VHE $\gamma$-ray Afterglow Emission from Nearby GRBs

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Abstract. Gamma-ray bursts (GRBs) are among the potential extragalactic sources of very-high-energy (VHE) $\gamma$-rays. We discuss the prospects of detecting VHE $\gamma$-rays with current ground-based Cherenkov instruments during the afterglow phase. Using the fireball model, we calculate the synchrotron self-Compton (SSC) emission from forward-shock electrons. The modeled results are compared with the observational afterglow data taken with and/or the sensitivity level of ground-based VHE instruments (e.g. STACEE, H.E.S.S., MAGIC, VERITAS, and Whipple). We find that modeled SSC emission from bright and nearby bursts such as GRB 030329 are detectable by these instruments even with a delayed observation time of $\sim 10$ hours.

Keywords: Gamma Rays: bursts — ISM: jets and outflows — radiation mechanism: non-thermal

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INTRODUCTION

Gamma ray bursts (GRBs) are believed to be one of the cosmological sources emitting GeV and higher energy photons. Tentative evidence of distinct high-energy components has been accumulated by EGRET’s observations of several GRBs including GRB 940217 and GRB 941017 [1, 2]. In the fireball model, synchrotron emission of shock-accelerated electrons is commonly considered to be responsible for prompt $\gamma$-ray emission as well as afterglow emission at lower energies, see, e.g. [3]. It is natural to expect that these photons are inverse-Compton up-scattered by electrons (e.g. synchrotron-self Compton, SSC), giving rise to a higher energy component peaking at GeV to TeV energies [4, 5].

Ground-based $\gamma$-ray instruments, such as MAGIC, VERITAS, and H.E.S.S. are operating at energies above $\sim 100$ GeV. These Cherenkov instruments have very large effective areas of $\sim 10^4 - 10^5$ m$^2$ and a high rejection rate of hadronic background, making them rather sensitive to VHE $\gamma$-rays. Hence, these instruments are well suited to test the prediction of the above picture.

THE MODEL

We employ the following leptonic jet model to calculate the afterglow emission from electrons accelerated in external forward shock, as described in [6]. The key elements of the model are summarized:

1. a homogeneous external medium with density $n$, or a wind profile $n \propto R^{-2}$;
2. constant fractions of the shock energy given to the electrons ($\varepsilon_e$) and the magnetic field ($\varepsilon_B$);
3. electron distribution follows $dN_e/dE \propto E^{-p}$;
4. energy injection in the form of
   (a) $E_k \propto [1 + (t/T)^2]^{-1}$; or
   (b) $E_k \propto t^{1-q}$
   is used, whenever necessary, to reproduce the flattening in some observed afterglow light curves. Parameters $L_{inj}$ (the rest-frame injected luminosity) and injection timescale $T_{inj}$ are also included;
5. both synchrotron and inverse Compton emission are calculated.

Klein-Nishina correction is required to estimate the VHE $\gamma$-ray emission. Attenuation by extra-galactic background light (EBL) is also included in the numerical calculations, using the ‘P0.45’ EBL level considered in [7].

To understand the model prediction, first consider a factitious burst with the following parameter values: initial (isotropic-equivalent) energy $E_{iso} = 10^{51}$ erg, initial half-opening angle $\theta_{0} = 0.4$, $n = 1$ cm$^{-3}$, $p = 2.2$, $\varepsilon_e = 0.3$, $\varepsilon_B = 0.01$, and $z = 0.16$. Time-integrated spectra (including both synchrotron and SSC components) from forward shocks are depicted in Figure [1]. The modeled spectra are integrated from 0.5 hour, 2 hours, and 10 hours after the burst for half an hour. One can see that
**FIGURE 1.** Time-integrated SSC spectra from forward shocks, integrated from 0.5 hour (top), 2 hours (middle) and 10 hours (bottom) after the burst for 0.5 hour (dotted lines). Fermi/LAT [8] and H.E.S.S. (assuming photon spectral index $\Gamma = 2.6$) sensitivities, both for an integration time of 0.5 hour, are also shown.

**TABLE 1.** Model parameters for six nearby GRBs.

| GRB      | $E_{\text{iso}}(\text{erg})$ | $\theta_0$ | $n(\text{cm}^{-3})$ | $p$ | $\varepsilon_e$ | $\varepsilon_B$ | $L_{\text{inj}}$ | $T_{\text{inj}}(\text{s})$ | reference |
|----------|-------------------------------|------------|---------------------|-----|-----------------|-----------------|----------------|-------------------|-----------|
| 030329   | $1.4 \times 10^{53}$          | 0.31       | 100                 | 2.01| 0.1             | 0.001           | No             | ...               | ...       |
| 050509B  | $2.75 \times 10^{48}$         | 0.5        | 1                   | 2.2 | 0.15            | 0.046           | No             | ...               | ...       |
| 050709   | $3.77 \times 10^{50}$         | 0.5        | $6 \times 10^{-3}$  | 2.6 | 0.4             | 0.25            | No             | ...               | ...       |
| 051221A  | $10^{52}$                      | 0.1        | 0.01                | 2.4 | 0.3             | $2 \times 10^{-4}$ | Yes $\uparrow$ | $2 \times 10^{48}$ | $< 1.5 \times 10^{4}$ |
| 060505   | $2.6 \times 10^{50}$          | 0.4        | 1                   | 2.1 | 0.1             | 0.008           | No             | ...               | ...       |
| 060614   | $5 \times 10^{50}$            | 0.08       | 0.05                | 2.5 | 0.12            | $2 \times 10^{-4}$ | Yes $\uparrow$ | $10^{48}$         | $10^3 - 2 \times 10^4$ |

* case (a)  
† case (b) with $q = 0$

for this factitious burst, current ground-based Cherenkov instruments such as H.E.S.S. would be more likely than Fermi/LAT to probe the modeled emission.

