Search for GeV Gamma Ray Bursts with the ARGO-YBJ Detector: Summary of Eight Years of Observations (Postprint)

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Date: 2016-09-09T00:00:00+00:00

Abstract

Using the Yangbajing Cosmic Ray Observatory (ARGO-YBJ) experiment, we have conducted a search for gamma-ray burst (GRB) radiation in the 1-100 GeV energy range, consistent with satellite detections. The experiment' s high-altitude location (4300 m above sea level), large effective detection area (approximately 6700 m^2 of Resistive Plate Chambers), wide field of view (approximately 2 sr, limited only by atmospheric absorption), and high duty cycle (>86%) make it particularly suitable for detecting transient and unpredictable events such as GRBs. By employing the scaler mode technique—counting all particles hitting the detector without measuring primary energy or incident direction—a lowest threshold of approximately 1 GeV can be achieved, overlapping with direct measurements from satellites. During the experimental operation period from December 17, 2004 to February 7, 2013, we analyzed 206 GRBs occurring within the ARGO-YBJ field of view (zenith angle $\leq 45°$). This represents the largest sample of GRBs studied with a ground-based detector. Two light curve models were assumed, and since no significant excess was found in either case, we derived corresponding flux upper limits in the 1-100 GeV energy region as low as 10^{-5} $\mathrm{erg} \cdot \mathrm{cm}^{-2}$. Analysis of a subsample of 24 GRBs with known redshifts has been used to constrain the extrapolation of flux to the GeV region and possible cutoffs under different spectral assumptions.

Full Text

Preamble

SEARCH FOR GEV GAMMA RAY BURSTS WITH THE ARGO-YBJ DETECTOR: SUMMARY OF EIGHT YEARS OF OBSERVATIONS

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Received; accepted

ABSTRACT

The search for Gamma Ray Burst (GRB) emission in the energy range 1-100 GeV in coincidence with satellite detection has been carried out using the Astrophysical Radiation with Ground-based Observatory at YangBaJing (ARGO-YBJ) experiment. The high altitude location (4300 m a.s.l.), the large active surface (~6700 m^2 of Resistive Plate Chambers), the wide field of view (~2 sr, limited only by atmospheric absorption), and the high duty cycle (>86%) make the ARGO-YBJ experiment particularly suitable for detecting short and unexpected events like GRBs. With the scaler mode technique—counting all particles hitting the detector without measuring primary energy and arrival direction—the minimum threshold of 1 GeV can be reached, overlapping the direct measurements carried out by satellites. During the experiment lifetime from December 17, 2004 to February 7, 2013, a total of 206 GRBs occurring within the ARGO-YBJ field of view (zenith angle $< 45°$) have been analyzed. This represents the largest sample of GRBs investigated with a ground-based detector. Two lightcurve models have been assumed, and since no significant excess was found in either case, corresponding fluence upper limits in the 1-100 GeV energy region have been derived, with values as low as 10^{-5} erg cm^{-2}. The analysis of a subset of 24 GRBs with known redshift has been used to constrain the fluence extrapolation to the GeV region together with possible cutoffs under different assumptions on the spectrum.

Subject headings: gamma rays: bursts —gamma rays: observations

INTRODUCTION

Gamma Ray Bursts (GRBs) are among the most powerful sources in the sky, covering a very wide energy range from radio to multi-GeV γ-rays. Even though they are located at cosmological distances (Costa et al. 1997), at higher energies they outshine all other sources, including the Sun, during their typical duration of a few seconds. GRBs occur at an average rate of a few per day, coming from the whole Universe. Their high-energy spectrum shows different features, the most important being a peak in the keV–MeV region. There are at least two classes of GRBs, classified in terms of burst duration.

Short GRBs last up to 2 s and show a harder spectrum with a typical peak energy in the F spectrum at Earth of ~490 keV (Nava et al. 2011). Their origin is believed to be due to the merging of two compact objects like neutron stars or a neutron star and a black hole (Ruffert & Janka 1999; Rosswog et al. 2003). Recent support for this model comes from the optical and near-infrared detection of a faint transient, known as a "kilonova," in the days following the short GRB130603B (Tanvir et al. 2013). Long GRBs have durations greater than 2 s with a softer spectrum and a typical F peak around 160 keV (Nava et al. 2011). In this case the origin is believed to be due to the core collapse of type Ic supernovae, and indeed the coincidence of the two events has been observed in several cases (see for example Weiler et al. 2001; Stanek et al. 2003; Gal-Yam et al. 2004; Campana et al. 2006). Most GRB spectra can be described by the Band function (Band et al. 1993), composed of two smoothly joined power laws. This function fits quite successfully the convex shape and broad peak of the spectral energy distribution of GRB prompt emission; however, being a phenomenological model, it does not take into account any physical explanation concerning either the acceleration processes or non-thermal radiative losses. Despite the bulk emission being concentrated in the keV–MeV energy region, EGRET (Kanbach et al. 1988) and more recently Fermi (Meegan et al. 2009) and AGILE (Longo et al. 2012) satellites observed photons in the MeV–GeV range.

At the time of writing this paper, the highest photon energy measured at Earth is 95 GeV, observed by the LAT instrument on the Fermi satellite from GRB130427A (Ackermann et al. 2014). The highest intrinsic energy (~147 GeV) detected from a GRB comes from a 27.4 GeV γ-ray observed during GRB080916C, which has a redshift of 4.35. This γ-ray was previously missed by the Fermi-LAT event analysis and was recently recovered using improved data analysis (Atwood et al. 2013). Previously, the maximum observed photon energy was 33.4 GeV from GRB090902B (~94 GeV when corrected for its redshift z=1.822). Up to now (May 2014) after almost 6 years of operation, Fermi-LAT detected photons above 10 GeV from one short (GRB090510) and 8 long GRBs (Abdo et al. 2009a,b; Ackermann et al. 2010, 2011, 2013, 2014; Kocevski et al. 2013; Vianello et al. 2013). Some of these GRBs (namely, GRB08916C, GRB090510, GRB090902B, GRB090926A, GRB130427A) cannot be well described at GeV energies with an extrapolation of the Band function seen at keV–MeV energies, but require a much harder energy spectrum starting from ~100 MeV with a photon index α.

