HIGH-ENERGY EMISSION OF GRB 130427A: EVIDENCE FOR INVERSE COMPTON RADIATION

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Received 2013 May 20; accepted 2013 August 16; published 2013 October 3

ABSTRACT

A nearby superluminous burst GRB 130427A was simultaneously detected by six \(\gamma\)-ray space telescopes (\textit{Swift}, the \textit{Fermi} GLAST Burst Monitor (GBM)/Large Area Telescope, Konus-Wind, SPI-ACS/\textit{INTEGRAL}, AGILE, and RHESSI) and by three RAPTOR full-sky persistent monitors. The isotropic \(\gamma\)-ray energy release is \(\sim 10^{53}\) \(\text{erg}\), rendering it the most powerful explosion among gamma-ray bursts (GRBs) with a redshift \(z > 100\). The high-energy \(\gamma\)-ray emission properties of gamma-ray bursts (GRBs) can help us to better understand the physical composition of the GRB outflow, the radiation mechanisms, and possibly also the underlying physical processes shaping the early afterglow (see Fan & Piran 2008 and Zhang & Mészáros 2004 for reviews). For example, the inverse Compton radiation from GRB forward shocks can extend to the very high energy (\(\gamma_{\nu} > 50\) GeV) range (Dermer et al. 2000; Sari & Esin 2001; Zhang & Mészáros 2001; Fan et al. 2008), while the synchrotron radiation can only give rise to emission up to \(\sim 10\) GeV \((T/100)(1 + z)^{-1}\), where \(T\) is the bulk Lorentz factor of the GRB blast wave and drops with time quickly. Therefore, the detection of very high energy emission of GRBs at a fairly early time can impose a very tight constraint on the radiation mechanism. However, very high energy photons are rare and are attenuated by the cosmic infrared/optical background before reaching us. Xue et al. (2009) investigated the detection prospect of very high energy emission of GRBs and found that with current ground-based Cerenkov detectors, only for those very bright and nearby bursts like GRB 030329 is detection of very high energy photons possible under favorable observing conditions and for a delayed observation time of \(\lesssim 10\) hr. Very bright and nearby bursts are very rare, and for the ground-based detectors the observation conditions are not under control. That is why so far no positive detection of very high energy emission from GRBs by the ground-based Cerenkov detectors has been reported (e.g., Albert et al. 2007; Horan et al. 2007; Aharonian et al. 2009; Jarvis et al. 2010; Acciari et al. 2011). In comparison with the ground-based Cerenkov detectors, space telescopes such as EGRET on board the \textit{Compton Gamma Ray Observatory}, GRID on board AGILE, and the Large Area Telescope (LAT) on board the \textit{Fermi} satellite have a much smaller effective area. However, these telescopes have a low-energy threshold \(\sim\) tens MeV and can monitor the high-energy emission since the trigger of some GRBs when the high-energy emission flux is expected to be much higher than that at late times. Since 1994, tens of GRBs with high-energy emission have been reported. In the pre-\textit{Fermi}-LAT era, the record of the most energetic \(\gamma\)-ray from GRBs is the \(\sim 18\) GeV photon following GRB 940217 (Hurley et al. 1994). The most energetic photon detected by \textit{Fermi}-LAT up through 2013 March is the 33.4 GeV \(\gamma\)-ray from GRB 090902B at a redshift \(z = 1.822\) (Abdo et al. 2009b, 2013). Such a record has been broken by GRB 130427A, a burst simultaneously detected by \textit{Swift} (Maselli et al. 2013), the \textit{Fermi} Gamma-Ray Telescope (Zhu et al. 2013a; von Kienlin et al. 2013), Konus-Wind (Golenetskii et al. 2013), SPI-ACS/\textit{INTEGRAL} (Pozanenko et al. 2013), AGILE (Verrecchia et al. 2013), RHESSI (Smith et al. 2013), and three RAPTOR full-sky persistent monitors (Wren et al. 2013). The highest energy LAT photon has an energy of \(\sim 90\) GeV (Zhu et al. 2013a). The redshift of this burst was measured to be \(0.3399 \pm 0.0002\) supported by the Chinese Academy of Sciences (Grant No. 11C01210200).

1. INTRODUCTION

The high-energy (\(\geq 100\) MeV) emission properties of gamma-ray bursts (GRBs) can help us to better understand the physical composition of the GRB outflow, the radiation mechanisms, and possibly also the underlying physical processes shaping the early afterglow (see Fan & Piran 2008 and Zhang & Mészáros 2004 for reviews). For example, the inverse Compton radiation from GRB forward shocks can extend to the very high energy (\(\gamma_{\nu} > 50\) GeV) range (Dermer et al. 2000; Sari & Esin 2001; Zhang & Mészáros 2001; Fan et al. 2008), while the synchrotron radiation can only give rise to emission up to \(\sim 10\) GeV \((T/100)(1 + z)^{-1}\), where \(T\) is the bulk Lorentz factor of the GRB blast wave and drops with time quickly. Hence, at \(t > 10^2\) s, usually we do not expect tens of GeV \(\gamma\)-rays coming from the synchrotron radiation of the forward shock. Therefore, the detection of very high energy emission of GRBs at a fairly early time can impose a very tight constraint on the radiation mechanism. However, very high energy photons are rare and are attenuated by the cosmic infrared/optical background before reaching us. Xue et al. (2009) investigated the detection prospect of very high energy emission of GRBs and found that with current ground-based Cerenkov detectors, only for those very bright and nearby bursts like GRB 030329 is detection of very high energy photons possible under favorable observing conditions and for a delayed observation time of \(\lesssim 10\) hr. Very bright and nearby bursts are very rare, and for the ground-based detectors the observation conditions are not under control. That is why so far no positive detection of very high energy emission from GRBs by the ground-based Cerenkov detectors has been reported (e.g., Albert et al. 2007; Horan et al. 2007; Aharonian et al. 2009; Jarvis et al. 2010; Acciari et al. 2011). In comparison with the ground-based Cerenkov detectors, space telescopes such as EGRET on board the \textit{Compton Gamma Ray Observatory}, GRID on board AGILE, and the Large Area Telescope (LAT) on board the \textit{Fermi} satellite have a much smaller effective area. However, these telescopes have a low-energy threshold \(\sim\) tens MeV and can monitor the high-energy emission since the trigger of some GRBs when the high-energy emission flux is expected to be much higher than that at late times. Since 1994, tens of GRBs with high-energy emission have been reported. In the pre-\textit{Fermi}-LAT era, the record of the most energetic \(\gamma\)-ray from GRBs is the \(\sim 18\) GeV photon following GRB 940217 (Hurley et al. 1994). The most energetic photon detected by \textit{Fermi}-LAT up through 2013 March is the 33.4 GeV \(\gamma\)-ray from GRB 090902B at a redshift \(z = 1.822\) (Abdo et al. 2009b, 2013). Such a record has been broken by GRB 130427A, a burst simultaneously detected by \textit{Swift} (Maselli et al. 2013), the \textit{Fermi} Gamma-Ray Telescope (Zhu et al. 2013a; von Kienlin et al. 2013), Konus-Wind (Golenetskii et al. 2013), SPI-ACS/\textit{INTEGRAL} (Pozanenko et al. 2013), AGILE (Verrecchia et al. 2013), RHESSI (Smith et al. 2013), and three RAPTOR full-sky persistent monitors (Wren et al. 2013). The highest energy LAT photon has an energy of \(\sim 90\) GeV (Zhu et al. 2013a). The redshift of this burst was measured to be \(0.3399 \pm 0.0002\) supported by the Chinese Academy of Sciences (Grant No. 11C01210200).
Table 1
The Observational Properties of Low-redshift GRBs ($z < 0.5$)

