Search for the GeV counterparts of two gamma ray bursts: Swift 317662 and Fermi bn081017474

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We examine the possibility of the ground observation of the GeV counterparts of two gamma ray bursts, the Swift GRB-080723 (Trigger = 317662) and the Fermi GRB081017474 (trigger = bn081017474). The data come from two small directional muon telescopes at sea level inside the South Atlantic Anomaly region. This characteristic offers the muon telescopes a low rigidity of response to primary and secondary charged particles (≥ 0.4 GV). In both cases, the GRB trigger coordinates are within the effective field of view of the vertical Tupi muon telescopes. There is a ground level enhancement (GLE) on the muon counting rate background, with a statistical significance above 4σ, 38.22 minutes after the Swift trigger occurrence, and there are at least two GLEs, with a significance above 4σ, at 7.2 minutes and 19.2 minutes after the Fermi trigger, respectively. We argue that the GeV counterpart of a keV GRB could be similar to the highest GRBs, observed by EGRET within BATSE's field of view, where the high-energy emission arrives at the detector in fragments, and they are delayed and/or anticipated with respect to the keV-MeV burst. This behavior is observed in both cases. In short, the analysis suggests that they may be physically associated. Details and some implications of this possible association are reported in this work.

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I. INTRODUCTION

Gamma ray bursts (GRBs) are among the most powerful astrophysical phenomena in the Universe. Most of the observed GRBs appear to be collimated emissions of gamma rays, observed in the deep sky at random places and at random times. Some of these bursts are followed by afterglows at x-ray, optical, and radio wavelengths. The GRBs were discovered accidentally in the 1960s during the cold war years by American military satellites (Vela project) designed to detect gamma rays produced by Soviet atomic bomb tests on Earth. So far, GRBs have been detected by several satellites mostly in the keV to MeV energy band, such as the CGRO. The major advances occurred in the 1990s with the Compton Gamma Ray Observatory (CGRO), which had four instruments (BATSE, EGRET, COMPTEL, and OSSE) covering an energy band from 30 keV to 30 GeV [1]. The main results were the discovery of an isotropic distribution of GRBs, where 70% of the GRBs are the long-soft type with approximately 30 seconds of duration on average and a second category of GRBs of the short-hard type with approximately 0.2 seconds of duration on average, following a bimodal distribution. The CGRO has observed the highest-energy GRBs in the GeV region, and discovered that blazer active galactic nuclei are the primary source of the highest-energy cosmic gamma rays. The first GRB afterglow was observed by the Beppo-SAX satellite in 1977. So far, the afterglow was observed only in some long type bursts, allowing the determination of their redshifts. In most cases, the measured redshift is higher than 0.5. Consequently they are of cosmological origin and they are connected with supernova events. In GRBs of short type, no afterglow has been observed, therefore making their redshifts uncertain. Probably these short bursts result from a different engine than long bursts. They could be connected to compact binary mergers, like two neutron stars or with a black hole component as well as binary pulsar.

Currently, there are Konus, INTEGRAL, Swift, AGILE, and Fermi in operation. Swift is a multiwavelength space-based GRB detector. Its three instruments work together to observe GRBs and their afterglows in the gamma ray, x-ray, ultraviolet, and optical wavebands [2]. The Fermi gamma ray burst monitor (GBM; formerly GLAST burst monitor) is the secondary instrument on the Fermi Gamma ray Space Telescope (formerly GLAST). It is as a support of the Large Area Telescope (LAT) in observing GRBs by providing low-energy measurements with high time resolution and by providing rapid burst locations over a large field of view (≥ 8 sr). The GBM will complement the LAT (energy range: 10 MeV to >100 GeV) measurements by observing GRBs in the energy range 10 keV to 30 MeV. The Fermi triggers are being included in the GCN Burst Trigger Information [3]. About 15 times per month, there will be a GRB in the field of view. Independently, the LAT will also detect about two bursts per month.

