IS THERE AN ENHANCEMENT OF MUONS AT SEA LEVEL FROM TRANSIENT EVENTS?

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Received 2004 March 9; accepted 2004 November 22

ABSTRACT

In a recent study of a search for enhancements from the Galactic center with muons at sea level using the TUPI muon telescope, we have found several ground-level enhancements (GLEs) as very sharp peaks above the count rate background. This paper reports a consistent analysis of two GLEs observed in 2003 December and detected after an upgrade of the data acquisition system, which includes a noise filter and allows us to verify that the GLEs are not mere background fluctuations. The main target of this study is a search for the origin of the GLEs. The results show that one of them has a strong correlation with a solar flare, while the other has an unknown origin, because there is no satellite report of a solar flare, no prompt X-ray emission, and no excess of nuclei during the raster scan in which the GLE was observed. Even so, two possibilities are analyzed: the solar flare hypothesis and the gamma-ray burst (GRB) hypothesis. We show, by using the FLUKA Monte Carlo results for photoproduction, that under certain conditions there is the possibility of an enhancement of muons at sea level from GeV GRBs.

Subject headings: elementary particles — gamma rays: bursts — Sun: flares

1. INTRODUCTION

In gamma-ray astronomy, an important energy band of the electromagnetic spectrum, the gap region between gamma rays up to 30 GeV covered by satellites and the region starting from ~0.2 TeV covered by ground-based experiments, is still not very well explored. In order to reach this energy region, the TUPI muon telescope, located in Niterói, Brazil, has been in operation since 2002 January. Because of a limited aperture (9°/5 of opening angle), the TUPI telescope is on the boundary between telescopes with a very small field of view, like the air Cerenkov telescopes, and the small air shower arrays, characterized by a large field of view.

On the other hand, a muon telescope at ground level can be used as an astronomical telescope even if the muon’s parent particles are neutral, such as photons. Muons are expected as products of cosmic-ray (protons, nuclei) interactions with the nuclei of the atmosphere via $\pi^\pm$ production followed by the decay $\pi^\pm \rightarrow \mu^\pm \nu_\mu$. However, a small fraction of muons have their origin in photonuclear reactions induced by gamma rays. The ability to distinguish these “photonuclear” muons from background muons depends on statistics, the strength and energy spectrum of the emitting source, and some characteristic of the experiment, such as the angular resolution.

In order to increase the sensitivity of the TUPI telescope, an upgrade of the acquisition system was made in 2003 December and included a new (online) discrimination level to increase the count rate background from approximately one per 20 s to approximately 18 per 10 s. In addition, as the experiment uses scintillator plastics and because of other limitations (see § 3), the count rate has a dependence on the (online) pulse-height discrimination, and this new data acquisition allows us to build a noise filter. The aim of this framework is to make a consistent analysis of ground-level events, observed as very sharp peaks above the count rate background and found during a study of a possible muon excess from the Galactic center.

In this paper we report two ground-level enhancements (GLEs) detected in 2003 December and obtained under these new conditions. We give emphasis to the study of their origin, including the temporal characteristics on the basis of the time profiles and duration of the GLEs. We show that the first GLE has a strong correlation with solar flares. Because the second GLE has an unknown origin, two possibilities are analyzed. The paper is organized as follows. In § 2, we present the TUPI telescope characteristics. In § 3, the raster search technique is presented. The analysis of the two GLEs is presented in § 4. In § 5 the local effects are analyzed. In § 6 the possible existence of a window to observe GRBs at the ground is discussed, and in § 7 we present our conclusions.

2. THE TUPI TELESCOPE

The TUPI muon telescope is installed on the campus of the Universidade Federal Fluminense, Niterói, Rio de Janeiro, Brazil. The position is latitude S22°54′33″, longitude W43°08′39″, at sea level. The telescope is inside a building and under two flagstones of concrete, as shown in Figure 1. The flagstones’ thickness has a dependence on the zenith angle (150 g cm$^{-2}$, on average). For large zenith angles ($\theta > 76°$) and in the south and west directions there are two walls with a thickness close to 165 g cm$^{-2}$, behind the walls there is open sea. However, for the north and east directions, besides the two walls, there are the buildings of Niterói City. Consequently, the north and east directions are opaque for almost horizontal atmospheric muons. The flagstones or walls increase the muon energy threshold. The telescope can detect muons at sea level with energies greater than the ~0.3 GeV required to penetrate the two flagstones. In addition, the flagstones contribute to the $e/\mu$ separation, consequently reducing the noise due to nonmuon particles.