| GRB          | $\xi$ | $E_{\text{peak}}$ (keV) | $E_{\gamma,\text{iso}}$ ($10^{51}$ erg) | Ref. |
|--------------|-------|-------------------------|----------------------------------------|------|
| 990712       | 0.434 | 93 ± 15                 | 6.7 ± 1.3                              | 1    |
| 980425       | 0.0085| 122 ± 17                | 9 × 10^{-4}                            | 2    |
| 010921       | 0.45  | 129 ± 26                | 9.5 ± 1                                | 1    |
| 011121I      | 0.36  | 1060 ± 265              | 78 ± 21                                | 1    |
| 020819B      | 0.41  | 70 ± 21                 | 6.8 ± 1.7                              | 1    |
| 020903       | 0.25  | 3.37 ± 1.79             | 0.024 ± 0.006                          | 1    |
| 030329       | 0.168 | 100 ± 23                | 15 ± 3                                 | 1    |
| 031205       | 0.105 | >100                     | 0.17                                   | 2    |
| 040701       | 0.215 | <6                      | 0.08 ± 0.02                            | 3    |
| 050206A      | 0.226 | ∼101                    | ∼9 × 10^{-3}                           | 4    |
| 050329       | 0.229 | ∼100                    | 0.033 ± 0.001                          | 1    |
| 050709       | 0.1606| 97.4 ± 11.6             | 0.003 ± 0.001                          | 1    |
| 050724       | 0.258 | ∼126                    | ∼0.35                                  | 4    |
| 050826       | 0.297 | ∼441                    | ∼0.33                                  | 4    |
| 051117B      | 0.481 | ∼107                    | ∼13                                    | 4    |
| 060218       | 0.0331| 4.9 ± 0.3               | 0.053 ± 0.003                          | 3    |
| 060505       | 0.089 | >160                    | 0.03 ± 0.01                            | 3    |
| 060614       | 0.125 | 55 ± 45                 | 2.5 ± 1                                | 1    |
| 061106       | 0.4377| 955 ± 267               | 2 ± 0.3                                | 1    |
| 061021       | 0.346 | 1046 ± 485              | 4.6 ± 0.8                              | 1    |
| 061210       | 0.4095| ∼767                    | ∼0.91                                  | 4    |
| 071227       | 0.383 | 1384 ± 277              | 1 ± 0.2                                | 2    |
| 080905A      | 0.1218| ∼503                    | ∼0.55                                  | 4    |
| 090417B      | 0.345 | ...                     | >6.3                                   | 5    |
| 091127       | 0.49  | 51 ± 1.5                | 16.1 ± 0.3                             | 1    |
| 100206A      | 0.4068| 618 ± 103               | 0.62 ± 0.03                            | 6    |
| 100316D      | 0.0591| 18^{+1}_{-2}            | 0.06                                   | 2    |
| 111211A      | 0.478 | ...                     | ∼11                                   | 4    |
| 120422A      | 0.283 | ∼53                     | 0.045                                  | 2    |
| 120714B      | 0.3984| ∼99                     | 7.95 ± 0.09                            | 4    |
| 130427A      | 0.3399| 1378 ± 11               | ∼850                                  | 7    |

Notes.

a The peak energy of the prompt emission in the burst frame.

References: (1) Zhang et al. 2012b and references therein; (2) Zhang et al. 2012a; (3)Amati et al. 2007; (4) Butler et al. 2007 (http://butler.lab.asu.edu/swift/); (5) Holland et al. 2010; (6) von Kienlin 2010; (7) Golenetskii et al. 2013.

(Flores et al. 2013; Levan et al. 2013; Xu et al. 2013), and a bright supernova SN 2013cq was identified (Xu et al. 2013). Its isotropic energy release in the energy range 20–10^51 keV is $E_{\gamma,\text{iso}} \sim 8.5 \times 10^{51}$ erg (Golenetskii et al. 2013), rendering it the most energetic among GRBs with a redshift $z \leq 0.5$ detected so far. As shown in Table 1, GRB 130427A is far more energetic than all other low-redshift GRBs.

The prompt emission of GRB 130427A lasted a few hundred seconds and overlapped with the forward shock region significantly. The forward shock protons and electrons are also cooled by the prompt emission, and high-energy neutrinos and $\gamma$-rays are powered by the ultra-high-energy protons interacting with the prompt $\gamma$-rays and by the electrons inverse Compton scattering off the prompt emission (Fan et al. 2005a, 2005b). As a result of the Klein–Nishina suppression, the forward shock electrons are mainly cooled by the X-ray photons (Fan et al. 2005b, Wang et al. 2006). Therefore, in Section 2 we analyze the Swift Burst Alert Telescope (BAT) data and then extrapolate the 0.3–10 keV flux of the prompt emission. The 100 MeV–100 GeV photon flux and the arrival time of the $>1$ GeV photons of GRB 130427A are also presented. In Section 3 we examine the models of the long-lasting GeV emission. In Section 4 we discuss the physical origin of the prompt emission. In Section 5 we summarize our work with some discussion.

Figure 1. Upper panel: prompt 0.3–10 keV emission of GRB 130427A extrapolated from the BAT data. The red line is the XRT light curve taken from http://www.swift.ac.uk/xrt_curves/00554620 (Evans et al. 2009). Lower panel: the photon index ($\Gamma_{\text{ph}}$) of the prompt emission detected by BAT in different intervals.

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

2. THE PROMPT 0.3–10 KeV EMISSION AND THE 100 MeV–100 GeV EMISSION

In this work $T_0$ denotes the trigger of Fermi GLAST Burst Monitor (GBM) at 07:47:06.42 UT on 2013 April 27 (von Kienlin et al. 2013). The Swift BAT was executing a pre-planned slew, so it was not triggered on time, but in the BAT light curve the main large peak started about 50 s before its trigger (Maselli et al. 2013; Barthelmy et al. 2013), consistent with the observations of Fermi–GBM, Konus-Wind, SPI-ACS/INTEGRAL, AGILE, and RHESSI.

The prompt 0.3–10 keV emission. The BAT quick-look data were analyzed using the standard BAT analysis software distributed within HEASOFT 6.13 and the latest calibration files. The BAT ground-calculated position is R.A. = 173.150, decl. = 27.706 deg. The mask-tagged BAT count-rate light curve was extracted in the standard 15–150 keV energy bands and converted to 15–150 keV flux with the energy conversion factor inferred from the spectral fitting in different time intervals shown in Figure 1, where a simple power-law model is adopted. Assuming that the spectrum is unchanged in the energy range 0.3–10 keV, the prompt X-ray emission light curve is extrapolated (see Figure 1).

The 100 MeV–100 GeV emission. The first reports of the LAT emission were made by Zhu et al. (2013a, 2013b). To better understand the high-energy emission, we analyzed the LAT data that are available at the Fermi Science Support Center,7 using the Fermi Science Tools v9r27p1 package. Events of energies between 100 MeV and 100 GeV were used. To reduce the contamination from Earth albedo $\gamma$-rays, we excluded events with zenith angles greater than 100°. Since we focused our work in the extended LAT emission that lasts for nearly a day, events classified as “P7SOURCE” and the instrument response functions “P7SOURCE_V6” were used.