In addition, several models for the origin of GRBs predict a GeV–TeV component [4–6]. These theories had motivated the construction of ground-based GRB detectors, with very large areas to collect secondary particles (air showers) produced by GeV–TeV gamma rays. So far the ground-based evidence in several years of a systematic search has been negative. A plausible explanation for the discrepancy between the observations and predictions in the GeV–TeV region is to invoke the attenuation of TeV photons by interaction with the intergalactic infrared radiation. This process would be responsible for a cutoff for

TeV GRBs whose sources are at distances larger than $z \sim 0.3$. For GRBs with $E_\gamma > 20$ GeV, the cutoff can be shifted to $z \sim 2$.

Without any doubt, the MILAGRO detector had opened a new generation of ground-based cosmic ray detectors using water Cherenkov technology and had enabled the construction of a large sensitive volume with a large field of view (2 sr) with a duty cycle higher than 90%. After seven years of operation, MILAGRO ceased operation in April 2008. Its impressive results have ushered in a new era for ground-based gamma ray astrophysics at TeV energies, such as the measurement of the spatial distribution of diffuse TeV gamma ray emissions [7] and TeV gamma ray sources from a survey of the galactic plane [8]. In addition, MILAGRO had searched for counterparts above 100 GeV, 17 short-duration (< 5 s) GRBs between January 2000 and December 2006, detected by the Swift and Hete satellites, which occurred within the field of view of MILAGRO, and found no significant emission correlated with these bursts [9]. Probably, due to the absorption of high-energy gamma rays by the extragalactic background light, detections are only expected for redshifts less than $\sim$0.5. On the other hand, long duration GRBs are of cosmological origin, most of them with redshift above 0.5, and they must be severely attenuated.

Other ambitious projects for GeV GRB detection at ground have been reported such as the ARGO air shower project at Tibet [10], the GRAND project of a muon air shower detector at Indiana, USA, [11], and the STACEE [12] and MAGIC [13] atmospheric Cherenkov detectors. There are also the HAWC project [14] using very large water Cherenkov tanks at the highest mountain in Mexico (5636 m above sea level), which is considered as the successor of the MILAGRO experiment, as well as the LAGO project [15] using water Cherenkov tanks (like the AUGER project tanks) on several high altitude mountains. The dream is to reduce the threshold energy of shower detection, with sensitivity to primary energies, to approximately 10 GeV, which is 10 times smaller than the sensitivity of the MILAGRO detector.

On the other hand, the South Atlantic Anomaly (SAA) is a region close to the south coast of Brazil in which the shielding effect of the magnetosphere is not perfectly spherical and shows a ‘‘hole’’ as a result of the eccentric displacement of the center of the magnetic field compared with the origin (center of mass). This behavior of the magnetosphere is responsible for several processes, such as the trapping and azimuthally drifting of energetic particles, bouncing between hemispheres coming deeper down into the atmosphere owing to the low field intensity over SAA, thereby interacting with the dense atmosphere resulting in ionization production and increasing electric conductivity. Thus, the cosmic rays less than several GeV including solar charged particles and charged particles produced by other transient events have a chance of generating a shower capable of reaching the ground in the SAA region.

In addition, the Earth's magnetic field deflects the charged particles of the shower initiated by a gamma ray. This deflection is caused by the component of the Earth's magnetic field perpendicular to the particle trajectory. This effect results in a decrease in the number of collected particles and therefore the telescope's sensitivity. This means that the sensitivity of telescopes is high in the SAA region, because in this region the transverse magnetic field is small, compatible with the magnetic field in the polar regions.

In this survey we have searched for the GeV counterparts of two GRBs, the Swift 317662 and the Fermi bn081017474, both GRBs having their trigger coordinates within the field of view of the vertical Tupi telescope located in the SAA region. The paper is organized as follows. In Sec. II, the Tupi experiment is described briefly, and some information is given on events observed in association with spacecraft GRB detectors. In order to understand a possible GeV counterpart of keV GRBs, the EGRET GRB detections near bright BATSE bursts are commented on in Sec. III. In Secs. IV and V, the search for the GeV counterparts of Swift and Fermi GRBs are described, and Sec. VI contains our conclusions.

