1 INTRODUCTION

A breakthrough of GRB observation, made by Swift satellite in 2008, is the discovery of the very bright burst GRB 080319B which was accompanied by a naked-eye optical flash (Racusin et al. 2008b). The optical observation was going on even before the onset of the γ-ray burst because TORTORA was monitoring the same region of the sky at that moment (Cwiok et al. 2008; Karpov et al. 2008). The X-ray telescope (XRT) onboard Swift satellite slewed to the source about 60 sec after the trigger of the burst and recorded a quickly decaying but extremely bright X-ray component. These continuous observations collected fruitful data (Racusin et al. 2008b; Bloom et al. 2008) and rendered GRB 080319B one of the best-studied bursts so far. Although no very high-energy emission was directly detected from GRB 080319B the unique spectrum of this burst and its afterglow suggest that it has been accompanied by a very strong GeV-TeV emission that would have already been detected by AGILE if not occulted by Earth at that moment. Based on a model in which the prompt optical and soft γ-ray emission are respectively the synchrotron and the first order inverse Compton (IC) radiation components of the internal shocks, Kumar & Panaitescu (2008), Racusin et al. (2008) and Fan & Piran (2008) suggested that the second order IC of the internal shocks would peak in GeV-TeV energy range and the isotropic energy might be high up to ~ 10^{55} erg (see however Piran, Sari & Zou 2008 and Fan, Zhang & Wei 2009). Because of the tight overlapping of the prompt emission with the reverse/forward shock regions, some soft γ-rays will be up-scattered by the reverse shock electrons and some prompt optical photons will be up-scattered by the forward shock electrons, i.e., the so-called external inverse Compton (EIC). As a result, two additional GeV-TeV emission components with a duration ~ 100 s are expected (Fan & Piran 2008). In this work, we discuss these possibilities in more detail. Moreover, we show that the early (60 ~ 2000 s) forward shock synchrotron and the synchrotron self-Compton (SSC) emission in the energy range 20MeV ~ 300GeV is as powerful as the high energy emission detected in GRB 080916C (Tajima et al. 2008). A schematic plot of the expected GeV-TeV signals from GRB 080319B is shown in Fig.1.

Since its successful launch on June 11 2008, the Fermi satellite has detected the prompt > 10 GeV emission in GRB 080916C (Tajima et al. 2008; Omodei 2008), and the GeV emission following a short burst GRB 081024B (Omodei et al. 2008). As GRB 080514B (Giuliano et al. 2008), GRB 080825C (Bouvier et al. 2008), and some other events detected by the Compton Gamma Ray Observatory (CGRO) satellite in 1991-2000 (Hurley et al. 1994; González et al. 2003), the high energy emission of both GRB 080916C and GRB 081024B lasted longer than the prompt soft γ-
rays. The detection of high energy signals sheds some lights on the bulk Lorentz factor of the ejecta, the radiation mechanisms, the physical composition of the outflow and the prolonged activity of the central engine. This is particularly the case if the simultaneous X-ray/optical emission data are available (see Fan & Piran 2008 for a recent review). In this work we’ll outline the origins of the GeV emission from GRB 080514B, GRB 080916C and GRB 081024B, based on the (preliminary) public data.

The paper is structured as follows. In Section 2, we calculate the possible prompt and afterglow GeV–TeV emission of GRB 080319B. In Section 3, we interpret the high energy emission detected in GRB 080514B, GRB 080916C and GRB 081024B. In section 4, we summarize our results with some discussions.

2 POSSIBLE GEV–TEV EMISSION FROM GRB 080319B

GRB 080319B (Racusin et al. 2008b) was most notable due to its huge total energy and especially its extremely luminous prompt optical emission that could be seen with naked eyes (Ćwiok et al. 2008; Karpov et al. 2008). This burst was located at a redshift $z = 0.937$ space (Vreeswijk et al. 2008) and duration was $\sim 575$ s. The peak energy of the $\nu F_\nu$ spectrum was $E_p \approx 675 \pm 22$ keV, and the photon indexes below and above $E_p$ were $-0.85 \pm 0.014$ and $-3.59 \pm 0.022$ respectively. Choosing standard cosmological parameters $H_0 = 70 \text{km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \Omega_L = 0.7$ (corresponding to a luminosity distance $D_L \approx 1.9 \times 10^{26}$ cm), we have a peak luminosity $L_{\text{peak}} \sim 1.0 \times 10^{53}$ erg s$^{-1}$ and an isotropic energy $E_{\text{iso}} \sim 1.3 \times 10^{54}$ erg (Racusin et al. 2008b; Bloom et al. 2008; Golenetskii et al. 2008; Karpov et al. 2008). Reported the optical V-band ($\sim 6 \times 10^{14}$ Hz) light curve in the prompt phase (from $\sim 10$ s to $\sim 100$ s). Variability was evident and there were at least 3 or 4 main pulses in the light curve. The peak V-band reached magnitude of 5.3, corresponding to a flux density $\sim 28.7$ Jy, and isotropic equivalent energy $E_{\text{opt}} \sim 2 \times 10^{52}$ erg if we take $\sim 20$ Jy as the average flux density. The variability and the very sharp decline of the prompt optical emission support an internal origin of these optical photons, though the underlying physical process is not clear yet (see Zou, Piran & Sarid 2009 for a discussion of various possible models).

Afterglow modeling can in principle constrain the total kinetic energy and the initial Lorentz factor of the GRB ejecta, and the physical parameters of the external shocks (Sari, Piran & Narayan 1998; Chevalier & Li 2000; Panaitescu & Kumar 2001). The behavior of the afterglow of GRB 080319B suggests a free wind medium (Kumar & Panaitescu 2008; Racusin et al. 2008; Wu et al. 2008). A self-consistent modeling of the X-ray and optical afterglow data favors a two-component jet model (Racusin et al. 2008; Wu et al. 2008). Moreover, the shock parameters of the narrow and wide ejecta components need to be very different, as found in GRB 051221A (Jin et al. 2007). Following Racusin et al. (2008) and Wu et al. (2008), we take the isotropic kinetic energy of the narrow ejecta (represented by the subscript “n”) $E_{\text{kin,n}} = 3 \times 10^{55}$ erg, the wind parameter $A_w \sim 0.01$, the fraction of forward shock energy given to the electrons $\epsilon_{e,n} \sim 0.1$, the fraction of forward shock energy given to the magnetic field $\epsilon_{B,n} \sim 10^{-4}$, the power-law index $p_n \sim 2.4$, and the half-opening angle $\theta_{1,n} \sim 0.2$ degree. We do not discuss the wide jet component because it plays a less important role in producing GeV–TeV afterglow emission. The average Lorentz factor of the narrow jet outflow ($\Gamma_t$) before getting decelerated by a stellar wind medium is very high. A lower limit can be set by the Lorentz factor of the forward shock at $\sim 70$ s, when the X-ray afterglow began to decline normally, i.e. (Blandford & McKee 1976; Dai & Lu 1998).