Events from a region of interest (ROI) of a 20° radius circular region centered on the enhanced X-Ray Telescope (XRT) position of GRB 130427A (GCN 14467) were analyzed using unbinned likelihood analyses. The Galactic diffuse emission

7 http://fermi.gsfc.nasa.gov/ssc/
The rate can be approximated by
\[ \dot{N} = 3 \times 10^{-4} \text{cm}^{-2} \text{s}^{-1}(\ell/100 \text{s})^{-1.2}. \]

We found that the background photons in the time bins before was shown that an isotropic component is enough to describe the background model. However, it was shown that an isotropic component is enough to describe other sources in the ROI during these short-duration intervals.

We proceeded to construct a light curve in the energy interval 100 MeV–100 GeV, using unbinned likelihood analyses of each time bin. The light curve is shown in Figure 2. Due to the brightness of the GRB, intervals were as short as 5–10 s in the early times, e.g., before \( T_0 + 50 \) s. As already noted in Zhu et al. (2013b), there is a possible break at around \( T_0 + 500 \) s. Spectral analyses on two time intervals, \( T_0 \) to \( T_0 + 138 \) s and \( T_0 + 138 \) s to \( T_0 + 70 \) ks, were carried out. Spectral analyses for the 0.1–100 GeV data during two time intervals, (I) \( T_0 \) to \( T_0 + 138 \) s and (II) \( T_0 + 138 \) s to \( T_0 + 70 \) ks, were carried out. Assuming single power laws for the spectra of the GRB, we found that \( \Gamma_{0.1–100 \text{GeV}} = -1.9 \pm 0.1 \) during period I and \( \Gamma_{0.1–100 \text{GeV}} = -2.1 \pm 0.1 \) during period II. Therefore, within uncertainties, the spectrum remains unchanged between the two periods. A more in-depth LAT analysis of GRB 130427A has been done by Tam et al. (2013).

In Figure 3 we also present the photon energies and arrival times of the photons (to increase the photon statistics, a looser selection criterion, “P7TRANSIENT,” is employed here) above 5 GeV since the trigger of Fermi GBM. The 95% contamination angle of LAT at 5 GeV is about 1°, which is why in our plot only the photons within the 1° aperture have been taken into account.

3. PHYSICAL ORIGINS OF THE GeV EMISSION

The circumburst medium can be either interstellar medium (ISM) or stellar wind, which may be hard to reliably distinguish. In view of such an uncertainty we discuss both scenarios. In the ISM model, the number density of the medium (\( n \)) is taken to be a constant, while for the wind medium we take
\[ n_w = 3 \times 10^{35} A_w R^{-2}, \]
where \( A_w \) is the dimensionless wind parameter and \( R \) is the radius of the forward shock. The fact that the forward shock X-ray emission may be in slow cooling phase at a time \( t \sim 0.1 \) day favors a low-density circumburst medium (gal_2year7v6_v0.fits) and the isotropic diffuse component (iso_p7v6source.txt), as well as sources in the second Fermi catalog, were included in the background model. However, it was shown that an isotropic component is enough to describe the background photons in the time bins before.

Figure 2. 0.1–100 GeV photon flux of GRB 130427A. At \( t > 100 \) s, the count rate can be approximated by \( \dot{N} = 3 \times 10^{-4} \text{cm}^{-2} \text{s}^{-1}(\ell/100 \text{s})^{-1.2}. \)

Figure 3. Arrival time of the ≥5 GeV photons as well as the expected maximal synchrotron radiation frequency of the forward shock emission given by Equations (8). The solid line is for the ISM case (\( n = 0.01 \) cm\(^{-3} \)), while the dotted line is for the wind medium (\( A_w = 0.01 \)). The isotropic-equivalent kinetic energy of the GRB ejecta is taken to be \( 10^{54} \) erg. The shaded area represents the time interval of the second episode of the prompt emission, in which strong GeV–TeV radiation of the forward shock electrons caused by inverse Compton scattering off prompt photons (Fan et al. 2005a, 2005b) is expected.

(Laskar et al. 2013). That is why in the following investigation we normalize \( n \) to 0.01 cm\(^{-3} \) and \( A_w \) to 0.01.

The absence of a clear jet breakup to \( t > 80 \) days suggests a half-opening angle of (Piran 1999; Mészáros 2002; Zhang & Mészáros 2004)
\[ \theta_j > \begin{cases} 0.23 E_{k,54}^{-1/8} n_{-2}^{1/8} (t/20 \text{days})^{3/8} (\frac{1+z}{1.5})^{-3/8}, & \text{ISM;} \\ 0.08 E_{k,54}^{-1/4} A_{-2}^{1/4} (t/80 \text{days})^{1/4} (\frac{1+z}{1.38})^{-1/4}, & \text{wind;} \end{cases} \]

and the intrinsic \( \gamma \)-ray energy release of the ejecta is
\[ E_{\gamma, \text{jet},51} > \begin{cases} 25 E_{\gamma,\text{iso},53.93} E_{k,54}^{-1/4} n_{-2}^{1/4} (t/20 \text{days})^{3/4}, & \text{ISM;} \\ 3 E_{\gamma,\text{iso},53.93} E_{k,54}^{-1/2} A_{-2}^{1/2} (t/30 \text{days})^{1/2}, & \text{wind;} \end{cases} \]

where \( E_k \) is the isotropic-equivalent kinetic energy of the GRB ejecta. Here and throughout this text, the convention \( Q_e = Q/10^5 \) has been adopted in cgs units except for specific notation.

Laskar et al. (2013) and Perley et al. (2013) adopted the wind medium model to interpret the multi-wavelength afterglow data and claimed the discovery of reverse shock optical/radio radiation components. In their modeling, the bulk Lorentz factor of the reverse-shock-heated ejecta is required to drop with time \( \Gamma \sim 130(t/200 \text{s})^{-5/3} \) (in the reverse shock theory, the drop cannot be quicker than \( t/200 \text{s} \)–1/3; S. Kobayshi & Y. C. Zou 2013, private communication). If correct, the absence of the jet effect in the radio afterglow data in at least 10 days suggests a very wide half-opening angle \( \theta_j > 0.35 \) and then an intrinsic \( \gamma \)-ray energy release \( E_{\gamma, \text{jet},51} > 5 \times 10^{52} \) erg. Such a huge \( E_{\gamma, \text{jet},51} \) is above the maximal kinetic energy of a quickly rotating neutron star and points toward a black hole central engine.

Liu et al. (2013) adopted a jet break at \( t \sim 0.6 \) days to interpret the afterglow model. In such a scenario \( E_{\gamma, \text{jet}} \sim 10^{51} \) erg and...
the early (i.e., $t < 0.6$ days) X-ray afterglow emission should be attributed to the prolonged activity of the central engine, which likely plays an important role in producing GeV–TeV emission via the external inverse Compton (EIC) process.

3.1. The Role of Synchrotron Radiation

The forward shock synchrotron radiation of some extremely bright GRBs can play a dominant role in producing <10 GeV afterglow emission, as found by Zou et al. (2009, Figure 3 therein) in modeling GRB 080319B. After the first official release of the Fermi-LAT data on GRBs, synchrotron radiation has been found to be necessary for interpreting the high-energy afterglow data (e.g., Kumar & Barniol Duran 2009; Gao et al. 2009; Ghisellini et al. 2010; He et al. 2011; Ackermann et al. 2013; cf. Tam et al. 2012).

