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Spectral cutoffs of Fermi-LAT GRBs 080916C and 090926A

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Abstract It is expected that there should be a spectral cutoff at the high energy end of emission from a prompt gamma-ray burst (GRB), due to, e.g. $\gamma\gamma$ absorption and/or a high energy cutoff in the electron distribution. We analyze the spectral data of Fermi-LAT detected GRBs 080916C and 090926A, aiming at locating the spectral cutoff. By assuming that the prompt GRB spectrum at the high energy end is a power law with an exponential cutoff, our analysis finds that the cutoff energy $E_{\rm cutoff}$ depends on the photon index β and the cutoff occurs at very high energy, $E_{\rm cutoff} = 161^{+533}_{-95}$ GeV in GRB 080916C and $E_{\rm cutoff} \gtrsim 100$ GeV (for $\beta \approx -2.3$) in GRB 090926A. Such high energy photons, if they exist, may disfavor the synchrotron origin and need alternative generation mechanisms.

Key words: gamma-rays: bursts — acceleration of particles

1 INTRODUCTION

Gamma-ray bursts (GRBs) are believed to be produced by relativistic jets released from newly formed stellar mass black holes (see reviews, e.g. Piran 1999 and Zhang 2007). The bulk Lorentz factors of GRB jets are constrained to be $\Gamma \gtrsim 100$ in the Compton-EGRET era. The argument is that since EGRET has detected several GRBs with energetic photons in the 100-MeV scale (Dingus 1995), the region producing the GRB emission must be expanding ultra-relativistically so that these energetic photons can escape, avoiding $\gamma\gamma \rightarrow {\rm e}^{\pm}$ absorption (e.g. Lithwick & Sari 2001).

Due to its relatively low sensitivity and small field of view, EGRET only detects a limited number of GRB events with photons in the 100-MeV scale. The Fermi satellite was launched in 2008. Compared to EGRET, the high energy detector LAT (Atwood et al. 2009) onboard the Fermi satellite has a much higher sensitivity in a wider energy range, about 100 MeV–300 GeV, and has a much larger field of view, covering one fifth of the whole sky. Until now, Fermi-LAT has detected 17 GRBs, with a detection rate comparable to the expectation by assuming that the LAT-band emission is the simple extrapolation of the high energy spectral tail in the MeV-range spectrum (Ando et al. 2008; Lv et al. 2010).

Researchers have long been very interested in looking for the spectral cutoff in the high energy end of prompt GRB emission, because there are several reasons that may lead to spectral cutoffs and their detection would be very important for constraining the properties of GRB jets. For example, the LAT has demonstrated that many bright GRBs show emission extending up to tens of GeV without hints of spectral cutoffs. By assuming that the $\gamma\gamma$ absorption is only important at photon energy larger than that of the highest photon energy in the LAT detections, the GRB jets have been constrained to have bulk Lorentz factors generally larger than the limits observed by EGRET, e.g. $\Gamma > 900$, $\Gamma > 1200$, and $\Gamma > 1000$, for GRBs 080916C, 090510 and 090902B, respectively (Granot et al. 2010). However, a detection of spectral cutoff has also been announced recently for GRB 090926A (Ackermann et al. 2011), where the cutoff is $E_{\rm cutoff} = 1.4$ GeV and hence the bulk Lorentz factor is constrained to be $\Gamma = 200 - 700$ by assuming $\gamma\gamma$ absorption as the cause of the cutoff. This is smaller than the other Fermi-LAT GRBs.

Here, we carry out more careful analysis on the spectral shape at the high energy end of the prompt emission for Fermi-LAT GRBs, with the goal of discovering the cutoff energy. We find that the cutoff energy is much larger than the highest observed photon energy, which gives more stringent constraints on the properties of GRB jets. We introduce the method of using the number of high energy photons to calculate the cutoff in Section 2; In Section 3 we apply the methods to two Fermi-LAT GRBs 080916C and 090926A; In Section 4 we have some discussion about the cutoff and the bulk Lorentz factors; Finally a general conclusion is given in Section 5.

2 METHOD

For a certain observed GRB, we assume that there should be a high energy spectral cutoff in the spectrum of the prompt emission, and assume that the spectral shape is a power law plus a high energy exponential cutoff. Therefore the detected count spectrum at the high energy end can be written as[1]

$$dn/dE = Bg(E)E^{\beta}\exp(-E/E_{\rm cutoff}), \tag{1}$$

where E is the photon energy, B is the normalization, $g(E)$ accounts for the photon energy dependent sensitivity of the detector, and $E_{\rm cutoff}$ is the cutoff energy.

