ARGO-YBJ constraints on very high energy emission from GRBs

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1. Introduction

Gamma-ray bursts (GRBs) are very strong gamma-ray photon emissions from cosmic unpredictable locations in a duration from milliseconds to tens of minutes. They are the most energetic form of energy released from a single object in such a short time. The total amount of light emitted in a GRB is usually a factor of hundreds brighter than a typical supernova. Using thousands of GRBs detected by satellite-based detectors, they have been thoroughly investigated in the keV–MeV energy range. They are isotropically distributed in the sky with a non-thermal origin. According to the time duration, GRBs are usually classified into long (>2 s) and short (<2 s) bursts. Since the first detection by the BeppoSAX satellite for GRB970228 [1], afterglows are observed after GRBs are discovered, and this enables the multi-wavelength investigation of GRBs from the optical band to X-rays. Redshift measurements show that GRBs occur at cosmological distances (the average redshift of GRBs observed by the Swift satellite is z = 2.3 [2]). Some short bursts come from inside old galaxies with little star formation, suggesting that they may be originated from mergers of binary neutron stars or black hole-neutron star systems [3]. Some long bursts are associated with supernovas and confirmed to be related to deaths of massive stars when central cores collapse to black holes [4].

High energy (HE) gamma-ray emissions from GRBs is also observed in several satellite-born experiments. Energetic Gamma-Ray Experiment Telescope (EGRET) detected several GRBs with photon energies ranging from 100 MeV to 18 GeV [5]. Both prompt and delayed emissions were detected and no high energy cutoff was found in the spectra. Most importantly, a distinct HE spectral component was evidently detected in GRB941017 [6]. Recently, Fermi Large Area Telescope (LAT) also detected GeV emissions from GRB080916C [7] and 081024B [8]. These observations at high energies can place important constraints on models of emission processes and on parameters of the environment surrounding the sources of bursts. Very high energy (VHE) emission up to ~TeV is predicted by several models in both prompt and afterglow phases [9]. Emission at such high energies could result from electron Self-Synchrotron Compton (SSC) scattering in either internal or external, forward or reverse shocks. In such cases, a spectrum with double-peak shape extending into the VHE band is expected. Some models [10] also predict VHE emission due to decays of secondary $\pi^0$ mesons in neutron-rich outflows. Observations of VHE emission could play a role in discriminating between these models. The difficulty is that the absorption of the VHE photons by the Extragalactic Background Light (EBL), due to the pair production $\gamma + \gamma_{\text{EBL}} \rightarrow e^+ + e^-$, causes a substantial reduction of the VHE photon flux. This sets a high upper limit on the sensitivity of a detector used for GRB search in this energy range. The gamma-ray fluxes from these GRBs become too small to be detected from current satellite-based experiments due to their small sensitive areas, so only ground-based experiments have areas large enough for the detection.

Search for VHE emission from GRBs has been done by many ground-based experiments including extensive air shower arrays and Cherenkov telescopes. No conclusive detection has been made up to now, while some positive indications were reported. The Tibet $\text{As}^\gamma$ experiment found an indication of 10 TeV emission in a stacked analysis of 57 bursts [11]. The Milagrito experiment reported evidence of emission above 650 GeV from GRB970417A with a chance probability of $1.5 \times 10^{-3}$ [12]. Evidence of emission above 20 TeV from GRB920915C was reported about 1 min earlier than the GRB trigger time at $2.7\sigma$ level by the HEGRA AIROBICC array, but the position deviated of about $9^\circ$ [13]. The muon detector GRAND found an excess during GRB971110 with a chance probability of $3 \times 10^{-3}$ [14]. Due to limited field of view (FOV), Cherenkov telescopes, like MAGIC and HESS, can only be operated in follow-up mode and at least 40 s (usually minutes) are needed to sway the telescopes to point to the GRB. However, this sets very low upper limits to the photon fluences at energies around hundreds of GeV during the afterglow phase [15,16].

With a large FOV (~2 sr) and high duty cycle (>90%), the ARGO-YBJ experiment, using a full coverage detector of Resistive Plate Chambers (RPCs) with area 5600 m$^2$, is well suited for GRB surveying. Following alarms by satellite-born observations of GRBs, the ARGO-YBJ detector is used to look for emission from them with a threshold of a few hundreds of GeV. No significant excess has been observed yet. In this paper, we place upper limits on the VHE emission fluences for the GRBs inside the FOV of the ARGO-YBJ detector. Two models with very different high energy cutoff are used. The detector performance is investigated using MC simulation. Based on this, the sensitivity of the ARGO-YBJ detector for GRB search at different time durations and incident zenith angles is presented in Section 3. The processes of the data analysis and the method to search for VHE emission are described in Section 4. The results are reported and discussed in Section 5.