To produce the $\gtrsim 0.1$ GeV afterglow emission, the synchrotron-radiating electrons should have a random Lorentz factor larger than

$$\bar{\gamma}_e \sim 10^2 \Gamma_2^{-1/2} B^{-1/2}(1 + z)^{1/2}.$$  (3)

In the case of ISM, the bulk Lorentz factor of the forward shock reads $\Gamma \sim 270 E_{54}^{1/8} n_{1/2}^{1/8} t_{52}^{3/8}[(1 + z)/1.34]^{1/3}$, $B \sim 0.5 G E_{54}^{1/8} n_{1/2}^{3/8} t_{52}^{3/8}[(1 + z)/1.34]^{1/3}$ is the strength of the shock-generated magnetic field (Piran 1999), and $\epsilon_b (\epsilon_e)$ is the fraction of the shock energy given to the magnetic field (electrons). In the wind medium, we have $\Gamma \sim 200 E_{54}^{1/3} n_{1/2}^{1/3} t_{52}^{4/3}[(1 + z)/1.34]$ and $B \sim 0.8 G E_{54}^{1/3} n_{1/2}^{3/3} t_{52}^{4/3}[(1 + z)/1.34]$ (Dai & Lu 1998).

The inverse Compton cooling is in the Klein–Nishina regime and thus gets suppressed if the seed photons are more energetic than

$$\bar{\epsilon}_s \sim m_e c^2 \gamma/4 \bar{\gamma}_e \sim \begin{cases} 3.5 eV E_{54}^{1/4} n_{1/2}^{3/4} t_{52}^{3/4} \left(1 + \frac{1}{T_{34}}\right)^{1/4}, & \text{ISM;} \\ 3 eV E_{54}^{1/4} n_{1/2}^{1/4} t_{52}^{-1/2}, & \text{wind.} \end{cases}$$  (4)

In most cases except in the presence of a giant optical flare, the power released in the energy range $\leq \epsilon_s$ of afterglow emission or late prompt emission powered by the extended activity of the central engine is expected to be (well) below that of the magnetic field in the forward shock region $\sim 10^{50} \text{ erg} \, \text{s}^{-1} E_{54} n_{1/2} (1 + z)/t_{52}$. We hence conclude that usually the electrons generating GeV synchrotron emission do not suffer from sizable inverse Compton cooling.

The electrons producing GeV synchrotron radiation are in fast cooling. The fraction ($f$) of the total electron energy given to such extremely energetic electrons can be estimated as $f \approx (\gamma_{e}^2 - \gamma_{n}^2)/(\gamma_{n}^2 - \gamma_{p}^2)$, where the shock-accelerated electrons are assumed to have an initial distribution $d\gamma_e/d\gamma_e \propto \gamma_e$ for $\gamma_n < \gamma_e < \gamma_m$, the maximal random Lorentz factor of the shock-accelerated electrons is limited by their energy loss via synchrotron radiation and is estimated by $\gamma_m \sim 10^8 B^{-1/2}$ (Cheng & Wei 1996), and

$$\gamma_m \sim \begin{cases} 8000 E_{54}^{1/8} n_{1/2}^{-1/8} t_{52}^{-3/8} \left(1 + \frac{1}{T_{34}}\right)^{3/8}, & \text{ISM;} \\ 6500 E_{54}^{1/4} n_{1/2}^{-1/4} t_{52}^{-1/4} \left(1 + \frac{1}{T_{34}}\right)^{1/4}, \text{wind;} \end{cases}$$  (5)

where $C_p \equiv 6(p - 2)/(p - 1)$.

The luminosity of GeV synchrotron emission can be estimated by

$$L_{\text{GeV,syn}} \sim f \epsilon_e E_{k,54} (1 + z)/t \sim 1.3 \times 10^{50} \text{ erg} \, \text{s}^{-1} E_{k,54} t^{-1} \left(1 + \frac{z}{1.34}\right)^{-1}.$$  (6)

Let us estimate the count rate. The averaged energy of the synchrotron photons above 100 MeV is

$$\langle E \rangle \sim 100 \text{ MeV} (\Gamma_{\text{ph}} - 1)/(\Gamma_{\text{ph}} - 2)[1 - (\epsilon_{\text{syn,M}}/0.1 \text{ GeV})^{2-\Gamma_{\text{ph}}}].$$

where $\epsilon_{\text{syn,M}}$ is given by Equation (8) and $\Gamma_{\text{ph}} = (p + 2)/2$ is the photon spectral index. For GRB 130427A, the X-ray and optical afterglow emission suggest that $p \sim 2.2$ and $\Gamma_{\text{ph}} \sim 2.1$. We then have $\langle E \rangle \sim 0.2$–0.4 GeV for $\epsilon_{\text{syn,M}} \sim 1$–10 GeV. Hence, the count rate of the GeV synchrotron radiation is expected to be

$$\dot{N} \sim \frac{L_{\text{GeV,syn}}}{4\pi D_L^2 \langle E \rangle} \sim 5 \times 10^{-4} \text{ photon cm}^{-2} \text{s}^{-1} E_{k,54}^{1/2} \left(\frac{1 + z}{1.34}\right) \times D_L^{2/3} \left(\frac{\langle E \rangle}{0.4 \text{ GeV}}\right)^{-1}.$$  (7)

Such a rate seems to be able to account for a good fraction of the observed photon flux presented in Figure 2, which can be approximated by $\dot{N} = 3 \times 10^{-4} \text{ cm}^{-2} \text{s}^{-1}(t/100 \text{ s})^{-1.2}$.

3.2. Limitation of the Electron and Proton Synchrotron Radiation Models, the Electromagnetic Cascade Model, and the Secondary Posterior Synchrotron Radiation Model

3.2.1. The Electron Synchrotron Radiation Model

At $t \sim (243, 256.3, 610.6, 3409.8, 34366.2)$ s after the trigger of Fermi-GBM, the photon with an energy $\sim (95.3, 47.3, 41.4, 38.5, 32)$ GeV was detected, respectively (see Figure 3). The detection of such energetic $\gamma$-rays alone imposes a tight constraint on the radiation mechanism. Due to the energy loss via synchrotron radiation, in the rest frame of the shocked medium there is an upper limit on the energy of the accelerated electrons, as well as their synchrotron radiation frequency. The maximal synchrotron radiation frequency reads (e.g., Cheng & Wei 1996)

$$\epsilon_{\text{syn,M}} \sim 100 \text{ MeV} (\Gamma_{\text{ph}} - 1)^{-1} \sim \begin{cases} 20 \text{ GeV} E_{k,54}^{1/8} t_{52}^{-1/8} \left(\frac{1}{T_{34}}\right)^{5/8}, & \text{ISM;} \\ 15 \text{ GeV} E_{k,54}^{1/4} t_{52}^{-1/4} \left(\frac{1}{T_{34}}\right)^{1/4}, \text{wind;} \end{cases}$$  (8)

which is well below the energy of some photons detected in GRB 130427A (see Figure 3 for the details), suggesting that these high-energy $\gamma$-rays might have an inverse Compton origin. Therefore, though in Section 3.1 we have shown that the count rate of the >100 MeV emission may be accounted for by the synchrotron radiation of the forward shock electrons alone, part of the high-energy afterglow emission is not (see also Figure 4 for numerical examples).

