SEARCH FOR GEV EMISSION FROM THE MAXI TRANSIENT EVENT (TRIGGER 580727270) DETECTED AT INTERNATIONAL SPACE STATION

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Abstract

On October 15, 2013, at 21:55:19.00 UT, the MAXI instrument on the International Space Station detected an unknown source of a transient radiation, classified as a gamma-ray burst (GRB) or an unknown X-ray transient event (trigger 580727270). The coordinates of this event were located in the field of view of the Tupi muon telescope at the time of the trigger occurrence. Since August 2013 the Tupi experiment has been operating a new extended array of five muon telescopes, located at ground level at (22.90\textdegree W, 43.28\textdegree S, 3 m above sea level). This location coincides with the South Atlantic Anomaly (SAA) central region. In this paper we examine the possibility of the ground observation of the GeV counterpart associated with the trigger 580727270. We show that the Tupi telescope registered at least one muon excess peak with a signal significance \( \Delta S \approx 5 \) and a duration of \( \Delta t \approx 6 \text{s} \) at \( T_0 + 25 \text{s} \), where \( T_0 \) is the MAXI/GMC trigger. We consider a hypothesis that this muon excess could be due to photo-nuclear reactions in the Earth’s atmosphere induced by gamma rays with energies above 10 GeV. Details of a possible correlation between the MAXI trigger and the Tupi observation, as well as an interpretation of this event are reported.

Subject headings: gamma rays: bursts - gamma rays: observations - instrumentation: miscellaneous

1. INTRODUCTION

There are some evidences indicating that the long duration GRBs occur when very massive stars run out of fuel for nuclear fusion in their cores. The collapse and subsequent intense explosion can rupture a star completely to pieces in a hypernova. Twin beams of gamma rays are hypothesized to burst from the event, and if the Earth is in the path of one of those beams, the gamma-ray burst can be detected. However, in most cases, no narrow gamma-ray lines have been detected. This means that some of these bursts could be produced by the collapse of a massive star without a supernova. Alternatively, the bursts could result from a different progenitor, such as the merger of two white dwarfs or a white dwarf with a neutron star or black hole, possibly in the cluster environment without a host galaxy.

In most cases, spectroscopic analysis on GRBs is consistent with the hard-to-soft evolution, as observed by BATSE in bright GRBs (Preese et al., 1998) or by BeppoSAX GRBs (Frontera et al., 2000). However, there are some discrepancies in the fluxes, for instance the INTEGRAL fluence was a factor of 10 smaller than the BATSE bright bursts (Gotz et al., 2003). Many GRB afterglow models (Zhang & Meszaros, 2001; Pe'er & Waxman, 2004; Wang et al., 2001) predict production of photons in the GeV-TeV energy range and GeV emission has indeed been detected by both, previous (EGRET at CGRO) (Hurley, 1994) and current generation (Fermi-LAT) space-based ray detectors (Abdo et al., 2009).

Among many remarkable detectors in operation there is the Monitor of All-sky X-ray Image (MAXI), the first astronomical payload installed on the Japanese Experiment Module - Exposed Facility (JEM-EF or Kibo-EF) on the International Space Station (ISS) Matsuoka et al., (2009). On October 15, 2013 the MAXI instrument detected an unknown transient source (trigger 580727270) with the preliminary flux \( 2.2 \times 10^{-3} \text{mCrab} \) at the detected position \((R.A., Dec) = (22.90^\circ, 43.28^\circ)\). The signal was classified as a GRB or unknown X-ray transient event. This particular transient event is interesting to us, because it is the second MAXI transient event candidate with the coordinates located within the field of view of the Tupi telescopes at the time of the trigger occurrence. The previous one was observed in the inclined (45 degrees relative to the vertical) Tupi telescope pointed to the West (Augusto et al. 2013). The muon excess observed at the ground could be an indication of

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\url{http://gcn.gsfc.nasa.gov/maxi_rbs.html}. In spite of the negative values in the flux fields, the MAXI messages are considered to be acceptable by the MAXI team.
the high energy tail of a GRB that might extend up to GeV energy range.