2. The ARGO-YBJ experiment

The ARGO-YBJ experiment, a collaboration among Chinese and Italian institutions, is designed for VHE $\gamma$-astronomy and cosmic
ray observations and located in Tibet, China at an altitude of 4300 m a.s.l. The detector consists of a single layer of RPCs, operated in streamer mode, with a modular configuration. The basic module is a cluster (5.7 × 7.6 m²), composed of 12 RPCs (2.850 × 1.225 m² each). The RPCs are equipped with pick-up strips (6.75 × 61.80 cm²) and the fast-OR signal of 8 strips constitutes the logical pixel (named pad) for triggering and timing purposes. Hundred and thirty clusters are installed to form a carpet of 5600 m² with an active area of ~93%. This central carpet is surrounded by 23 additional clusters (“guard ring”) to improve the core location reconstruction. The total area of the array is 110 × 100 m². More details about the detector and the RPC performance can be found elsewhere [17].

The RPC carpet is connected to two independent data acquisition systems, corresponding to the shower and scaler operation modes. With the scaler mode, each cluster of the ARGO-YBJ detector counts the rate of events that have total number of hits $\geq 1$, $\geq 2$, $\geq 3$ and $\geq 4$ every 0.5 s. Using the count rates, GRBs in the ARGO-YBJ detector FOV (zenith angle smaller than 45°) are investigated without direction information [18].

In shower mode, the ARGO-YBJ detector is operated by requiring at least 20 particles within 420 ns on the entire carpet detector. The high granularity of the apparatus permits a detailed spatial-temporal reconstruction of the shower front. The temporal information is the arrival time of particles measured by Time to Digital Converters (TDCs) with a resolution of approximately 1.8 ns. This results in an angular resolution of 0.2° for showers with energy above 10 TeV and 2.5° at approximately 100 GeV [19]. In order to calibrate the 18,360 TDC channels, an off-line method [20] is developed using cosmic ray showers. The calibration precision is 0.4 ns by using 24 h of data and the calibration result is updated every month [21].

The central 130 clusters began taking data in June 2006, and the “guard ring” was merged into the DAQ stream in November 2007. The trigger rate is ~3600 Hz and the average duty cycle is higher than 90%.

## 3. Simulation and sensitivity

The effective area of the ARGO-YBJ experiment for detecting gamma-ray showers is estimated by using a full Monte Carlo simulation driven by CORSIKA 6.502 [22] and GEANT3-based code ARGO-G [23]. Five zenith angles ($\theta = 0°$, 10°, 20°, 30° and 40°) are chosen in the simulation and the sampling area is $300 \times 300$ m² around the carpet center. The threshold multiplicity of hits ($N_{hit}$) which triggers ARGO-YBJ is 20. The effective areas for this threshold at the three zenith angles $\theta = 0°$, 20° and 40° are shown in Fig. 1.

In order to avoid strong absorption of VHE photons by the EBL, two models of GRB emission with sharp cutoff of their spectra at 100 GeV and 1 TeV are investigated. Since the multiplicity of hits $N_{hit}$ in an event is related to the shower primary energy, the optimization of the ARGO-YBJ sensitivity can be done by choosing a corresponding cutoff on $N_{hit}$. As results of the optimization, ranges of $N_{hit}$ are found corresponding to the two $E_{\text{cut}}$ models as reported in Table 1. Given the ranges of $N_{hit}$, the corresponding optimal opening angle radii $\phi_{\text{opt}}$ inside which 70% of the signal events is included, are reported in Table 1. This result is almost independent of zenith angle. After using the event selection listed in Table 1, the average effective areas ($A$) over the energy ranges from 10 GeV to 100 GeV and from 10 GeV to 1 TeV with a differential spectral index $-2.0$ (this assumption is used in all the following analyses) are calculated as functions of the zenith angle $\theta$. They fit a functional form $A(\theta) = A_0 \cos^6 \theta$, where $A_0 = 4.36 \pm 0.04$ m² and $119.3 \pm 0.8$ m² are the average effective areas at $\theta = 0°$, with the parameter $n = 14.26 \pm 0.11$ and $10.56 \pm 0.13$ for the two energy ranges, respectively (see Fig. 2); with these functions the average effective areas at any zenith may be obtained. At $\theta = 20°$, the effective area of the ARGO-YBJ detector is about 1.8 m² above 10 GeV if the cut-off energy $E_{\text{cut}}$ of the GRB spectrum is chosen as 100 GeV. On the other hand, it is 64.3 m² if $E_{\text{cut}} = 1000$ GeV.