Most of the particles (~95% at $E > 1$ GeV) observed at sea level are muons. This means that the telescope computes mainly the muon intensity in the atmosphere initiated by cosmic rays (mainly protons), giving the coincidence count rate of multielements (plastic scintillator detectors with 0.5 m x 0.5 m x 35 cm). Each plastic scintillator is viewed by a 5 cm diameter Hamamatsu R521 photomultiplier. The unit has an energy threshold of ~10 MeV and is fed by very stable power supplies. A servomechanism (with an equatorial assembly) allows the axis of the telescope to be pointed so as to accompany a given source. Details of the experimental setup of the TUPI muon
telescope, as well as a study of the muon background characteristics, have previously been reported (Augusto et al. 2003).

In our experiment, only particles close to the telescope axis are detected (65.3 cm$^2$ sr$^{-1}$ of aperture and $9^\circ$5 of opening angle). Essentially, shower particles coming from other directions are rejected by a combination of coincidence between the two telescope detectors and anticoincidence with another detector off the telescope axis, constituting a trigger system, as shown in Figure 2.

The relative efficiency of the detection of charged particles by the plastic scintillators in relation to NaI(Tl) crystals is approximately 50%. The plastic scintillator light emission does not reach the optimum frequency region of the photomultiplier, the de-excitation and light emission do not always occur preferentially via low-lying impurity levels, and the wavelength of maximum emission happens in a band of waves. In addition, the efficiency is also compromised, because the coupling between the scintillator and the photocathode (light guide) in our experiment is air and there is the possibility of reflection in the walls of the container in which each unit of detection is mounted. Consequently, two identical charged particles can give different light-pulse amplitudes. In our experiment, a pulse-height discriminator (online) is used to select only those pulses above a certain amplitude. This eliminates electronic noise and reduces the background (random) count rate of the system. The count rate (even of single muons) has a dependence on the pulse-height discrimination (online) used in the experiment. In order to see the count rate dependence on the pulse-height discrimination, every time the trigger conditions are satisfied the heights of the pulses in all the detectors are read and stored in a file. This allows us to choose several (off-line) pulse-height discriminator levels via software starting from a certain value.

The data acquisition is made on the basis of the Advantech PCI-1711/73 card with an analog-to-digital conversion up to a 1000 kHz sampling rate. All the steps, from signal discrimination to the coincidence and anticoincidence, are made via software using the virtual instrument technique. The application programs were written using the LabVIEW tools.

3. RASTER SEARCH TECHNIQUE

The observation of the Galactic center began on 2003 June 26 and consisted of on-source and off-source raster scans across parallel lines in declination during a sidereal half-day (12 hr). This is approximately the time that the Galactic center is above our horizon in every 24 hr. Starting from 2003 December, the count rate every 10 s was used to observe a possible muon excess in the direction of the Galactic center (decl. = $-29^\circ$, R.A. = $17^h42^m$).

The atmospheric muon flux originating from the decay of charged pions and kaons produced by cosmic rays in the atmosphere is nearly isotropic. However, at lower energy (sub-GeV to GeV) the muon flux is influenced by the magnetic field of the Earth (Hayakawa 1969). Consequently, the muon angular distributions are quite different for different sites on the globe. There are two main geomagnetic effects on the muon flux observed at ground level. One is the east-west effect, in which the muon flux is highest (lowest) coming from the west (east). The effect is a consequence of the fact that the electric charge of the primary cosmic ray is mainly positive. The muon flux is a convolution of the primary spectrum and carries the imprint of this geomagnetic effect. The other is the azimuthal dependence on the positive-to-negative ratio of muons, in which a considerable amount of the negative excess is observed for muons coming from the east. The effect is a consequence of the geomagnetic deflection being different for positive and negative...
particles, as well as the dependence of the path length of a muon on azimuth; a positive muon coming from the east has a longer path length than a negative one. These geomagnetic effects distort the zenith angle distribution of sub-GeV to GeV muons during a raster scan, because the measures (Galactic center) begin around the east direction and finish around the west direction.

