretations of the \( E_p \propto L \) 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 Two other highly relevant correlations are the \( \eta_{\gamma} \propto E_{\gamma} \) correlation (Amati et al. 2002) as well as the \( E_{\gamma} \propto \Gamma \) correlation (Liang et al. 2010), where \( E_{\gamma} \) is the isotropic energy of the prompt \( \gamma \)-rays. Both of them are interpretable if one takes the duration of the bursts to be roughly constant.
peak of the prompt emission forms\(^7\) and the Lorentz factor can be expressed as (see Equation (9) therein)

\[
\Gamma \propto E_p^{3/5} \tilde{\eta}_{\gamma}^{-1/5} L^{1/10} f_{\pm}^{1/5} (\eta / \Gamma)^{-1/5},
\]

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

\[
\Gamma \propto L^{1/4} \tilde{\eta}_{\gamma}^{-1/4} R_0^{-3/10} f_{\pm}^{1/5} (\eta / \Gamma)^{-1/5}.
\]

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

\(^8\) Numerically one gets \(\Gamma \approx 120L/10^{52} \text{erg s}^{-1} \tilde{\eta}_{\gamma}^{1/4}(\tilde{R}_b/0.2)^{1/4}\) \((R_0/10^8 \text{cm})^{-3/10}(f_{\pm}/S)^{1/5}(\eta / \Gamma)^{-1/5}\) and then \(E_p \approx 160 \text{keV} \left(L/10^{52} \text{erg s}^{-1}\right)^{1/4}\) \((\tilde{R}_b/0.2)^{3/4}(R_0/10^8 \text{cm})^{-1/2}\). These coefficients are comparable with that of the observed correlations as long as \(R_0 \sim 10^7 \text{cm}\).
With the relation $\eta \propto L^{p-1} \tilde{\eta}_\gamma^k$, Equations (11) and (12) give

$$E_p \propto L \frac{10^{(10-1)}}{\tilde{\eta}_\gamma} \frac{10^{k}}{\eta} \beta^1(\eta/\Gamma)^{-4/3}$$

(13)

and

$$\tilde{\eta}_\gamma \propto L \frac{10^{(10-1)}}{R_0} \frac{10^6}{\eta} \beta^4(\eta/\Gamma)^{16/3},$$

(14)

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

$$\Gamma \propto L \frac{10^{\frac{29}{3}}}{\bar{R}_0} \frac{10^6}{\eta} \beta^4(\eta/\Gamma)^{16/3}$$

(15)

and

$$E_p \propto L \frac{10^{(10-1)}}{R_0} \frac{10^6}{\eta} \beta^4(\eta/\Gamma)^{16/3},$$

(16)

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

$$\Gamma \propto L^{0.29}, \quad E_p \propto L^{0.37}, \quad \Gamma \propto E_p^{0.78}, \quad \tilde{\eta}_\gamma \propto E_p^{0.4},$$

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

Both long and short GRBs follow the $E_p$–$L$ correlation (Ghirlanda et al. 2009; Zhang et al. 2012) and the $\tilde{\eta}_\gamma$–$E_p$ 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 $\Gamma$–$L$ 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 $\sim 20\%$, the bulk Lorentz factors of the outflow shells can be evaluated in a straightforward manner. We plot the inferred $\Gamma$ together with the simultaneous luminosity in the $\Gamma$–$L$ diagram presented by Liu 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 Liu et al. (2012), the measurement of $\Gamma$ 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 $\Gamma$. In Figure 1(b) we plot the time-resolved spectral peak energy versus the simultaneous luminosity of GRB 090902B in the $E_p$–$L$ 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 $E_p \propto L^{1/2} \Gamma^{-2}$ (e.g., Zhang et al. 2002; Dai & Lu 2002; Fan & Wei 2005) and we expect no evident positive correlation between $E_p$ 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 $-(\Gamma_f/\Gamma_s)^{3.4}$ that of the duration needed to eject the fast shell, where $\Gamma_f$ and $\Gamma_s$ 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 $\Gamma$–$L$ 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).

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