Using measured cosmic ray data, the background event rate (see Fig. 3) is estimated according to the selected $N_{hit}$ ranges reported in Table 1. Combining this with the effective areas shown in Fig. 2, the minimum detectable fluences for GRBs requiring a 5σ excess are estimated and shown in Fig. 4. The sensitivity worsens with the increase of the zenith angle. The GRB time duration in this figure is fixed at $T = 12$ s and the fluence scales with $T^{1/2}$. We find that the ARGO-YBJ detector has a sensitivity of $10^{-8}$ erg/cm² in the energy range [10,1000] GeV for GRBs with a duration of 12 s at $\theta = 20°$.

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**Table 1**

$N_{hit}$ ranges and corresponding angular window sizes for gamma-rays.

| $E_{\text{cut}}$ (GeV) | $N_{hit}$ | $\phi_{\text{opt}}$ (°) |
|----------------------|----------|------------------|
| 100                  | 20–60    | 3.8              |
| 1000                 | 20–500   | 2.6              |

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![Fig. 1. Effective areas of ARGO-YBJ for gamma-rays with $N_{hit} \geq 20$ as a function of the energy for the three zenith angles $\theta = 0°$, 20° and 40°.](image1)

![Fig. 2. The average effective area in two energy ranges after using the event cut listed in Table 1 as a function of zenith angles. The lines are the fitting result using the function $A_0 \cos^6 \theta$.](image2)
Energy (GeV) Redshift

The absorption factor

Table 2

5. Results and discussion

The data used in this work were collected by the ARGO-YBJ experiment in the periods July 2006–July 2007 and November 2007–January 2009. Twenty-six GRBs detected by satellites were within the FOV of the detector array while it was on. Angular resolution, pointing accuracy and stability of the ARGO-YBJ detector were thoroughly tested by measuring the Moon shadow in cosmic rays over all observational periods [30]. The Crab Nebula and flares of Mrk 421 in years 2006 and 2008 were successfully detected [31].

No significant excess was observed for any of the 26 GRBs, neither as prompt nor prior/delayed emission (see Fig. 5). Upper limits to fluences in the VHE range are listed in Table 3. The upper limits for the number of events, \( N_{\text{on}} \), with confidence level of 99% is calculated with Helene’s method (Eq. (10) in [28]). Using the effective area and assuming a differential power law photon spectrum, the upper limit to the fluence of a GRB in the VHE range is obtained. Guided by the average spectrum of the four bright bursts observed by EGRET, where a power law index of \(-1.95 \pm 0.25 \) was found over the energy range from 30 MeV to 10 GeV [5], an energy spectrum \( \phi \propto E^{-2} \) is assumed. At first, the normalization constant \( C \) is calculated by solving the equation

\[
N_{\text{on}} = \int A(E) \phi(E) dE = C \int A(E) \phi(E) dE
\]

The total fluences can be obtained by integrating \( A(E) \phi(E) dE \) from 10 GeV to 100 GeV and to 1 TeV. The optical depth due to the EBL absorption, and the optical depths predicted by A. Franceschini [29] are used in this work. The absorption factor, which is defined as the ratio

\[
K(z) = \frac{\int A(E) \phi(E) dE}{\int A(E) \phi(E) dE} e^{-\tau_{\text{EBL}}} \]

for GRBs at redshift \( z = 0, 0.1, 0.5, 1.0 \) and 2.3 are listed in Table 2. According to these results, the EBL effect for gamma-rays below 100 GeV is negligible, however, it could be substantial for farther GRBs in the range [10,1000] GeV. With the absorption factor \( K(z) \) and the average effective area \( A \) shown in Fig. 2, the parameter \( C \) can be directly calculated by solving the equation

\[
N_{\text{on}} / (K(z) / A) = \int \phi(E) dE.
\]