Figure 3 summarizes the situation for the raster scan on 2003 December 22. In the upper part, the telescope output, raw data (count rate vs. universal time) are shown. In the lower part the squares represent the integral $(\text{count rate vs. universal time})$ are shown. In the lower part the squares represent the integral $(\text{count rate vs. universal time})$ are shown. In the upper part, the telescope output, raw data around the east direction and finish around the west direction.

Fig. 3.—Integral intensity of muons obtained during a typical raster scan. The zenith angle is indicated in the lower panel.

A quantitative result of the west-east effect during a raster scan can be obtained from two symmetrical points with the same zenith angle, one pointing to the west and the other pointing to the east. Table 1 shows some TUPI results in which the west-east asymmetry is defined as the ratio $(W - E)/(W + E)$. This relative value is free from the detection bias and normalization. In Table 1 the Okayama results (Tokiwa et al. 2003) are also included for comparison.

On the other hand, measurements of the absolute muon intensities by telescopes require measurements of the muon energy. In the present stage of our experiment, the detector is only a directional muon counter telescope, and only relative intensities can be obtained. The obtaining of absolute muon flux requires normalization to available absolute measurements. Even so, it is well known that below 1 GeV there is a systematic dependence on location due to Earth’s magnetic field (geomagnetic effect). In addition, ground observations using new generations of spectrometers such as CAPRICE (1997; see Boezio et al. 2000; Kremer et al. 1999) and BESS (2001; see Tanizaki et al. 2003), both at Fort Sumner, New Mexico (892 g cm$^{-2}$), have shown that the difference in the muon intensity is as large as about 20% around 1 GeV. The difference can be attributed to the effect of solar modulation. An annual variation of the muon flux at sea level has also been reported, with changes of about 5% at 1 GeV expected.

Here we have opted for the following strategy. Measurements of the integral muon intensities have been made at axis orientations of $0^\circ$–$84.5^\circ$. In order to reduce the geomagnetic effects, the measurements are made at a fixed azimuth angle (the telescope’s axis always pointed southerly), and a fit with the AMH (Texas A&M–University of Houston) function (Green et al. 1979), after a numerical integration and extrapolation to 0.3 GeV, has been made. Figure 4 summarizes the situation. We can see that the TUPI muon intensities are systematically a little higher than the AMH fit for a large zenith angle. However, the TUPI muon intensities are consistent with the AMH fit. The several sources of modulation of sub-GeV to GeV muons can explain these differences.

4. GROUND-LEVEL EVENTS

The two GLEs reported in this paper were detected in 2003 December under new conditions of (online) pulse-height discrimination level. The duration of the two GLEs is long enough that they cannot be interpreted as a surviving solitary small shower or the remains of an extensive shower, both begun by conventional cosmic rays. Besides this, the chance of detection of showers with the telescope is small, because they are rejected.

4.1. The First Ground-Level Event (2003 December 2)

The GLE of 2003 December 2 was detected during a raster scan off-source. The light-curve shape presents several peaks, as shown in Figure 5 (lower panel), with two peaks being

| Experiment  | Azimuth       | Zenith (deg) | Rigidity Cutoff (GV) | Energy (GeV) | West-East Asymmetry (%) |
|------------|---------------|--------------|----------------------|--------------|-------------------------|
| TUPI$^*$   | Southeast-southwest | $\theta = 60$ | 9.8                  | $>0.3$       | $(15 \pm 3)$            |
| TUPI       | East-west     | $\theta = 20$ | 9.8                  | $>0.3$       | $(18 \pm 3)$            |
| Okayama    | East-west     | $\theta = 20$ | 12                   | 1–3          | $(17 \pm 4)$            |

Note.—In the case of the TUPI experiment, the error is only statistical.

* In raster scan regime.
dominant at the beginning and the end of the GLE. The excesses for these two peaks can be seen over a background rate of approximately 18 coincidences per 10 s with significance levels of 9.7 and 10.5 $\sigma$, respectively.