Another feature that characterizes the GeV emission is the light curve, with its onset delayed with respect to the keV–MeV range and a longer duration, appearing as a very high-energy afterglow. Current models include emission in both internal (Guetta & Granot 2003; Finke et al. 2008) and external (Kumar & Barniol Duran 2010; Ghisellini et al. 2010; Ghirlanda et al. 2010) shock scenarios, with γ-rays produced by leptonic or hadronic processes via inverse Compton scattering or neutral pion decay. The emission is believed to happen in highly relativistic narrow jets pointing towards Earth. The study of the GeV energy region could be of great help in discriminating between different models. As an example, the delayed onset of the high-energy emission seen in most LAT-detected GRBs, if intrinsic, should favor production from external shocks in the early GRB afterglow (Fan et al. 2008) instead of the reverse shock formed when the GRB ejecta encounter the interstellar medium (Wang et al. 2005).

GRBs have been detected throughout the universe, from the local one to redshift z=8.2, corresponding to 95% of the age of the universe. Unfortunately, the energy resolution of the instruments onboard Fermi prevents the detection of clear spectral lines while their large angular uncertainty hampers optical identification and follow-up. For these reasons, only GRBs seen in the keV–MeV region with arcmin resolution (as with Swift-BAT) have measured redshifts. In this same energy region the spectral index is usually measured, but when the detected signal is weak the time-averaged spectrum is poorly constrained. The absorption in the Extragalactic Background Light (EBL) greatly reduces the high-energy photon flux from extragalactic sources. The detection of >10 GeV photons from high-redshift sources can be used to constrain the EBL amount from regions where it is highly uncertain. Finally, the spectral slope in the GeV region could be of great help in discriminating between different GRB models. In particular, the detection of a cutoff energy could be indicative of e^+e^- pair production at the source, allowing measurement of the Lorentz boost factor of the jet (Ackermann et al. 2011). On the other hand, the spectral cutoff may be due to attenuation by the EBL, thus depending on the source redshift: GRBs at different distances could be used to disentangle these two effects.

At present, all experimental data in the MeV–GeV range have been obtained only from satellite detectors, which however, due to their limited size and the fast decrease of the source energy spectra, hardly cover the energy region above 1 GeV. Ground-based experiments can easily reach much larger effective areas exploiting two different techniques, which correspond to two different types of detectors: Extensive Air Shower (EAS) arrays and Imaging Atmospheric Cherenkov Telescopes (IACTs). Concerning the latter, the huge telescope recently installed at the HESS site or the planned CTA observatory can allow detection of γ-rays with energy as low as 20–30 GeV (Becherini et al. 2012; Bernlöhr et al. 2013), even if only at moderate zenith angles. However, IACTs can operate only during nights with good weather conditions and no or limited moonlight, leading to a duty cycle of 10–15%. Another disadvantage is given by the limited full field of view, about 5°, which requires a fast slew after an external alert in order to observe a GRB, but as pointed out by Gilmore et al. (2013), the MAGIC experience shows that most observations started after considerably longer times despite the instrument' s rapid slew capabilities, with only a minority occurring with total delay times of <100 s, preventing the detection of short GRBs and the study of the very prompt phase of long GRBs. Due to the limited field of view, the prompt GRB location area must be quite small in order to be contained within it, but this is not the case for most GRBs detected by Fermi-GBM. Until now, all major Cherenkov telescope arrays (MAGIC, HESS, VERITAS) attempted to detect GRBs with follow-up observations, but no robust positive result has been obtained, and even with the new generation CTA only ~1 detection per year is expected (Gilmore et al. 2013).

On the contrary, EAS arrays have a large field of view (~2 sr) and a very high duty cycle (in principle 100%); however, the requirement of a sufficient number of secondary particles to reconstruct the shower arrival direction and primary energy leads to an energy threshold of at least ~100 GeV. A possible technique to reduce the energy threshold of EAS detectors is working in scaler mode (Vernetto 2000) instead of shower mode—that is, recording the counting rates of the detector in search of an increase in coincidence with a burst detected by a different experiment. Even if this technique does not allow reconstruction of the arrival direction and thus an independent search, it benefits from the large effective area and field of view and from the very low dead time, with an energy threshold typically around 1 GeV, thus overlapping the highest energies investigated by satellite experiments. The resulting sensitivity is limited, but for GRBs observed at low zenith angles it is comparable to the highest fluxes measured by satellites.

The ARGO-YBJ detector operated in scaler mode from December 17, 2004 to February 7, 2013. In this period, a total of 206 GRBs (selected from the GCN Circulars Archive[1], the Second Fermi GBM Gamma-Ray Burst Catalog (von Kienlin et al. 2014; Gruber et al. 2014), and the Fermi GBM Burst Catalog website[2]) in the field of view of the detector were investigated for an increase in detector counting rates. No significant excess was found, and corresponding upper limits to the fluence and energy cutoff under different assumptions on the spectrum are presented and discussed in this paper. A detailed description of the scaler mode technique, including the effective area calculation for γ-rays and protons, the comparison between measured and simulated counting rates, the long-term counting rate behavior, and detector stability over short and long time periods, can be found in Aielli et al. (2008), while the analysis procedure is described in Aielli et al. (2009a) together with results on the first sample of GRBs analyzed. The GRB search can be done both in shower and scaler mode; here only the results obtained with the latter are presented and discussed. Shower mode results on a reduced sample of GRBs are given in Aielli et al. (2009b).