For the LAT onboard the Fermi satellite, Atwood et al. (2009) have presented the effective area as a function of photon energy (their fig. 14). We use the following function to fit the effective area

$$g(E) = \begin{cases} 9519 - 7266\exp(-E/54.65\,{\rm MeV}) - 5097\exp(-E/361.1\,{\rm MeV}), & E \leq 1355\,{\rm MeV}, \\ 9400, & E > 1355\,{\rm MeV}. \end{cases} \tag{2}$$

The fit is precise enough, with less than 3% error, that we will use this function for the following analysis of LAT detected GRBs.

β and $E_{\rm cutoff}$ in Equation (1) are free parameters. Using Equations (1) and (2) we perform Monte Carlo simulations to reconstruct the observations, and derive the probability P that the simulation successfully reconstructs the observation. For a given GRB, we have learned that N_i photons are detected at energy above E_i – we will use this observational result as the criterion of whether the simulation reconstructs the observational results. We will generate a total of $N_{\rm tot}$ spectra for given parameters β and $E_{\rm cutoff}$; if the number of simulated spectra that fit the criterion is $N_{\rm c}$ then the probability of successful simulation is $P = N_{\rm c}/N_{\rm tot}$. In the phase space of parameters β and $E_{\rm cutoff}$, the set of parameters with maximal value of P is the most favored values. We will use this method to calculate the cutoff energy $E_{\rm cutoff}$.

3 APPLICATION

3.1 GRB 080916C

GRB 080916C is a bright, long GRB which has 145 photons detected by LAT at $E > 100$ MeV, within which 14 show $E > 1$ GeV and one has $E > 10$ GeV, consistent with a power law spectrum

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[1] This shape is consistent with the prediction of spectral cutoff due to $\gamma\gamma$ absorption (e.g. Granot et al. 2008).

Table 1 Observational Results of Two Fermi-LAT Detected GRBs

Name	β	Photon Number (> 100 MeV)	 (> 1 GeV)	 (> 10 GeV)
GRB 080916C	-2.3^a	145	14	1
GRB 090926A	-1.7^b, -2.3^a	123	14	$-^c$

The five columns correspond to the GRB name, the high energy photon index, and the photon number above 100 MeV, 1 GeV and 10 GeV, respectively.

[a] Spectral index resulting from the fit of a single Band function.

[b] Spectral index resulting from the fit of a Band function plus a power law.

[c] For GRB 090926A, we do not know the number of photons above 10 GeV.

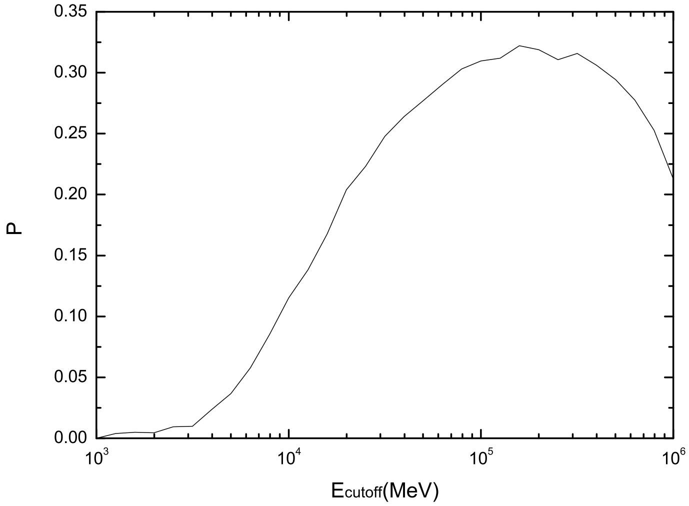

Fig. 1 The relation between the probability P (see the text) and the cutoff energy $E_{\rm cutoff}$ for GRB 080916C. The power law index is taken to be $\beta = -2.3$, which resulted from the spectral fit with a single Band function from a few keV up to 100 GeV. The P value peaks around 200 GeV.

with index $\beta \sim -2$ up to the $\sim 10\,$GeV scale. The time integrated spectrum is well fit by the empirical Band function (Band et al. 1993), which is a function of two smoothly joined power laws. There is not an additional component at high energies. The highest photon energy is 13.2 GeV, for which a photon was detected 17 s after the GRB trigger. The redshift of this burst is $z = 4.35$ (Greiner et al. 2009). The observational results used as the criterion in the Monte Carlo simulation are summarized in Table 1.