The analysis began with a search for the origin of the GLE. Following Figure 5 it is possible to see the similarity between the light curve of the last two solar flares on 2003 December 2, reported by the GOES satellite, and the light curve of the GLE.

We have verified from the literature that there is reported for most of the cases of GLEs linked with energetic solar flares, those with an X-ray prompt emission are classified as X-class (above $10^4$ W m$^{-2}$). These observations of solar flares (Smart 1996 and references therein) have led to the identification of two classes of acceleration events: impulsive (prompt) and gradual (posteruptive or delayed). The impulsive events require selective acceleration, such as the gyroresonant interaction with plasma waves. The energetic particles from these events arrive very quickly, around 15 minutes after a flare. In contrast, the gradual events have a strong association with coronal mass ejection (CME) and suggest that the particles in these events are accelerated by CME-driven shocks. The energetic particles of these events are observed up to several hours after a flare. The effect on the interplanetary medium occurs preferentially during this posteruptive phase (Kocharov et al. 1995). In the case of the first GLE, the association is with the last two flares on 2003 December 2; the X-ray prompt emission of the first of these flares is of low intensity (C5.0 class) and that of the second is of medium intensity (M1.5 class). The delay between the X-ray prompt emission and the GLEs is 1.5 hr. Consequently, they can be associated with the gradual, or posteruptive, events. We would like to point out that the temporal shift between the two prompt X-ray emissions and the GLEs' peaks is practically the same.

Besides the GOES report of X-ray prompt and proton emissions, there is also the report by the Advanced Composition Explorer (ACE) Electron, Proton, and Alpha Monitor (EPAM) WART60 of energetic nuclei, such as flows of nuclei (E > 100 MeV) of hydrogen, helium, oxygen, and iron, emitted by the Sun during the flares in the proportion (at 1 AU from the Sun) $\approx 5000 : 100 : 10 : 10$ in units of (cm$^2$, s, sr, MeV/nucleon)$^{-1}$ as hourly average flux. The beginning of the GLE coincides approximately with the decline of the Sun when the Sun was not far from the field of view of the TUPI telescope (see Table 2).

On the other hand, an accurate determination of the fluence of solar energetic particles from the flare that might generate muons requires the obtaining of the muon energy spectrum. As has already been indicated, in the present stage of our experiment, the detector is only a directional counter telescope of muons above an energy threshold (0.3 GeV).

We have also examined the light curve for this GLE for other pulse-height amplitude discrimination, as shown in Figure 6. The signal persists even when a high pulse amplitude is used as the discrimination level. We would like to comment that there was a third solar X-ray flare (M1.4 class) on 2003 December 2,

1 Available at http://sec.noaa.gov/ftpmenu/plots/xray.html.

2 Available at http://sd-www.jhuapl.edu/ACE/EPAM/janice/epmwww.cgi?2320+current+e.
beginning at 12:47 UT. We did not register this because the raster scan only began at 13:31 UT.

4.2. The Second Ground-Level Event (2003 December 16)

The GLE of 2003 December 16 was also detected during an off-source raster scan. The light-curve shape is like that of a fast rise, exponential decay (FRED), as shown in Figure 7 (lower panel). The excesses for this FRED GLE can be seen over a background rate of approximately 18 coincidences per 10 s with significance levels of 7.9σ. The origin of this GLE is unknown, because there is no satellite report of a solar flare, no prompt X-ray emission, and no excess of protons or heavy particles during the raster scan in which the GLE has been observed. We would like to highlight that the GLE’s duration is 416 s. This means that the GLE is not the remains of showers produced by conventional cosmic rays.

The enhancement of muons at sea level from solar flares is linked with the most energetic particles (i.e., protons, alphas, etc.), those with energies above the pion production threshold and the cutoff rigidity of the region in which the detector is located. In fact, the pitch angle (where 0° represents sunward initial mass function direction) of high-energy particle excess linked with solar flares presents a large anisotropy distribution (Duldig 2001) with a systematic intensity excess around 0° pitch angle and decreases up to 60°. The excess at a large pitch angle, up to 180° as observed by large field-of-view detectors such as neutron monitors, are made up of low-energy particles. They are in the tail of the distribution, where the intensity is minimum.

