Search for Gamma Ray Bursts with the ARGO-YBJ Detector in Scaler Mode

T. Di Girolamo*, P. Vallania†, C. Vigorito‡, F.R. Zhu§

on behalf of the ARGO-YBJ Collaboration[1]

‡*IFSI-Torino, INAF, University of Torino and INFN-Torino, Italy*
†*IFSI-Torino, INAF and INFN-Torino, Italy*
**University of Napoli and INFN-Napoli, Italy*
§*Key Laboratory of Particle Astrophyics, Institute of High Energy Physics, Beijing, P.R. China*

***Abstract*. We report on the search for Gamma Ray Bursts (GRBs) in the energy range 1-100 GeV in coincidence with the prompt emission detected by satellites using the Astrophysical Radiation Ground-based Observatory at YangBaJing (ARGO-YBJ[1]). With a big active surface (∼6700 m^2) and large field of view (∼2 sr) the ARGO-YBJ air shower detector is particularly suitable to detect unpredictable and short duration events such as GRBs.**

The search has been performed using the single particle technique both in time coincidence with satellites and piling up all the GRBs in time and in phase. Between 2004 December 17 and 2009 April 30, 85 GRBs detected by satellites occurred within the field of view of ARGO-YBJ (zenith angle $\theta \leq 45°$). For 66 of these we searched for a GeV counterpart in the ARGO-YBJ data finding no statistically significant emission. The obtained fluence upper limits reach values as low as 10^{-5} erg cm^{-2} in the 1-100 GeV energy region.

***Keywords*: Gamma Ray Bursts;Observations**

I. INTRODUCTION

The study of GRBs has been done mainly from space detecting the primary photons. Due to the fast decrease of the energy spectrum, the operating energy is usually in the keV-MeV range, and only EGRET in the past and now the Fermi Gamma Ray Space Telescope reached the GeV region, with maximum detectable energies of 30 and 300 GeV respectively. From ground level, the search can be done by means of large area extensive air shower detectors operating at high altitude, detecting the secondary particles generated by the interaction of the primary photons with the atmosphere nuclei. This search, which started several years ago (see for example [1],[2],[3],[4] and [5]) as a particular research of experiments that investigate different physics items, requires very stable and reliable detectors; moreover, at lower energies the number of secondary particles reaching the ground, often only one, does not allow the measurement of the arrival direction, making unfeasible an independent detection.

Forty years after their discovery and more than ten years after the detection of the first afterglow by BeppoSAX, the physical origin of the enigmatic GRBs is still under debate. The scarcity of information generates a confused situation, allowing a great variety of very different models. In these conditions, and mainly in the > 1 GeV energy region, any result could be of great importance to approach the solution of the GRB mystery.

In this paper, the search for emission in the 1-100 GeV range carried out by ARGO-YBJ using the single particle technique in coincidence with the prompt emission detected by satellites, is presented for several GRBs.

II. THE DETECTOR

ARGO-YBJ is an extensive air shower detector located at an altitude of 4300 m a.s.l. (atmospheric depth 606 g cm^{-2}) at the Yangbajing Cosmic Ray Laboratory (30.11°N, 90.53°E) in Tibet, P.R. China. The detector is made by a single layer of Resistive Plate Chambers (RPCs), operated in streamer mode and grouped into 153 units called "clusters" (5.7×7.6 m^2) [6]. Each cluster is made by 12 RPCs (1.225×2.850 m^2) and each RPC is read out by using 10 pads, with dimensions 55.6×61.8 cm^2, representing the space-time pixels of the detector. The clusters are disposed in a central full coverage carpet (130 clusters, ∼5600 m^2, ∼93% of active surface) and a sampling guard ring (∼40% of coverage) to increase the effective area and improve the core location reconstruction in shower mode.

