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Sensitivity Study of Gamma-Ray Burst Detection by ARGO*

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Abstract ARGO is a "full coverage" air shower detector currently under construction in Tibet, China. One of the main goals of this experiment is to search for possible gamma-ray bursts (GRBs) with $E > 10$GeV. In this work, the sensitivity in observing a GRB (with a certain significance) by ARGO is found to be dependent on the flux of the GRB, the slope and the energy cutoff of its spectrum, as well as its time duration and the zenith angle at the observation.

Key words YBJ-ARGO experiment, GRBs, sensitivity

1 Introduction

GRB, a violent energy release at unpredictable time and from unpredictable sky direction, though having had more than 30 years' history since its first discovery, is still one of the most mysterious astronomical phenomena. The satellite experiment BATSE on aboard the CGRO launched in 1991 has found thousands of GRBs, about one per day on average. Their results showed that the arrival direction of GRBs is highly isotropic and it supports GRB's origin at cosmological distance[1]. Furthermore, the accurate location of GRBs with X-ray afterglow observation by BeppoSAX satellite manifested that at least part of GRBs was indeed originated from cosmological distance[2]. Now, several satellite experiments such as HETE, INTEGRAL and Swift are searching for GRBs with energies from keV to MeV. At the same time, theoretical studies are going on very actively.

Though much progress has been achieved from both experimental and theoretical efforts, lots of basic questions such as the emission mechanism of GRBs still remain unresolved. Some theoretical models predict the existence of higher energy GRBs[3]. However, most up-to-date known GRBs were observed in energy range between several keV and several MeV and the only exception is from EGRET on aboard the CGRO which has detected GeV photons in coincidence with 3 BATSE GRBs. In order to understand the complete picture of the process, it is important to improve the sample statistics of high energy GRBs and to measure their multi-band width energy spectrum. The ground-based AS (air shower) experiments possess many advantages such as wide field of view and high duty cycle, therefore, are especially suitable for GRB detection. Compared with many existing AS arrays, ARGO has two additional advantages: high altitude and full coverage, with which the threshold energy of ARGO is significantly decreased and ARGO is expected to have higher sensitivity in detecting GRBs than other AS arrays.

In this work, we study the ARGO sensitivity in detecting GRBs with photon energies greater than 10GeV for the cases of different power law indexes and cut off energies, as well as the zenith angles of GRBs in the ARGO's field of view.

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2 The ARGO experiment

Located at Yangbajing in Tibet, 4,300m a.s.l., the ARGO detector consists of a 74m×78m central carpet made of a single layer of resistive plate counters (RPCs). In order to improve the performance of the apparatus in determining the shower core position, a guard ring is designed to surround the central carpet. The size of the detector is 99m×111m with a total active area about 6400m^2(see Fig. 1). The basic element of the detector is called a "pad" with a dimension of 56cm×62cm, providing the space-time pattern of the shower front which is used to determine the shower direction and size. The details of ARGO were described elsewhere[4].

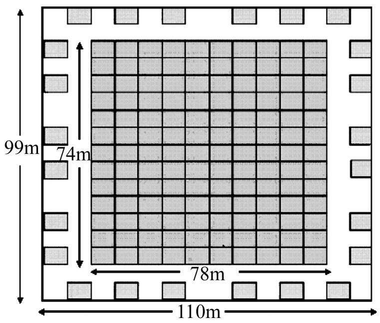

Fig. 1. The map of ARGO apparatus, showing the central carpet and the outer guard ring.