$$\Gamma \approx 600 E_{\text{kin,n},55.5} A_{-2}^{-1/2} (t/70s)^{-1/4} [(1 + z)/2]^{1/4}.$$  

So a choice of $\Gamma_t \sim 1000$ is rather reasonable. Throughout this work we adopt the convenience $Q_x = Q/10^7$ in units of erg.

In the leading fireball model for GRBs (see Piran 2004; Mészáros 2002; Zhang 2007, for reviews), the synchrotron and IC radiation will give rise to a high-energy component that will be emitted along with the prompt sub-MeV photons and the afterglow radio/optical/X-ray emission (Fan & Piran 2008). Depending on the seed photons’ origins, IC can be SSC or EIC. Below we’ll show that for GRB 080319B both processes plausibly played an important role in producing GeV–TeV emission. This suggests that similar bursts will provide promising sources for the Fermi high energy satellite.

\footnote{An $E_{\text{kin},h}$ high up to $\sim 10^{55}$ erg is rather unusual. Similar result has only been reported in the afterglow modeling of GRB 060418 (Fan & Piran 2007). However we believe that such a huge value is possible for GRB 090819B because the XRT flux at $t \sim 70$ s is as bright as $\sim 10^{-7}$ erg cm$^{-2}$ s$^{-1}$, which is the brightest X-ray afterglow detected so far and is even much brighter than most prominent X-ray emission of Swift GRBs. On the other hand both the spectral and the temporal behaviors of the early ($60 - 2000$) s X-ray emission strongly favor a fireball model in the slow cooling phase, which requires small $\epsilon_{B,n}$ and $A_w$. As a result, we do need an $E_{\text{kin},n} \sim 10^{55}$ erg to reproduce the observation data (see footnote 2).}

\footnote{We do not take $\epsilon_{e,B} \sim 10^{-6}$ as in Racusin et al. (2008) (see section 2.3 below) because the peak flux density of the forward shock synchrotron emission is $F_{\text{sync}} \sim \epsilon_{e,B}^{1/2} \epsilon_{B,n}^{3/2} D_L^{1/2} \times 10^{-12}$ Jy. At $t \sim 60$ sec, the X-ray (at 1 keV) flux $\sim 20$ mJy (Bloom et al. 2008) disfavors an $\epsilon_{e,B}$ as small as $\sim 10^{-6}$. On the other hand, an $\epsilon_{e,B} \sim 10^{-6}$ will give rise to a too large cooling Lorentz factor $\gamma c \sim \sqrt{E_{\text{kin},h}/m_{\text{e}}}$, where the forward shock SSC parameter $Y_{\text{SSC}} \ll \sqrt{E_{\text{kin,n}}/m_{\text{e}}}$ since the SSC emission of such energetic electrons should be in Klein-Nishina regime and thus be effectively suppressed.}
2.1 Prompt GeV-TeV IC emission

(Zou, Piran & Sari 2009) showed that the SSC models in which the soft γ-rays are the IC component of the optical photons cannot explain the observations. The major obstacle is the resulting high synchrotron self-absorption frequency and then the X-ray spectrum that is inconsistent with the observation. If we ignore this problem, there is a solution with a Compton parameter $Y \sim 1$ and a stochastic Lorentz factor $\gamma_e \sim 100$. Then the 2nd IC peaks at $2\gamma_e^2E_0 \sim 15$ GeV, and the number of the detectable photons is $N_{\text{det},S_{\text{det}}/4\pi D_L^2h_{\nu}T_{\text{obs},\text{IC}}}$ corresponding to detected ~ 130 photons by LAT, with $S_{\text{det}} \sim 10^{41}$ cm$^2$ at GeV energies. Other models with larger $Y$ lead to even stronger signals (Kumar & Panaitescu 2008, Racusin et al. 2008, Fan & Piran 2008).

As discussed in (Zou, Piran & Sari 2009), too much energy should be hidden either in the high energy component if using the SSC model, or in the low energy component of electrons if we assume the prompt optical emission and γ-rays were from synchrotron emission by two components of electrons in the same region. It indicates that the two different bands of prompt photons should come from different geometrical regions. Below we consider these two different regions (possibly but not necessarily two sets of different internal shocks) within the same outflow cone, denoted by the subscripts ”opt” and ”γ” respectively. Strong high energy prompt emission is still possible, and it can be estimated even though the details of the internal shocks are still unclear. The possible high energy emission consists of four components: self-IC scattering in the optical emission region; self-IC scattering in the γ-ray producing region; optical photons IC scattered in the γ-ray producing region; and soft γ-rays IC scattered in the optical emission region. Note that because of the steep decline of the high energy slope ($\gamma_e \sim 2.6$) extrapolation of the soft γ-ray emission gives only a very weak signal.

2.1.1 Prompt optical emission region

The observed optical flux density limits the temperature of this region (see the Appendix for the derivation):

$$f_{\nu,\text{opt}} \leq \frac{2\nu^2_{\text{opt}}(1+z)^3T_{\text{opt}}kT_{\text{opt}}}{c^2} \left( \frac{R_{\text{opt}}}{\Gamma_{\text{opt}}D_L} \right)^2,$$

where $\Gamma_{\text{opt}}$ is the bulk Lorentz factor, $k$ is Boltzmann constant, $T_{\text{opt}}$ is the temperature (while the minimal temperature $T_{\text{opt},\text{min}}$ corresponds to the equality), and $R_{\text{opt}}$ is the emission region radius. Thus

$$kT_{\text{opt},\text{min}} = 6 \times 10^{-5}T_{\text{opt},3}R_{\text{opt},16}^{-2},$$

where $T_{\text{opt},3}$ is the temperature in units of $10^3$ K.