2. THE DETECTOR

The Astrophysical Radiation with Ground-based Observatory at YangBaJing (ARGO-YBJ) (Aielli et al. 2012) is an EAS 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. It is mainly devoted to γ-ray astronomy (Aielli et al. 2010; Bartoli et al. 2011, 2012a,b,c, 2013a,b) and cosmic ray physics (Aielli et al. 2009c, 2011; Bartoli et al. 2012d,e, 2013c). The detector consists of a single layer of Resistive Plate Chambers (RPCs), operated in streamer mode and grouped into 153 units named "clusters," each of size 5.7 × 7.6 m^2 (Aielli et al. 2006). Each cluster is made of 12 RPCs (1.23 × 2.85 m^2), and each RPC is read out by 10 pads (55.6 × 61.8 cm^2), representing the space-time pixels of the detector. The clusters are arranged in a central full-coverage carpet (130 clusters covering an area of 74 × 78 m^2 with >92% active surface) surrounded by a partially instrumented area up to ~110 × 100 m^2, which increases the effective area and improves reconstruction of the core location in shower mode.

In scaler mode, total counts are measured every 0.5 s: for each cluster, the signal from its 120 pads is summed and placed in coincidence in a narrow time window (150 ns), giving the counting rates for \$ \$3 and \$ *4pads,whicharereadbyfourindependentscalerchannels.Thesecountingratesarereferredtointhefollowinga* and C_4, respectively, with corresponding rates of ~40 kHz and ~2 kHz. Since for the GRB search in scaler mode, authentication is only given by a satellite detection, the stability of the detector and the probability that it mimics a true signal are crucial and must be deeply investigated.

The main sources of counting rate variations are atmospheric pressure, acting on shower development in the atmosphere, and ambient temperature, acting on detector efficiency. The time scale of both variations is much larger than the typical GRB duration (seconds to minutes), so they can be neglected provided that the behavior of individual cluster counting rates is Poissonian. A secondary local effect is due to radon contamination in the detector hall. Electrons and γ-rays from short-lived radon daughters (mainly ^{214}Po) produced in the radon decay chain are expected from β decays and isotope de-excitations. It has been shown that they can influence cluster counting rates at a level of a few percent of the reference value. Even in this case, the time variations are larger (hours) than typical GRB durations and can be neglected in data processing (Bartoli et al. 2014; Giroletti et al. 2011).

A very rapid variation can be induced by nearby lightning. For this reason, two electric field monitors (EFM-100) located at opposite sides of the experimental hall and a storm tracker LD-250 (both devices by Boltek industries[3]) have been installed to monitor electric field variations. Details of this study are widely discussed in Zhou et al. (2011).

3. DATA SELECTION AND ANALYSIS

The ARGO-YBJ detector was completed in spring 2007; however, thanks to its modularity, data taking started already in November 2004 (corresponding to the launch of the Swift satellite), ending in February 2013 when the detector was definitively switched off. In this period, a total of 223 GRBs detected by satellite instruments occurred inside the ARGO-YBJ field of view (zenith angle < 45°, corresponding to 1.84 sr). The present analysis was carried out on 206 of them, since the other GRBs occurred during periods when the detector was inactive or not properly working. Unlike Δt_{90}, defined as the time during which 90% of the GRB keV-MeV photons are detected, the redshift and spectrum in the same energy range are not always measured due to the difficulties introduced in Section 1. The spectra measured by satellites can be fitted with a simple power law, a smooth double power law (Band or Smoothly Broken Power Law, SBPL (Kaneko et al. 2006)), or a Cutoff Power Law (CPL). Figure 1a [Figure 1: see original paper] shows the Δt_{90} distribution, with the dashed area on the left indicating the short (<2s) GRB population, while Figure 1b gives the distribution of fluences measured by satellites, all normalized to the energy interval 15-150 keV. For 103 GRBs in our sample, the simple power-law spectral index in the keV-MeV region was measured by satellite detectors, and the corresponding distribution (with mean value $<\alpha> = 1.6$) is shown in Fig. 1c. For 24 of them, the redshift is also known, and the corresponding distribution is shown in Fig. 1d, with = 2.1 being the mean value of this subset. The durations Δt_{90} and spectral indices α of GRBs with known redshift are highlighted in Fig. 1a and 1c, respectively, with a dashed area (colored red in the online version). For this subset, the mean value and width of the three distributions are compatible with those for the whole GRB sample. The detailed list of the 24 GRBs with known redshift is given in Table 1 , while Table 2 reports the same information for the remaining 182 GRBs.

For each GRB, the following standard procedure was adopted: check of detector stability, cluster selection by means of quality cuts, and calculation of the significance of the coincident signal in the ARGO-YBJ detector. In order to extract maximum information from the experimental data, two analyses were implemented: coincidence search for each GRB; and cumulative search for stacked GRBs. Details on quality cuts and detector stability are carefully discussed in Aielli et al. (2008), while background evaluation and significance calculation, as well as the analysis technique itself, are described in Aielli et al. (2009a).

3.1. Coincidence Search

The counting rates of clusters surviving the quality cuts (with average efficiency over the whole data set of 87%) are added up, and the normalized fluctuation function f = (c - b)/σ, where $\sigma = \surd(b + b/\Delta t_{90}[s])$, is used to evaluate the significance of excess observed in coincidence with satellite detection. Here, c is the total number of counts in the Δt_{90} time window starting at t_0 (the trigger time) of the signal, both given by the satellite detector, 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. This analysis can be done for counting rates of all multiplicities $ $1, $ $2, $ $3, and
$ $4, wherethecountingratesC_iareobtainedfromthemeasuredcountingratesusingtherelationC_i =$
$C(i = 1, 2, 3).Inthefollowing, unlessotherwisespecified, allresultsareforcountingrateC\{1\}, whichcorrespon$
$YBJscalermode.DetectorstabilityovershorttimeperiodsisdiscussedinAiellietal.(2008), showingthatPoissoni$
plus the background interval 2 × 300 s) is less than 30 minutes. This condition is satisfied for all GRBs included in our data sample; therefore, no long-time

corrections of counting rates were applied.