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 ≥ 1, ≥ 2, ≥ 3, and ≥ 4 pads, that are read by four independent scaler channels. These counting rates are referred in the following respectively as $C_{\geq 1}$, $C_{\geq 2}$, $C_{\geq 3}$, and $C_{\geq 4}$, and the corresponding rates are $\sim$ 40 kHz, $\sim$ 2 kHz, $\sim$ 300 Hz, and $\sim$ 120 Hz. A detailed description of the detector performance can be found in [7] and references therein. The installation of the whole detector was completed

[1]See the full ARGO-YBJ Collaboration list attached to the ICRC Proceedings

in 2007, but since the clusters are working independently, physical studies started since the beginning of the installation, with the active area increasing with time. Although the single particle technique does not provide information about the energy and arrival direction of the primary gamma rays, it allows to push the energy threshold 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 [8].
Since for the GRB search in scaler mode the authentication is only given by the satellite detection, the stability of the detector and the probability that it mimics a true signal are crucial and have to be deeply investigated. Details of this study are widely discussed in [8], together with the determination of the effective area, upper limit calculation and expected sensitivity. A detailed description of the analysis procedures and the results obtained on the first set of 62 GRBs can be found in [9].
The GRB search can be done in both shower and scaler modes; in this paper only the results obtained with the latter are presented and discussed.

III. GRB SEARCH

Data have been collected from November 2004 (corresponding to the Swift satellite launch) to April 2009, with a detector active area increasing from $\sim$700 to $\sim$6700 m^2. During this period, a total of 85 GRBs was inside the ARGO-YBJ field of view (i.e. with zenith angle $\theta \leq 45°$, limited only by the atmospheric absorption); for 66 of these ARGO-YBJ data were available and they have been investigated by searching for a significant excess in the ARGO-YBJ counting rates coincident with the satellite detection. In order to extract the maximum information from the data, two GRB analyses have been implemented:

- search for a signal from every single GRB;
- search for a signal from the pile up of all GRBs.

For both analyses, the first step is the data cleaning and check. For each event, the Poissonian behaviour of the counting rates for multiplicities $\geq$1, $\geq$2, $\geq$3, $\geq$4 for all the clusters is checked in a period of $\pm$12 h around the GRB trigger time using the normalized fluctuation function:

$$f = (s - b)/\sigma, \qquad \sigma = \sqrt{b + b/20}. \qquad (1)$$

In this formula, s is the number of counts in a time interval of 10 s, b the number of counts in 10 s averaged over a time period of 100 s before and after the signal, and σ the standard deviation, with about 400 independent samples per distribution. The interval of 10 s has been chosen to avoid any systematic effect caused by environment and instrument (such as atmospheric pressure and detector temperature variations). The expected distribution of f is the standard normal function; all the clusters giving a distribution with measured σ > 1.2 or with anomalous excesses in the tail σ > 3 (i.e. > 2%) in at least one multiplicity channel are discarded. This guarantees that our data fulfill the requirements on stability and reliability of the detector.

A. Search for single GRB

The counting rates of the clusters surviving our quality cuts ($\sim$87%) are added up and the normalized fluctuation function

$$f' = (s' - b')/\sigma', \qquad \sigma' = \sqrt{b' + b'\frac{\Delta t_{90}[s]}{600}} \qquad (2)$$

is used to give the significance of the coincident on-source counts. In this formula, s' is the total number of counts in the Δt_{90} time window given by the satellite detector and b' 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 the counting rates of 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 again in an interval of $\pm$12 h around the GRB trigger time, using equation (17) of [11] (for more details see [8]). The analysis can be carried out for the counting rates for all the multiplicities $\geq$1, $\geq$2, $\geq$3, $\geq$4, and also 1, 2, 3, where the counting rates C_i are obtained from the measured counting rates $C_{\geq i}$ using the relation:

$$C_i = C_{\geq i} - C_{\geq i+1} \quad (i = 1, 2, 3) \qquad (3)$$

All the results presented here are obtained using the counting rate C_1, since it corresponds to the minimum primary energy in the ARGO-YBJ scaler mode. Figure 1 shows the distribution of the significances for the whole set of 66 GRBs.
No significant excess is shown, 3.52 σ being the maximum significance obtained, with a chance probability of 1.5 % taking into account the total number of GRBs analyzed.
With the lack of a positive signal the fluence upper limits are 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 equation (6) of [10]. 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 [12], we expect the true upper limits to lie between these two values. For GRBs with known redshift, an exponential