Noticing that the bulk Lorentz factor in the afterglow is high (Racusin et al. 2008), we take a fiducial value of $\Gamma_{\text{opt}} \sim 10^3$ for the prompt phase. Considering the variability of the light curves and the deceleration radius, which constrains the radius should not be too large, then the choice $10^{16}$ cm is reasonable. The corresponding typical stochastic Lorentz factor of the electrons is

$$\gamma_{e,\text{opt},\text{min}} \sim kT_{\text{opt},\text{min}}/(m_e c^2) \sim 75T_{\text{opt},3}R_{\text{opt},16}^{-2},$$

where $m_e$ is the rest mass of the electron.

The first order IC is in the soft γ-ray band. As mentioned above, before the prompt soft γ-rays are unlikely to be the first order IC component of the optical emission. So the first order IC radiation of the electrons emitting optical photons would be much smaller than the detected soft γ-rays. Correspondingly, the 2nd order IC radiation in GeV-TeV energy range is unimportant as it falls below the IC radiation that arises when the prompt soft γ-rays cross the optical emission region.

2.1.2 γ-rays IC scattered in the prompt optical emission region

If the soft γ-rays pass through the prompt optical emitting electrons, the “optical depth” for electrons is approximately $\sigma_T N_{\text{opt}}(4\pi R_{\text{opt}}^2 ) \sim 3N_{\gamma,60}R_{\text{opt},0.5}^2$, where $\delta_{\text{opt}} \sim 0.3 R_{\text{opt},16}^3\nu_{\text{opt},8}^2$ is the typical variability timescale of the prompt optical emission. For each collision the electron loses energy $\gamma_{e,\text{opt}}u_\nu/T_{\text{opt}} \sim \gamma_{e,\text{opt}}mc^2$ as long as $\gamma_{e,\text{opt}} \leq \Gamma_{\text{opt}}$.

Assuming that almost all electrons carried by the GRB outflow contributed to the prompt optical emission, which should be an upper limit, we estimate the number of electrons that participate in a typical optical pulse (with a variability timescale $\delta t_{\text{opt}}$):

$$N_{\gamma,\text{opt}} \sim \frac{E_{\text{IC},\text{opt}}}{\Gamma_{\text{opt}}m_e c^2 T_{90}} \sim 10^{55}E_{\text{IC},\text{opt},55}R_{\text{opt},-0.5}^{-1}.$$

Using this value we estimate the optical depth for soft γ-rays being scattered by the electrons emitting the prompt optical emission as $\tau \sim \sigma_T N_{\gamma,\text{opt}}/(4\pi R_{\text{opt}}^2) \sim 5 \times 10^{-5}E_{\text{IC},\text{opt},55}R_{\text{opt},-0.5}^{-1}R_{\text{opt},16}^{-2}$.

The total number of the IC photons detectable by LAT is thus

$$N_{\text{det},\gamma_{\text{opt}}} \sim \frac{\tau N_{\gamma,\text{opt}}S_{\text{det}}}{4\pi d_L^2} \leq 100E_{\text{IC},\text{opt},55}R_{\text{opt},-0.5}^{-3}R_{\text{opt},16}^{-2}N_{\gamma,60},$$

where $N_{\gamma}$ is the total number of prompt soft γ-rays. The typical energy of the IC photons is greater than $E_{\text{IC},\gamma_{\text{opt}}} \sim 2\gamma_{\text{opt}}E_{\gamma,90}R_{\text{opt},16}^3$ GeV. The corresponding total energy of these photons is $\sim 5 \times 10^{53}$ ergs.

2.1.3 Soft γ-ray emission region

Since there may be no suitable IC model for the soft γ-rays, we assume that these soft γ-rays are the synchrotron emission at a radius $R_{\gamma}$. To match the peculiar spectrum of the soft γ-rays, the cooling Lorentz factor $\gamma_{e,\gamma} \sim (1+z)^{6}\gamma_{e,\text{opt}}$ should be comparable to the typical Lorentz factor of the electrons $\gamma_{e,\text{opt}}$ (Zou, Piran & Sari 2009), $\sigma_T$ is the Thompson’s cross section and $\delta t_{\gamma} \sim 0.1s$ (Margutti et al. 2008) is the variability timescale of the soft γ-rays. The condition

$$E_{\gamma} \sim \Gamma_{\gamma}^2\gamma_{e,\gamma}^2m_e^2c^3/(1+z)$$

where $\gamma_{e,\gamma}$ is the electron’s charge. The typical Lorentz factor of the emitting electrons is thus

$$\gamma_{e,\gamma} \sim 6 \times 10^5\Gamma_{\gamma,3}^{-1/3}\delta t_{\gamma,1/3}^{-1}$$

This value is relatively too high for internal shocks. However, here we don’t need it come from the internal shocks necessarily. The other energy dissipation mechanisms may produce high $\gamma_{e}$. The SSC will be deep in the Klein-Nishina regime, and pair avalanche effect might exist (Piran, Sari & Zou 2008), additional component of high energy photons would peak around energy $E_{\gamma}^\gamma\sim 4000\Gamma_{\gamma,3}^3$ GeV, where $h$ is the Plank constant.

Using $f_{\nu,\max} = (1+z)N_{\gamma,\gamma}\Gamma_{\gamma}m_e^2c^2\gamma_{e,\gamma}^B/4\pi D_L^2$, we get the number of electrons for each pulse $N_{\gamma,\gamma} \sim 9 \times 10^5\Gamma_{\gamma,3}^{-2/3}\delta t_{\gamma,1/3}$, and the total number of electrons is then $N_{\gamma,\gamma} \sim N_{\gamma,\gamma,60}T_{90}/\delta t_{\gamma} \sim 5 \times 10^{52}\Gamma_{\gamma,3}^{-2/3}\delta t_{\gamma,1/3}^{-1}$.