Several scenarios have been suggested to explain a possible high energy component of GRBs. For instance, the synchrotron self-Compton (SSC) model (Panaitescu & Meszaros, 2000; Kumar & McMahon, 2008) provides a natural explanation of the optical and gamma ray correlation seen in some GRBs. It as also shown that a relatively strong second-order inverse Compton (IC) component of the GRB spectrum should peak in the tens of GeV energy region (Racusin et al., 2008). Observations by the Tupi experiment can be complementary to other techniques in setting the limits on the strength of this IC peak.

This article is organized as follows. Section 2 explains the experimental setup, showing that the coordinates of the MAXI trigger 580727270 were within the effective field of view of the vertical Tupi telescope. Section 3 gives a brief description of the MAXI detector on the ISS. Section 4 provides the data sets, describes the methods and the analysis of the raw Tupi data, the results of search of the muon excess registered by the Tupi telescope in probable association with the MAXI event, as well as the study of the muon excess fine structure, which was used for an estimation of the significance and duration of the observed signal. In addition, we include a spectral analysis based on a hybrid method that combines Monte Carlo simulation and analytical calculations. This approach allows us to evaluate the gamma ray spectrum and fluence associated with the observed muon excess. Section 5 presents the results of an additional Monte Carlo simulation of the lateral distribution of gamma rays and muons. Section 6 is devoted to a confidence analysis, and Section 7 summarizes our conclusions.

2. TUPI SETUP

Since August, 2013 the Tupi experiment has been operating an extended array of five muon telescopes (Augusto et al. 2011). The first one has a vertical orientation. The other four have orientations to the North, South, East, and West, each telescope is inclined 45 degrees relative to the vertical. Fig. 1 shows the field of view (FOV) of five telescopes during the occurrence of the MAXI trigger 580727270 on October 15, 2013.

Each telescope was constructed on the basis of two detectors (plastic scintillators 50 cm x 50 cm x 3 cm) separated by a distance of 3 m, one of them is shown in Figure 2.

Each telescope counts the number of coincident signals in the upper and lower detector. The output raw data consists of coincidences counting rate of 1 Hz versus universal time (UT). The Tupi telescopes are placed inside a building, under two flagstones of concrete (150 g/cm²). The flagstones increase the detection muon energy threshold up to ~ 0.1 – 0.2 GeV required to penetrate the two flagstones. Each Tupi telescopes has an effective field of view ~ 0.37 sr. To the vertical telescope, this correspond to an aperture (zenith angle) of 20 degrees from the vertical.

Time synchronization is essential for correlating event data in the Tupi experiment, and this is achieved by using the GPS receiver. All steps from signal discrimination to the coincidence and anticoincidence are made via software, using the virtual instrument technique. The

FIG. 1.— The equatorial coordinates of the Tupi telescope’s axes (black circles). Squares represent the effective field of view of the telescopes and the asterisk is the position (coordinates) of the MAXI transient event (trigger 580727270)

FIG. 2.— Left: General layout of the vertical Tupi telescope, including the logic in the data acquisition system using the virtual instrument technique. Right: Photograph of the vertical Tupi telescope.
application programs were written using the LAB-VIEW tools. The Tupi experiment has a fully independent power supply, with an autonomy of up to 6 h to safeguard against local power failures. As a result, the data acquisition is basically carried out with a duty cycle of 95%. The Tupi experiment is in the process of constant expansion and upgrade. Work is underway in setting up new telescope sites in Campinas (Brazil) and La Paz (Bolivia).

