Search for High-Energy Emission from GRBs with the ARGO-YBJ Detector

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Abstract. ARGO−YBJ is a "full coverage" air shower detector consisting of a 6700 m^2 carpet of Resistive Plate Counters, located at Yangbajing (Tibet, P.R.China, 4300 m a.s.l). Its large field of view (~ 2 sr, limited only by the atmospheric absorption) and high duty-cycle make ARGO-YBJ particularly suitable to detect unpredictable and short duration events such as GRBs. ARGO-YBJ works using two techniques: the "Scaler Mode", which reaches the lower energy limit (~ 1 GeV) of the detector, and the "Shower Mode", with an energy threshold of a few hundreds of GeV. Here we present the results of the search for high-energy emission from GRBs in coincidence with satellite detections.

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INTRODUCTION

The Astrophysical Radiation with Ground-based Observatory at YangBaJing (ARGO-YBJ), located at the Yangbajing Cosmic Ray Laboratory (30.11°N, 90.53°E, vertical atmospheric depth 606 g/cm^2), was completely installed in spring 2007. It is made by a single layer of Resistive Plate Counters (RPCs), with a full coverage (93% of active surface) of an area of $\sim$5600 m^2, surrounded by a sampling guard ring for a total of $\sim$6700 m^2. The apparatus has a modular structure, the basic module being a "cluster" (5.7×7.6 m^2), consisting of 12 RPCs (2.850×1.225 m^2 each). The RPCs are working at a high voltage 7200 V with a gas mixture made by 15% Argon, 10% Isobutane and 75% Tetrafluoroethane and a resulting efficiency of 95%. Since the clusters are working independently, physical studies started at the beginning of the installation, with the active area increasing with time.

The detector is connected to two independent data acquisition systems, corresponding to operations in "shower mode" and "scaler mode". In shower mode the arrival time and location of each particle are recorded using the highest space-time granularity of the detector, the "pad", with dimension 55.6×61.8 cm^2 (10 pads on each RPC). The present trigger threshold is set to 20 fired pads, corresponding to an energy threshold for photons of a few hundreds of GeV and a trigger rate of $\sim$3.8 kHz. In scaler mode the total counts are measured every 0.5 s: for each cluster the signal coming from its 120 pads is added up and put in coincidence in a narrow time window (150 ns), giving the counting rates of $\geq$1, $\geq$2, $\geq$3 and $\geq$4 pads, that are read by four independent scaler channels. The corresponding counting rates are $\sim$40 kHz, $\sim$2kHz, $\sim$300 Hz and $\sim$120 Hz. This "single particle technique" does not allow the measurement of the energy and arrival direction of the primary gamma rays, but the energy threshold can be pushed down to $\sim$1 GeV, overlapping the highest energies investigated by satellite experiments. Moreover, with four measurement channels sensitive to different energies, in case of positive detection valuable information on the high energy spectrum slope and possible cutoff may be obtained. A detailed description of the detector and its performance can be found in [1, 2] and references therein; the single particle technique applied to the ARGO-YBJ experiment, including the determination of the effective area, can be found in [3].

SEARCH FOR HIGH-ENERGY EMISSION FROM GRBS

Data have been collected from November 2004 (corresponding to the Swift satellite launch) to September 2008, with a detector active area increasing from $\sim$700 to $\sim$6700 m^2. During this period, a total of 61 GRBs was inside the ARGO-YBJ field of view (i.e. with zenith angle $\theta \leq 45°$); for 19 of them the detector and/or data acquisition were not active or not working properly. The remaining 42 events were investigated by searching for a significant excess in coincidence with the satellite detection. In order to extract the maximum information from the data, two GRB analyses have been implemented: 1) search for a signal from every single GRB; 2) search for a signal from the stack of all GRBs.