The corresponding optical depth for Thompson scattering is $\tau \sim \sigma_T N_{\gamma,\gamma}/(4\pi R_{\gamma}^2) \sim 5 \times 10^{-3}$.
And the Compton parameter in KN regime is $Y \sim \gamma_{e,\gamma}^2 \gamma_{\gamma,\gamma}^2 / (\Gamma \Gamma m_e c^2) \sim 0.03 \gamma_{e,\gamma}^2 \Gamma \Gamma \gamma_{\gamma,\gamma}^2 \gamma_{\gamma,\gamma}^2 / (\Gamma \Gamma m_e c^2)$ (Fan, Sari & Zauderer 2008). The total energy of the avalanche loaded pairs is in the order of $2Y E_{\gamma}$, even all the first produced very high energy photons are cooled into steady pairs. The number of detectable photons by LAT is then $\sim 0.1 \gamma_{\gamma,\gamma}^2$. It is thus undetectable even without taking into account the large optical depth ($\sim 10$) of the universe to such energetic photons (Stecker et al. 2006).

2.1.4 Optical photons IC scattered in γ-rays region

If the optical photons are produced in smaller radii than the soft γ-rays ($R_{\gamma} \gg R_{\text{opt}}$), they would be IC scattered in the γ-rays region. In this case, the electrons will be cooled to a random Lorentz factor $\gamma_{e,\gamma} < 1.8 \times 10^4 \gamma_{e,\gamma}^2 \gamma_{\gamma,\gamma}^2 L_{\gamma,\gamma}^{-1} \gamma_{\gamma,\gamma}^2 < \gamma_{e,\gamma}$ (Fan & Piran 2008), where $L_{\gamma,\gamma} > 5 \times 10^{35} \text{erg s}^{-1}$ is the luminosity of the prompt optical emission, suggesting that all the electrons were cooled by the IC scattering. The typical energy of the IC scattered photons is $E_{\text{IC, opt}} \sim 2\gamma_{e,\gamma} h\nu_{\gamma,\gamma} \sim 10 \text{erg} \gamma_{e,\gamma}^3 \gamma_{\gamma,\gamma}^2 \text{GeV}$. Since the electrons lost almost all the energy, the number of the detectable photons by LAT is

$$N_{\text{det, opt}} \sim \frac{E_{\gamma,\gamma} S_{\text{det}}}{4\pi D_L^2 E_{\gamma,\gamma}} \sim 240 \pi^{5/3} \gamma_{\gamma,\gamma}^2 \gamma_{\gamma,\gamma}^2 \dot{m}_{\gamma,\gamma}^{-2/3} \gamma_{\gamma,\gamma}^{-1/3} \quad (8)$$

where $E_{\gamma,\gamma} \sim \Gamma \gamma_{e,\gamma} \gamma_{e,\gamma} m_e c^2$ is the total energy carried by the electrons emitting soft γ-rays.

This discussion is valid only for $R_{\gamma} \gg R_{\text{opt}}$ that is less likely. As long as $R_{\text{opt}} \lesssim \text{few} R_{\gamma}$, the prompt optical emission cannot cool the accelerated electrons emitting soft γ-rays, because the photons from $R_{\text{opt}}$ reach $R_{\gamma}$ in a time $\sim (R_{\text{opt}} - R_{\gamma}) / c \sim 3 \times 10^5 R_{\text{opt},16} \text{sec}$ when the photons at $R_{\gamma}$ had been disappeared long before. For the same reason, there would be no high energy photons produced by the optical region electrons as presented in section 2.1.2 (i.e., $N_{\text{det, opt}} = 0$) if $R_{\gamma} > R_{\text{opt}}$.

2.2 Very early EIC emission

Whatever the mechanism is, the prompt emission should have an internal origin, in view of the high variability of the light curves and the very sharp decline at $t \gg T_{90}$. External reverse-forward shock formed very quickly. Consequently, the prompt photons passing through the reverse-forward shock regions were IC scattered by the shock accelerated electrons. As a result, two additional GeV-TeV EIC components were present.

2.2.1 EIC in reverse shock region

Racusin et al. (2008) and Wu et al. (2008) argued that the reverse shock emission of the narrow jet component had not been seen. Its physical parameters are thus unknown. In some optical flash modeling, the $\epsilon > 3 \text{keV}$ (or/and $\epsilon > 3 \text{keV}$) of RS is found to be much larger than that of the FS (Fan et al. 2002; Zhang, Kobayashi & Meszaros 2003; Kumar & Panaitescu 2003; cf. Nakar & Piran 2005). However, if such a phenomena is popular very bright optical flashes would be frequently detected (McMahon, Kumar & Piran 2006), inconsistent with current optical afterglow observations. For the particular burst GRB 080913B, Racusin et al. (2008) argued that the RS of the wide jet component has an $\epsilon > 0.1$, much larger than that of the corresponding FS. However, if $\epsilon > 0.1$ holds for the RS of the narrow core too, the resulting optical emission would be too strong to match the data (X. F. Wu, 2008, private communication). On the other hand, assuming that these two parameters are the same as those of the forward shock, it is straightforward to show that the RS optical emission of the narrow core is $\sim 0.3 \text{Jy}$ at the crossing time, outshone by the simultaneous prompt emission and consistent with the data. So below we simply assume that the shock parameters of the FS and RS are the same for the narrow jet component.

The reverse shock emission must have overlapped the prompt gamma-rays and optical emission. Therefore the electrons accelerated by the reverse shock front were cooled by the prompt emission and gave rise to an EIC radiation component (Beloborodov 2005; Fan, Zhang & Wei 2005).

The number of electrons in the reverse shock region is

$$N_{\text{det}, r} \sim \frac{E_{\gamma,\gamma}}{\Gamma m_e c^2} \sim 3 \times 10^{55} \frac{E_{\gamma,\gamma}}{\Gamma m_e c^2} \sim 10^{55} \text{erg cm}^{-2} \text{s}^{-1} \quad (9)$$

The typical radius of the reverse shock can be estimated as

$$R_{\gamma} \sim 2 \Gamma^2 c \tau_{90} (1 + z) \sim 5 \times 10^{17} \text{erg cm}^{-2} \text{s}^{-1} \quad (10)$$

The optical depth of the prompt photons being scattered by the electrons was

$$\tau_{\gamma} \sim \frac{N_{\gamma}}{\gamma_{\gamma,\gamma}} \sim 7 \times 10^{-6} \frac{E_{\gamma,\gamma}}{\Gamma m_e c^2} \sim 10^{-6} \text{erg cm}^{-2} \quad (11)$$

On the other hand, the total number of the prompt soft γ-rays that reached us (per area) can be estimated as (Fan & Piran 2006)

$$N_{\gamma, r} \sim \beta_{\gamma}^{-1} \frac{\mathcal{F}}{\mathcal{F}_{\gamma,\gamma}} \quad (12)$$

where $\mathcal{F} \sim 10^{-4} \text{erg cm}^{-2}$ is the energy fluence of the prompt γ-rays and $\beta_{\gamma} \sim 2.6$ is the high energy spectral index of the prompt γ-ray emission.

