HIGH ENERGY EMISSION OF GRB 130821A: CONSTRAINING THE DENSITY PROFILE OF THE CIRCUM-BURST MEDIUM AS WELL AS THE INITIAL LORENTZ FACTOR OF THE OUTFLOW

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ABSTRACT

GRB 130821A was detected by Fermi-GBM/LAT, Konus-WIND, SPI-ACS/INTEGRAL, RHESSI and Mars Odyssey-HEND. Although the data of GRB 130821A are very limited, we show in this work that the high energy γ-ray emission (i.e., above 100 MeV) alone imposes tight constraint on the density profile of the circum-burst medium as well as the initial Lorentz factor of the outflow. The temporal behavior of the high energy γ-ray emission is consistent with the forward shock synchrotron radiation model, and the circum-burst medium likely has a constant-density profile. The Lorentz factor is about a few hundred, similar to other bright GRBs.

Key words: gamma rays: general – radiation mechanisms: non-thermal

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1. INTRODUCTION

Gamma-ray bursts (GRBs) are short/brief intense flashes of soft γ-rays, which have fascinated astronomers and astrophysicists since their unexpected discovery in the 1960s (Klebesadel et al. 1973). Their physical origin has been debated for a long time mainly due to the lack of an exact position and a reliable estimate of the distance to us. In 1997, quite a few GRBs were accurately localized by the BeppoSAX satellite, leading to the discovery of their X-ray, optical and radio counterparts, and their redshifts (Costa et al. 1997; van Paradijs et al. 1997; Frail et al. 1997). The cosmological origin of GRBs was thus directly confirmed. In the standard fireball model, the fit of the optical/radio/X-ray afterglow emission plays a key role in constraining the physical parameters including the forward shock parameters, the density profile of the circum-burst medium, the initial Lorentz factor, and sometimes even the structure, of the outflow (e.g., Panaitescu & Kumar 2001, 2002; Huang et al. 2004; Molinari et al. 2007; Jin & Fan 2007).

Since the launch of the Fermi satellite in 2008, more than 30 GRBs have been detected above 100 MeV by the Large Area Telescope (LAT) on board the satellite (Abdo et al. 2009; Zhang et al. 2011; Tam et al. 2012; Ackermann et al. 2013b), confirming the long-lived MeV–GeV emission (i.e., longer than the prompt soft γ-rays) of GRBs first revealed by EGRET (Hurley et al. 1994).

One of the most surprising findings in the Fermi-era may be that the long-lived MeV–GeV emission is likely dominated by the synchrotron radiation (see Figure 3 of Zou et al. 2009 for a pioneering prediction and see, e.g., Kumar & Barniol Duran 2009; Gao et al. 2009; Ghisellini et al. 2010; Ackermann et al. 2013a for modeling the Fermi-LAT data in such a way) rather than the widely believed inverse Compton radiation of the forward shock electrons (see, e.g., Fan & Piran 2008 for a review on various inverse Compton processes). In contrast, the first clear evidence of an inverse Compton component of a GRB was found only recently (Fan et al. 2013; Tam et al. 2013). Within the synchrotron radiation model, the long-lived MeV–GeV emission alone can impose tight constraint on some physical parameters. This is very important since for some bursts only the Fermi GBM/LAT-data are available. As demonstrated in this work, GRB 130821A is such an example.

This work is structured as follows. In Section 2, we briefly introduce GRB 130821A. In Section 3, we present our data analysis results of the Fermi GBM and LAT data. In Section 4, we discuss the implications of the data.

2. GRB 130821A

At 16:10:28.011 UT (T0) on 21 August 2013, the Fermi Gamma-Ray Burst Monitor triggered on GRB 130821A (trigger 398794231; Jenke 2013), which resulted in an Autonomous Repoint Request (ARR) and the LAT slewed to the GBM position. The best LAT on-ground location was reported to be R.A. = 314°1, Decl. = −12°0 (J2000) with an error radius of 0.1 (68% containment, statistical error only; Kocevski et al. 2013). The GBM light curve showed a multiple-peaked structure with a duration (T90) of about 84 s (50–300 keV).