Even if the distributions of single cluster counter rates for integrated times up to half an hour are Poissonian, this is not true for the sum of different clusters, which shows larger fluctuations. This effect has been carefully analyzed and was found to be due to correlation between counting rates of different clusters given by the air shower lateral distribution—that is, counts in different clusters due to the same EAS are not independent. The resulting widening can be taken into account by introducing a Fano factor F (Fano 1947), where σ^2__p is the Poissonian variance equal to the mean value of the counting rate distribution, σ^2 = Fσ^2__p, and σ^2 is the measured variance. The Fano factor increases with the number of detector units used and the integration time (i.e., GRB duration) while decreasing for a sparse detector layout, and its effect is to reduce sensitivity by a factor √F. For each GRB, √F is listed in Tables 1 and 2, and the mean value calculated over the whole data sample is <√F> = 2.22. In order to account for this effect and properly calculate signal significance, we studied the local fluctuation of the normalized function f (defined in equation 1) in an interval of 12 h around the GRB trigger time and used equation (17) of Li & Ma (1983). Figure 2 [Figure 2: see original paper] (dark solid line) shows the distribution of resulting significances for all 206 GRBs. No significant excess is measured, the largest being 3.52σ for GRB080727C, with a post-trial chance probability of 4.5×10^{-2}. Since long GRBs typically show a softer spectrum with lower Band peak energy, the same distribution for only the 27 short GRBs is shown in the same figure (dark dashed area, colored red in the online version). Even in this case, no significant excess is measured, the most significant event being GRB051114 with 3.37σ and a post-trial chance probability of 1.0×10^{-2}. For this GRB, since we expect a harder energy spectrum from short GRBs, we carried out the same analysis using higher multiplicity channels C_2, C_3, and C_4, obtaining significances of 1.16σ, 1.09σ, and 1.95σ, respectively.

Besides this search, a time window broader than Δt_{90} was considered to account for possible high-energy afterglow. Ghisellini et al. (2010) found that the flux of 8 among the 11 brightest bursts detected by Fermi-LAT above 100 MeV (in the first 13 months of operation) decays as a power law with typical slope $t^{-1} \cdot {}^{5}$. In this analysis we assumed this trend in the afterglow phase ($t > \Delta t_{90}$) and a constant flux during the GRB prompt emission, since we consider only time-averaged behavior:

$A(t) = A_0$ for $t \leq \Delta t_{90}$
$A(t) = A_0(t/\Delta t_{90})^{-1} \cdot {}^{5}$ for $t > \Delta t_{90}$

with A_0 corresponding to the mean flux during the low-energy emission time Δt_{90}. With this assumption, 2/3 of total emission comes after Δt_{90}. To search for such delayed emission, a longer time interval $\Delta t'_{90}$ must be used. Its value is chosen to maximize signal significance. Assuming Poissonian fluctuations and introducing a mean background counting rate k in units of Δt_{90}, the significance is:

$\sigma(\mathrm{t}) = {}_0\ \mathrm{A(t)dt} / \sqrt{}(\mathrm{kt})$

The maximum of this function occurs at $\mathrm{t}/\Delta\mathrm{t}_{90} = 16/9$. In our case, since fluctuations are not purely Poissonian and the Fano factor F depends on integration time, we searched for maximum significance of the modified function:

$\sigma\text{'}\ (\mathrm{t}) = \sigma(\mathrm{t})/\sqrt{}\mathrm{F(t)}$

using an iterative procedure, increasing the time window for each GRB by the minimum 0.5 s step. The Fano factor is then calculated, giving the resulting significance from equation (6). This procedure is repeated covering the time interval from $\Delta\mathrm{t}_{90}$ to $2\Delta\mathrm{t}_{90}$. The significance curve in this time window is then fitted by a second-order polynomial, and the $\Delta\mathrm{t}\text{'}\ _{90}$ corresponding to its maximum is used instead of $\Delta\mathrm{t}_{90}$ for this extended search. Since the Fano factor increases with time, $\Delta\mathrm{t}\text{'}\ _{90}$ is always shorter than the purely Poissonian value and certainly falls within the search interval. This procedure searches for a maximum in the $[\Delta\mathrm{t}_{90}\text{-}2\Delta\mathrm{t}_{90}]$ range in steps of 0.5 s; therefore, the analysis was limited to GRBs with $\Delta\mathrm{t}_{90} \geq 1.5$ s, allowing a second-order fit of function (6). Moreover, for longer GRBs with $\Delta\mathrm{t}_{90} \geq$ ~100 s, the Fano factor is so large that increasing $\Delta\mathrm{t}_{90}$ does not improve sensitivity and a clear maximum cannot be found. For these events, $\Delta\mathrm{t}\text{'}\ _{90} = \Delta\mathrm{t}_{90}$ was used, since this value maximizes the signal-to-noise ratio for a constant signal during $\Delta\mathrm{t}_{90}$. The $\Delta\mathrm{t}\text{'}\ _{90}$ values obtained for the 185 GRBs with $\Delta\mathrm{t}_{90} \geq 1.5$ s are listed in Tables 1 and 2 (for 61 of them, $\Delta\mathrm{t}\text{'}\ _{90} = \Delta\mathrm{t}_{90}$). The corresponding significance distribution is shown in Figure 3 [Figure 3: see original paper]. No significant excess is found in this case either, the largest being 3.52σ for GRB080727C, with a post-trial chance probability of 4.1×10^{-3}.

3.2. Stacked Analysis

Besides the coincidence analysis for each GRB, a stacked analysis was carried out to search for common features of all GRBs in Time or Phase.