The number of the reverse shock EIC photons detectable by the Fermi satellite and their typical energy can be estimated as

$$N_{\text{det}, r} \sim \tau_{\gamma} N_{\gamma, r} S_{\text{det}} \sim 3, \quad (13)$$

and

$$h\nu_{\text{EIC, r}} \sim 2 \gamma_{e,\gamma}^2 \tau_{90} \sim 13 \text{GeV} \left(\frac{\gamma_{e,\gamma}}{100}\right)^2, \quad (14)$$

where $\gamma_{e,\gamma}$ is the minimal Lorentz factor of the electrons accelerated in the reverse shock front. The electrons are in slow cooling phase since the cooling Lorentz factor is (Fan & Piran 2008)

$$\gamma_{e,\gamma} \sim 10^3 \frac{10^7 T_{17,2} R_{17,7} L_{17,7}^{-1}}{\gamma_{e,\gamma}} \quad (15)$$

The Compton parameter $Y_{\text{EIC, r}} \geq \gamma_{e,\gamma}^2 \tau_{90} \sim 1$. So the energy of this EIC component was much smaller than that of the prompt soft γ-rays.

Here we do not take into account the cooling caused by the synchrotron radiation because $U_{\gamma} \sim \gamma_{e,\gamma}^2 AR_{\gamma}^{-2} \sim 3 \times 10^{-3} \gamma_{e,\gamma}^2 \gamma_{\gamma,\gamma}^2 \gamma_{\gamma,\gamma}^2 \text{erg cm}^{-3}$, which is much smaller than $U_{\gamma} \sim \gamma_{e,\gamma}^2 \gamma_{\gamma,\gamma}^2 \gamma_{\gamma,\gamma}^2 \text{erg cm}^{-3}$.

\footnote{\textsuperscript{3}By the time a single photon passes through a sub-shell, this sub-shell expands by a factor of $\sim 2$ in radius. Therefore subsequent scattering in other sub-shells will be negligible and when considering the optical depth a single sub-shell should be taken into account.}$^3$
Some prompt optical photons will be up-scattered by the reverse shock electrons and will be boosted to an energy \( \sim 2\gamma_{m,t} h\nu_{opt} \sim 10\text{ keV} \), which is too low to be of interest.

2.2.2 EIC in forward shock region

The prompt emission will cool the forward shock electrons as well (Fan, Zhang & Wei 2005; Wang & Mészáros 2006). However, for the prompt \( \gamma \)-rays, this EIC process is unimportant since it is in the Klein-Nishina regime. Because the large radius lowers the optical depth, pair avalanche does not exist in this case. Here we focus on the EIC radiation of the prompt optical emission. The energy density of the emitted prompt photons is \( U_{opt} \sim \frac{L_{opt}}{4\pi R^2} \sim 0.05\; L_{opt,51}\gamma_{2,7}^2 R_{17,7}^2\text{erg cm}^{-3} \), which is larger than \( U_B \). So the cooling of the forward shock electrons is dominated by the EIC process.

The number of the electrons swept by the forward shock is

\[
N_{e,t} \approx 4\pi AR \simeq 1.8 \times 10^{52} A_{8,2} R_{17,7}. \tag{16}
\]

The optical depth of the prompt photons for being scattered is thus

\[
\tau_\gamma \approx \frac{N_{e,t}}{\pi R^2} \sim 3 \times 10^{-9} A_{8,2} R_{17,7}^{-1}. \tag{17}
\]

Noticing that we don’t know the spectrum in the optical band, we can only evaluate the lower limit by taking the observed optical emission as the peak. The total number of the optical photons reaching us (in unit area) can be estimated as

\[
N_{\text{tot, opt}} \approx \frac{F_{opt}}{h\nu_{opt}} \sim 10^{6}\text{cm}^{-2}. \tag{18}
\]

where \( F_{opt} \) is the fluence of the prompt optical emission.

For Fermi, the detectable number of the forward shock EIC radiation can be estimated as

\[
N_{\text{det,f}} \approx \tau_\gamma N_{\text{tot, opt}} S_{\text{det}} \sim 30. \tag{19}
\]

Usually for an integration time \( t_{\text{int}} \lesssim 10^7 \text{ sec} \), LAT needs 5 high energy photons to claim a significant detection (e.g., Zhang & Mészáros 2001; Fan, Zhang & Wei 2005). With a duration of 120 s, and for the typical energy of \( \sim 10\text{ GeV} \), this detection corresponds to \( 8 \times 10^{-5}\text{erg s}^{-1}\text{cm}^{-2} \). We plot such a threshold in Fig. 2, and find out that the forward shock EIC emission component is detectable in \( \sim 100\text{ s} \), longer than the prompt soft gamma-ray emission.

The typical energy of these forward shock EIC photons is

\[
h\nu_{EIC,f} \sim 2 \min\{\gamma_{C,f}^2, \gamma_{m,f}^2\} h\nu_{opt} \sim 10\text{ GeV}, \tag{20}
\]

where \( \gamma_{C,f} \sim 10^3\gamma_{2,8} R_{17,7}^{1/3}L_{opt,51}^{-1} \) and \( \gamma_{m,f} \sim 4 \times 10^4\Gamma_{2,8} \).

The Compton parameter \( Y_{EIC,f} \sim \gamma_{m,f}^2 \tau_\gamma \sim 10 \). As the emitted energy of the optical photons was \( 3 \times 10^{51}\text{ergs} \) (isotropic), the total energy of the EIC photons by forward shocked electrons is \( \sim 3 \times 10^{53}\text{ergs} \).