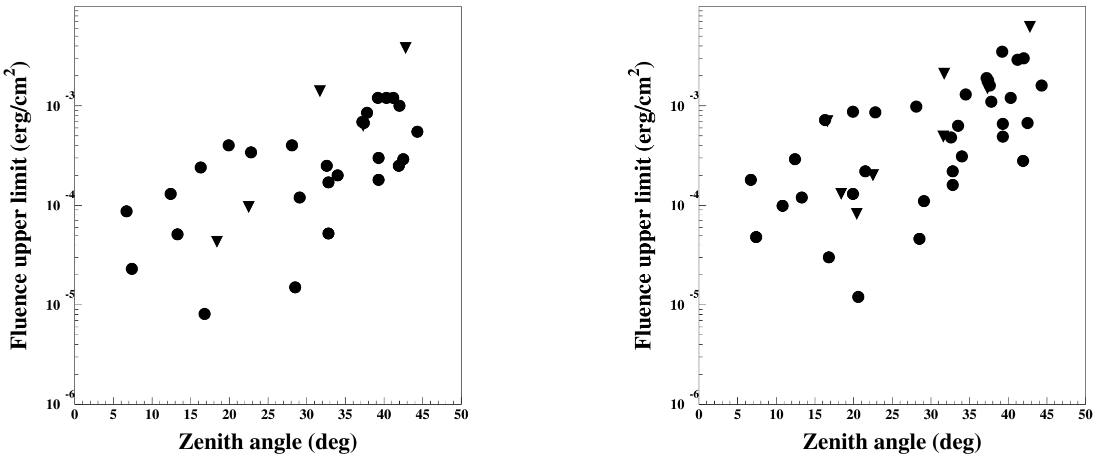

FIGURE 1. Fluence upper limits as a function of the zenith angle in the 1-100 GeV range obtained extrapolating the measured keV-MeV spectra (left) or assuming a differential spectral index 2.5 (right). For those GRBs with known redshift the upper limits are calculated taking into account the extragalactic absorption (triangles), otherwise $z = 1$ is assumed (circles).

For both analyses, the first step is the data cleaning and check. The counting rates of the clusters surviving our quality cuts (∼92%) are then added up and the normalized fluctuation function $f = (s-b)/\sigma$, where $\sigma = \sqrt{b + b\,\Delta t_{90}/600}$ is used to give the significance of the coincident on-source counts. In this case s is the total number of counts in the Δt_{90} time window given by the satellite detector (corresponding to the collection of 90% of the photons) and b is the number of counts in a fixed time interval of 300 s before and after the signal, normalized to the Δt_{90} time. Due to the correlation between different clusters (given by the air shower lateral distribution), the distributions of the sum of the counts are larger than Poissonian and this must be taken into account to calculate the significance of a possible signal. The statistical significance of the on-source counts over the background is obtained in an interval of ±12 h around the GRB trigger time. This calculation is made using equation (17) of Li & Ma [4]; a detailed analysis of the correlation effect and detector stability on counting rates can be found in [3]. The analysis can be done for all the multiplicity channels ≥1, ≥2, ≥3, ≥4 and 1, 2, 3, where the counting rates C_i are obtained from the measured counting rates $C_{\geq i}$ using the relation $C_i = C_{\geq i} - C_{\geq i+1} \quad (i = 1,2,3)$. In the following, all the results are obtained using the counting rate C_1, since it corresponds to the minimum primary energy in the ARGO-YBJ scaler mode. The distribution of the significances for the whole set of 39 GRBs shows no significant excess: the mean value is 0.26σ and the maximum significance is obtained for GRB051114 (3.10σ), with a chance probability of 3.8% taking into account the total number of GRBs analyzed.