Since the spectrum shows a single component with high energy index $\beta = -2.3$ (Abdo et al. 2009), we take this value for β in Equation (1) and set $E_{\rm cutoff}$ as a free parameter. We simulate $N_{\rm tot} = 10^4$ spectra, each with 145 photons at $E > 100$ MeV. We set the criterion as being: there are 14 photons at $E > 1$ GeV and one photon at $E > 10$ GeV.

Figure 1 shows the probability P as a function of the cutoff energy $E_{\rm cutoff}$ for GRB 080916C. We can see that P increases slowly with $E_{\rm cutoff}$ up to 160 GeV, and then decreases at $\gtrsim 300$ GeV. This indicates that there exists a cutoff at $E_{\rm cutoff} = 161^{+533}_{-95}$ GeV for the 1 σ confidence level in the spectrum of this burst.

One may comment that it is the fluence, rather than photon number, that should be fixed for the simulated spectra. We actually also perform a simulation with a fixed fluence above 100 MeV. However, because the photon number is more or less constant, only varying by $\sim 10\%$ for cutoff energy changing from 100 MeV to ~ 1 TeV, the simulation results are similar and the conclusion does not change.

3.2 GRB 090926A

As reported by Ackermann et al. (2011), GRB 090926A is also a bright, long burst. In the first 30 s after trigger, there were 123 photons with $E >$100 MeV detected by LAT, among which 14 showed $E > 1$ GeV. It can also be fit by a Band function with $\beta \sim -2.3$. The highest energy photon was detected with 19.6 GeV at 25 s after the GRB trigger. The observational result is summarized in Table 1.

Ackermann et al. (2011) use three models to fit the spectrum of prompt emission of GRB 090926A from 3.3 s to 21.6 s: Band, Band + power law, and Band + power-law with an exponential cutoff (CUTPL). In the Band + CUTPL model, they find a cutoff in $1.41^{+0.22}_{-0.42}$ GeV with a high energy index of -1.7. However, although the additional power law is statistically preferred over the Band function alone, the fit of the Band function alone is also statistically justified, with a high energy index of $\beta = -2.3$ (Ackermann et al. 2011; Zhang et al. 2011). Therefore, we consider that the high energy index in Equation (1) could be $\beta = -2.3,\ -2,\ -1.7$ in the simulation. Moreover, here we consider the prompt emission from the trigger to be up to 30 s.

The result is shown in Figure 2. We can see that if $\beta = -1.7$, there is a clear cutoff at $E_{\rm cutoff} = 2.6^{+4.3}_{-1.0}$ GeV for the 1σ confidence level. This is consistent with the result by Ackermann et al. (2011) that a cutoff is detected at 1.4 GeV for the case of $\beta = -1.7$. If $\beta = -2.0$, we can also see a peak at $E_{\rm cutoff} = 14^{+657}_{-6}$ GeV at the 1σ confidence level. If taking $\beta = -2.3$, the case of a single Band function fit to the prompt emission, there is no clear peak of the P value, which indicates that if there exists a cutoff in this burst, the cutoff should be $E_{\rm cutoff} > 100$ GeV.

4 DISCUSSION

Let us discuss the implication of the results of the above analysis to the GRB physics, in particular the bulk Lorentz factor of GRB jets. There are several reasons that an intrinsic, exponential spectral cutoff is expected in the prompt GRB emission. First, if there is a high-energy cutoff in the accelerated electron distribution, the corresponding synchrotron spectrum should show a cutoff at the high energy end. The electrons are supposed to be accelerated by some electromagnetic processes, and a general bound can be derived for the maximum synchrotron photon energy, due to the competition between acceleration and synchrotron cooling (e.g. Li 2010), $E_{\rm cutoff} = 50\Gamma f^{-1}(1+z)^{-1}$ MeV, where f is a correction factor accounting for uncertainties of acceleration and z is the GRB redshift. It should be that $f > 1$, and $f \sim$ a few is expected (e.g. Lemoine & Revenu 2006). Therefore the bulk Lorentz factor is