In the rest frame of the forward shock, the seed optical photons have a typical energy \( \sim \gamma_{e,f} h\nu_{opt}/\Gamma < m_e c^2 \) for \( \gamma_e < 10^3\gamma_{2,8} \). The EIC scattering in the forward shock front is well in the Thompson regime. The resulting spectrum for \( \nu < \nu_{EIC,f} \) is expected to be not steeper than \( F_\nu \propto \nu^{-p/2} \sim \nu^{-1.2} \). On the other hand, the absorption depth for a 30 GeV photons from a redshift \( z \sim 1 \) is only about 1 (Stecker, Malkan & Scully 2000). We expect that, if Fermi worked at that moment, it could have detected some photons as energetic as \( \sim 30\text{ GeV} \).

Though very bright optical flashes from GRBs are very rare, a few such events are still possible during Fermi’s 10 years of operation. Since the EIC component from the forward shock region can give rise to a significant detection for a Fermi-like satellite, here we use the numerical code by Fan et al. (2008) for a more detailed estimate. For simplicity, we approximate the prompt optical emission flux by \( F = 10^{-5}(t/10)^6\text{erg s}^{-1}\text{cm}^{-2} \) for \( t < 10\text{ sec} \), a constant plateau lasting till \( t \sim 60\text{ sec} \), and \( F = 0 \) afterward. The optical spectrum is set as a typical Band function (Band et al. 1993), for which (the break energy, the low energy spectral index, the high energy spectral index) are taken as \( \begin{array}{ccc} 2 \text{ eV}, & -1, & -2.25 \end{array} \), respectively. Notice that it is also a lower limit, as we take the V band as the peak. As shown in Fig. 2, the forward shock EIC emission lasts about twice that of the prompt emission. This is because the duration of the high-energy emission is affected by the spherical curvature of the blast wave (Beloborodov 2005) and is further extended by the highly anisotropic radiation of the up-scattered photons (Fan & Piran 2006; Wang & Mészáros 2006). We also find out that the total energy of the EIC emission is about 10 times that of the prompt optical emission, consistent with our analytical estimate.

2.3 The late GeV-TeV emission of the external forward shock

The high energy emission of the external forward shock has been extensively discussed in literature since 1994 (Mészáros & Rees 1994; Dermer, Chiang & Mitman 2000; Sari & Esin 2001; Wang, Dai & Lu 2001; Zhang & Mészáros 2001; Fan et al. 2008). GRB 080319B is distinguished from most bursts by its huge \( E_k \), and by the large contrast between \( \epsilon_{e,n} \) and \( \epsilon_{e,B} \), both indicating a very strong high energy radiation component.

In the very early afterglow phase (\( t \lesssim 60\text{ s} \)), the Lorentz factor of the forward shock is almost a constant. The typical Lorentz factor of the shocked electrons is \( \gamma_{m} \sim 4 \times 10^4 \epsilon_{e,n,-1}\Gamma_{2,8} \).

After that, the forward shock forms a self-similar profile and its Lorentz factor can be estimated as

\[
\Gamma \sim 310(1 + z)^{1/4} E_{k,55.5}^{1/4} A_{1/2,4}^{-1/4}. \tag{21}
\]
The typical Lorentz factor of the shocked electrons is
\[ \gamma_m \sim 2 \times 10^4 (1 + z)^{1/4} \epsilon_{e,n}^{-1/4} \epsilon_{k,n,55.5}^{-1/4} A_{-2/3}^{-1/4}. \] 

At this stage, the forward shock is in the slow cooling phase (Racusin et al. 2008), and \( \nu_m < \nu_c < \nu_{\text{BAT}} < \nu_c \), where \( \nu_{\text{BAT}} \sim 10^{20} \text{ Hz} \) is the frequency of the BAT detector onboard Swift satellite and \( \nu_c \) is the cooling frequency\(^5\). On the other hand, \( \Gamma \epsilon_{c,1/2} \sim \epsilon_{m,2}^{1/2} / \gamma_m \sim m_2^{1/2} / 100 > 10^{18} \text{ Hz} < \nu_c \), implying that the SSC emission of the electrons with a Lorentz factor \( \sim \gamma_c \) is in extreme Klein-Nishina regime and it is effectively suppressed. So we expect that the SSC emission will peak at an energy
\[ h\nu_p^{\text{SSC}} \sim \Gamma \gamma_m \epsilon_{m,2} c^2 \sim 2.3 \left( \frac{1+z}{2} \right) \epsilon_{e,1/2} \epsilon_{k,n,55.5} A_{-2/3}^{-1/2} \gamma_{-2/3}^{-1/2} \text{ TeV}, \] 
for the late afterglow. The SSC emission of the forward shock in the very early afterglow phase overlap with the GeV-TeV emission of the prompt phase and is very likely to be outshone. Below we just discuss the SSC emission of the forward shock in the normal decline phase \((t > 60 \text{ sec})\).

To check our estimate, we calculate numerically with Fan et al.’s code (2008) the forward shock emission spectrum. As shown in Fig.3, the SSC emission peaks at TeV energies, with a fluence \( \sim 6 \times 10^{-6} \text{ erg cm}^{-2} \), and an isotropic energy \( \sim 3 \times 10^{52} \text{ erg} \). The detection of the TeV emission is beyond the scope of the Fermi satellite. Ground based Cherenkov telescopes, like MAGIC and H.E.S.S, may be suitable to detect these energetic signals. However, before reaching us, these TeV photons would have been absorbed by the infrared background photons, and such emission could be seen only from rare very nearby sources.

We find in Fig.3 that for a Fermi-like satellite the MeV-GeV synchrotron radiation of the forward shock may give rise to a detectable signal. In our calculation, we take a maximal Lorentz factor of the shocked electrons \( \gamma_M \sim 4 \times 10^6 B_1^{-1/2} \) (Cheng & Wei 1996), where \( B \) is the magnetic field generated in the shock front. This leads to the synchrotron GeV cutoff (see Fig.3). As a numerical example, following Fan et al. (2008), we take a real effective area of LAT and integrate the spectrum over the frequencies to estimate the number of detectable photons. For this particular example, the LAT onboard Fermi can detect \( \sim 400 (\sim 20 \text{ MeV}) \), \( \sim 20 (\sim 1 \text{ GeV}) \), and \( \sim 0.1 (\sim 10 \text{ GeV}) \), without the correction due to the absorption by the infrared background photons) high energy photons. This would be a very exciting detection.