GRB detection is one of the major goals for ARGO. In the past few years, several ground-based experiments such as Milagro[5], Tibet ASγ[6] and L3+C[7] have devoted to the search for high energy GRBs, but all reported negative results. This may be explained by that the GRB flux at higher energy is much lower than that from background cosmic rays at the same energy. From the experimental point of view, it indicates not high enough sensitivities of those apparatus. According to EGRET observation, GRBs showed a hard power law spectrum with a slope of α around 2[8] (differential spectrum) without energy cutoff up to about 10GeV. However, an energy cutoff may arise from either the intrinsic cutoff due to electron injection at the source or the absorption of the photons by the intergalactic radiation field on the way to the observer. The steep spectrum implies the importance of low energy photons while the cutoff indicates the maximum energy possibly reached in a GRB. Beside, the zenith angle θ of the GRB appearance is also an important factor relevant to the sensitivity. For a larger θ an EAS event faces a smaller detector cross section, at the same time, which passes through thicker atmosphere and suffers more attenuation. In the following all of these parameters will be discussed.

3 Effective area of ARGO apparatus in observing GRBs

To select as many as possible γ ray signals, the ARGO trigger condition will be set to have more than 20 fired pads, below which the direction of the event will no longer be reconstructed well1).

Firstly we calculate the effective area, $A_{\rm eff}$, of ARGO in detecting primary gamma-rays. It depends on the gamma-ray energy E and the zenith angle θ as mentioned in last section. We calculate $A_{\rm eff}$ at E=10, 20, 30, 50, 70, 100, 200, 300, 500, 700 and 1000GeV, for θ=0, 10, 20 and 30 degrees, and then use a power-law spectrum having different α and with different cutoff $E_{\rm max}$ to calculate the energy weighted mean effective area $\langle A_{\rm eff}\rangle$ that is therefore a function of α, $E_{\rm max}$ and θ.

$A_{\rm eff}$ is calculated by means of a full MC simulation. The code Corsika2) was used to simulate the gamma-ray induced showers in the atmosphere and ARGOG package based on GEANT33), for the response of the ARGO detector. A sampling area of 210m×210m was used to enclose ARGO at its center. To account for the occasional muons hitting ARGO detector from un-correlated cosmic ray showers, a noise rate of 380Hz per pad based on the on-site measurement was taken into account in the simulation. By definition, $A_{\rm eff}$ can be calculated as:

$$A_{\rm eff}=\frac{n}{N}\cdot A_{\rm s}\cdot\cos\theta. \quad (1)$$

1) http://argo.na.infn.it/argoart/perugia_2003.ps
2) http://www-ik.fzk.de/~heck/corsika/
3) http://www.fisica.unile.it/~argo/analysis/argog/index.html

Here, n is the number of triggered events, N is the number of dropped events, and A_s is the sampling area (210m×210m). The resultant effective area $A_{\rm eff}$ as a function of primary energies are displayed in Fig. 2 for zenith angles θ=0, 10, 20 and 30 degrees.

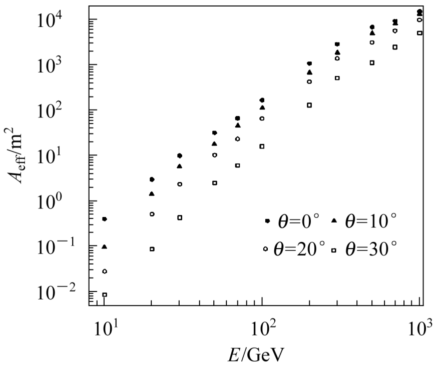

Fig. 2. The $A_{\rm eff}$ of ARGO for gamma-rays from different zenith angles, as a function of primary energies.

It can be seen from Fig. 2 that, with $N_{\rm pad} \geqslant 20$ condition, the efficiency of ARGO in detecting gamma-rays at $E <$10GeV is very small. On the other hand, the angular resolution for those events is rather poor, it is therefore reasonable to ignore the gamma ray events if the energy is below 10GeV in the following study. For a certain zenith angle, after assuming an index α of the GRB differential spectrum and a cutoff energy $E_{\rm max}$, the energy weighted mean effective area $\langle A_{\rm eff}\rangle$ of ARGO can be calculated by

$$\langle A_{\rm eff}\rangle = \frac{\int_{10\rm GeV}^{E_{\rm max}} A_{\rm eff}(E)\cdot E^{-\alpha}\cdot {\rm d}E}{\int_{10\rm GeV}^{E_{\rm max}} E^{-\alpha}\cdot {\rm d}E} \ . \tag{2}$$

Here, $A_{\rm eff}(E)$ is the parameterized function according to the points in Fig. 2, and for $E_{\rm max}$, values between 50 and 1000GeV are considered.