3. MAXI DETECTOR

The monitor of all-sky X-ray image (MAXI) instrument is mounted on the Japanese Experimental Module of the International Space Station. MAXI can detect $\sim 1-2$ “unknown” source transients per month, and $\sim 5$ “known” source transients per month. $^3$ The “unknown” source notice contains detections that do not match anything in the catalogs. The instantaneous FOV of the MAXI instrument is estimated as 2% of the whole sky. The expected number of GRB in the MAXI FOV is 3.5 per year, and the GRB with afterglow is 2.5 per year (Matsuoka et al., 2009). The MAXI data are processed automatically. When the MAXI instrument discovers a transient, it sends the data to GRB Coordinates Network (GCN). $^4$ The typical position uncertainty of the detection is 0.5-1.0 deg radius (“stat+sys” errors, 90% containment).

4. RESULTS

4.1. The Tupi observation

On October 15, 2013 at 21:55:44 UT a peak (muon excess) with a significance of $5\sigma$ at 68% confidence level was found in the 24 hours raw data (counting rate 1 Hz) of the vertical Tupi telescope. The Tupi signal significance was calculated according to the bin selection criteria (BSC) algorithm Mitrofanov et al., (2004); Augusto et al. (2010). According to this algorithm, the signal statistical significance $S$ in the $i$-th bin is defined as $S_i = (C_i - B) / \sqrt{B}$ where $C_i$ is the measured number of counts in the $i$-th bin and $B$ is the average background count. It was possible to recognize this peak in the time profile of the muon counting rate just by naked eye as is shown in Fig. 3. The peak was found at $T_0 + 25.7 \text{s}$, where $T_0 = 21 : 55 : 19 \text{ UT}$ is the occurrence of the MAXI trigger. In addition, a second narrow peak with a significance of $\sim 4\sigma$ can be observed at $T_0 + 297.2 \text{s}$.

Fig. 4 shows in details the experimental data in the vertical Tupi telescope as a function of time elapsed since the trigger 580727270 signal. The top panel represents the muon counting rate (in Hz) and the bottom panel represents the signal significance measured (in units of standard deviation).

We would like to point out that in present case the peak is not a spike of a short duration, but a signal with a structure that can be fit by a Gaussian distribution, with a FWHM.

The signal duration is $T_{90} = 6.1 \text{ s}$ at the confidence level of 68%, as is shown in Fig. 5.

In addition, once can notice that there is a second muon excess spike-like peak at $T_0 + 295.3 \text{ s}$ with an estimated duration of $T_{90} = 1.0 \text{ s}$. At this moment it is

$^3$ http://gcn.gsfc.nasa.gov/maxi\_rbs.html

$^4$ http://gcn.gsfc.nasa.gov/burst\_info.html
difficult to say whether this spike with a significance of \( \sim 4\sigma \) is related to the MAXI event. Table 1 shows several quantities related to these two peaks.

### 4.2. Spectral analysis

The observed energy spectra of gamma-ray bursts reveal a diverse phenomenology. The spacecrafts observed gamma rays up to 33 GeV (Abdo et al., 2009). While some energy spectra can be fitted by a simple expression over many decades (Abdo et al., 2009b), others require a few separate components to explain the high energy emission (Abdo et al., 2009). In most cases (at low energies) the GRB spectrum is well described by a phenomenological “Band function” in “Comptonized model” using a power law with an exponential cutoff:

\[
N(E) = kE^{-\alpha}e^{-E/E_0},
\]

where \( \alpha \) is the power law exponent and \( E_0 \) is the cutoff energy.

At high energies the spectrum is well described a power-law function with steeper slope

\[
N(E) = A_\gamma E^{-\beta},
\]

where \( \alpha > \beta \), and the spectral parameters \( \alpha, \beta \), and \( E_0 \) vary from burst to burst. For instance, “a blast wave model”, usually considered for GRB sources, is quite sensitive to the relationship between these two power-law indices.