In the Time analysis, counting rates for all GRBs in 9 windows ($\Delta\mathrm{t} = 0.5$, 1, 2, 5, 10, 20, 50, 100, and 200 s) starting at t_0 were added up to investigate a possible common duration of high-energy emission. A positive observation at a fixed $\Delta\mathrm{t}$ could be used as an alternative value to the observed $\Delta\mathrm{t}_{90}$ duration and provide a different way to look for a possible high-energy delayed component. Since the bins are not independent, the distribution of significances of the 9 time intervals is compared with random distributions obtained for starting times different from t_0 in a time interval of 12 hr around the true GRB trigger time. Moreover, for the sample of GRBs with known redshift (with z ranging from 0.48 to 5.6), the time windows were corrected for the cosmological dilation factor $(1 + \mathrm{z})$. The most significant excess (1.5σ) is observed for the sample of 182 GRBs with no redshift at $\Delta\mathrm{t} = 0.5$ s with a chance probability of 0.60, while analysis of the 24 GRBs with measured redshift led to a maximum significance of 0.7σ in the shorter time window ($\Delta\mathrm{t} = 0.5$ s at z=0).

In the Phase analysis, only 165 GRBs with duration $\Delta t_{90} \geq 5$ s were added up, scaling their duration to a common phase plot (i.e., 10 bins each sampling a 10% wide interval of Δt_{90}, with 0.5 s being the minimum duration for scaler mode data acquisition). This analysis should reveal a common feature of all GRBs in case of GeV emission correlated with GRB duration at lower energy. Even in this case, no excess is found, and the most significant bin, corresponding to phase [0.7-0.8] of Δt_{90}, has only marginal significance of 1.78σ.

4. FLUENCE AND CUTOFF UPPER LIMITS

The fluence upper limits can be derived in the [1-100] GeV range from our experimental data by making some assumptions on the GRB primary spectrum. For this calculation, we used the maximum number of counts at 99% confidence level (c.l.) following equation (6) of Helene (1983). The interaction of GRB photons with the EBL results in e^+e^- pair production that originates a spectral cutoff. This effect depends on GRB redshift, with lower cutoff energy for more distant GRBs. For this reason, the most meaningful upper limits are obtained for the sample of 24 GRBs with known redshift (see Table 1), while for the others (Table 2) values of z=2 and z=0.6 have been adopted for long and short GRBs, respectively, according to their measured distributions (Jakobsson et al. 2006; Berger et al. 2005; Berger 2014). For the differential spectral indices, we used two extrapolations to estimate the expected high-energy fluence for each GRB: (a) the spectral index $\alpha\{sat\}$ *measured by satellite detectors in the keV-MeV energy range (corresponding to the* $f\{\mathrm{sat}\}$ values in Tables 1 and 2), and (b) the conservative value $\alpha = 2.5$ (f_2.5 values in Tables 1 and 2). For case (a), when Band or SBPL spectral features were identified, the higher-energy spectral index (i.e., above the peak in the keV-MeV region) was used. These assumptions represent respectively the most and least favorable spectral index hypotheses. The absorption effect due to the EBL is taken into account using the model described in Kneiske et al. (2004) and applying an exponential cutoff to the spectrum according to redshift. Figure 4 [Figure 4: see original paper] shows the 99% c.l. upper limits as a function of z for GRBs with known redshift. For 5 of them, whose spectrum is best fitted by a CPL, only the upper limits for case (b) are given.

For GRB090902B (the GRB in the ARGO-YBJ field of view with the highest-energy photon detected), the fluence extrapolated from Fermi-LAT observations in the same energy range is shown. Only for this GRB was the GeV spectral index measured by Fermi-LAT used, and the dashed area in Figure 4 was obtained by applying an energy cutoff to the GRB spectrum running from 30 GeV (approximately the maximum energy measured by Fermi-LAT) to 100 GeV. According to our calculation, in the case of a spectrum extending up to 100 GeV, the extrapolated GRB fluence is just a factor 2.7 lower than our expected sensitivity. Due to the peculiar GeV emission of this GRB, the search was also performed in different time windows: in particular, in coincidence with the extended Fermi-LAT emission [-90 s], the maximum density of events with energy

>1 GeV [6-26 s], and the time of the 33.4 GeV photon [82-83 s], respectively. The resulting significances are -0.03σ, 1.00σ, and -0.52σ.

A comparison between the expected fluence, obtained by extrapolating the keV-MeV spectra measured by satellites and including EBL absorption, and the fluence upper limit determined with ARGO-YBJ scaler data has been performed for the 19 GRBs with measured redshift and energy spectrum best fitted by a simple power law, excluding the 5 events that present a CPL spectrum. The result is shown in Figure 5. The 7 points on the right side of the line Upper Limit (UL) = Expected Fluence (EF) (i.e., in the region where upper limits are lower than extrapolated fluences) indicate that, since the corresponding GRBs were not detected, the chosen extrapolation is not feasible up to our range [1-100 GeV] or a cutoff should be present in the high-energy tail of the spectrum.

Therefore, assuming the spectral index measured at low energies, the maximum cutoff energy was estimated as follows. The extrapolated fluence is calculated together with the fluence upper limit as a function of cutoff energy E_{cut}. If the two curves cross in the [2-100 GeV] interval, the intersection gives the upper limit to the cutoff energy. This occurs for four of them (GRB050802, GRB081028A, GRB090809A, and GRB110128A), for which knowledge of the redshift allows estimation of extragalactic absorption and hence more accurate fluence upper limit and cutoff energy determination. For three of them (GRB071112C, GRB090424, and GRB130113B), the estimated E_{cut} upper limit is below 2 GeV; we can conclude that in these cases the low-energy spectrum cannot be extended to the GeV region and some additional features occur in the keV-MeV range. The values obtained for E_{cut} are reported in the last column of Table 1 and shown in Figure 6 [Figure 6: see original paper] (triangles) as a function of spectral index. The same calculation can be made for GRBs with unknown redshift, assuming for EBL absorption z=2 and z=0.6 for long and short GRBs, respectively, and the resulting E_{cut} values are given in the last column of Table 2 and shown in Figure 6 (dots).