4 Minimum signal event rate required for a 5 sigma observation

In ARGO experiment, a GRB appears to be a shower cluster in a given small sky window and a time interval (Δt) with an appropriate significance. In this work 5σ was taken as the necessary significance to specify a GRB from the background fluctuation. From full MC simulation we know that, under the trigger condition $N_{\rm pad} \geqslant 20$, the angular resolution of ARGO is 1.65°[9], and the optimal angular radius of the on-source window is 2.6° (a factor of 1.58 of the angular resolution)[10]. In the following the angular radius 2.6° is used to define the size of on-source and off-source windows

For a simulated GRB with a given zenith angle, the "equi-zenith-angle" method was used to estimate the cosmic ray background. According to MC, this background event rate is $\sim 2\times10^4$Hz[1]. Taking this value, together with the experimentally measured zenith angle and azimuth angle distributions into account, the number of events in the background windows is determined.

In general, any time interval (Δt) should be tried as the duration time when searching for a GRB. As an example, in the case of $\Delta t = 1$s the expected average number of background events $\langle N_{\rm b}\rangle$ can be obtained as a function of zenith angle and shown in Fig. 3. According to Fig. 3 the minimum number of signals $N_{\rm on}$ within 1s (i.e., the minimum signal event rate k_0) required for a 5σ observation can be obtained and shown in Fig. 4.

For a more general case, when time duration Δt (in s) is not 1, the minimum signal event rate can be calculated by

$$k = k_0/\sqrt{\Delta t}\ . \tag{3}$$

Here, both k and k_0 are in photons/s.

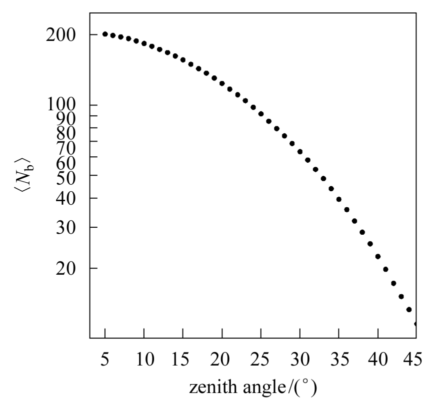

Fig. 3. The background event rate $\langle N_{\rm b}\rangle$ of ARGO within 1s as a function of zenith angles.

1) http:// argo.na.infn.it/argoart/perugia_2003.ps

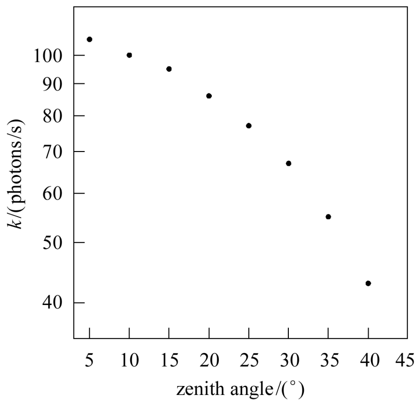

Fig. 4. The minimum signal event rate k to make a GRB having 5σ significance in ARGO as a function of zenith angles.