**A SAMPLE OF NEARBY GRBS**

We chose six nearby GRBs (i.e. $z < 0.55$): GRB 030329, GRB 050509B, GRB 050709, GRB 051221A, GRB 060505, and GRB 060614 in this study. The available radio to X-ray afterglow observation data were then used to obtain the parameter values in the model. Data from at least two different wavebands were required. We reproduced the multi-frequency afterglow behaviour of GRB 030329 and GRB 060614 using a set of parameters shown in Table 1 (c.f. [9] for details). For the other four GRBs, parameters were taken from [10], [11], [12], and [13].

**COMPARISON WITH OBSERVATIONS**

Based on the parameters obtained as described in the previous section, the modeled GeV–TeV emission was calculated. Figure 2 shows the modeled time-integrated 0.1 GeV – 20 TeV afterglow spectra of GRB 030329, GRB 050509B, and GRB 060505, where VHE $\gamma$-ray observational data (upper limits) are available for comparison. The SSC spectra with and without EBL-correction are shown for each GRB. The spectra were integrated over the respective time intervals during which the upper limits were derived, as shown in Table 2.

Do we expect the current generation of VHE instruments, like MAGIC, H.E.S.S. or VERITAS, to detect the predicted VHE $\gamma$-rays from nearby GRBs during the afterglow phase? Assuming that observations begin 10 hours after the burst and last for 2 hours, the EBL-attenuated energy fluxes above 200 GeV for these six GRBs, together with the H.E.S.S. sensitivity ($\Gamma = 2.6$, same energy range), are shown in Figure 5.
TABLE 2. Observational time intervals for three nearby GRBs

| GRB   | $z$     | VHE instrument | $t_{\text{obs}} - t_{\text{burst}}$ | exposure     | reference |
|-------|---------|----------------|-------------------------------------|--------------|-----------|
| 030329| 0.1685  | H.E.S.S.       | 11.5 days                           | 30 min       | [14]      |
|       |         | Whipple        | 64.55 hours                         | 65 min       | [15]      |
| 050509B| 0.2248 | STACEE         | 20 min                              | 30 min       | [16]      |
| 060505| 0.089   | H.E.S.S.       | 19.4 hours                          | 120 min      | [14]      |

FIGURE 2. Modeled time-integrated 0.1 GeV – 20 TeV afterglow spectra of GRB 030329, GRB 050509B and GRB 060505, in comparison with VHE upper limits. Dotted and solid lines represent the spectra with and without EBL-correction, respectively. The spectra were integrated over the corresponding time intervals during which the upper limits were derived, as shown in Table 2. For GRB 030329, thick (upper) lines indicate the modeled curve for the Whipple observation time, and thin (lower) lines for the H.E.S.S. observation time. The upper limit points are plotted at the corresponding average photon energies.
FIGURE 3. Comparison between modeled VHE integral energy fluxes above 200 GeV (indicated by dots) for six nearby GRBs, and the H.E.S.S. sensitivity level of $6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (vertical line). The sensitivity flux level is defined as the minimum detectable point source flux for a 5 significance level detection in a 2-hour observation [17]. The shaded region is above the sensitivity level. It is assumed that observations begin 10 hours after the burst.

For GRB 030329, the expected energy flux is $1.4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which is higher than the H.E.S.S. sensitivity level of $6 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ [17]. Therefore, predicted VHE γ-ray emission of forward-shock electrons from a burst similar to GRB 030329 is detectable using the current generation of VHE instruments.

CONCLUSIONS

In this proceeding, we discuss the prospects of detecting VHE γ-rays with current ground-based instruments during the afterglow phase. The SSC emission model from forward-shock electrons [6] was used to predict VHE γ-ray emission in the afterglow phase. Klein-Nishina correction and EBL attenuation, both known to suppress the VHE γ-ray spectra, were taken into account. We chose a sample of six nearby GRBs in this study. Our calculated results are consistent with the upper limits obtained by the VHE γ-ray observations of GRB 030329, GRB 050509B, and GRB 060505. Assuming observations taken 10 hours after the burst, the VHE γ-ray flux predicted from five GRBs is below the sensitivity level of current Cherenkov instruments like MAGIC, H.E.S.S., and VERITAS. However, for those bright and nearby bursts like GRB 030329, a VHE γ-ray detection is possible even with a delayed observation time of $\sim$10 hours after the burst.

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