More realistic models for the spectrum shape and/or different hypotheses on the photon spectral index in the GeV region can be considered. Since all 7 GRBs falling on the right side of the UL=EF line in Figure 5 are long, we first assumed a Band spectrum with an E_{peak} value of 160 keV and spectral index -2.34, corresponding to the mean peak energy and high-energy slope for this class of GRBs (Nava et al. 2011). With this model, all 7 GRBs fall below threshold (i.e., the extrapolated fluence is lower than our upper limit).

Another possibility is to suppose a fixed ratio between GeV and keV-MeV fluences. Simultaneous observation of GRBs in these energy bands has been performed in the past by EGRET and BATSE onboard the CGRO satellite and more recently by Fermi-LAT and Fermi-GBM for a handful of events. As pointed out by Dermer et al. (2010), for long GRBs this ratio is close to 0.1 when the energy ranges considered to determine fluence are 100 MeV-10 GeV and 20 keV-2 MeV. For the GeV spectral index, we used a value of -2, consistent with both EGRET and Fermi-LAT mean values. This high-energy component represents a strong deviation from the Band spectrum, increasing the expected GeV fluence significantly, even if to a smaller extent than extrapolating the keV–MeV spectra. Even under these hypotheses, all 7 long GRBs fall on the left side of the UL=EF line in Figure 5.

5. DISCUSSION AND CONCLUSIONS

The detection of high-energy photons by the Fermi-LAT instrument clearly demonstrates that at least a small fraction of GRBs emits in the GeV range. The detected photons experience two main processes: generation at the source and propagation through the intergalactic medium. Several models have been proposed to explain the production of high-energy photons in GRBs, but according to the standard fireball shock model they are essentially caused by internal or external shocks. Once produced, a fraction of these photons are converted into electron-positron pairs due to interaction with low-energy photons, mainly from the infrared-optical-ultraviolet cosmic background (EBL). This mechanism limits the photon mean free path and thus the visible horizon, which decreases with energy up to 10^{15} eV, where interaction with the Cosmic Microwave Background Radiation makes it smaller than the Galactic radius. The signal reaching Earth is the final result of all these production and propagation mechanisms, bringing valuable information on all of them but simultaneously making them difficult to separate. Features like the maximum energy as a function of redshift, the photon index, and other temporal and spectral characteristics, if seen with sufficient statistics, could discriminate between different mechanisms and shed light on this still largely unknown field. For these reasons, the study of GRBs would greatly benefit from the contribution of ground-based detectors to direct satellite measurements.

In this paper, a search for GRBs in coincidence with satellite detections has been carried out using the complete ARGO-YBJ data set. During approximately 8 years, a total of 206 GRBs were analyzed, producing the largest GRB sample ever studied using the scaler mode technique. In the search for GeV γ-rays in coincidence with GRB satellite detections, no evidence of emission was found for any event, both for the whole sample and for separate analyses of the two populations of long and short GRBs. For GRBs with duration $ $1.5 s, the search for a signal in a time window extended with respect to the low-energy one was carried out with similar results. The stacked search, both in time and phase, showed no deviation from statistical expectations. The subset of 24 GRBs with known redshift was carefully analyzed in terms of fluence and cutoff upper limits.

For GRB090902B, the fluence upper limit using the GeV spectral index is very close to the Fermi-LAT measurement (a factor 2.7 higher), assuming high-energy emission extending from the observed 30 GeV up to 100 GeV. This GRB was certainly our best candidate for detection; however, an area 7.2 times larger would have been necessary. For the other GRBs with known redshift, fluence upper limits as low as 2.9×10^{-5} erg cm^{-2} in the 1–100 GeV energy range have been set, assuming a high-energy spectral index equal to that measured by satellites. Under this hypothesis, for 7 of them an upper limit to the cutoff energy was also determined; otherwise, an average Band spectrum or a fixed ratio between high- and low-energy fluences must be assumed.

The expected rate of GRBs that could be observed by the ARGO-YBJ experiment, based on Swift satellite detections, was between 0.1 and 0.5 year^{-1} (Aielli et al. 2008) and should have doubled with the later launch of the Fermi satellite. The value of 0.3 year^{-1} obtained for our 90% c.l. upper limit is close to our lower expectation, partially because the predicted Fermi detection rate was overestimated and partially because LAT-detected GRBs have a spectrum softer than presumed.

In the near future, three large ground-based detectors could continue this search with improved sensitivity. HAWC, a water Cherenkov detector with a surface of 22,000 m^2, is under construction in Mexico at an altitude of 4100 m a.s.l. Its expected detection rate is 1.55 year^{-1} for short GRBs and 0.25 year^{-1} for long GRBs, mainly using the shower mode technique in the range 50–500 GeV (Taboada & Gilmore 2014). CTA will observe the night sky detecting atmospheric Cherenkov light. Its huge telescopes for detection of low-energy γ-rays have been designed also for fast slewing, allowing repointing times <100 s. Apart from a very lucky serendipitous observation, the CTA search is limited to long GRBs after the very prompt phase, with an expected detection rate ranging from 0.6 to 2 year^{-1} according to baseline or optimistic assumptions and with strong dependence on energy threshold (more than on pointing delay) (Gilmore et al. 2013). GRB detection from ground via the water Cherenkov technique will also be possible with the proposed LHAASO experiment (Cui et al. 2014), whose detection rate has not yet been estimated.

Thirty years after the first proposal by Morello et al. (1984), the first solid detection of a GRB from ground seems at hand.