The angle of the GRB position was about 37° from the LAT boresight at T0 and the ARR brought the source within the LAT field of view for the next 2400 s, so the LAT observed the GRB position with good sensitivity over the entire prompt phase. Multi-peaked emission lasting roughly 40 s can be seen using the non-standard LAT Low Energy (LLE) photons, which are dominated by 30–100 MeV γ-rays, with a significance of 13σ (Kocevski et al. 2013).

Konus-WIND also triggered on GRB 130821A (Golenetskii et al. 2013). The Konus-WIND team reported that the 20 keV to 18 MeV time-averaged spectrum from 0 s to 78.08 s after the Konus-WIND trigger time is best fitted by the Band function with α = −1.3 ± 0.11, β = −2.25 ± 0.19, and Eγ = 260 ± 47 keV; emission was seen up to ~9 MeV. The burst fluence is (9.9 ± 0.9) × 10−2 erg cm−2 (Golenetskii et al. 2013). RHESSI, INTEGRAL SPI-ACS, and Mars Odyssey-HEND also triggered on this GRB (Hurley et al. 2013).

Upper limits in the optical and X-ray bands were drawn because no source was found (Xu et al. 2013; Page et al. 2013) within the LAT error circle reported in Kocevski et al. (2013).
However, we will show that the GRB location is likely outside of this reported error circle and therefore such limits do not apply to GRB 130821A.

3. DATA ANALYSIS AND RESULTS

3.1. Joint GBM and LAT Spectral Analysis During the Prompt Phase

We extracted both LAT and GBM data from the Fermi Science Support Center. Joint spectral fits of both LAT and GBM data were performed over the whole prompt phase and for the four time intervals listed in Table 1, using the software package RMFIT (version 4.32). Because of the small number of photons detected by the LAT, we used C-statistic rather than chi-squared statistic to fit the data. Time Tagged Event data from the NaI detectors n6,n7 and the BGO detector b1 were used to make spectral fits for GBM, and the LAT data contains TRANSIENT class photons from 100 MeV to 300 GeV within 10° around the localization of (314°27, −11°70), while LLE data were also included. All spectra are well fitted by the Band function (Band et al. 1993), and we report the best fit model parameters in Table 1. We found that adding a blackbody component did not improve the fits.

To better understand how spectral parameters evolve with time, the best-fit values of spectral parameters derived from GBM data in different intervals are shown in Figure 1. From the figure, there is a trend that $\alpha$ increases as the flux of the burst, while change in $\beta$ is marginal. The $E_{\text{peak}}$ value gradually becomes smaller with time, which is consistent with a hard-to-soft pattern (Lu et al. 2012).

3.2. LAT Data Analysis During the Prompt and Afterglow Phases

The Fermi Science Tools v9r31p1 package was used to analyze the data. To filter out the Earth’s limb emission, we excluded events with zenith angles greater than 100 degrees in our analysis. We also used gtfindsrc to find the best-fit position of this burst. When doing this, “P7SOURCE” data in the time interval from $T_0 + 0 \text{s}$ to $T_0 + 1400 \text{s}$ of energies between 100 MeV and 300 GeV from a region of interest (ROI) of a 10° radius circular region centered on R.A. = 314°1, Decl. = −12°0 (J2000) (Kocevski et al. 2013) were selected. The derived best location is R.A. = 314°27, Decl. = −11°70 (J2000) with an error radius of 0°085. Following Ackermann et al. (2013b), we produced a test-statistic (TS) map (here we choose 0°05 grid), and the maximum in the TS map is located at R.A. = 314°24, Decl. = −11°68 (J2000) with an error radius of 0°1, consistent with the result obtained by gtfindsrc. We found that our derived GRB position is well consistent with the InterPlanetary Network (IPN) annulus (Hurley et al. 2013), suggesting this position is more accurate than the one reported in Kocevski et al. (2013). A count map, using the 100 MeV to 20 GeV “P7TRANSIENT” data in the time interval from $T_0 + 0 \text{s}$ to $T_0 + 1400 \text{s}$, is shown in Figure 2.