**3 ORIGINS OF GEV EMISSION OF SOME RECENT GRBS**

Recently high energy emission has been detected by AGILE: GRB 080514B (Giuliani et al. 2008), and by Fermi: GRB 080825C (Bouvier et al. 2008), GRB 080916C (Tajima et al. 2008) and GRB 081024B (Omodei et al. 2008). We can apply the above considerations for GRB 080319B to all these bursts, though the very early

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\(^5\) For \( \nu > \nu_c \), the synchrotron radiation spectrum is \( \propto \nu^{-3/2} \). On the other hand, the maximum synchrotron radiation frequency \( \nu_{\text{MAX}} \sim 30 \alpha / (1 + \alpha) \text{ MeV} \) (Cheng & Wei 1996) is up to a few GeV for \( \Gamma \geq 300 \). It is straightforward to show that the fluorescence of the high energy afterglow emission in the energy range of LAT is in order of \( 10^{-5} \text{ erg cm}^{-2} \), comparable to the fluence of the soft X-ray-\(\gamma\)-ray afterglow emission. Such a conclusion is almost independent of the afterglow models.
The peak luminosity is thus as high as $\sim 5 \times 10^{53}$ erg s$^{-1}$. The typical variability timescale is suggested to be as long as $\sim 2 \times 10^3$ sec (Abdo et al. 2009). With these information, the detection of > 10 GeV prompt emission gives a tight constraint on the initial bulk Lorentz factor of the GRB outflow, i.e. (Lithwijk & Sari 2001; Fan & Piran 2008; Gupta & Zhang 2008),

$$\Gamma_1 > 400 \left( \frac{\nu_{\text{cut}}}{1 \text{ GeV}} \right)^{0.4 \pm 0.1} \left( \frac{\nu_0}{10^{15} \text{ Hz}} \right)^{-0.4 \pm 0.1}.$$\

Using the maximal synchrotron radiation frequency of the shocks $\nu_{\text{sh}} \approx 30 \nu_0^6/(1 + z)$ GeV (Cheng & Wei 1996), we find that if the high energy emission up to $\sim 10$ GeV is attributed to the synchrotron radiation of internal shocks, the initial Lorentz factor should satisfy:

$$\Gamma_1 \approx \frac{1 + z}{5.5} \frac{\nu_{\text{cut}}}{1 \text{ GeV}}.$$\

A $\Gamma_1$ much higher than 2000 is unlikely. So this strongly suggests that the internal shocks can accelerate high energy particles (both protons and electrons) very efficiently and the highest energy of electrons is limited by the loss via synchrotron radiation. The energy distribution index of the shock-accelerated electrons ($p \sim 2.4$) is also close to that predicted in the theory. This is a very encouraging news for the people interested in the ultra-high energy particle acceleration in GRBs. However, we’d like to caution that it is only the case among the 70 events observed so far by Fermi (Abdo et al. 2009). It might be too early to say more at this moment.

The internal shock synchrotron radiation cannot account for the delayed high energy emission (Abdo et al. 2009). The possible mechanisms that can produce this emission are (i) the EIC emission from the reverse-forward shock regions, (ii) the SSC emission of the forward shock and (iii) SSC emission of the weak internal shocks powering an extended X-ray emission component that is below the threshold of GBM.

The spectrum of the $\gtrsim 100$ MeV emission in the time interval $\sim 200 - 1400$ sec is $F_\nu \propto \nu_0^{1.8 \pm 0.5}$ (Abdo et al. 2009). Such a soft spectrum imposes a tight constraint on the models. In the standard afterglow model, the late time infrared and X-ray afterglow (Greiner et al. 2009) can only be interpreted as the forward shock emission of an ejecta expanding into a weak stellar wind. Like in GRB 080319B, an $\Lambda_0 \sim 0.01$ is needed to have a cooling frequency above the XRT energy range at $t \gtrsim 1$ day (Gao et al. 2009, in preparation). An electron energy distribution index $p \sim 2.2$ can reproduce both the infrared to X-ray spectrum $F_\nu \propto \nu_0^{-0.63}$ and the X-ray (infrared) afterglow decline $\propto t^{-1.29\pm 0.09}$ ($t^{-1.40\pm 0.05}$). The spectrum of the SSC or the EIC emission of the forward shock should have a spectrum not steeper than $\nu^{-p/2} \gtrsim \nu^{-1.1}$, and can only marginally match the data. So we prefer the possibility (iii). For the X-ray emission powered by the prolonged activity of the central engine, the SSC emission can peak at an energy $\lesssim 550 [1/(1 + z)/5.5]$ MeV (see section 5.1 of Fan et al. 2008 for details). In this case, the electron energy distribution index is irrelevant to that of the afterglow electrons and can be as large as $\sim 3$, as found in the spectrum analysis of X-ray flares (Butler & Kocevski 2007). As a result, the soft spectrum of the delayed $> 100$ MeV emission may be interpreted.

The LAT saw the emission from this source up to 3 GeV, in the first 5 seconds after the trigger. Here we consider two possible interpretations. One is that the delayed emission is the SSC component of an extended/prompt soft X-ray emission. Following Fan & Piran (2008; see their eqs.(47-49)), the typical frequency of the internal shock SSC emission can be estimated as

$$\nu_{\text{in}} \approx 75 \text{ MeV} \left( \frac{\nu_0}{0.3 \text{ keV}} \right)^2 R_{\text{int,14}} L_{X,40}^{-1/2} (1 + Y_{\text{sec}})^{1/2},$$\

where $R_{\text{int}}$ is the radius of the continued but weak internal shocks that power the underlying prompt X-ray emission with a luminosity $L_X$ and $Y_{\text{sec}}$ is the SSC parameter of the internal shocks. This model requires an unmagamnetized outflow launched by the continued activity of the central engine, in contradiction with most models proposed so far (see Zhang 2006 for a review). If confirmed, a stringent constraint on the nature of the extended emission following short GRBs will be established. So, in principle, the cooperation of Swift and Fermi satellite can reveal the nature of the late outflow powering the extended emission. The other possible origin of the delayed high energy emission is the SSC emission of the forward shock. It is straightforward to show that the outflow with an initial Lorentz factor $\Gamma_1 \approx 400$ gets decelerated in the interstellar medium with a number density $\sim 1 \text{ cm}^{-3}$ in $\sim 5$ sec. The typical SSC emission frequency of the forward shock can be estimated as

$$h\nu_{\text{in}} \approx 25 \text{ GeV} \left[ \frac{\epsilon_{\nu}}{1_{\text{MeV}}} \right]^{1/2} \left[ \frac{13(p - 2)}{3(p - 1)} \right]^{1/2} \left[ \frac{E_{\text{iso}}}{54.1} \right]^{-9/4}.$$\