This work is supported in China by NSFC (Grant No. 10120130794), the Chinese Ministry of Science and Technology, the Chinese Academy of Sciences, the Key Laboratory of Particle Astrophysics, CAS, and in Italy by the Istituto Nazionale di Fisica Nucleare (INFN). We also acknowledge the essential support of W.Y. Chen, G. Yang, X.F. Yuan, C.Y. Zhao, R. Assiro, B. Biondo, S. Bricola, F. Budano, A. Corvaglia, B. D' Aquino, R. Esposito, A. Innocente, A. Mangano, E. Pastori, C. Pinto, E. Reali, F. Taurino, and A. Zerbini in the installation, debugging, and maintenance of the detector.

REFERENCES

Abdo, A. A., Ackermann M., Ajello M., et al. 2009a, ApJ, 706, L138
Abdo, A. A., Ackermann M., Arimoto M., et al. 2009b, Science, 323, 1688
Ackermann, M., Asano, K., Atwood, W. B., et al. 2010, ApJ, 716, 1178
Ackermann, M., Ajello, M., Asano, K., et al. 2011, ApJ, 729, 114
Ackermann, M., Ajello, M., Asano, K., et al. 2013, ApJS, 209, 11

Ackermann, M., Ajello, M., Asano, K., et al. 2014, Science, 343, 42
Aielli, G., Assiro, R., Bacci, C., et al. 2006, Nucl. Instrum. Methods, A562, 92
Aielli, G., Bacci, C., Barone, F., et al. 2008, Astropart. Phys., 30, 85
Aielli, G., Bacci, C., Barone, F., et al. 2009a, ApJ, 699, 1281
Aielli, G., Bacci, C., Bartoli, B., et al. 2009b, Astropart. Phys., 32, 47
Aielli, G., Bacci, C., Bartoli, B., et al. 2009c, Phys. Rev. D, 80, 092004
Aielli, G., Bacci, C., Bartoli, B., et al. 2010, ApJ, 714, L208
Aielli, G., Bacci, C., Bartoli, B., et al. 2011, ApJ, 729, 113
Aielli, G., Bacci, C., Bartoli, B., et al. 2012, Nucl. Instrum. Methods, A661, S50
Atwood, W. B., Baldini, L., Bregeon, J., et al. 2013, ApJ, 774, 76
Band, D., Matteson, J., Ford, L., et al. 1993, ApJ, 413, 281
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2011, ApJ, 734, 110
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2012a, ApJ, 745, L22
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2012b, ApJ, 758, 2
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2012c, ApJ, 760, 110
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2012d, Phys. Rev. D, 85, 022002
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2012e, Phys. Rev. D, 85, 092005
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2013a, ApJ, 767, 99
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2013b, ApJ, 779, 27
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2013c, Phys. Rev. D, 88, 082001
Bartoli, B., Bernardini, P., Bi, X. J., et al. 2014, Radiation Measurements, 68, 42
Becherini, Y., Punch, M., & H.E.S.S. Collaboration 2012, AIP Conf. Proc., 1505, 741
Berger, E., Kulkarni, S. R., Fox, D. B., et al. 2005, ApJ, 634, 501
Berger, E. 2014, Annu. Rev. Astron. Astrophys., 52 (arXiv:1311.2603v1)
Bernlöhr, K., Barnacka, A., Becherini, Y., et al. 2013, Astropart. Phys., 43, 171
Campana, S., Mangano, V., Blustin, A. J., et al. 2006, Nature, 442, 1008
Costa, E., Frontera, F., Heise, J., et al. 1997, Nature, 387, 783
Cui, S., Liu, Ye, Liu, Yujuan, & Ma, X. 2014, Astropart. Phys., 54, 86
Dermer, C.D., & Fermi Collaboration 2010, AIP Conf. Proc., 1279, 191
Fan, Y. Z., Piran, T., Narayan, R., & Wei, D-M. 2008, MNRAS, 384, 1483
Fano, U. 1947, Phys. Rev., 72, 26
Finke, J. D., Dermer, C. D., & Böttcher, M. 2008, in AIP Conf. Ser. 1000, eds. M. Galassi, D. Palmer, E. Fenimore, 385
Gal-Yam, A., Moon, D.-S., Fox, D. B., et al. 2004, ApJ, 609, L59
Ghirlanda, G., Ghisellini, G., & Nava, L. 2010, A&A, 510, L7
Ghisellini, G., Ghirlanda, G., Nava, L., & Celotti, A. 2010, MNRAS, 403, 926
Gilmore, R. C., Bouvier, A., Connaughton, V., et al. 2013, Experimental Astronomy, 35, 413
Giroletti, E., Bolognino, I., Cattaneo, C., et al. 2011, Proc. 32nd ICRC (Beijing), 1, 18
Gruber, D., Goldstein, A., Weller von Ahlefeld, V., et al. 2014, ApJS, 211, 12
Guetta, D., & Granot, J. 2003, ApJ, 585, 885
Helene, O. 1983, Nucl. Instrum. Methods, 212, 319

Jakobsson, P., Levan, A., Fynbo, J. P. U., et al. 2006, A&A, 447, 897
Kanbach, G., Bertsch, D. L., Favale, A., et al. 1988, Space Sci. Rev., 49, 69
Kaneko, Y., Preece, R. D., Briggs, M. S., et al. 2006, ApJS, 166, 298
Kneiske, T. M., Bretz, T., Mannheim, K., & Hartmann, D. H. 2004, A&A, 413, 807
Kocevski, D., Vianello, G., Chiang, J., et al. 2013, GCN Circ. 14532
Kumar, P., & Barniol Duran, R. 2010, MNRAS, 409, 226
Li, T., & Ma, Y. 1983, ApJ, 272, 317
Longo, F., Moretti, E., Nava, L., et al. 2012, A&A, 547, A95
Meegan, C., Lichti, G., Bhat, P. N., et al. 2009, ApJ, 702, 791
Morello, C., Periale, L., & Navarra, G. 1984, Il Nuovo Cimento, 7C, 6
Nava, L., Ghirlanda, G., Ghisellini, G., & Celotti, A. 2011, A&A, 530, A21
Rosswog, S., Ramirez-Ruiz, E., & Davies, M. B. 2003, MNRAS, 345, 1077
Ruffert, M., & Janka, H.-Th. 1999, A&A, 344, 573
Stanek, K. Z., Matheson, T., Garnavich, P. M., et al. 2003, ApJ, 591, L17
Taboada, I., & Gilmore, R. C. 2014, Nucl. Instrum. Methods, A742, 276
Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Nature, 500, 547
Vernetto, S. 2000, Astropart. Phys., 13, 75
Vianello, G., Desiante, R., & Longo, F. 2013, GCN Circ. 15357
von Kienlin, A., Meegan, C. A., Paciesas, W. S., et al. 2014, ApJS, 211, 13
Weiler, K. W., Panagia, N., & Montes, M. J. 2001, ApJ, 562, 670
Wang, X. Y., Cheng, K. S., Dai, Z. G., & Lu, T. 2005, A&A, 439, 957
Zhou, X. M., Ye, N., Zhu, F. R., et al. 2011, Proc. 32nd ICRC (Beijing), 11, 287