![Table 1](image1.png)

| Interval (s) | $E_{\text{peak}}$ (keV) | $\alpha$ | $\beta$ | Photon Flux (cm$^{-2}$ s$^{-1}$) | Energy Flux (10$^{-7}$ erg cm$^{-2}$ s$^{-1}$) | C-stat/ dof |
|-------------|--------------------------|----------|---------|-------------------------------|--------------------------------------|-------------|
| All         | $-2.0$–$100.1$           | 374.4 ± 15.0 | $-1.10 \pm 0.02$ | $-2.75 \pm 0.04$ | 4.30 ± 0.03 | 7.14 ± 0.08 | 830/391 |
| a           | $-2.0$–$21.0$            | 588.5 ± 55.7 | $-1.06 \pm 0.03$ | $-3.11 \pm 0.18$ | 4.00 ± 0.06 | 8.34 ± 0.17 | 520/391 |
| b           | 21.0–46.6                | 332.6 ± 10.5 | $-0.98 \pm 0.02$ | $-2.75 \pm 0.05$ | 10.45 ± 0.07 | 17.9 ± 0.20 | 630/391 |
| c           | 46.6–66.3                | 151.2 ± 33.3 | $-1.22 \pm 0.13$ | $-2.53 \pm 0.06$ | 1.69 ± 0.07 | 1.82 ± 0.09 | 441/391 |
| d           | 80.4–100.1               | 111.1 ± 19.5 | $-1.21 \pm 0.14$ | $-2.34 \pm 0.06$ | 2.00 ± 0.07 | 1.91 ± 0.08 | 423/391 |

Table 2

| Time (s) | Flux$^a$ | Index$^b$ | TS Value | Npred$^c$ |
|---------|---------|-----------|----------|---------|
| 0–60    | $1.24 \times 10^{-5}$ | ... | 0.0 | 0.0 |
| 60–150  | $(2.51 \pm 1.08) \times 10^{-5}$ | $-2.1 \pm 0.4$ | 32.66 | 6.75 |
| 150–350 | $(1.19 \pm 0.23) \times 10^{-5}$ | $-1.9 \pm 0.1$ | 40.36 | 9.78 |
| 350–700 | $(7.80 \pm 1.16) \times 10^{-6}$ | $-2.1 \pm 0.1$ | 56.18 | 12.57 |
| 700–1400| $(3.63 \pm 2.09) \times 10^{-6}$ | $-2.1 \pm 0.4$ | 23.50 | 9.80 |
| 1400–2500| $(1.48 \pm 0.36) \times 10^{-6}$ | $-1.9 \pm 0.2$ | 22.47 | 5.88 |
| 2500–5000| $1.24 \times 10^{-6}$ | ... | 0.0 | 0.0 |
| 5000–8000| $(1.77 \pm 1.08) \times 10^{-6}$ | $-2.7 \pm 0.6$ | 10.22 | 10.78 |
| 8000–10500| $9.80 \times 10^{-7}$ | ... | 1.35 | 1.42 |
| 10500–15000| $5.60 \times 10^{-7}$ | ... | 0.0 | 0.0 |
| 15000–21000| $5.84 \times 10^{-7}$ | ... | 0.0 | 0.0 |
| 21000–27500| $8.23 \times 10^{-7}$ | ... | 0.0 | 0.0 |

Notes:

$^a$ In the unit of photons cm$^{-2}$ s$^{-1}$; values without uncertainty are upper limits.