Even so, the FRED GLE could be an event connected via the field magnetic lines with a flare on the other side of the Sun and not seen by satellites. The probability of detection using a directional telescope of small field of view (0.082 sr of angular window) pointed in a random direction at an event above the horizon is approximately $p \approx 0.082/2\pi = 0.013$. However, because the telescope can detect a fraction of muons, $\Delta_n(r)$, even when the core of the air shower is at a distance $r (\geq 2$ km) from the telescope center, the probability is enhanced to $\sim 3\%$ (or $5\%$ for primary gamma rays). The $\Delta_n(r)$ is calculated using

![Figure 6](image1.png)

**Fig. 6.—Light-curve shapes of the GLE of 2003 December 2 for different discrimination levels.**

| Data                  | Time (UT) | Significance Level (σ) | R.A. (deg) | Decl. (deg) | Satellite Notification | R.A. (deg) | Decl. (deg) |
|-----------------------|-----------|------------------------|------------|------------|------------------------|------------|------------|
| 2003 Dec 2            | 22:31     | 10.5                   | 295.5      | -29        | 21:09 (GOES-12) flare  | Sun (247.9) | Sun (-22)  |
| 2003 Dec 16           | 20:26     | 7.9                    | 303.0      | -29        | 19:34:22 (HETE-2974) GRB | 94.32      | +9.24      |

*a At the peak.
*b With reference to the telescope axis.

![Figure 7](image2.png)

**Fig. 7.—Comparison between the light-curve shapes of the GRB BATSE trigger 7989 and the GLE of 2003 December 16.**
the lateral distribution function of muons (see § 6). The detection of an event that happens on the other side of the Sun would correspond to a very large pitch angle, and, from the considerations mentioned above, we estimate the probability of detecting a solar flare connected to the back of the Sun at less than 4%.

Another possibility (although remote) that might explain the origin of this GLE is the GRB hypothesis. The temporal and directional coincidences of a GLE with satellite observations of GRBs are strong indications of a common detection. In fact, this has been the main objective of several ground experiments—not only the detection of the GRBs’ TeV counterpart but also their afterglows at X-ray, optical, and radio wavelengths. Nowadays it is expected that the rate of observation of GRBs by the GRB coordinate network (GCN) satellites\(^3\) with the field of view of a large ground-based detector such as MILAGRO is smaller than one per month (Smith 2001).

However, we have found GRB satellite notification around 2 hr from the beginning of the FRED GLE (see Table 2). While we do not have other evidence that indicates a common detection with GRBs from GCN satellites, Figure 7 shows a comparison between the light-curve shapes of the BATSE burst trigger 7989 and the GLE of 2003 December 16. Both are genuine FREDs. We have also examined the light curve for this GLE for other pulse-height amplitude discrimination levels, as shown in Figure 8. The signal persists even when a high pulse amplitude is used as a discrimination level, while the background is basically eliminated. It is possible to see that the signal observed in the GLE linked with the solar flare is more intense when compared with the signal of the FRED GLE.

On the other hand, there is evidence of two classes of bursts when they are classified according to their duration. The result comes from the BATSE catalog (Paciesas et al. 1999), as shown in Figure 9. We can see that the duration distribution of 1234 BATSE bursts is bimodal. The first is centered around the small value \(T_{90} = 0.2–0.3\) s and the second around the large value \(T_{90} = 40–60\) s, where \(T_{90}\) is the duration for 90% of the bursts to occur. The arrow in Figure 9 shows the duration of the FRED GLE. We can see that its duration (416 s) is still inside that of the BATSE \(T_{90}\) distribution.

5. LOCAL EFFECTS

The count rate of scintillator detectors at ground level is subject to several sources of modulation. The main ones are due to atmospheric pressure variation, solar activity, and the 24 hr sidereal anisotropy. However, the temporal scales of these modulation phenomena are much larger than the GLEs’ duration.

In the case of a tracking telescope like the TUPI, it is necessary to take into account the geomagnetic effect responsible for the muon flux dependence on azimuth angle (see § 3). Again, the temporal scale for observing this effect is much larger than the GLEs’ duration.