In view of the weak dependence of $\epsilon_{\text{syn,M}}$ on both $E_k$ and $n$ or $A_e$ for almost all GRBs, the electron-synchrotron radiation origin of >10 GeV afterglow photons detected at $t >$ a few hundred seconds is disfavored.
Figure 4. Integral of high-energy synchrotron radiation spectrum (dotted line) and the synchrotron self-Compton radiation spectrum (dashed line) of a GRB 130427A-like burst in the time interval $10^2$–$4 \times 10^5$ s. The initial bulk Lorentz factor of the outflow is taken to be 300. Other physical parameters involved in the calculation are $E_{\gamma} = 10^{54}$ erg, $\epsilon_{e} = 0.05$, $\epsilon_{B} = 0.01$, $p = 2.2$, and $z = 0.34$. Evidently the cascade emission. The total energy of these very high energy photons will not be significantly absorbed by the cosmic background photons and then produce $\delta \varepsilon_{e}$ is much smaller than $\epsilon_{e}$. As found in Equation (7), $E_{\gamma} \sim 10^{54} \text{erg} (\epsilon_{e}/0.1)^{-1}$ is needed in the electron synchrotron radiation model. Hence, in the proton synchrotron radiation model the kinetic energy of the ejecta should be $\sim 10^{53} \text{erg} (m_{p}/m_{e})^{3}(p-1)(1-\nu^{-1}) \sim 10^{58}$ erg, which is too high to be realistic.

3.2.3. Electromagnetic Cascade of TeV $\gamma$-rays

As the $\gamma$-rays with an energy $\varepsilon_{\gamma} \sim 1$ TeV travel toward the observer, a significant fraction of them will be absorbed due to the interactions with the diffuse infrared background (Plaga 1995; Cheng & Cheng 1996; Dai & Lu 2002), yielding $e^{\pm}$ pairs with Lorentz factor $\gamma_{\gamma} \sim 10^{8} (\varepsilon_{\gamma}/1 \text{TeV})$. Such ultra-relativistic electron/positron pairs will subsequently Compton scatter on the ambient cosmic microwave background (CMB) photons and boost them to the energy $h_{\nu_{\text{CMB}}} \sim 0.63(1+z)(\varepsilon_{\gamma}/1 \text{TeV})^{2} \text{GeV}$. Usually the duration of the resulting GeV emission is expected to be determined by the deflection of the pairs by the intergalactic magnetic fields $B_{\text{IG}}$, i.e. (Dai & Lu 2002; Fan & Piran 2008),

$$\Delta t_{B} \sim 6.1 \times 10^{11} \left(\frac{\varepsilon_{\gamma}}{1 \text{TeV}}\right)^{-5} \left(\frac{B_{\text{IG}}}{10^{-16} \text{G}}\right)^{2} \left(1+z\right)^{-11}. \quad (9)$$

To interpret the $\sim 32 \text{GeV}$ photon detected at $t \sim 3 \times 10^{4}$ s, we need $\varepsilon_{\gamma} \sim 6 \text{TeV}$ and $B_{\text{IG}} \lesssim 3 \times 10^{-17} \text{G}$. The origin of the $\geq 6 \text{TeV}$ seed photons is unclear. Moreover, in the electromagnetic cascade scenario, as long as the magnetic deflection time governs the duration of the GeV emission, it is straightforward to show that the GeV emission should drop with the time as $t^{-1/2}$, inconsistent with the data. Such a result holds as long as the TeV seed photons have an initial duration $\ll \Delta t_{B}$. This is because the total energy loss of the $e^{\pm}$ pairs before losing most of its initial energy is roughly proportional to the distance they traveled, i.e., $\delta \varepsilon_{e} \propto l$ for $l \lesssim \lambda_{\text{MC}}$, where $\lambda_{\text{MC}} \approx 3 m_{e} c^{2}/(4 \gamma_{\gamma} \epsilon_{\gamma} u_{\text{cmb}})$ is the cooling distance of the $e^{\pm}$ pairs and $u_{\text{cmb}}$ is the energy density of the CMB radiation. The magnetic deflection angle reads $\theta_{B} = 1/R_{l}$, where $R_{l} = \gamma_{\gamma} c m_{e}^{2}/eB_{\text{IG}}$ is the Larmor radius of the electrons. On the other hand, the arrival time of the inverse Compton GeV radiation is proportional to $t_{B}^{2}$, i.e., $t \propto l^{3}$. Hence, the observed flux is proportional to $d(\delta \varepsilon_{e})/dt \propto t^{-2/3}$.

3.2.4. The Secondary Positron Synchrotron Radiation Model

In the external forward shock emitting region, ultra-relativistic positrons can be produced in the photomeson interaction between the X-ray photons and the ultra-relativistic protons. The possibility of the photomeson interaction can be estimated as $t_{\gamma p} \sim 1.2 \times 10^{-5} L_{x,48} / \Gamma_{17} \Gamma_{12}^{0.7} (\epsilon_{\text{peak}} / 10 \text{keV})^{-0.3} (\epsilon_{\gamma}/10 \text{keV})^{-0.7} (1+z)^{-1}$, where the X-ray spectrum $F_{\gamma} \propto \nu^{-0.7}$ has been taken into account, $L_{x} \propto t^{-3.55}$ for $t > 10^{3}$ s is the luminosity of the X-ray emission, and $\epsilon_{\text{peak}}$ is the
peak energy of the X-ray emission and $\epsilon_s$ is the energy of the seed photons. The energy of the protons should be $\varepsilon_p \approx 1.2 \times 10^{17} \text{eV} \Gamma_e^2 (\varepsilon_s / 10 \text{keV})^{-1}$, and the resulting positrons have an initial energy $\varepsilon_{e^+}^r \approx 6 \times 10^{15} \text{eV} \Gamma_e^2 (\varepsilon_s / 10 \text{keV})^{-1}$. Their synchrotron radiation in the forward shock region can generate $\sim 10 (\varepsilon_s / 10 \text{keV})^{-2} \text{GeV}$ synchrotron radiation. Therefore, this kind of process can give rise to GeV–TeV synchrotron radiation. It is straightforward to show that the total energy of the positrons produced in the photomeson interaction can be estimated as $L_{e^+} \approx \int_{p_{\text{min}}}^{p_{\text{max}}} A_0 p^{-\gamma} \rho_{\gamma} \gamma_0 \Gamma \approx \Gamma \gamma_0^2 p^{-1} L_{\gamma} / t$, where $A_0 = (p - 2)\varepsilon_0 \gamma_0^2 \rho_{\gamma}^{1/2} E_0 / t$, $\varepsilon_{0,\gamma} \approx 1.2 \times 10^{17} \text{eV} \Gamma_e^2$, $\varepsilon_{p,\gamma} \approx 1.2 \times 10^{19} \text{eV} \Gamma_e^2$, and $\gamma_0 = \gamma_{0,\gamma} \Gamma^{-3/4} L_{\gamma}^{-1} (1 + z)^{-1}$ have been taken into account. Since $\Gamma \propto t^{-3/8} / \rho$, and $R \propto t^{1/4} / \rho$ for ISM and wind medium models, respectively, $L_{e^+}$ drops with time more quickly than $t^{-1.8}$, at odds with the data.