II. THE TUPI EXPERIMENT AND SOME RESULTS

Since April 2007 we have been operating the phase II of the Tupi experiment, with two directional muon telescopes at sea level located at 22S and 43W, inside the SAA region and close to its center. This characteristic offers the muon telescopes a low rigidity of response to cosmic protons and ions (≥ 0.4 GV). Each telescope is constructed on the basis of two plastic scintillators (see Fig. 2 in [16]). One of them has a vertical orientation, and the other is oriented near 45 degrees to the vertical (zenith) pointing to the west. The directionality of the vertical muon telescope is guaranteed by a veto or anti-coincidence guard, using a detector of the inclined telescope and vice versa. Thus, the incidence of an air shower activates the four detectors, and it is not registered. Only muons with trajectories close to the telescope axis are registered. Some details of the experimental setup were reported in [16]. Each telescope has an effective aperture of 0.27 sr.

So far, the main results obtained during phase II have been the observation of particle precipitation in the SAA region, with a high confidence level, in association with Swift-BAT, MILAGRO, and Fermi-GLAST GRB triggers [16,17]. We also look for a possible GeV counterpart to the GRBs in the keV energy region observed by GRB spacecraft detectors. We have identified nine GRB triggers within the telescope's field of view, seven of which were detected by the Swift-BAT and two by the Fermi-GBM GRB detectors. Of these GRB triggers, four Swift-BAT triggers are compatible with the precipitation of particles in the SAA, and they are considered as noise triggers. The associated muon enhancements look like sharp peaks with high confidence level. Two of them are reported in [16]. In all these cases, the trigger occurrences are between 12 h UT and 21 h UT, and that is the traditional precipitation time interval. Three Swift and two Fermi GRB triggers have been observed out of the precipitation time interval. However, only one Swift-BAT trigger and one Fermi-GBM trigger have possible GLE association with high confidence level (above 4σ) within two hours around the trigger occurrence, and they are analyzed here.

We would like to point out an event on August 7, 2008, having a peak at 21:15:59 with a GLE of 4.4 sigma, in coincidence with the SWIFT-BAT trigger 287222 occurrence within the 10-second counting interval [18]. However, the Swift Star Tracker had lost stellar lock minutes before, and the trigger was not confirmed as a GRB. The GLE peak is close to the transition between a high and a low muon intensity background. Now, we know that the effect is attributed to precipitation of particles in the SAA, and the peak is just the sunset enhancement, closing the precipitation.

III. THE EGRET GRB DETECTIONS NEAR BRIGHT BATSE BURSTS

The analysis of the EGRET GRB detections near bright BATSE bursts can be useful for us to understand the possible GeV counterparts of keV GRBs. EGRET on the CGRO had observed several high-energy and hour-long GRB triggers [19]. The strongest detection was the GRB of February 17, 1994, with emissions at nearly 20 GeV and with durations over 10 times longer than that detected by BATSE at MeV range. There were at least four long EGRET GRBs [19–22] detected simultaneously with the bright BATSE sub-MeV emissions, and one of them (the highest energy) is shown in Fig. 1.

The above signature of long duration EGRET GRBs, with large time differences with BATSE, could be explained by a shock front hitting an interstellar medium leading to sub-TeV to TeV gamma rays interacting with the infrared and cosmic microwave background radiations

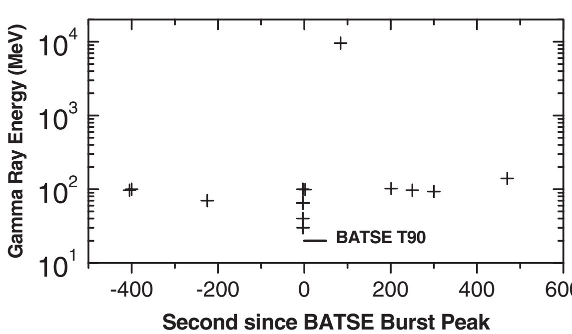

FIG. 1. The highest-energy EGRET gamma ray detection is shown near a bright sub-MeV BATSE burst.

