Study of Gamma-Ray Bursts of energy $E > 10$ GeV with the ARGO-YBJ detector

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Abstract

The study of high energy gamma-ray bursts can be performed by large area air shower arrays operating at very high mountain altitudes. ARGO-YBJ is a detector optimized to observe small size air showers, to be constructed at the Yangbajing Laboratory (Tibet, China) at an altitude of 4300 m. One of the goals of the experiment is the study of gamma-ray bursts of energies $E > 10$ GeV. This can be achieved using the "single particle" technique, more profitable in the energy region $E < 50$ GeV, and the "low multiplicity" technique, suitable to observe GRBs at higher energies. The sensitivity of ARGO-YBJ allows the detection of GRBs with energy fluences in the range 1÷100 GeV as low as $F \sim 10^{-6} \div 10^{-5}$ erg cm$^{-2}$, depending on the spectral characteristics of the burst.

1 Introduction

The observation of GeV photons by EGRET during few intense gamma-ray bursts suggested the idea that a large part of events could have a high energy component, not observed so far due to the low fluxes (Catelli 1997a). Gamma-ray emission in the GeV-TeV energy range is predicted by some fireball models (see Baring 1997, for a review). The study of the high energy part of the spectrum would be of great importance to investigate the physical conditions of the emitting region, restricting the range of fundamental parameters as the magnetic field, the density and the bulk Lorentz factor.

Unfortunately, due to the cosmological distances of the GRBs sources, the high energy gamma-rays would be absorbed by pair production on starlight photons during their travel towards the Earth. According to Salomon and Stecker (1998), the flux of gamma rays of energy $E > 500$ GeV is strongly reduced if the distance of the source is $z > 0.1$. Since the minimum redshift so far measured among six host galaxies is $z = 0.695$ (Djorgovski 1999), even assuming that GRBs emits gamma rays in the TeV region, most of the spectra observed at Earth would cutoff at energies less than few hundreds GeVs.

Observation of high energy GRBs can be performed by ground based experiments, as air shower arrays, detecting the secondary particles produced in the atmosphere by primary gamma-rays. Their large field of view ($\Omega \sim \pi$ sr) and their duty cycle of almost 100% make them suitable to observe unpredictable events as GRBs. Due to the absorption of the high energy part of the spectrum, the detectors must be sensitive to gamma-rays of energy as low as 10-100 GeV. This can be achieved with two basic conditions:

a) by operating at very high mountain altitude, in order to increase the number of detectable particles (as an example, the mean number of charged particles produced by a 100 GeV gamma-ray reaching the altitude of 2000 m is $n_c \sim 1.3$, while at 5000 m $n_c \sim 25$).

b) by disposing of a very large and "full-coverage" detection surface, in order to detect the largest number of shower particles.

These conditions are fully satisfied by the ARGO-YBJ air shower detector. In the following we present the sensitivity of ARGO-YBJ to observe gamma-ray bursts as a function of the GRB spectral characteristics.

2 The ARGO-YBJ detector

The ARGO-YBJ experiment has been conceived with the aim of detecting small size atmospheric air showers. It is under construction at the Yangbajing High Altitude Cosmic Ray Laboratory (Tibet, China), at an altitude of 4300 m above the sea level. It consists of a central core made by a single layer of Resistive Plate
3 Detection of gamma-ray bursts

The detection of high energy gamma-ray bursts can be performed by the ARGO-YBJ detector by using two different modes of operation:

a) the "single particle" technique;

b) the "low multiplicity" technique.

In the following we discuss both methods and make a comparison of their sensitivity in the energy range $10 \text{ GeV} < E < 1 \text{ TeV}.$

3.1 The "single particle" technique (SP).

An air shower array can be sensitive to primary energies as low as 10-100 GeV operating in "single particle mode", i.e. recording all single secondary particles hitting the detector with energy larger than the detection energy threshold $E_{\text{th}}.$ In this detection mode most of the events are due to solitary muons and electrons of air showers generated by low energy cosmic rays. A gamma-ray burst is detectable if the secondary particles due to the gamma-rays interactions in the atmosphere give a short time excess in the single particle counting rate, of amplitude larger than the statistical fluctuations of the all-sky cosmic rays background. The directions and energies of gamma-rays are not measurable; however this technique could provide a measurement of the total high energy flux and the temporal behaviour of the high energy emission (Vernetto 1999, Aglietta 1999, Cabrera 1999).