3.3. GeV–TeV Emission Powered by the Forward Shock Electrons Inverse Compton Scattering Off of Prompt Photons

For GRB 130427A the prompt X-ray emission was very strong and lasted a few hundred seconds (see Figure 1). Simultaneously, the ultra-relativistic GRB outflow drives energetic blast waves and accelerates a large amount of electrons. Some prompt photons will be upscattered by the shock-accelerated electrons and get boosted to GeV–TeV energies when crossing the forward (possibly also reverse) shock region(s). The resulting high-energy $\gamma$-rays account for part of the observed GeV–TeV emission.

For illustration here we only calculate the high-energy emission resulting in the EIC scattering process in the second episode of the prompt emission ranging from $\sim 120$ s to $\sim 260$ s (Golenetskii et al. 2013). This is because at such a relatively late time the deceleration of the GRB outflow is most likely in the Blandford–McKee self-similar regime (Blandford & McKee 1976) and the forward shock cooling/emission can be calculated in the standard way (Piran 1999). We would like to also point out that the very different temporal behaviors of the GeV and X-ray/soft $\gamma$-ray emission in such a time interval suggest that these emissions are not from the same region.

The inverse Compton scattering is efficient if it is in the Thompson regime, requiring that in the rest frame of the electron the seed photon has an energy smaller than $m_e c^2$, i.e., the random Lorentz factor of the electrons should not be higher than

$$\gamma_s \sim \Gamma m_e c^2 / 4 \epsilon_s,$$

(10)

where $\epsilon_s$ is the energy of the seed photon (prompt photon). Therefore, most electrons with a random Lorentz factor $\sim \gamma_m$ are cooled by the prompt photons at energies $\epsilon_s \lesssim 4.3 \text{keV}$.

Such an $\epsilon_s$ seems to be well below the peak energy $\sim 240 \text{keV}$ of the prompt emission in the second episode (Golenetskii et al. 2013). However, the total energy released in the energy $\sim \epsilon_s \sim 4.3 \text{keV}$ is not ignorable since the current prompt emission spectrum is softer than the typical ones $F_{\gamma} \propto \nu^{-0.7}$. With the observed spectrum $F_{\gamma} \propto \nu^{-0.6}$ (Golenetskii et al. 2013), we find out that $\sim 1/5$ of the total energy was released below $\epsilon_s$, i.e., $F_{\gamma,\epsilon_s} \sim \mathcal{F} / 4 \sim 2.3 \times 10^{-5} \text{erg cm}^{-2}$, where $\mathcal{F} \sim 9 \times 10^{-5} \text{erg cm}^{-2}$ is the 20–1200 keV energy fluence. The corresponding time-averaged luminosity is $L_{\gamma,\epsilon_s} \sim 5 \times 10^{49} \text{erg s}^{-1}$, consistent with the Swift data (see Figure 1).

Below we estimate the importance of the cooling of forward shock electrons by prompt emission.

In the rest frame of the shocked ISM, the energy density of the seed photons can be estimated as $U_{\gamma} \sim L_{\gamma,\epsilon_s} / 4 \pi R^2 \Gamma_c c$.

The convolving energy density of the shock-generated magnetic field is $U_B \sim 4 \pi^2 \epsilon_B m_p c^2$ for ISM or $\sim 4 \pi^2 \epsilon_B n_w m_p c^2$ for wind medium. The importance of the inverse Compton cooling caused by the prompt emission is given by the dimensionless parameter (Fan & Piran 2006)

$$\mathcal{Y} = U_{\gamma} / U_B \approx \left\{ \begin{array}{ll}
0.22L_{\gamma,\epsilon_s} E_{\gamma,\epsilon_s}^{-1} & \text{ISM;} \\
1L_{\gamma,\epsilon_s} E_{\gamma,\epsilon_s}^{-1} & \text{wind.}
\end{array} \right.$$ 

(11)

Such a $\mathcal{Y}$ seems to suggest not very important inverse Compton cooling effect. However, as demonstrated below, intriguing radiation is expected.

The number of high-energy $\gamma$-rays generated by the forward shock electrons inverse Compton scattering off prompt emission can be straightforwardly estimated (e.g., Fan et al. 2005b, Gao et al. 2009). The possibility of one seed photon being upscattered (i.e., the optical depth) in the forward shock region can be estimated as (Fan & Piran 2006)

$$\tau \sim \left\{ \begin{array}{ll}
1.4 \times 10^{-9} E_{\gamma,\epsilon_s}^{1/4} h_{\gamma_s}^{-1/2} f_2^{-1/2} & \text{ISM;} \\
6 \times 10^{-9} E_{\gamma,\epsilon_s}^{-1/2} h_{\gamma_s}^{1/2} f_2^{-1/2} & \text{wind.}
\end{array} \right.$$ 

(12)

The total number of seed photons is

$$N_{\text{seed}} \sim \mathcal{F} / \langle \epsilon_s \rangle \sim 2.5 \times 10^4 \text{cm}^{-2},$$

(13)

where $\langle \epsilon_s \rangle \sim 0.6 \text{keV}$ is the averaged energy of the seed photons within the energy range of $\sim 0.1 \text{keV}–4.3 \text{keV}$ for a spectrum $F_{\gamma} \propto \nu^{-0.6}$. The total number of high-energy photons detectable for Fermi with an effective area $S \sim 10^4 \text{cm}^2$ is

$$N_{\gamma,\text{EIC}} \sim \tau N_{\text{seed}} S \sim \left\{ \begin{array}{ll}
0.3, & \text{ISM;} \\
1.5, & \text{wind.}
\end{array} \right.$$ 

(14)

The typical energy of the generated high-energy $\gamma$-rays is expected to be

$$\langle \epsilon_{\gamma,\text{EIC}} \rangle \sim \min \left\{ \gamma_m^2 \epsilon_c^2 \langle \epsilon_s \rangle \right\} \sim 24 \text{GeV},$$

(15)

where the cooling Lorentz factor of the forward shock electrons reads

$$\gamma_{c,\epsilon_s} \sim \left\{ \begin{array}{ll}
4.1 E_{\gamma,\epsilon_s}^{-3/8} h_{\gamma_s}^{-1/2} f_2^{-5/8} f_2^{1/8} & \text{ISM;} \\
1.9 E_{\gamma,\epsilon_s}^{-1/4} h_{\gamma_s}^{-1/2} f_2^{-5/4} f_2^{-3/4} & \text{wind.}
\end{array} \right.$$ 

(16)

and $Y$ is the inverse Compton parameter (including both the synchrotron-self Compton and the EIC radiation).

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8. Liu et al. (2013) argued that $n \sim 1 \text{cm}^{-3}$. For such a large $n$, we have $N_{\gamma,\text{EIC}} \sim 10$ and almost all the $> 10 \text{GeV}$ photons detected in the time interval of 120–260 s can be accounted for. Moreover, the EIC emission likely plays a dominant role in producing GeV–TeV afterglow emission up to $t \sim 0.6$ days since in Liu et al. (2013)’s modeling the early ($t \sim 0.6$ days) strong soft X-ray emission should be mainly powered by the prolonged activity of the central engine.
For GRB 130427A at a redshift $z = 0.34$, the optical depth of the universe for $300$ GeV-like $\gamma$-rays from interactions with photons of the intergalactic background light is expected to be $\sim 1$ (Gilmore et al. 2012). Therefore, whether the tens-GeV photons can be detected or not mainly depends upon their chance of escaping the emitting region. With Equation (13) of Zou et al. (2011) it is straightforward to show that even for $300$ GeV photons the optical depth caused by the overlapping of the prompt photons with the forward shock region is $\sim 2.5 \times 10^{-3}$, which is so small that it can be ignored. Hence, we conclude that the resulting tens of GeV photons can reach us.