in interstellar space, producing different path lengths from the source to the observer, and dispersion of the arrival time to the detector. According to the EGRET results, the rate of the high energy (~ 100 MeV) and long duration GRBs is one per year [23]. However, this rate must be bigger, because the EGRET spark chamber detector had only an effective area of 1500 cm^2, given an effective angular opening of 18 degrees. In short, the highest GRBs (GeV region) observed by EGRET within BATSE's field of view had shown that the high-energy emission arrived to the detector in fragments, and they were delayed and/or anticipated with respect to the keV-MeV burst.

IV. SEARCH FOR THE GEV COUNTERPARTS OF SWIFT GRBS

According to the GNC Circular Number 8000 [24], at 04:19:24 UT, the Swift Burst Alert Telescope (BAT) located the GRB 080723 (trigger 317662), whose coordinates are (RA, Dec) = (274.512, −6.923). The BAT light curve has not been received. But there is a strong 8.4 sigma excess detected in the scaled map image, with 80×80 pixel covering 40×40 arcsec, using the XRT position. The first important characteristic observed in the Swift GRB-080723 is that the trigger coordinates are inside the effective field of view of our vertical muon telescope, as shown in Fig. 2, where the two telescope axes equatorial coordinates are indicated together with the GRB coordinates. The "ellipses" represent the effective field of view of the telescopes.

The vertical telescope output (raw data) is shown in Fig. 3 (upper panel), which represents the muon counting rate at every 10 seconds. For comparison, we have also

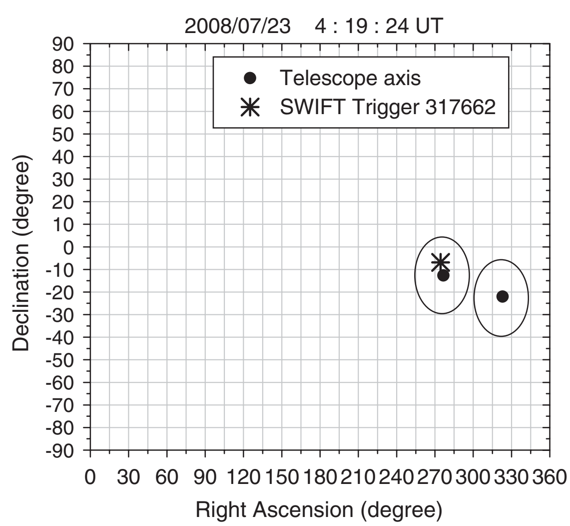

FIG. 2. The equatorial coordinates show the positions of the two Tupi telescope axes at GRB trigger time, as well as the Swift trigger position. The ellipses represent the effective field of view (0.27 sr) of the Tupi vertical telescope.