In order to take into account possible anomalous pressure variations as being responsible for the GLEs, we have monitored the barometric pressure and included this in our data acquisition system. Every 10 s the count rate and the atmospheric pressure are registered. Under normal conditions, the daily (24 hr) variations of the atmospheric pressure present a maximum value and a minimum value. This tendency has been found during the raster scan in which GLEs have been found.

\[^3\] For more information, see http://gcn.gsfc.nasa.gov/gcn_main.html.
Fig. 10.—Time series for the atmospheric pressure on 2003 December 2. The arrow indicates the beginning of the GLE (upper panel) and its power spectrum (lower panel).

Figure 10 summarizes the situation in which the pressure time series on 2003 December 2 is shown in the upper panel and its corresponding fast Fourier transformation is shown in the lower panel. The arrow in the upper panel indicates the beginning of the GLE. The absence of peaks in the power spectrum means that there are no scintillation phenomena as indications of anomalies. The power spectrum gives an estimate of the mean square density varies as $f^{-1.96}$, and this quite steep spectral density is close to a correlated Brownian noise with $1/f^2$ over many decades, or, in other words, over all 12 hr of the raster scan.

Consequently, pressure variation could not be a cause of the origin of the first GLE. A similar situation has been found for the second GLE.

6. IS THERE AN ENHANCEMENT OF MUONS AT SEA LEVEL FROM GRBs?

There are several reports of ground-level observations of solar flares, especially those of high intensity (Bieber et al. 2002; Falcone & Ryan 1999; Swinson & Shea 1990); in addition, the enhancement of muons at ground level from solar flares of large scale has been reported (Poirier & D’Andrea 2002; Munakata et al. 2001). However, the enhancement of muons at ground level from GRBs remains open; at least, they have not been observed with a high confidence level. The Milagrito experiment, a predecessor of the (water Cerenkov) MILAGRO experiment, has reported evidence of the TeV counterpart of a BATSE GRB (970417; Atkins et al. 2000). The GRAND project (muon detector array at ground level) has reported some evidence of GRB detection in coincidence with one BATSE GRB (971110; Poirier et al. 2003), although with a low significance.

Besides the experimental evidence, several models for the origin of GRBs predict a TeV component (Totani 1999; Dermer et al. 2000; Pilla & Loeb 1998). A plausible explanation for the extremely low rate of events observed in the 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 $z \sim 0.3$. However, for GRBs with $E_\gamma > 20$ GeV, the cutoff can be shifted to $z \sim 2$. Consequently, in order to increase the rate of GRB detection at ground level, a search for GRBs in an energy region above $\sim 20$ GeV has to be undertaken.

A primary photon converts to an $e^+e^-$ pair after one radiation length (on average), $\lambda_R \sim 37$ g cm$^{-2}$ in the atmosphere. In a subsequent radiation length the electromagnetic particles lose further energy by bremsstrahlung, $e^\pm \rightarrow \gamma e^\pm$. The processes are repeated, forming an electromagnetic air shower. All shower gamma rays (including the primary) above the photoproduction cross section can contribute to the muon content in the shower. Despite the fact that gamma rays in the energy band of 30 GeV to several TeV have only a 0.5%–3% chance of undergoing interactions in the atmosphere that yield pions, the photons are more efficient at producing energetic, forward-directed pions. The result comes from the Feynman $x$-distribution of charged pions obtained by using the FLUKA Monte Carlo simulation (Fassò & Poirier 2001). The $\gamma$ – Air interaction has a larger fraction of high-$x$ secondaries (pions) than the $p$ – Air interaction. The FLUKA results also show that the distribution of height above sea level at which the detected muons are produced has a peak at $\sim 20$ km for proton showers (Battistoni et al. 1998) and $\sim 12$ km for photon showers (Poirier et al. 2002). In addition, the distribution of the generation number of the grandparent of the sea-level muon in gamma showers is a very narrow distribution and is peaked at generation one for energies below a few hundred where the parent is mainly produced in a photoproduction process of the primary photon. This means that “photomuons” have a good chance of reaching ground level.