The effective area to detect a primary gamma-ray of energy $E$ and zenith angle $\theta$, can be expressed as $A_{\text{eff}}(E, \theta) \sim A_d f_g n_e(E, \theta),$ where $A_d = 6100 \text{ m}^2$ is the sensitive area, $n_e(E, \theta)$ is the mean number of particles reaching the detector level (with an energy larger than the detection threshold) and $f_g$ is the gain factor due to the photons conversion in the lead layer ($f_g \sim 1.1$). The curve A in Fig.1 shows the ARGO-YBJ effective area as a function of the gamma-ray primary energy $E$, for a zenith angle $\theta=20^\circ$.

Given a GRB with an energy spectrum $dN/\gamma dE$ (photons per unit area per unit energy) and zenith angle $\theta$ the number of events detected is $N_{SP} = A_d f_g \cos \theta \int dN_\gamma/dE n_e(E, \theta) dE$.

The signal is observable if the number of detected particles $N_{SP}$ is significantly larger than the background statistical fluctuations $N_b = \sqrt{A_d B \Delta t},$ where $B$ is background rate (events per unit area and unit time) and $\Delta t$ is the GRB duration. The measured single particle background rate at the Yangbajing site is $B \sim 1500 \text{ events m}^{-2} \text{ s}^{-1}.$ Requiring for the GRB signal a minimum statistical significance of 4 standard deviations, the number $N_{SP}$ of events in ARGO-YBJ from a GRB of time duration $\Delta t = 1 \text{ s}$ must be larger than $\sim 1.2 \times 10^4$.

3.2 The low multiplicity technique (LM).

The low multiplicity technique (LM) consists in the detection of very small air showers, by requiring at least 6 fired pads per shower (a pad is a detection unit of $56 \times 56 \text{ cm}^2,$ see Abbrescia 1996). The effective area $A_{\text{eff}}$ of ARGO-YBJ to detect primary gamma-rays and protons using this technique has been obtained by simulations and it is shown in Fig.1 for primaries with zenith angle $20^\circ$ (curve B for gamma-rays and curve C for protons). The LM effective area for gamma-rays is 2-3 orders of magnitude smaller than the "single particle" one (curve A), due to the higher number of particles required to satisfy the trigger condition ($\geq 6$ instead of 1). However the possibility to measure the primary arrival directions using the standard reconstruction technique of the shower front, reduces significantly the background, limited to cosmic rays with directions inside the angular error box. The angular resolution for primaries with energy $E \sim 10 \text{ GeV}$ (defined as the opening angle around the source containing the 70% of the signal showers) is $r \sim 5^\circ$ (Abbrescia 1996). Using the cosmic ray primary proton spectrum measured
Figure 1: Effective area of ARGO-YBJ to detect primary gamma-rays using the "single particle" technique (curve A) and the "low multiplicity" technique (curve B); effective area to detect primary protons using the "low multiplicity" technique (curve C). The primary zenith angle is 20°.

Figure 2: Minimum energy fluence in the 1-100 GeV range observable by ARGO-YBJ, as a function of the maximum energy of the spectrum $E_{\text{max}}$, using the LM technique (solid line) and the SP technique (dashed line). The points represent the extrapolations to 100 GeV of 14 EGRET spectra.

by Honda (1995), the number of background events with arrival directions in a cone of radius $r = 5°$ and zenith angle $\theta = 20°$ are expected to be $B_{LM} \sim 160$ s$^{-1}$. The number of events in ARGO-YBJ due to the burst is: $N_{LM} = 0.7 \int A_{eff} dN_{\gamma}/dE\ dE$. Requiring for the GRB signal a minimum statistical significance of 4 standard deviations, the number $N_{LM}$ of events in ARGO-YBJ due to a GRB of time duration $\Delta t = 1$ s and zenith angle $\theta = 20°$ must be larger than $\sim 50$.