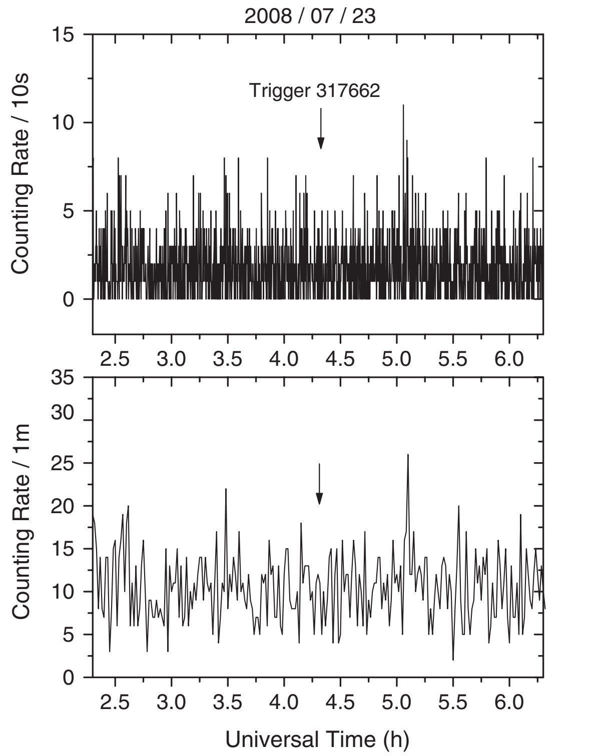

FIG. 3. The muon counting rates are shown at $1/10\ \mathrm{s}^{-1}$ (upper panel) and at $1/60\ \mathrm{s}^{-1}$ (lower panel), observed on July 23, 2008, in the vertical muon telescope around two hours before and after the Swift trigger. The vertical arrow indicates the occurrence of the Swift-BAT GRB trigger.

included the counting rate at every minute (lower panel). In both cases, the overall time interval covers a period of about two hours before and after the Swift GRB trigger.

From these figures, it is possible to see that there is a GLE with a peak at 38.22 minutes after the Swift-BAT trigger occurrence. In order to obtain accurately the statistical significance of the GLE, we have used the likelihood ratio method of Li and Ma [25]. This method is useful, especially when the time on source differs from the time off source, and it is defined as

$$\mathrm{Sig} = \sqrt{2}\left\{N_{\mathrm{on}} \ln\left[\frac{1+\lambda}{\lambda}\left(\frac{N_{\mathrm{on}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right] + N_{\mathrm{off}} \ln\left[(1+\lambda)\left(\frac{N_{\mathrm{off}}}{N_{\mathrm{on}}+N_{\mathrm{off}}}\right)\right]\right\}^{1/2}, \quad (1)$$

where $\lambda = t_{\mathrm{on}}/t_{\mathrm{off}}$. Since the BAT light curve is not available for this GRB, the time of duration is unknown, even for the gamma ray emission in the keV region. Thus, we have initially chosen exactly the raw data bin (10 s) as t_{on} (see Fig. 3, upper panel), and afterwards a $t_{\mathrm{on}} = 60$ s (see Fig. 3, lower panel), to analyze one specific peak, with a confidence level above 4σ. The results are summarized in Table I for two different values of λ.

Figure 4 shows the cumulative distribution of the Poisson probability P_i of a signal (counting rate enhancement) to be a background fluctuation with $\Delta t = 10$ s, applied to a time window of two hours on each side of the Swift trigger 317662. A true signal appears on this figure with a low probability.

TABLE I. The statistical significance for the GLE near the GRB Swift trigger 317662 is estimated using the likelihood ratio method of Li and Ma for different parameters.

$\lambda = t_{\mathrm{on}}/t_{\mathrm{off}}$	$t_{\mathrm{on}}(s)$	$\sigma/\sqrt{N}$
0.05	10	4.9
0.01	10	4.7
0.05	60	4.1
0.01	60	4.2

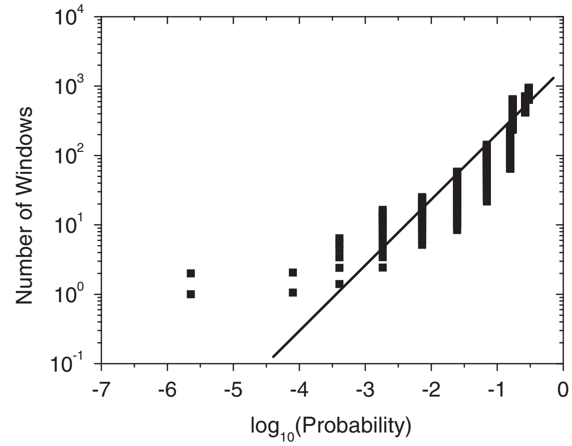

FIG. 4. Cumulative distribution of the Poisson probability P_i of a signal to be a background fluctuation, in the time bin of $\Delta t = 10$ s, obtained by shifting this window inside a two-hour interval around the Swift trigger 317662. The solid line is the expected distribution under the assumption of no signals.