In order to estimate the number of muons reaching detection level that are initiated by primary gamma-ray interactions in the atmosphere, we have used the muon kinetic energy spectrum within a radial distance $R(=10$ km) of the shower center, on the basis of the FLUKA Monte Carlo program (Fassò & Poirier 2001). For simplicity, only vertical incidence of primary gamma rays is taken into account. The spectrum per incident photon can be parameterized as

$$\frac{dN_\mu(>E_\mu)}{dE_\gamma} \sim \frac{N^0_\mu}{A(R)} \left( \frac{E_\gamma}{\text{GeV}} \right)^{1/3} \left( \frac{E_\mu}{\text{GeV}} \right)^{-\beta},$$

with all energies in GeV units. The parameters are $N^0_\mu \sim 3.1 \times 10^{-4}$, $\alpha \sim 1.3$, $\beta$ is close to zero (integral flat distribution) in the muon energy band from $0.3$ to $\sim 20$ GeV, and $A(R) = \pi R^2$. A very small fraction of these muons are detected by the TUPI counter of a BATSE GRB (970417; Atkins et al. 2000). The GRAND project (muon detector array at ground level) has reported some evidence of GRB detection in coincidence with one BATSE GRB (971110; Poirier et al. 2003), although with a low significance.
where \( a_\mu^0 \sim 3.44 \times 10^{-5}, \delta \sim 1.88, \) and \( \Delta(r) \) is the fraction of muons that hit the telescope when the core of the photon shower is at a distance \( r \) from the telescope center. The \( \Delta(r) \) is calculated using the lateral muon distribution function. According to the FLUKA results (Poirier et al. 2002) and for photon primary energies between 3 and \( 10^4 \) GeV, the lateral muon function distribution extends to more than 10 km, whereas the sea-level distribution has a relatively flat shape up to \( r \sim 2 \) km. This means that \( \Delta(r) \sim 1 \) up to \( r \sim 2 \) km.

The biggest uncertainty of a GeV to TeV GRB is the shape of the primary photon spectrum. We assume a GRB as constituted by \( N_\gamma^0 \) photons \( \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \), arriving at the top of the atmosphere inside the field of view of the TUPI telescope and with an energy spectrum of

\[
\frac{dN_\gamma}{dE_\gamma} = N_\gamma^0 \left( \frac{E_\gamma}{\text{GeV}} \right)^{-\gamma},
\]

extending from \( E_{\text{min}} \sim 1.0 \) GeV up to \( E_{\text{max}} \) (several TeVs) and with a duration \( \Delta T \). The highest energy GRB observed by EGRET (Hurley et al. 1994) suggests fluxes around \( N_\gamma^0 \sim 10^{-5} \) photons \( \text{cm}^{-2} \text{s}^{-1} \text{GeV}^{-1} \) and a spectral index around \( \gamma \sim 2.0 \) for energies near \( E_\gamma \sim 1.0 \) GeV. These values are used in the calculation.

Under these conditions, the number of muons (GeV muons) reaching the TUPI telescope can be expressed as

\[
N_\mu(>E_\mu) \sim A_{\text{eff}} \Delta T a_\mu^0 \left[ N_\gamma^0 / A(R) \right] \times N_\gamma^0 \int_{E_{\text{min}}}^{E_{\text{max}}} \left( \frac{E_\gamma}{\text{GeV}} \right)^{\alpha - \gamma + \delta} dE_\gamma \int_0^R \Delta(r) 2\pi dr,
\]

where \( A_{\text{eff}} = \text{Aper} / \Delta \Omega \sim 5023 \text{ cm}^2 \) is the effective area, \( \text{Aper} = 65.3 \text{ cm}^2 \text{ sr} \) is the aperture, and \( \Delta \Omega = 0.013 \text{ sr} \) is the angular window of the TUPI telescope.

The signal in the detector, \( S = N_\mu(>E_\mu) \), must be compared with the square root of noise, \( \sqrt{N} \), given by

\[
\sqrt{N} = \sqrt{I_\mu \Delta T \times \text{Aper}},
\]

where \( I_\mu \) is the background muon intensity due to cosmic-ray–induced atmospheric showers. The value of \( S / \sqrt{N} \) necessary to consider an excess signal as a positive detection is above 4.

The sensitivity of TUPI muons for gamma bursts is shown in Figure 11 for several spectral indices in the power-law energy spectrum and for a duration of the burst of \( \Delta T = 100 \) s. The observation of the bursts at ground level is strongly limited by the spectral index value, as well as by the highest photon energies of the spectrum. Bursts of very long duration, of very high photon maximum energy, and with energy spectra not quite so steep can be observed at ground level by using telescopes with a small muon energy threshold (\( \sim 0.3 \) GeV).