3.3 Sensitivity to detect GRBs

For simplicity we assume a burst giving a gamma-ray flux at the top of the atmosphere as $dN/dE = KE^{-\alpha}$ photons m$^{-2}$ and a power law energy spectrum extending with unchanged slope up to a maximum energy $E_{\text{max}}$, with $E_{\text{max}} > 10$ GeV. This assumption is supported by EGRET observations, which report power law spectra extending with no visible cutoff up to the maximum energy determined by the instrument sensitivity (in some cases above 1 GeV). The average spectral slope observed in the 30 MeV-10 GeV region is $\alpha = 1.95 \pm 0.25$ (Dingus 1997). Obviously a sharp cutoff at $E = E_{\text{max}}$ is unrealistic, but for our purposes this simple parametrization can be adopted. The energy cutoff can be due to an intrinsic cutoff at the source or/and to the absorption of gamma-rays in the intergalactic space, as previously mentioned. The latter effect could affect the spectra at relatively low energy: according to Salomon and Stecker (1998), gamma-rays of energy larger than $\sim 40$ (100) GeV would be strongly absorbed if the GRB distance is $z=1.0 \ (0.5)$.

In order to evaluate the ARGO-YBJ sensitivity, it is convenient to work in terms of $F_{\text{min}}$, defined as the minimum energy fluence in the energy range 1 GeV $\div E_{\text{max}}$ necessary to make a GRB observable by ARGO-YBJ, assuming that the spectrum extends with unchanged slope up to $E_{\text{max}}$. Fig. 2 shows $F_{\text{min}}$ as a function of $E_{\text{max}}$, with $E_{\text{max}}$ in the range 10 GeV $\div 1$ TeV, using the SP and the LM techniques. The curves are given for a GRB duration $\Delta t = 1$ s and a spectral slope: $\alpha = 2.0$. The minimum fluence for a different duration $\Delta t$
The minimum required statistical significance of the signal is $\sigma = 4$ standard deviations. Obviously the sensitivity increases with $E_{\text{max}}$. The dependence on $E_{\text{max}}$ is stronger for LM than for SP, given the different behaviour of the effective areas as a function of the gamma-ray energy (moreover, the angular resolution improves with the energy, an effect which is not accounted for in the present calculations). This makes the SP technique more profitable when the energy spectrum has a relatively low energy cutoff, in this case, for $E_{\text{max}} < 50$ GeV. This value ranges between 35 and 70 GeV if the slope $\alpha$ varies from 1.5 to 2.5.

To compare the ARGO-YBJ sensitivity with the fluxes that can be reasonably expected at high energy, in the same figure we report the fluences in the $1 \div 100$ GeV energy range obtained extrapolating (with the observed slopes) the spectra measured by EGRET during the 15 events detected by the TASC instrument (Catelli 1997b) (one of the events, showing an unusual steep spectrum with $\alpha=3.67$, is not shown, since the extrapolated fluence $F = 10^{-10}$ erg cm$^{-2}$ falls well out of the plot). As can be seen in the figure, most of the events have an energy fluence larger than the ARGO-YBJ limits.

4 Conclusions

The ARGO-YBJ detector could observe GRBs in the energy range $E > 10$ GeV using the ”single particle” technique (SP) and the ”low multiplicity” technique (LM). The SP method is more suitable for gamma-ray bursts with energy spectra not extending more than $\sim 50$ GeV, while the LM method is preferable for more energetic spectra. Adopting both techniques, ARGO-YBJ could detect GRBs with energy fluence in the range $1 \div 100$ GeV as low as $F \sim 10^{-6} \div 10^{-5}$ erg cm$^{-2}$, if the spectral slope is $\alpha \sim 2$.

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