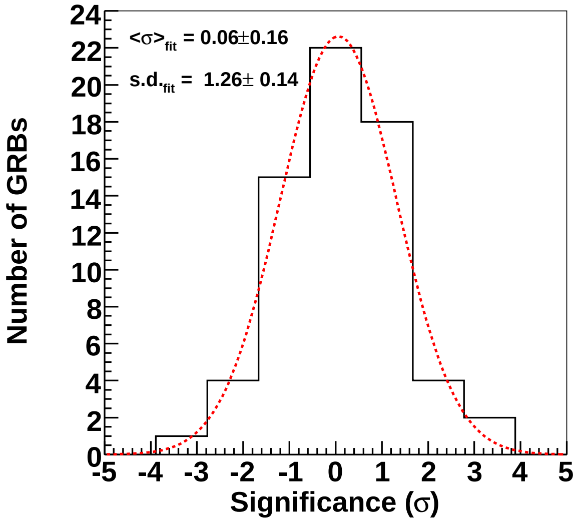

Fig. 1: Distribution of the statistical significances of the set of 66 GRBs with respect to background fluctuations, compared with a Gaussian fit.

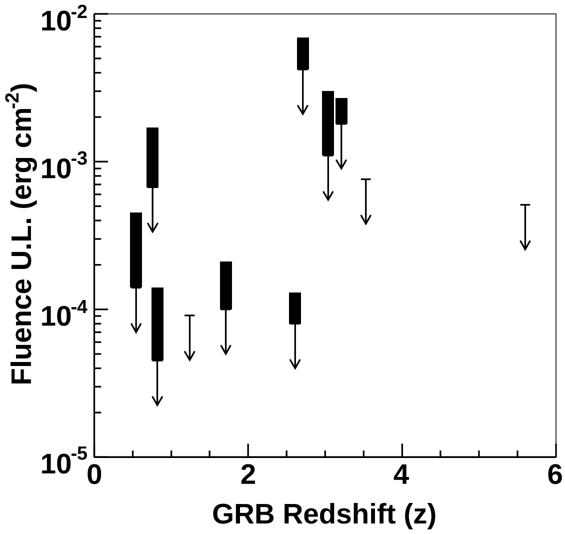

Fig. 2: Fluence upper limits (99 % c.l.) as a function of the redshift. The rectangles refer to the assumed spectra with differential indexes ranging from the low energy measurement to $\alpha = -2.5$; the three arrows are the upper limits for this latter case only (GRBs with CPL spectrum; see text for details).

cutoff in the spectrum is considered to take into account the effects of the extragalactic absorption. The extinction coefficient is calculated using the values given in [13].
For the set of 11 GRBs with known redshift, the fluence upper limits for the two assumed spectra are shown in figure 2. Since the measured low energy differential spectral indexes for these GRBs are always greater than -2.5, the higher upper limits refer to this extrapolation; for 3 GRBs the measured low energy spectrum is a Cutoff Power Law (CPL) and only the value obtained assuming $\alpha = -2.5$ is shown. For the other GRBs the rectangles indicate all the upper limits corresponding to differential spectral indexes ranging from the low energy measurement to -2.5.

Since the cutoff energy of GRBs is unknown, the following procedure is developed in order to determine an upper limit to this energy at least for some GRBs. When using as the GRB spectrum the extrapolation of the spectral index measured in the keV-MeV region by satellite experiments, 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. For these GRBs we can state that their spectra do not extend over the obtained E_{cut} upper limit, with a 99% c.l.. Figure 3 shows the cutoff energy upper limits as a function of the spectral index for the 16 GRBs for which the intersection occurs in the quoted energy range. For two of them (red triangles in figure 3) the knowledge of the redshift allows the estimation of the extragalactic absorption. When the GRB redshift is unknown a value z=1 is adopted.