As widely discussed, the acceleration mechanism for VHE emission could be different from that at low energies, so that it could be on a different time scale. Even if the duration of every burst detected by satellite is known, the duration of VHE emission is still unknown. It is believed that (a) the most probable emission time is still in the prompt phase; (b) the emission may be delayed even by hours, like in the case of the 18 GeV photon in GRB940217, detected 1.5 h after the prompt emission [26]; (c) the high energy emission could be produced earlier according to some models [27]. The GRB counterpart is first searched in a window \( T_{90} \), which is defined as the time in which 90% of the GRB photons is released. If no signal is found, we continue the search from 1 h before to 1 h after the GRB. Time intervals of 1 s, 6 s, 12 s, 24 s, 48 s and 96 s are used in this search with steps 1 s, 2 s, 3 s, 6 s, 12 s and 24 s, respectively. If no signal is found, we set an upper limit to the fluence in \( T_{90} \).

Given the observed \( N_{\text{on}} \) and the expected background \( N_{\text{bg}} \) in \( T_{90} \), the upper limits for the number of events, \( N_{\text{hit}} \), with confidence level of 99% is calculated with Helene’s method (Eq. (10) in [28]). Using the effective area and assuming a differential power law photon spectrum, the upper limit to the fluence of a GRB in the VHE range is obtained. Guided by the average spectrum of the four bright bursts observed by EGRET, where a power law index of \(-1.95 \pm 0.25 \) was found over the energy range from 30 MeV to 10 GeV [5], an energy spectrum \( \phi \propto E^{-2} \) is assumed. At first, the normalization constant \( C \) is calculated by solving the equation

\[
\int A(E) \phi(E) dE = C \int A(E) \phi(E) dE
\]

The total fluences can be obtained by integrating \( A(E) \phi(E) dE \) from 10 GeV to 100 GeV and to 1 TeV. The optical depth due to the EBL absorption, and the optical depths predicted by A. Franceschini [29] are used in this work. The absorption factor, which is defined as the ratio

\[
K(z) = \frac{\int A(E) \phi(E) dE}{\int A(E) \phi(E) dE} e^{-\tau_{\text{EBL}}} \]

for GRBs at redshift \( z = 0, 0.1, 0.5, 1.0 \) and 2.3 are listed in Table 2. According to these results, the EBL effect for gamma-rays below 100 GeV is negligible, however, it could be substantial for farther GRBs in the range [10,1000] GeV. With the absorption factor \( K(z) \) and the average effective area \( A \) shown in Fig. 2, the parameter \( C \) can be directly calculated by solving the equation

\[
N_{\text{on}} / (K(z) / A) = \int \phi(E) dE.
\]
EBL absorption, while the others can be easily corrected using the factors listed in Table 2 assuming $z = 0.1, 0.5, 1.0$ and 2.3. The fluences in keV bands measured by the satellite experiments are also listed in Table 3.

It is known that GRB spectra can be well fitted with a Band function with a break at energy $E_{\text{b}}$ mostly between 100 keV and 1 MeV, and the average index $\alpha$ below the break is $\sim -1$ and the average index $\beta$ above the break is $\sim -2.3$ [32]. Most GRBs observed by Swift do not have such a clear spectral structure with a break since its effective energy range is often lower than the break energy. GRB060805B was detected by the Inter Planetary Network (IPN) from 30 keV to 10 MeV and the result of fitting the data with the Band function ($\alpha = -0.66$, $\beta = -2.52$ and $E_{\text{b}} = 240$ keV) is shown in Fig. 6 (solid line). If this GRB spectrum extends to TeV energies only following the Band function, it will no significant excess is found, we have set upper limits to fluences for that the transition energy should be above 620 MeV (see model 1 in Fig. 6). The other possibility is that if the transition energy is 100 MeV for this burst, the source should be farther than $z = 0.15$ (see model 2 in Fig. 6). In addition, if the SSC mechanism used by Finke et al. ([33]) to interpret the spectrum of GRB 940217 also works on GRB060805B, the limit found by this work will provide a strong constraint.

In conclusion, we have investigated 26 gamma-ray bursts in the field of view of ARGO-YBJ in about two years in the GeV–TeV energy range searching for prompt, delayed or prior emission. Since no significant excess is found, we have set upper limits to fluences for most of those bursts.