Interestingly, in the time interval $140 \text{s} < t < 260 \text{s}$ in coincidence with the second episode of the prompt emission, five afterglow photons at energies above $10$ GeV have been recorded. Though the synchrotron self-Compton origin of such photons cannot be ruled out considering the somewhat small $\gamma$, the EIC scattering origin due to the overlapping of prompt emission with the forward shock region is $\sim 2.5 \times 10^{-3}$, which is so small that it can be ignored. Hence, we conclude that the resulting tens of GeV photons can reach us.

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4. A POSSIBLE UNIFIED MODEL FOR THE PROMPT SOFT GAMMA-RAY, OPTICAL, AND GEV EMISSION OF GRB 130427A, GRB 080319B, AND GRB 090902B

Instead of proposing a model dedicated to fitting the data of prompt emission of GRB 130427A, we try to outline a unified scenario to understand GRB 130427A, GRB 080319B, and GRB 090902B together, motivated by the similarities displayed in the observational features summarized in Table 2. Please note that $\alpha_{\text{Band}}$ and $\beta_{\text{Band}}$ are the low- and high-energy spectral indexes of the GRBs fitted by the Band function (Band et al. 1993) and $E_p$ is the observed peak energy of the spectrum.

**Prompt emission from the photosphere.** Prominent thermal radiation components have been identified in the prompt soft $\gamma$-ray emission of GRB 090902B (e.g., Ryde et al. 2010; Zhang et al. 2011), which is the smoking-gun signature of the photospheric radiation. For GRB 080319B, some people tried to interpret both the ultra-strong soft $\gamma$-ray emission and the naked-eye optical flash within the internal shock scenarios (e.g., Kumar & Panaitescu 2008; Li & Waxman 2008; Yu et al. 2009).

Moreover, the tight correlation $\Gamma \propto L^{0.3}$ found in the data analysis of GRBs (Lü et al. 2012; Fan et al. 2012) predicts an extremely low internal shock efficiency unless the slow material shell has a width much wider than that of the fast shell, at odds with the data, where $L$ is the total luminosity of the outflow. Therefore, we suggest that the internal shock origin of the prompt soft $\gamma$-ray emission is less likely. One attractive alternative is the so-called photospheric radiation model, in which the GRB prompt emission is mainly the internal shock origin of the prompt soft $\gamma$-ray emissions are, respectively, the synchrotron and the first-order inverse Compton radiation components of the internal shocks is found to be disfavored (Piran et al. 2009). Moreover, the tight correlation $\Gamma \propto L^{0.3}$ found in the data analysis of GRBs (Lü et al. 2012; Fan et al. 2012) predicts an extremely low internal shock efficiency unless the slow material shell has a width much wider than that of the fast shell, at odds with the data, where $L$ is the total luminosity of the outflow. Therefore, we suggest that the internal shock origin of the prompt soft $\gamma$-ray emission is less likely. One attractive alternative is the so-called photospheric radiation model, in which the GRB prompt emission is mainly

### Table 2

| Quantity                  | GRB 080319B | GRB 090902B | GRB 130427A |
|---------------------------|-------------|-------------|-------------|
| $\alpha_{\text{Band}}$    | $0.833 \pm 0.014$ | $0.61 \pm 0.01$ | $0.789 \pm 0.003^a$ |
| $\beta_{\text{Band}}$    | $3.499 \pm 0.364$ | $3.8 \pm 0.25$ | $3.06 \pm 0.066^a$ |
| $E_p$                     | $651 \pm 15$ keV | $726 \pm 8$ keV | $830 \pm 3$ keV |
| $z$                       | $0.937$      | $1.822$     | $0.3399$     |
| $E_{\gamma,\text{iso}}$  | $1.3 \times 10^{52}$ erg | $4 \times 10^{52}$ erg | $8.5 \times 10^{52}$ erg |
| Duration of prompt emission | $57$ s | $26$ s | $\sim 138^a$ |
| Prompt optical emission   | $\sim 20$ Jy | No observation | $\sim 4$ Jy |
| Prompt GeV emission       | No observation | $\sim 10^{-4}$ erg cm$^{-2}$ | $\sim 10^{-4}$ erg cm$^{-2}$ |
| Main references           | 1, 2, 3, 4, 5, 6 |

Notes.

a The time-averaged spectrum of the main phase of the burst (from $T_0 + 0.002$ s to $T_0 + 18.432$ s) measured by Fermi-GBM (von Kienlin et al. 2013).

b Most of the energy was released in the first $\sim 18$ s.

References. (1) Racusin et al. 2008; (2) Abdo et al. 2009b; (3) Cucchiara et al. 2009; (4) von Kienlin et al. 2013; (5) Zhu et al. 2013b; (6) Golenetskii et al. 2013; (7) Wren et al. 2013.

**Prompt optical emission**

Bright optical flash from the synchrotron radiation of inter-

**Table 2** General Features of GRB 080319B, GRB 090902B, and GRB 130427A

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|---------------------------|-------------|-------------|-------------|
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| $\beta_{\text{Band}}$    | $3.499 \pm 0.364$ | $3.8 \pm 0.25$ | $3.06 \pm 0.066^a$ |
| $E_p$                     | $651 \pm 15$ keV | $726 \pm 8$ keV | $830 \pm 3$ keV |
| $z$                       | $0.937$      | $1.822$     | $0.3399$     |
| $E_{\gamma,\text{iso}}$  | $1.3 \times 10^{52}$ erg | $4 \times 10^{52}$ erg | $8.5 \times 10^{52}$ erg |
| Duration of prompt emission | $57$ s | $26$ s | $\sim 138^a$ |
| Prompt optical emission   | $\sim 20$ Jy | No observation | $\sim 4$ Jy |
| Prompt GeV emission       | No observation | $\sim 10^{-4}$ erg cm$^{-2}$ | $\sim 10^{-4}$ erg cm$^{-2}$ |
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References. (1) Racusin et al. 2008; (2) Abdo et al. 2009b; (3) Cucchiara et al. 2009; (4) von Kienlin et al. 2013; (5) Zhu et al. 2013b; (6) Golenetskii et al. 2013; (7) Wren et al. 2013.
10^{15} \text{ Hz} \left( \frac{3e_{B,\text{in}}}{e_{\text{e}}/c} \right)^{1/2} L_{25}^{2} \left( \frac{p_{\text{opt}}}{p_{\gamma}} \right)^{2/3} \left( \frac{p_{\text{opt}}^2}{p_{\gamma}^2} \right)^{1/2} \left( \frac{\gamma_{\text{m,in}}}{40} \right)^{2(1-\epsilon_1)/p+4} \Gamma_{1,2,7}^{-2(2p+1)/(p+4)} \left( \frac{\delta t}{0.5 \text{ s}} \right), \text{i.e., above the optical band, and then the optical emission is somewhat suppressed.} \text{ The internal shock electrons with random Lorentz factor}\ \Gamma_{\gamma,e} \leq \gamma_{e,\text{kn}} \equiv \Gamma_{\text{m,in}} c e^2/[(1+z)E_p] \sim 250 \Omega_{i,2,7}(1+z)E_p/1 \text{ MeV}^{-1} \text{ are mainly cooled by the prompt soft } \gamma-\text{rays (i.e., the EIC process), and the cooling Lorentz factor can be estimated as } \gamma_{e,\text{kn}} \sim 6 \Gamma_{i,2,7}^{-2} L_{25}^{-1} \text{ (Fan \\ & Piran 2008), where } L_{25} \text{ is the luminosity of the prompt soft } \gamma-\text{ray emission. So the comoving temperature of the emitting region is } kT_{\gamma,e} \sim \min\{\gamma_{\text{m,in}}, \gamma_{e,\text{kn}}\} \Gamma_{1,2,7}^{-2} \text{, and the prompt optical flux density can be estimated as (Zou et al. 2009)} \ \ f_{\gamma,\text{opt}} \sim \frac{2 \pi v_{\text{opt}}^2 (1+z)^3 \Gamma_{i,2,7}^{-2} kT_{\gamma,e}}{c^2} \left( \frac{R_i}{\Gamma_{i,2,7} D_{L,25}^{2.3}} \right)^2 \sim 3.4 Jy v_{\text{opt}}^2 \Gamma_{i,2,7}^{-2} R_i^{2} \left( \frac{1+z}{2} \right)^3 D_{L,25}^{-2.3}. \tag{17} \end{equation}