The fluence upper limits are then obtained in the 1-100 GeV energy range adopting a power law spectrum and considering the maximum number of counts at 99% confidence level (c.l.), following [5]. For this calculation, two different assumptions are used for the power law spectrum: a) extrapolation from the keV-MeV energy region using the spectral index measured by the satellite experiments; b) a differential spectral index α = -2.5. Since the mean value of spectral indexes measured by EGRET in the GeV energy region is α = -2.0 [6], we expect the true upper limits to lie between these two values. For those GRBs with known redshift, an exponential cutoff is considered to take into account the effects of the extragalactic absorption. The extinction coefficient is calculated using the values given in [7]. When the redshift is not known, a value z = 1 is adopted. Figure 1 shows the upper limits obtained extrapolating the keV power law spectra measured by satellites (left) and those obtained assuming a differential index 2.5 (right). Triangles represent GRBs with known redshift.

When using as the GRB spectrum the extrapolation from the keV-MeV region with the spectral index measured by satellite experiments, the upper limit to the cutoff energy can be determined at least for some GRBs. The procedure is the following: the extrapolated fluence is plotted together with our fluence upper limit as a function of the cutoff energy E_{cut}. If the two curves cross in the 2-100 GeV energy range, the intersection gives the upper limit to the cutoff energy. Figure 2 shows the resulting cutoff energies as a function of the spectral index for the 14 GRBs for which the intersection happens in the quoted energy range. For one of them (GRB050802) the knowledge of the redshift allows the estimation of the extragalactic absorption.

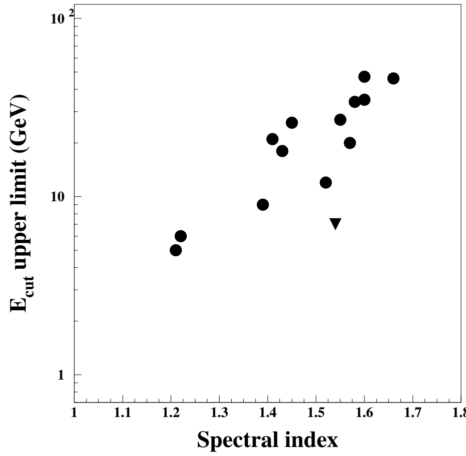

FIGURE 2. Upper limits to the cutoff energy as a function of the differential spectral index. The triangle represents GRB050802, whith redshift z=1.71.

A different analysis is done supposing a common timing feature in all the GRBs. First, all the events during a time window Δt (with Δt=0.5, 1, 2, 5, 10, 20, 50, 100, 200 *s*) after T_0 (the low energy trigger time given by the satellite) for all the GRBs have been added up. This is done in order to search for a possible cumulative signal with a fixed duration after T_0. The resulting significances for the 9 time bins show that there is no evidence of emission for a certain Δt. The resulting overall significance of the GRBs stacked in time with respect to random fluctuations is 0.27 σ.

A second search is done to test the hypothesis that the high energy emission occurs at a certain phase of the low energy burst, independently of the GRB duration. For this study, all the 36 GRBs with $\Delta t_{90} \geq 5\ s$ (i.e. belonging to the "long GRB" population) have been added up in phase scaling their duration. This choice has been done for both physical and technical reasons, adding up the counts for GRBs of the same class and long enough to allow a phase plot with 10 bins given our time resolution of 0.5 s. The resulting significances for the 10 phase bins show that there is no evidence of emission at a certain phase, and the overall significance of the GRBs stacked in phase (obtained adding up all the bins) with respect to background fluctuations is 0.36 σ.

CONCLUSIONS

In the search for high energy emission in coincidence with GRBs detected by satellites, no significant excess was found for any event. The search for a cumulative signal, stacking GRBs both in time and phase, has shown no deviation from the statistical expectations. The derived fluence upper limits reach values as low as $\approx 10^{-5} erg/cm^2$ in the 1-100 GeV energy region. Since upper limits to the cutoff energy can be set in this range for several GRBs, we can conclude that a simple extrapolation of the power law spectra measured at low energies is not always possible [8]. Combining operations in scaler and shower modes, the ARGO-YBJ experiment allows the study of GRBs in the whole 1 GeV$-$1 TeV range.

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