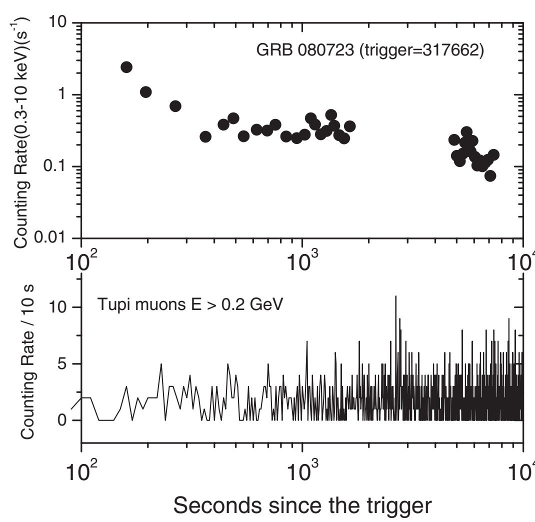

FIG. 5. Upper panel is the XRT light curve of the GRB-080723 (trigger = 317662), and lower panel is the muon light curve observed at ground in the vertical Tupi telescope.

The second characteristic is the most interesting. It shows a possible GeV counterpart of the Swift GRB analyzed here. Figure 5 shows the Swift GRB 080723 XRT light curve (upper panel) [26] and the ground muons light curve (lower panel). The muon peak with a confidence level above 4σ in the GeV energy range is detected 38.22 minutes after the GRB trigger. From this figure, it can be inferred that the keV GRB still emits photons with the same intensity, before and after the muon peak. The XRT redshift limit for this Swift GRB is less than 2.4.

V. SEARCH FOR THE GEV COUNTERPARTS OF FERMI GRBS

According to the Fermi GBM Catalog (fermigrbst) [27], at 11:22:34 UT, it registered a GRB trigger bn081017474, whose coordinates are $(\mathrm{RA, Dec}) = (106.75, -14.45)$. However, so far the peak flux as well as the T90 GRB duration are not determined. As in the previous case, the Fermi GRB has trigger coordinates inside the effective field of view of the vertical Tupi telescope, as shown in Fig. 6. Similarly, Fig. 7 represents the muon counting rates in the upper panel at every 10 seconds (raw data), and in the lower panel we have also included the counting rates at every minute. In both cases, this is done over a period of about two hours before and after the Fermi GRB trigger.

In the upper panel of Fig. 7, it is possible to see two GLEs with peaks at 7.2 minutes (peak A) and 19.2 minutes (peak B), respectively, after the Fermi trigger, and a third peak at 59.4 minutes (peak C) before the trigger occurrence. However, in the counting rates at every minute (lower panel), peak A and peak C are suppressed, which means that peak A and peak C are of short durations.