$$\Gamma = 2\times 10^3 \frac{E_{\rm cutoff}}{100\ {\rm GeV}} f(1+z). \tag{3}$$

Second, pair production ($\gamma\gamma \rightarrow {\rm e}^+{\rm e}^-$) within the emitting region is expected to result in a cutoff at high energy. If the high energy photons are produced in the same region as the photons in the MeV range, which is assumed to be uniform, isotropic, and time-independent in the comoving frame of the emission region, the bulk Lorentz factor can be derived to be a function of the spectral cutoff (Abdo et al. 2009),

$$\Gamma = \left[\sigma_T \left(\frac{d_L}{c\Delta T}\right)^2 E_c f(E_c) F(\beta) \times (1+z)^{-2(1+\beta)} \left(\frac{E_{\rm cutoff} E_c}{m_e^2 c^4}\right)^{-\beta-1}\right]^{\frac{1}{2(1-\beta)}}, \tag{4}$$

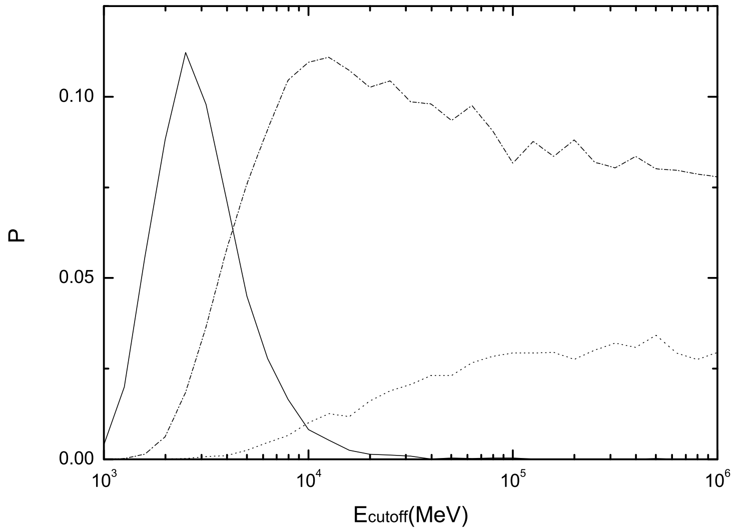

Fig. 2 The relation between the probability P (see the text) and the cutoff energy $E_{\rm cutoff}$ for GRB 090926A. The solid curve is for $\beta = -1.7$, dash-dotted for $\beta = -2$, and dotted for $\beta = -2.3$. A peak appears at $E_{\rm cutoff} \simeq 2$ GeV if $\beta = -1.7$, and at $E_{\rm cutoff} \simeq 10$ GeV if $\beta = -2$, but there is no clear peak for $\beta = -2.3$. Thus $E_{\rm cutoff} > 100$ GeV if we consider a single Band function fit to the prompt emission.

where d_L is the luminosity distance and E_c is the pivot energy fixed at 1 MeV. GRB 080916C shows only one component, i.e. the spectrum can only be fit by a Band function without an additional component from X-ray up to the 10 GeV range. This is consistent with the synchrotron mechanism being the radiation mechanism of prompt GRB emission (see Wang et al. 2009 for a more detailed discussion). Taking $\beta = -2.3$, our analysis finds the cutoff around 160 GeV (Fig. 1), or $E_{\rm cutoff} >$ 70 GeV at the 1σ confidence level. This lower limit is much larger than the highest photon energy of detected photons in this burst. Using this lower limit and $z = 4.35$, the cooling limit of Equation (3) gives $\Gamma > 2.3{\times}10^4 f_{0.5}$ (where $f_{0.5} = f/10^{0.5}$). Moreover, quoting the relevant values of parameters in the absorption limit (Eq. (4)) from Abdo et al. (2009), we have $\Gamma > 1230$.

As for GRB 090926A, a spectral fit with only a Band function is also statistically justified, so this burst could also be mainly produced by synchrotron radiation if all photons are generated in a single region, i.e. assuming a one-zone model. If taking $\beta = -2.3$, we also have $E_{\rm cutoff} > 100$ GeV for this burst. This constraint gives $\Gamma > 2 \times 10^4 f_{0.5}$ in the cooling limit (Eq. (3)). Taking $z = 2.1$ (hence $d_L = 5.2 \times 10^{28}$ cm), $\Delta T = 0.15$ s and $F(E_c) = 2.3 \times 10^{-4}$ photons cm^{-2} keV^{-1} s^{-1} (Ackermann et al. 2011), we get $\Gamma > 1300$ in the absorption limit (Eq. (4)).