The analysis on the basis of FLUKA’s results shows a real possibility of observing a GRB with the TUPI telescope under certain conditions. A more accurate analysis, given the complexity of the processes, requires a full Monte Carlo study, including the detector response and geomagnetic effects on the charged muons.

### 7. CONCLUSIONS

We have reported a description and an analysis of two GLEs observed in 2003 December during a search for enhancements from the Galactic center with muons at sea level and detected by using the TUPI telescope after an upgrade of the data acquisition system. The main conclusions are summarized as follows:

1. The TUPI telescope can detect muons at sea level with energies greater than the 0.3 GeV required to penetrate the two flagstones or walls surrounding the telescope. The concrete reduces the noise due to other nonmuon particles; for example, it is opaque to electrons. The telescope is sensitive to the conventional atmospheric muon flux. The muon flux obtained during a raster scan of 12 hr presents the well-known west-east effect. In addition, the geomagnetic effects distort the zenith angle distribution of sub-GeV to GeV muons.

2. The two GLEs analyzed here have been unambiguously detected, because in both cases the GLE signal survives even when a large amplitude discrimination is used, while the background is eliminated. This means that the chance of them being a fluctuation of the background is close to zero. In both cases, the GLEs are observed with a high significance level (above 7.5 \( \sigma \); see Table 2).

3. The observation of the two GLEs is not restricted to a simple excess. It is possible to see their temporal structures, such as the light curves. The first GLE has a strong correlation with the last two solar flares on 2003 December 2. The second GLE (the FRED GLE) has an unknown origin, because there is no satellite report of solar flares, no prompt X-ray emission, and no excess of nuclei during the raster scan in which the GLE was observed. We estimate the probability of the origin of the FRED GLE being a solar flare connected to the back of the Sun as less than 4%.

4. The muon flux is subject to several sources of modulation, such as the atmospheric pressure variation, solar activity, and west-east effect, among others. However, the temporal scales of

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**Fig. 11.—Signal-to-noise ratio due to a transient event of 100 s duration and several spectral indices in the power-law energy spectrum (see § 6), according to photoproduction FLUKA results and under the TUPI telescope conditions.**
these modulation phenomena are much larger than the GLEs’ duration. In addition, no anomalous changes in the atmospheric pressure have been observed during the raster scan in which the two GLEs were found.

5. We have found GRB satellite notification 52 minutes before the beginning of the FRED GLE (see Table 2), and, despite the FRED GLE duration being large (416 s), it is still inside the BATSE $T_{90}$ duration distribution. In addition, the long duration of the FRED GLE indicates that it is not the remains of showers produced by conventional cosmic rays. However, we do not have other evidence that indicates a correlation with the GRBs detected by the GCN satellites.

6. Finally, we show, by using the FLUKA Monte Carlo results, that there is a window for observed GRBs made up of photons with energies above 10 GeV via “photomuon” production with energies at ground level above $E_{\mu} \sim 0.3$ GeV. The enhancement of muons at sea level from primary gamma rays (for energies below 100 GeV) is a consequence of the lateral distribution function of muons at sea level in photon showers being close to a flat distribution. The fraction of muons that hit the telescope when the core of the photon shower is at a distance $r$ from the telescope center is the same for $r$ up to $\sim 2$ km. In addition, for GRBs with flatter spectra, large duration, and high maximum photon energy, the possibility of observation is enhanced (see Fig. 11).

We are waiting for the next round of satellites with large area telescopes, such as the Gamma-Ray Large Area Space Telescope (GLAST; Atwood 1994); they will be able to detect GRBs up to 300 GeV. GLAST will be able to confirm the estimates mentioned above. Until then, we conclude that the FRED GLE analyzed here is only a potential candidate for sub-TeV GRBs.

We are grateful to A. Ohsawa from Tokyo University for help in the first stage of the experiment and to M. Olsen for reading the manuscript. This work was partially supported by FAPERJ (Research Foundation of the State of Rio de Janeiro) in Brazil.

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