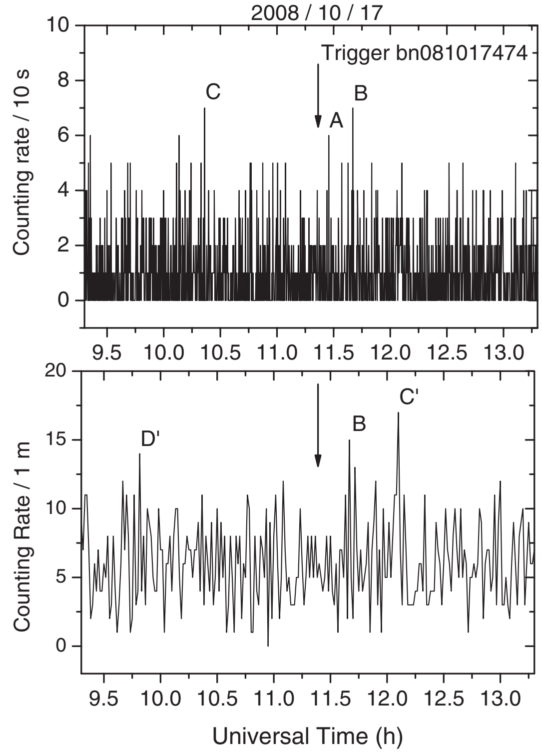

FIG. 7. The muon counting rates are shown at $1/10\ \mathrm{s}^{-1}$ (upper panel) and at $1/60\ \mathrm{s}^{-1}$ (lower panel), observed on October 17, 2008, in the vertical muon telescope around two hours before and after the Fermi trigger. The vertical arrow indicates the occurrence of the Fermi-GBM GRB trigger.

Meanwhile peak B is enhanced, as are peaks C' and D'. As before, we have also used the Li and Ma method to obtain the statistical significance, and the results for the highest GLEs (above 4σ) near the Fermi GRB trigger are summarized in Table II.

Figure 8 shows the cumulative distribution of the Poisson probability P_i of a signal (counting rate enhancement) to be a background fluctuation with $\Delta t = 10$ s, applied to a time window of two hours on each side of the Fermi-GBM trigger bn081017474.

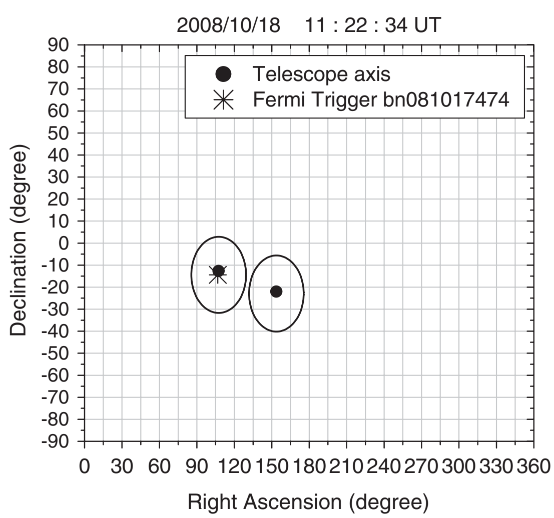

FIG. 6. The equatorial coordinates show the position of the two Tupi telescope axes at GRB trigger time, as well as the Fermi trigger position. The ellipses represent the effective field of view (0.27 sr) of the Tupi vertical telescope.

TABLE II. The statistical significance for the highest GLEs near the GRB Fermi trigger (see Fig. 7) is estimated using the likelihood ratio method of Li and Ma, for different parameters.

GLE	$\lambda = t_{\mathrm{on}}/t_{\mathrm{off}}$	$t_{\mathrm{on}}(s)$	$\sigma/\sqrt{N}$	Delay (minutes)
A	0.01	10	4.5	+7.2
B	0.01	10	5.0	+19.2
C	0.01	10	5.0	−59.4
B	0.01	60	8.1	+19.2
C'	0.01	60	9.1	+45.6
D'	0.01	60	7.1	−91.2

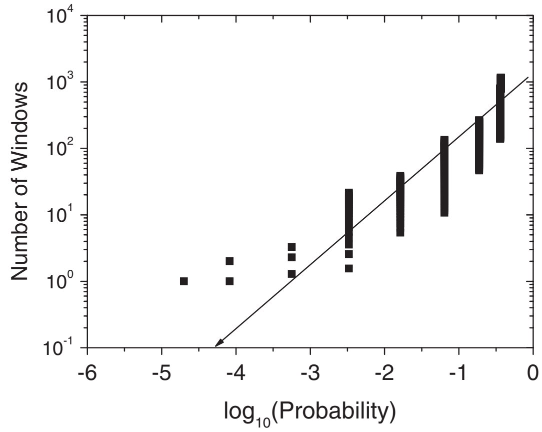

FIG. 8. Cumulative distribution of the Poisson probability P_i of a signal to be a background fluctuation, in the time bin of $\Delta t = 10$ s, obtained by shifting this window inside a two-hour interval around the Fermi GRB trigger bn081017474. The solid line is the expected distribution under the assumption of no signals.