5 ARGO sensitivity to detect $E>$ 10GeV GRBs

The minimum signal event rate k obtained in last section depends on the detailed ARGO performance feature. To compare with the results from other experiments and theoretical predictions, the corresponding minimum signal integral flux $F_{\min}$ (from 10GeV to $E_{\max}$) outside the earths' atmosphere should be calculated by

$$F_{\min}=k/\langle A_{\mathrm{eff}}\rangle. \quad (4)$$

Here, $\langle A_{\mathrm{eff}}\rangle$ and k are from Eqs. (2) and (3), respectively. And $F_{\min}$ characterizes the sensitivity of ARGO in detecting GRBs with energies higher than 10GeV. Since $\langle A_{\mathrm{eff}}\rangle$ depends on the slope α of the gamma-ray spectrum, the energy cutoff $E_{\max}$ and the zenith angle θ of the GRB, and k depends on the zenith angle θ and the time duration Δt of a GRB, $F_{\min}$ have a combined dependence on all these parameters. Assuming $\theta=20°$ and Δt=1s, three numbered curves in Fig. 5 show the $F_{\min}$ as a function of $E_{\max}$ for α=2.5, 2.0, 1.5, respectively. As an example, in case of α=2.0 and $E_{\max}$=1TeV, $F_{\min}$ is about 7×10^{-5} phontons/(cm^2·s).

During its livetime, EGRET has detected GeV photons in coincidence with 3 BATSE GRBs: GRB910503, GRB930131 and GRB940217. With the joint analyses of BATSE data and EGRET data, the slopes of their spectra were determined to be 2.24[1)], 1.97 and 2.53[11], respectively. Assuming the power law spectra of these three GRBs can be extended to $E_{\max}$ between 50GeV to $E_{\max}$ <1TeV, their integral fluxes from 10GeV to $E_{\max}$ can thus be calculated. The dots and circles in Fig. 5 are for the integral fluxes of GRB930131 and GRB910503, respectively. The flux of GRB940217 is not shown in Fig. 5 because it is much lower than the ARGO sensitivity.

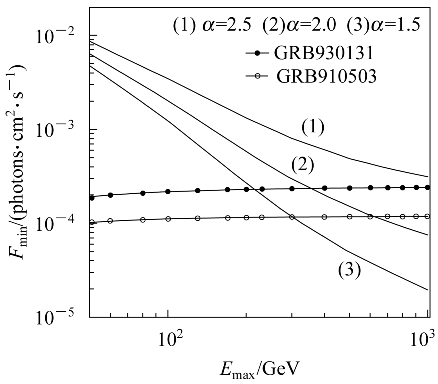

Fig. 5. The $F_{\min}$ of ARGO and the extrapolating fluxes of 3 EGRET GRBs as the function of $E_{\max}$ (curves 1, 2 and 3 are the $F_{\min}$ of ARGO for α=2.5, 2.0, 1.5, respectively; dots and circles are for the integral fluxes of GRB930131 and GRB910503, respectively).

From Fig. 5 we can see that ARGO is able to observe GRB930131 if its $E_{\max}$ is above 300GeV. And if $E_{\max}$ of GRB910503 spectrum is larger than 1TeV, it can also be observed by ARGO. In conclusion, 2 out of these 3 GRBs could be observed by ARGO if they would happen again with a high enough cutoff energy and a θ angle smaller than 20°.

6 Conclusion

The ARGO sensitivity in detecting a GRB, i.e. the minimum signal integral flux outside the atmosphere, is found to depend on the slope, the energy cutoff of the spectrum, and depend on the time duration of the GRB and its zenith angle. In this paper it is shown that for a GRB with a zenith angle smaller than 20°, a slope around 2.0 (or flatter), and the cutoff energy above 1TeV, and if the duration time lasts longer than 1s, ARGO will be sensitive enough to

1) http://argo.na.infn.it/argo_pub_artic.html (Proposal, 1996)

discover it. Typically, the required minimum signal integral flux outside the earths' atmosphere is about 10^{-5}—10^{-4} photons/(cm^2·s).

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ARGO实验探测γ暴的灵敏度研究*

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摘要　西藏羊八井ARGO实验是对广延大气簇射事例进行观测研究的“全覆盖式”地面宇宙线观测实验, 其主要目的之一就是探测$E>$10GeV的γ暴. 通过Monte Carlo模拟, 估算了ARGO实验探测10GeV γ暴所具有的灵敏度.

关键词　YBJ-ARGO实验　γ暴　灵敏度

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