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Fig. 5. Left: distribution of the statistical significance of the 26 GRBs with data available during their prompt phase using both events selections of Table 1. Right: distribution of the statistical significance derived from 2 h of observations around the 26 GRBs analysed with different time durations. The solid lines are normal Gaussian functions for given comparison.

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### Table 3

| GRB         | Satellite | Redshift | $T_{\text{90}}$ (s) | $\theta$ (°) | keV fluence (keV range) | 10–100 GeV (erg cm$^{-2}$) | 10–1000 GeV (erg cm$^{-2}$) |
|-------------|-----------|----------|---------------------|--------------|------------------------|----------------------------|----------------------------|
| 060714      | Swift     | 2.71     | 115                 | 42.8         | 2.9E–6 (15–150)         | 2.10E–2                    | 3.11E–2                    |
| 060805B     | ...       | 8        | 29.1                | 1.1E–4 (30–10000) | 1.29E–4                | 5.08E–6                    |
| 060807      | ...       | 43.3     | 12.4                | 8.5E–7 (15–150) | 7.32E–5                | 4.32E–6                    |
| 060927      | Swift     | 5.47     | 22.6                | 31.6         | 1.2E–6 (15–150)         | 6.63E–3                    | 1.56E–2                    |
| 061028      | Swift     | 106      | 42.5                | 9.7E–7 (15–150) | 6.23E–3                | 1.08E–4                    |
| 061110A     | Swift     | 0.76     | 41                   | 37.3         | 1.1E–6 (15–150)         | 1.23E–3                    | 5.32E–4                    |
| 061122      | ...       | 18       | 33.5                | 2.3E–5 (20–2000) | 4.27E–4                | 8.45E–6                    |
| 070506      | Swift     | 1.50     | 210                 | 19.9         | 5.5E–6 (15–150)         | 5.86E–4                    | 9.63E–4                    |
| 070531      | Swift     | 44       | 44.3                | 1.1E–6 (15–150) | 3.99E–3                | 7.82E–5                    |
| 070615      | ...       | 30       | 37.6                | ...          | ...                    | 1.42E–3                    | 3.93E–5                    |
| 071112C     | Swift     | 0.82     | 15                   | 22.1         | 3.0E–6 (15–150)         | 2.02E–4                    | 1.04E–4                    |
| 080207      | Swift     | 340      | 27.7                | 6.1E–6 (15–150) | 8.95E–4                | 3.31E–5                    |
| 080324      | Swift     | 13.6     | 14.6                | ...          | ...                    | 6.83E–5                    | 5.90E–6                    |
| 090128      | Swift     | 90.6     | 37.2                | 9.4E–6 (15–150) | 3.31E–3                | 1.32E–4                    |
| 090602      | Swift     | 74       | 42.0                | 3.2E–6 (15–150) | ...                    | ...                        |
| 090613B     | Swift     | 105      | 39.2                | 5.8E–6 (15–150) | 2.49E–3                | 7.32E–5                    |
| 090726      | AGILE     | 125      | 36.7                | ...          | ...                    | 2.38E–3                    | 5.21E–5                    |
| 090727C     | Swift     | 79.7     | 34.5                | 5.3E–6 (15–150) | 8.15E–4                | 3.18E–5                    |
| 090822B     | Swift     | 64       | 40.4                | 1.7E–7 (15–150) | 2.55E–3                | 9.46E–5                    |
| 090823      | Swift     | 66       | 21.5                | 1.5E–6 (15–150) | 1.73E–4                | 7.03E–6                    |
| 090825      | Swift     | 23       | 30.5                | 1.9E–6 (15–150) | 3.75E–4                | 1.56E–5                    |
| 090828      | Swift     | 3.04     | 250                  | 29.9         | 3.7E–6 (15–150)         | 7.72E–3                    | 1.25E–2                    |
| 091105      | Swift     | 10       | 36.7                | ...          | ...                    | 4.09E–4                    | 1.30E–5                    |
| 091128      | Swift     | 101.7    | 31.7                | 2.5E–6 (15–150) | 6.21E–4                | 2.05E–5                    |
| 091010      | Swift     | 12.2     | 40.1                | 2.3E–7 (15–150) | 7.38E–4                | 3.21E–5                    |
| 091118      | Swift     | 16       | 13.4                | 4.0E–7 (15–150) | 6.68E–5                | 3.68E–6                    |
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