For reasonable parameters of GRB 080319B and GRB 130427A (i.e., \( \Gamma_{i,2,7} \approx 500-1000 \) and \( R_i \approx 10^{16} \text{ cm} \)), very bright optical flashes are expected, consistent with the data.

**Energetic GeV emission from the EIC radiation of internal shocks.** As a result of the overlapping of the prompt emission and the optical radiation region, the electrons will scatter off the prompt emission and then produce high-energy emission with a luminosity \( \sim L_{\text{in}} \) (Beloborodov 2005; Zou et al. 2009). The EIC radiation flux peaks at \( \sim \min\{\gamma_{\text{m,in}}, \gamma_{e,\text{kn}}\} \left( \frac{1+z}{2} \right)^3 D_{L,25}^{2.3} \text{, and the flux is } F_{\text{EIC}} \approx v^{-\nu/2} \text{ can extend up to the energy } E_{\gamma,e} \sim 0.25 \text{ TeV} \Gamma_{i,2,7}^{-1/3} (E_p/1 \text{ MeV})^{-5/3} (1+z)^{-2} \text{, as observed in GRB 090902B and GRB 130427A. Adopting Equation (13) of Zou et al. (2011), it is straightforward to show that the tens of GeV photons can escape without being significantly absorbed by the prompt } \gamma-\text{rays.} \text{ The emission above } 100 \text{ MeV lasted about one day (see Figure 2). As demonstrated by Zou et al. (2009), for bursts as energetic as GRB 080319B, the forward shock synchrotron radiation may be the dominant component of the afterglow emission below } \approx 10 \text{ GeV, while the inverse Compton radiation mainly contributes at higher energies (see Kumar \\ & Barniol Duran 2009; Gao et al. 2009; Ghisellini et al. 2010 for interpreting the } \text{Fermi-LAT GeV afterglow data with the synchrotron radiation model). Such a conclusion seems to hold for GRB 130427A as well (see Figure 4 for numerical examples). In particular, for some photons at energies of tens of GeV, the forward shock synchrotron radiation model has been convincingly ruled out (see Figure 3) and an inverse Compton radiation origin is needed (see Section 3.2 for discussion on alternative models). We also find out that the EIC scattering of the prompt emission (the second episode, i.e., } t \approx 120-260 \text{ s) by the forward-shock-accelerated electrons is expected to produce a few } \gamma-\text{rays at energies of tens of GeV, which may account for some } \gamma-\text{rays at energies } > 10 \text{ GeV detected in the same time interval.} \text{ We have also outlined a possible unified model for the prompt soft } \gamma-\text{ray, optical, and GeV emission of GRB 130427A, GRB 080319B, and GRB 090902B. In such a model the prompt soft } \gamma-\text{rays are mainly the photospheric radiation, while the subsequent internal shocks produce bright optical flash via synchrotron radiation and energetic GeV flash via the EIC scattering (see Section 4).} \text{ The IceCube collaboration reported their null detection of } > 1 \text{ TeV neutrinos in spatial and temporal coincidence with GRB 130427A (Blaufuss 2013). Such a result is a bit disappointing but not unexpected. For example, even in the internal shock model that is most favorable for producing PeV neutrinos, no detectable neutrino is expected if the proton spectrum is as soft as the electron spectrum (i.e., } dn/dE_\gamma \propto E_\gamma^{-4}, \text{ as inferred from the prompt MeV emission). Only for the proton spectrum as hard as } dn/dE_\pi \propto E_\pi^{-2} \text{ and kinetic energy of protons of about 10 times that of electrons is significant detection (i.e., about one event at PeV energies) by IceCube possible. The high-energy prompt emission does suggest such a hard spectrum. However, it is likely powered at a radius } R_i \approx 10^{16} \text{ cm (see Section 4), which is too large for efficient pion production. The possible high radiation efficiency of GRB 130427A (Laskar et al. 2013) further reduces the chance of detecting the associated high-energy neutrinos. In the photospheric radiation model for the prompt MeV emission, the non-detection of the associated TeV neutrino emission may suggest the absence of significant proton acceleration in the physical processes modifying the photon spectrum. Finally, we would like to mention that the detection of one LAT photon of energy } \sim 72 \text{ GeV at } t \approx 18.6 \text{ s after the } \text{Fermi-GBM trigger of GRB 130427A can also be used to constrain the possible variation of the speed of light arising from quantum gravity effects. However, the limit is weaker than that set by the detection of one } 31 \text{ GeV photon at } t \sim 0.7 \text{ s after the trigger of GRB 090510 (Abdo et al. 2009a).} \text{ We thank the anonymous referee for the insightful comments/suggestions. We are also grateful to S. Kobayashi, Y. C. Zou, L. Shao, and D. Xu for helpful discussion and D. A. Kann for suggestions. This work was supported in part by the 973 Program of China under grants 2013CB837000 and 2009CB824800; the National Natural Science of China under grants 11073057, 11163003, and 11273063; and the China Postdoctoral science foundation under grants 2010490139 and 2012M521137. Y.Z.F. is also supported by the 100 Talents program of the Chinese Academy of Sciences and the Foundation for Distinguished Young Scholars of Jiangsu Province, China (No. BK2012047). P.H.T. is supported by the National Science Council of the Republic of China (Taiwan) through grant NSC101-2112-M-007-022-MY3.} \text{ The Astrophysical Journal, 776:95 (9pp), 2013 October 20} \text{ Fan et al.} \text{ REFERENCES} \text{ Abdo, A., Ackermann, M., Ajello, M., et al. 2009a, Natur, 462, 331} \text{ Abdo, A., Ackermann, M., Ajello, M., et al. 2009b, ApJL, 706, L138} \text{ Abdo, A., Ackermann, M., Ajello, M., et al. 2009a, Natur, 462, 331} \text{ Abdo, A., Ackermann, M., Ajello, M., et al. 2009b, ApJL, 706, L138} \text{ Abdo, A., Ackermann, M., Ajello, M., et al. 2009a, Natur, 462, 331} \text{ Abdo, A., Ackermann, M., Ajello, M., et al. 2009b, ApJL, 706, L138}
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