One may be able to distinguish between the above two scenarios by analyzing the spectrum. If the delayed high energy emission is the SSC component of extended but weak internal shocks, the 0.1 – 3 GeV spectrum is expected to be steeper than $\nu^{-1}$. If the delayed high energy emission is the SSC component of external forward shock, the 0.1 – 3 GeV spectrum is expected to be $\nu^{-1/2}$ unless $p \sim 2$. The forward shock synchrotron radiation can also give rise to GeV emission. It is, however, difficult to say more concerning this possibility because the early afterglow physics of short GRBs is still poorly understood.

4 CONCLUSIONS AND DISCUSSIONS

High-energy emission provides a new window into prompt emission/afterglow physics and can provide an independent test of models. Motivated by this, we calculate the possible high-energy prompt/afterglow emission in GRB 080319B that was distinguished by a naked-eye optical flash and by an unusual strong early X-ray afterglow. Two possible GeV-TeV emission components may be related to the naked-eye optical flash. The first is the Inverse Compton scattering of the prompt optical photons by electrons producing the soft $\gamma$-rays. The second is the very early EIC emission from the forward shock region when the prompt optical emission overlaps the shock front. The difference is their duration. The former is expected to be simultaneous with the prompt soft $\gamma$-ray emission while the latter lasts longer (see Fig. 2). The synchrotron radiation of the forward shock can give rise to a significant detection, too (see Tab. I for a summary). This component may be more common than the two that depend on a strong optical flash as which is quite rare. The detection prospect of the forward shock synchrotron
radiation by LAT is fairly good. For the Swift GRBs detected so far, GRBs 060105, 061007, 070419B and 080721 have a $0.3 - 10$ keV flux $\sim 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ at $t \sim 100$ s after the trigger (http://www.swift.ac.uk/xrt_curves/). Evans et al. (2007). Though about one order of magnitude lower than that of GRB 080319B, they are strong enough to produce a GeV synchrotron emission detectable by LAT as long as the synchrotron spectrum can indeed extend to an energy $\sim 30\Gamma / (1 + z)$ MeV. The forward shock SSC emission of these very bright events may be more suitable for the ground-based Cherenkov telescopes, like MAGIC or H.E.S.S.

In section 3, we discussed the possible physical origin of the high energy emission of GRB 080514B, GRB 080916C and GRB 081024B. We find that these detections can be generally understood by the synchrotron and inverse Compton radiation of the internal shocks or external shocks. For example, the delayed sub-GeV flash detected in GRB 080514B may be the EIC emission from the reverse shock region and the prompt GeV-emission of GRB 080916C may be dominated by the synchrotron radiation of the internal shocks. The “long lasting” high energy emission detection in the short burst GRB 081024B may be attributed to the SSC emission of the decelerated forward shock or the internal shocks powering an extended X-ray component which is below the threshold of GBM. However, as lack of detailed observations, it is difficult to draw a firm conclusion.

Finally we focus on the common feature that the high energy emission usually lasts longer than the prompt soft $\gamma$-rays, as detected in GRB 080514B, GRB 080916C and GRB 081024B. Such a phenomena, peculiar in pre-afterglow era, may be explained as: (1) The synchrotron and the SSC emission of the long lasting forward external shock can contribute to the high energy emission significantly. (2) The GRB central engines usually do not turn off abruptly. The SSC emission of the continued but weak internal shocks may peak at GeV energies. (3) If a (mildly) relativistic reverse shock formed, the prompt optical/X-ray/$\gamma$-rays photons overlap the external shock fronts tightly and cool the accelerated electrons effectively. This process will produce a GeV emission component with a duration about twice that of the prompt photons. For a sub-relativistic reverse shock, the prompt soft $\gamma$-ray photons exceed the external shock fronts quickly. Its effect on cooling the reverse/forward shock electrons can be ignored. However in such a case the electrons/protons accelerated in reverse shock contain just $\lessapprox 10\%$ of the total energy of the GRB ejecta (Nakar & Piran 2004) and cannot play an important role in producing high energy emission. (4) The EIC in the late afterglow phase caused by X-ray flares can also give rise to GeV emission. However the luminosity is lowered since its duration has been significantly extended. Usually LAT is unable to catch such a weak signal.

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**Table 1.** The expected emission of high energy photons (mostly inverse Compton scattering) from different origins for GRB 080319B, which should be detectable by LAT onboard Fermi satellite.

| Seeds | region for electrons | duration (s) | typical photon energy (GeV) | detectable photons |
|-------|----------------------|--------------|-----------------------------|-------------------|
| $\gamma$-rays | prompt opt | $\sim 60$ | $\gtrsim 8$ | $\lesssim 100$ |
| opt | prompt $\gamma$-ray | $\sim 60$ | $\sim 15$ | $\sim 240$ $^1$ |
| $\gamma$-rays | reverse shock | $\sim 10^2$ | $\sim 13$ | $\sim 3$ |
| opt | forward shock | $\sim 10^2$ | $\sim 10$ | $\sim 30$ |
| afterglow (Synchrotron) | $\sim 10^3$ | $0.01-0.1$ | $\sim 400$ |
| afterglow external shock | $\sim 10^3$ | $\lesssim 10^3$ | $\lesssim 0.04$ $^2$ |

$^1$This case is less likely, and possibly alternates with the former case.

$^2$Supposing an instrument with effect area $10^3$ cm$^2$ and without considering the absorption on the way to the observer.

Mimica et al. (2008) and can not play any important role in producing high energy emission. (4) The EIC in the late afterglow phase caused by X-ray flares can also give rise to GeV emission. However the luminosity is lowered since its duration has been significantly extended. Usually LAT is unable to catch such a weak signal.
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