### Table 1

<table>
<thead>
<tr>
<th>Peak Times</th>
<th>Significance</th>
<th>T90s</th>
<th>Muon excess</th>
<th>Fluence ( \epsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_0 - 25.5 )</td>
<td>5.0( \sigma )</td>
<td>6.1</td>
<td>39.1 ( \pm 7.2 )</td>
<td>( 2.5 \pm 0.5 )</td>
</tr>
<tr>
<td>( T_0 + 297.2 )</td>
<td>4.0( \sigma )</td>
<td>1.0</td>
<td>16.5 ( \pm 3.3 )</td>
<td>( 1.1 \pm 1.8 )</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>55.6 ( \pm 11.1 )</td>
<td>( 3.6 \pm 0.7 \times 10^3 )</td>
</tr>
</tbody>
</table>

We assume here that the energy spectrum of gamma rays above 10 GeV, that is in the high energy tail of a GRB, can be fitted by a single power law function. There are two unknown quantities in the single parameter power law function, the coefficient \( A_\gamma \) and the spectral index \( \beta \).

A convolution between the yield function \( S(E) \) (the number of muons per gamma ray is shown in Fig. 6 (Fasso & Poirier, 2001)) and the particle spectrum \( N(E) \) gives the response function, that is the number of muons in the excess signal generated by the GRB photons during the time period \( \bar{T} \). This convolution can be expressed as

\[
N_\mu = S_{eff} \times \bar{T} \int_{E_{min}}^{\infty} S(E_\gamma) A_\gamma E_\gamma^\beta dE_\gamma.
\]

The specific yield function as a function of photon energy (assuming the vertical incidence) is determined according to the FLUKA\(^5\) Monte Carlo results (Fasso & Poirier, 2001). This FLUKA output can be described by the following fit

\[
S(E_\gamma > 10\text{GeV}) = A_\mu E_\gamma^\nu \exp\left(-\frac{E_0}{E_\gamma}\right), \tag{4}
\]

where \( A_\mu = (6.16 \pm 0.60) \times 10^{-5}, \) \( \nu = 1.183 \pm 0.014, \) \( E_0 = 7.13 \pm 0.56 \text{ GeV}, \) \( \lambda = 1.58 \pm 0.12, \) as are shown in Fig. 6. Furthermore, the integrated time fluence can be obtained as

\[
\int E_\gamma N_\mu dE_\gamma = \int E_\gamma S(E_\gamma) dE_\gamma \approx 1.0 	imes 10^{-2} \text{ GeV} \cdot \text{cm}^2 \cdot \text{s}^{-1}.
\]

\(^5\) FLUKA (“FLUktuierende KAskade”) is a detailed general purpose tool for calculations of particle transport and interactions with matter.
\[ F = T \int_{E_{\text{min}}}^{\infty} dE_{\gamma} A_{\gamma} E_{\gamma}^{-\beta} \]  (5)

The terms on the left side of Eq. 3 and Eq. 5 are known (see Table 1). Thus, we can consider all possible values of \( \beta \) and \( A_{\gamma} \) compatible with the observed muon excess value \( N_{\mu} \) and the integrated fluence \( F \). Fig. 7 shows that one can obtain the best estimate for the spectral index using the intersection of two lines defined by Eq 3 and Eq. 5.

From this analysis we can find out that the best estimate for the spectral index is compatible with \( \beta = -2.13 \pm 0.43 \) and \( A_{\gamma} = (3.34 \pm 0.67) \times 10^{-4} (\text{cm}^2\text{sGeV})^{-1} \).

In this case the integrated time fluence (defined by Eq. 5) is \( F = (2.10 \pm 0.42) \times 10^{-7} \text{erg/cm}^2 \) in the GeV energy region. Considering that the second peak at \( T_0 + 297.2 \text{s} \) is a part of the same GRB, we can obtain the gamma ray flux as \( 7.07 \times 10^{-10} \text{erg/cm}^2/\text{s} \) or 29 mCrab. This value is in agreement with the gamma ray flux reported by the MAXI team (22 mCrab).

5. ADDITIONAL MONTE CARLO RESULTS

Using FLUKA (Fasso & Poirier, 2001) and CORSIKA, we performed a Monte Carlo simulation to produce muons at sea level with the energy threshold 100 MeV, originated by \( 10^7 \) collimated photons with a spectral index \( \beta = -2.13 \) in the 10-100 GeV energy range and incident vertically at the top of the atmosphere. The result is shown schematically in Fig. 8. It is found that there are \( 3.6 \times 10^4 \) muons within a circle of 1 km radius at sea level.