$^b$ Index values are not well constrained for the time intervals with TS < 9.

$^c$ Predicted photon number given by the unbinned likelihood analysis.

4 http://fermi.gsfc.nasa.gov/ssc/data/access/

5 http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/make2FGLxml.py
power law for the time bins with TS > 9 and found the slope of the best-fit line to be $-0.82 \pm 0.11$, which is shown as the solid line in Figure 3. If the last flux point (i.e., 6200 s–8200 s) is not included, the decay index is $-0.84 \pm 0.13$, which is consistent with the above value.

An interesting point we note from Figure 3 is that there is no significant $>100$ MeV emission up to $\sim T_0 + 60$ s. To verify this, we calculate probabilities of each photon being associated to GRB 130821A by using the Fermi Science Tool gtsrcprob, assuming a photon index of $\Gamma = -2.1$, and plot the probabilities versus photons’ arrival times in Figure 4. All those TRANSIENT class events in a 30° radius circular region centered on (314°27, −11°70) were considered, but only events with a probability being associated to GRB 130821A greater than 0.1 are plotted. Only two photons with probabilities larger than 0.5 arrived in the first 60 s of the prompt emission, energies of both of which are less than 300 MeV.

The fact that there is no significant detection at $>100$ MeV by the LAT during the first 60 s after the GRB onset, during which most of the prompt MeV emission was seen, and $E_{\text{peak}}$ was the highest, suggests that (1) the $>100$ MeV emission is not an extrapolation to the Band function during the prompt phase, and (2) the LAT and the GBM emission evolve independently. In turn, GRB 130821A may be the first-ever GRB where most or all $>100$ MeV emission is unrelated to the prompt emission. The $>100$ MeV emission must have a different origin than the prompt emission.

4. DISCUSSION

As shown in Figure 1, most of the prompt emission concentrated in the first 40 s after the burst onset. However, one can see from Figures 3 and 4 that very rare $>100$ MeV photons have been detected in such an interval (see also Table 2) and the most energetic $\gamma$-ray at an energy $\sim 6$ GeV arrived at 219 s after the trigger. The Fermi-LAT data likely peaked at $t_p \sim 100$s, thus lagging behind the soft $\gamma$-ray peak emission significantly. After the high energy peak emission, the count rate drops with time as $t^{-0.82 \pm 0.11}$. All these behaviors are consistent with the forward shock synchrotron radiation model. Below we take such a model and show that some interesting results can be achieved.

The rising behavior of the forward shock synchrotron radiation light-curve sheds valuable light on the density profile
of the circum-burst medium (see Table 1 in Xue et al. 2009 for a summary). For GRB 130821A, the high energy emission occurred significantly after the strongest soft gamma-ray emission phase had ended, hence the GRB outflow should be in the thin shell regime (for which \( t_p > T_{90} \), where \( t_p \) is the time when reverse shock crosses the ejecta), as defined in Xue et al. (2009). For \( t < t_p \) and the number density of the medium \( n \propto R^{-k} \) (\( k = 0 \) for interstellar medium and = 2 for free...
stellar wind), we have the typical synchrotron radiation (cooling) frequency
\( \nu_m \propto t^{-k/2} (\nu_c \propto t^{3/2-k/2}) \) and the maximal specific flux
\( F_{\nu, \text{max}} \propto t^{3(1-k/2)} \). For typical forward shock parameters, the observer’s frequency \( \nu_{\text{obs}} = 100 \text{ MeV} \) is well above both \( \nu_c \) and \( \nu_m \) and we have \( F_{\nu_{\text{obs}}} \propto t^{2} (\nu_{\text{obs}}^{2-p/2}) \) for \( k = 0 \) (= 2), where \( p > 2 \) is the power-law index of shocked electrons, as suggested by the simultaneous Fermi-LAT spectrum. Thus, in order to reproduce the quick rise (quicker than \( t^{1/2} \); see Figure 3) of the high energy emission for \( t < 100 \text{ s}, \) the particle density of the circum-burst medium should be a constant. The stellar wind medium model might be able to marginally match the data if the typical synchrotron radiation frequency of the forward shock \( \nu_m > 100 \text{ MeV} \) at \( t \approx 100 \text{ s} \) (see Table 1 of Xue et al. 2009; For current discussion, one should replace \( \nu_c \) therein by \( \nu_{\text{obs}} \)). However, as already mentioned in the footnote 6, in the standard fireball model, for reasonable parameters, \( \nu_m \) is expected to be \( \ll 100 \text{ MeV}, \) so is \( \nu_c. \) For \( t > t_p \), the forward shock synchrotron radiation at energies above 100 MeV drops with time as \( \propto t^{-1} \) for \( p \approx 2 \) and \( \max(\nu_{\text{obs}}, \nu_c) < \nu_{\text{obs}}, \) in agreement with the detected decline, where \( p \) is the power-law index of the shock-accelerated electrons. The high energy emission is thus \( F_{\nu_{\text{obs}}} \propto t_{\text{obs}}^{-p/2} \sim \nu_{\text{obs}}^{-1}, \) consistent with the data, too (see the right panel of Figure 3).