Because our analysis gives much more stringent constraints on the spectral cutoff energy, our derived bulk Lorentz factors are much larger than those from previous authors. As discussed in Li (2010), too large a bulk Lorentz factor may lead to several problems in the standard fireball shock model of GRBs: The internal shock radius may be larger than the GRB ejecta deceleration radius, which is physically impossible (Lazzati et al. 1999); The electrons may be slowly cooling and not radiating efficiently which raises the problem of GRB energetics (Derishev et al. 2001); In order for the thermal pressure of the initial fireball to accelerate the baryon content to a large Lorentz factor, the baryon content should be small enough that most of the fireball's energy is released as thermal photons, which contradicts most GRB spectra; In the synchrotron internal shock models, a large

Lorentz factor leads to a large internal shock radius, where the magnetic field may be too low to generate MeV synchrotron photons (e.g. Li & Waxman 2008).

If the very large bulk Lorentz factor is a problem for the synchrotron internal shock model, then some revision to the model should be considered. One may try to abandon synchrotron radiation as the main mechanism in GRBs. However, compared with inverse Compton, synchrotron is still the more favored mechanism (e.g. Wang et al. 2009; Piran et al. 2009; Daigne et al. 2011). So one should abandon the assumption that the highest energy part of the GRB spectrum has a synchrotron origin; for example, use an inverse Compton origin instead. On the other hand, one can also abandon the simple one zone assumption, i.e. the highest energy photons can be generated at different radii from the MeV photons. Indeed, under the framework of the standard internal shock model, one naturally expects that internal collisions happen in a wide range of radii and each shell of the outflow should experience many collisions at different radii. Li (2010) predicts that the inverse Compton radiation at large radii smears out the spectral cutoff at high energy. Furthermore, in this case both the cooling and absorption limits are not available. Relaxing the one-zone assumption, the analysis by Zhao et al. (2011) and Zou et al. (2011) suggests that the bulk Lorentz factors could be much lower than 1000. Actually, the systematic time delay of high energy photons implies that the bulk Lorentz factor could have a typical value, i.e. a few hundred (Li 2010).

It should also be noted that the analysis shows that the resulting cutoff depends on the β value - the harder the β, the lower the value for cutoff energy, as shown in Figure 2 for GRB 090926A. If taking $\beta = -1.7$ as in Ackermann et al. (2011), we find a cutoff at a few GeV, similar to their result. The bulk Lorentz factor constrained by this value of spectral cutoff is a few hundred, well below 1000 (Ackermann et al. 2011). However, since a single Band function still gives a satisfactory fit (Ackermann et al. 2011; Zhang et al. 2011), taking the β value from a single Band function fit, the cutoff becomes much larger than 100 GeV.

However, in the case of GRB 080916C, since there is no extra component in the spectrum, we only take $\beta = -2.3$ which results from a single Band function fit. In principle, β and $E_{\rm cutoff}$, as well as other spectral parameters, should be simultaneously determined by spectral fitting. However, because the β value in a single Band function fit mainly depends on the slope from a low energy range, $\lesssim$MeV up to $\gtrsim 10$ GeV, whereas the $E_{\rm cutoff}$ value depends on the spectral shape at $\gtrsim 100$ GeV, there should be no strong degeneracy between β and $E_{\rm cutoff}$ in the spectral fit. So we can reasonably use the presumed value $\beta = -2.3$ and not try the other values for GRB 080916C.

5 CONCLUSIONS

We analyze the spectral data of Fermi-LAT detected GRBs 080916C and 090926A, aiming at locating the spectral cutoff. By assuming that the prompt GRB spectrum at the high energy end is a power law with an exponential cutoff (Eq. (1)), our analysis finds that the cutoff energy $E_{\rm cutoff}$ depends on the photon index β and the cutoff occurs at very high energy, $E_{\rm cutoff} \sim 160$ GeV and $E_{\rm cutoff} \gtrsim 100$ GeV (for $\beta \approx -2.3$) in GRBs 080916C and 090926A, respectively. Such high energy photons, if they exist, require a very large bulk Lorentz factor of GRB jets, $\Gamma > 10^3$, in order to avoid $\gamma\gamma$ absorption (Eq. (4)), or even $\Gamma > 10^4$ in order to avoid cooling of electrons suppressing acceleration (Eq. (3)). Since $\Gamma > 10^4$ is difficult to reach, the high energy photons disfavor a synchrotron origin, and need alternative mechanisms.

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