B. *Pile-up of all GRBs*

A different analysis is performed 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 satellites) for all the GRBs are added up. This is done in order to search for a possible cumulative high energy emission with a fixed duration after T_0. The resulting overall significance of the GRBs stacked in time with respect to random fluctuations is -0.40 σ.
A second search is done to test the hypothesis that the high energy emission occurs at a specific phase of the low energy burst, independently of the GRB duration. For this study, all the 56 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. 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 -1.17 σ.
The search for cumulative effects by stacking all the GRBs either in fixed time durations or in phases of Δt_{90} could enhance a possible signal, making it significant, even if the emission of each GRB is below the sensitivity of the ARGO-YBJ detector. In this case, less information

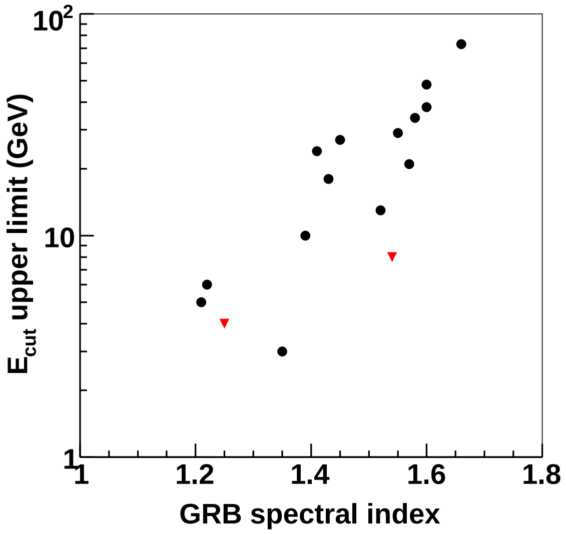

Fig. 3: Cutoff energy upper limits as a function of the spectral index obtained extrapolating the measured keV spectra. The values represented by the red triangles are obtained taking into account the extragalactic absorption for the two GRBs with known redshift; for the others z=1 is adopted.

could be given with respect to the single GRB coincident detection, but we must consider that with the stacked analysis we increase our sensitivity by increasing the number of GRBs, while for the single GRB search we decrease our sensitivity because of the increasing number of trials.

IV. Conclusions

The satellite-borne detectors have detected GRBs mostly in the sub-MeV energy region. However, several GRBs with emission beyond 100 MeV have been detected by EGRET [14], [15], [16] and, more recently, by AGILE [17] and by the LAT instrument on the Fermi Gamma Ray Space Telescope [18]. These detections indicate that at least a fraction of GRBs, in addition to sub-MeV photons, may also emit much higher energy photons, possibly extending to the GeV-TeV region.
In this paper we have reported a study concerning the search for GeV photons from 66 GRBs carried out by the ARGO-YBJ air shower detector operated in scaler mode. In the search for GeV gamma rays in coincidence with the low energy GRBs detected by satellites, no evidence for VHE emission was found for any event. The stacked search, both in time and phase, has shown no deviation from the statistical expectations.
The fluence upper limits obtained in the 1-100 GeV energy range depend on the zenith angle, time duration and spectral index, reaching values down to 10^{-5} erg cm^{-2}. These values greatly depend on the energy range of the calculation. If we consider our sensitivity in terms of expected number of positive detections, our estimate of GRBs detection reported in [8] must be doubled due to the alert rate provided by the recently launched Fermi satellite, with a field of view close to that of Swift, up to a rate between 0.2 and 1 per year, which is comparable with similar evaluations for other experiments working in different energy regions (e.g.[19]).
Finally, the capability of the detector shower mode to measure the arrival direction and energy of individual showers above a few hundred GeV allows the ARGO-YBJ experiment to study the GRBs in the whole 1 GeV$-$1 TeV range. (See S.Z. Chen et al., "Constrains on very high energy emission from GRBs with ARGO-YBJ experiment in shower mode", in these proceedings).

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