In the thin shell case, the afterglow peak time traces the deceleration of the forward shock and in turn can be used to constrain the initial Lorentz factor of the GRB outflow (e.g., Sari & Piran 1999; Molinari et al. 2007)

\[
\Gamma_0 = \left[ \frac{24E_k(1+z)^2}{\pi n m_p c^3 t_p^2} \right]^{1/8},
\]

where \( m_p \) represents the proton mass, \( c \) the speed of light, and \( t_p \) the peak time of the \( > 100 \text{ MeV} \) emission, respectively. We assume the ambient density \( n = 1 \text{ cm}^{-3} \). The isotropic energy of the outflow \( E_c \) can be estimated based on the total energy of prompt gamma-ray emission \( E_c \) assuming a certain radiation efficiency \( \eta. \) For GRB 130821A, the redshift is unknown, and we take the typical redshift of current GRBs, i.e., \( z = 1 \).

Using the energy fluence given by the Konus-WIND, we have \( E_c = (2.5 \pm 0.2) \times 10^{53} \text{ erg}. \) We take \( \eta = 0.2 \) in the calculation according to Guetta et al. (2001). As a result, we get \( \Gamma_0 \approx 440 \).

The initial bulk Lorentz factor can be estimated in an alternative way. In the forward shock synchrotron model, it is widely known that the maximal radiation frequency can be estimated as (e.g., Cheng & Wei 1996)

\[
\epsilon_M \approx 100 \text{ MeV} \Gamma/(1+z).
\]

Therefore, the fact that the highest energy LAT photon at an energy of \( \approx 6 \text{ GeV} \) arrived \( 219 \text{ s} \) after the GRB trigger suggests an initial Lorentz factor \( \Gamma_0 \gtrsim 200[1+(1+z)]/2 \), where the temporal decay of the Lorentz factor \( \Gamma \propto (t/t_p)^{-3/8} \) has been taken into account. Interestingly, the result, i.e., \( \Gamma_0 \approx 350 \), is consistent with the independent constraint using the forward shock deceleration argument.

In view of these facts, we conclude that (1) the high energy emission of GRB 130821A may indeed have a forward shock synchrotron radiation origin; (2) the circum-burst medium likely has a constant density profile; (3) the outflow is jetted and ultra-relativistic with an initial Lorentz factor of a few hundred. Our results demonstrate that the long-lived MeV–GeV emission alone can impose tight constraints on some physical parameters.

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\[ \frac{dE_{\gamma}}{dt} = \frac{1}{2} m_n c^2 \left( \frac{1}{2} \pi n m_p c^3 \right)^{1/2} \left( \frac{t}{t_p} \right)^{3/2} \]

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