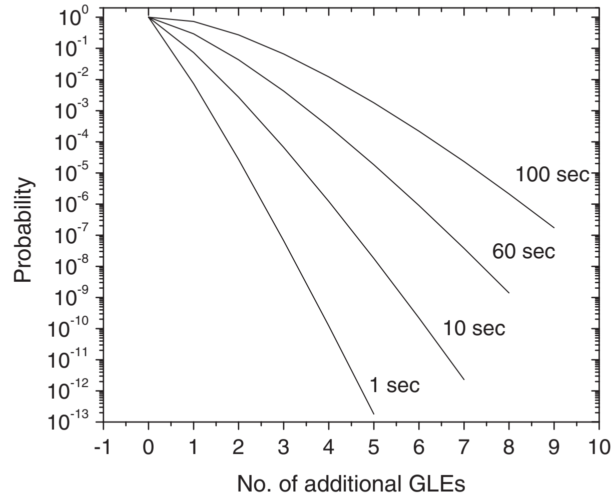

FIG. 9. Poisson fluctuation probabilities of finding additional GLEs for four values of the sub-MeV GRB duration.

VI. CONCLUSIONS

We searched for GeV photons counterparts of two GRBs, the Swift-BAT trigger = 317662, and the Fermi-GBM trigger = bn081017474. We have compared the muon background with the possible associated GLEs. Following Figs. 4 and 8, we can conclude that the chance of observing a GLE with a confidence level above 4σ due to background fluctuation is less than 0.1%. In most cases, GLEs with a confidence level above 4σ have been observed in association with GRBs triggers observed by space-borne detectors in the schedule of precipitation of particles in the SAA region (~ 12 UT to ~21 UT). However, in such cases the muon enhancement is observed in both telescopes [16,17]. This means that the enhancement is produced by an omni-directional radiation, which is characteristic of the precipitation of particles in the SAA region.

The two GRB triggers analyzed here are out of the schedule of precipitation, and in order to see whether a keV GRB can be associated with more than two GLEs we have adopted the Tibet team analysis [28] to obtain the number of additional GLEs due to a GeV GRB, each with a confidence level above 4 sigma, on the basis of the GeV EGRET events inside the field of view of the BATSE sub-MeV GRBs. The mean number of additional GLEs depends on the sub-MeV GRB duration, and is found to be 0.02, 0.2, 0.8, and 2.0 for 1 sec, 10 sec, 60 sec, and 100 sec windows, respectively, at vertical incidence.

In Fig. 9, we show the Poisson fluctuation probabilities of finding additional GLEs for four values of the GRB duration. We would like to point out that a particular EGRET burst has a duration of 90 minutes, which includes the detection of an 18 GeV photon [19]. As a comparison, typical Swift GRBs emit photons (gamma rays) in the keV energy region, and last up to some dozens of seconds.

Finally, we believe that the low values of the Earth's magnetic field perpendicular to the particle (muon) trajectory in the SAA region can enhance the telescope's sensitivity by ~6 times, when compared with other regions except the polar regions. In addition, EGRET has shown that the MeV to GeV GRBs of long duration consist of gamma ray packages, arriving at the detector in intervals of different time (see Fig. 1). This means that the GRB components of higher energies suffer severe fragmentations during their propagation, and probably many of these fragments do not arrive at the detector. These characteristics and the possible GeV counterpart of 2 keV GRBs analyzed here have encouraged us to use the ground-based method to detect GRBs inside the SAA region. The Tupi experiment is in the process of expansion, and we will operate 14 more telescopes within six months, increasing the field of view of the Tupi experiment 16-fold.

ACKNOWLEDGMENTS

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