This manuscript was prepared with the AAS LATEX macros v5.2.

Figure Captions

Figure 1. Details of the GRB sample analyzed in coincidence with ARGO-YBJ: (a) Δt_{90} durations of the whole sample (solid line) and of GRBs with known redshift (filled area); (b) Fluences measured by satellites (all normalized to energy range 15–150 keV) for the whole available sample (solid line) and for events with known redshift (filled area); (c) Photon index values in the keV-MeV band for the whole available sample (solid line) and for events with known redshift (filled area); (d) Redshift distribution. The dashed area on the left in plot (a) indicates the short (<2s) GRB population. (A color version of this figure is available in the online journal.)

Figure 2. Distribution of statistical significances of the 206 GRBs with respect to background fluctuations (dark solid line) compared with a free Gaussian fit (dotted line). Mean value and r.m.s. of the fit are shown. The light and dark dashed distributions refer to long and short GRBs, respectively. (A color version of this figure is available in the online journal.)

Figure 3. Distribution of statistical significances of the 185 GRBs with Δt_{90} $\geq$ 1.5 s with respect to background fluctuations (solid line) compared with a

free Gaussian fit (dotted line) for the extended time window search (see text). Mean value and r.m.s. of the fit are shown. (A color version of this figure is available in the online journal.)

Figure 4. Fluence upper limits of GRBs in the 1-100 GeV interval as a function of redshift. Rectangles represent values obtained with differential spectral indices ranging from 2.5 to the satellite measurement α_{sat}. The 5 arrows give upper limits for the former case only, these GRBs being best fitted at lower energies with a cutoff power-law spectrum. The dot shows the fluence extrapolated in the 1-100 GeV range from Fermi-LAT observations of GRB090902B; only for this GRB was the GeV spectral index used, and the dashed area was obtained by applying an energy cutoff running from 30 to 100 GeV. (A color version of this figure is available in the online journal.)

Figure 5. ARGO-YBJ upper limits (in the 1-100 GeV interval) vs. fluence extrapolation for GRBs with measured redshift and low-energy power-law spectral index. (A color version of this figure is available in the online journal.)

Figure 6. Cutoff energy upper limits as a function of spectral index obtained by extrapolating measured keV spectra. Values represented by triangles are obtained taking into account extragalactic absorption at the known GRB redshift. For other GRBs (dots), z=2 and z=0.6 are assumed for long and short ones, respectively. (A color version of this figure is available in the online journal.)

Table 1. GRBs with measured redshift observed by ARGO-YBJ.

Note.–(a) Using the spectrum determined by satellites. (b) Assuming a differential spectral index of 2.5. (c) 99% c.l. (d) Derived from the f_{sat} Fluence U.L. (see text). (e) For high-energy emission extending up to 30 GeV only (see text).

Column 1: GRB name corresponding to detection date in UT (YYMMDD). Column 2: Satellite that detected the burst. Column 3: Burst duration Δt_{90} as measured by the respective satellite. Column 4: Extended burst duration $\Delta t'_{90}$. Column 5: Zenith angle with respect to detector location. Column 6: GRB redshift. Column 7: Square root of the Fano factor. Column 8: Spectral index ("CPL" means satellite spectrum better fitted with cutoff power law). Column 9: Detector active area for that burst. Columns 10-11: Statistical significance of on-source counts over background for standard and extended burst duration. Columns 12-13: 99% confidence upper limits on fluence between 1 and 100 GeV for spectral index of Column 8 and fixed value -2.5, respectively. Column 14: Cutoff upper limit, if any.

Table 2. GRBs with no measured redshift (z = 2 and z = 0.6 assumed for long and short GRBs, respectively) observed by ARGO-YBJ.

Note.—(a) Using the spectrum determined by satellites. (b) Assuming a differential spectral index of 2.5. (c) 99% c.l. (d) Derived from the f_{sat} Fluence U.L. (see text).

Column 1: GRB name corresponding to detection date in UT (YYMMDD). Column 2: Satellite that detected the burst. Column 3: Burst duration Δt_{90} as measured by the respective satellite. Column 4: Extended burst duration $\Delta t'_{90}$. Column 5: Zenith angle with respect to detector location. Column 6: Square root of the Fano factor. Column 7: Spectral index ("CPL" means satellite spectrum better fitted with cutoff power law; italic indicates higher-energy spectral index for Band or SBPL functions). Column 8: Detector active area for that burst. Columns 9-10: Statistical significance of on-source counts over background for standard and extended burst duration. Columns 11-12: 99% confidence upper limits on fluence between 1 and 100 GeV for spectral index of Column 7 and fixed value -2.5, respectively. Column 13: Cutoff upper limit, if any.

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[1] http://gcn.gsfc.nasa.gov/gcn3_{archive}.html
[2] http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigbrst.html
[3] http://www.boltek.com/

Note: Figure translations are in progress. See original paper for figures.