In addition, the energy spectra of gamma rays (input) and muons (output) at sea level are shown in Fig. 9.

CORSIKA (COrsicA Ray Simulations for KAscade) is a physics computer software for simulation of extensive air showers initiated by high energy cosmic particles (http://web.ikp.kit.edu/corsika/).
This simulation shows that if a cluster of vertical gamma rays reach the top of the atmosphere, basically only those within a circle of up to 1 km radius, can produce muons at sea level and in the central region. For instance, $10^7$ gamma rays within the circle, with an energy spectrum ($\beta = -2.13$) in the energy region $10 - 100$ GeV, can produce around 900 muon ($E_\mu > 0.1$ GeV) in the central region marked by a red arrow, as is shown schematically in Fig. 11.

Assuming that the muons were produced in photonuclear reactions induced by gamma rays from the MAXI trigger 580727270, we estimated the energy spectrum of muons to be observed in the vertical Tupi telescope, as shown in Fig. 12.

6. CONFIDENCE ANALYSIS

In order to see with more accuracy the background fluctuations, we have examined the time profiles up to half hour before and after the trigger time, because in this time interval the coordinates of the MAXI event are still inside of the FOV of the vertical Tupi telescope. For longer time intervals, due to the rotation of the Earth, the coordinates of the trigger are no longer in the FOV of the Tupi telescopes. A confidence analysis has been made for a one hour interval around the MAXI trigger time, as is shown in Fig. 13.

From this analysis, it is possible to identify the Tupi signals with a significance above $4\sigma$ in association with the MAXI transient event, and these points are outside of the muon background from the galactic cosmic ray background.
component that follows a Gaussian distribution (solid line). We found no flare or transient events, as well as no anomalous changes in the environmental condition (atmospheric pressure, temperature) in the time period close to the signal detection.

7. CONCLUSIONS

We have reported a description and an analysis of a muon excess flux in temporal and spatial correlation with the unknown X-ray transient event (trigger 580727270) observed on October 15, 2013 by the MAXI instrument on the ISS. We started this analysis assuming the hypothesis that the observed on 15 October 2013 excess is not a fluctuation of the background.

The Tupi muon telescopes are sensitive to primary particles (including photons) with energies above the pion production threshold. The Tupi telescopes can detect muons at sea level with energies greater than $\sim 0.1$ GeV. The Tupi experiment is located at sea level and within the South Atlantic Anomaly (SAA) region, where the shielding effect of the magnetosphere has a "dip" due to the anomalously weak geomagnetic field strength. This characteristic allows the observation of transient events of diverse origins.

The first Tupi detection of a muon excess in probable association with the MAXI transient GRB was of a spike type (Augusto et al. 2013), with a duration compatible to the raw data bin (1 s). However, in the present case the muon excess has a Gaussian structure with a FWHM of 2.6 s and the signal duration $T_{90} = 6.1$. Based on Monte Carlo simulations and analytical calculations, we estimated the primary gamma ray spectrum and the integrated time fluence of the burst $F = (2.10 \pm 0.42) \times 10^{-7}$ erg/cm$^2$. This fluence is for the high energy emission (photons with energies above 10 GeV). However, considering that the second peak at $T_0 + 297.2$ s is a part of the same GRB, we can estimate the expected gamma ray flux as $7.07 \times 10^{-10}$ erg/cm$^2$/s or 29 mCrab. This value is in agreement with the gamma ray flux of 22 mCrab reported by the MAXI team.

In our Monte Carlo simulations we showed that muons from photons can be detected at a lateral distance of up to 1 km. This feature, together with other favorable experimental conditions, allows the detection of signals from GRBs. In some cases the non-detection of the high energy component may be due to several reasons, such as absorption in the extragalactic background medium (background light), or an intrinsic spectral cutoff.

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7 So far there were no reports on the light curve or the duration of the event.
REFERENCES