Tupi detection of muons increase in association with the GRB trigger 090315

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Abstract. On 15 March 2009 at 04:13:00 UT a bright long (~ 8s) Gamma Ray Burst (GRB) in the ~ 50 – 200 KeV energy region was detected by many space-borne instruments, such as the Konus-Wind, Odyssey, Messenger, AGILE (MCAL and SuperAGILE) and Suzaku-WAM. This burst is temporally coincident with a muon excess observed in the inclined (45 degrees) Tupi telescope, located inside the South Atlantic Anomaly (SAA) region. The GRB coordinates for this burst were obtained first by the Tupi telescope and later confirmed by the IPN triangulations. Thus this GRB is the first observed at ground and confirmed by satellites. The muon energy threshold is 0.1 GeV, corresponding to primary photons around 10 GeV. Thus we believe that the energy spectrum of this burst extended at least into the multi-GeV energy range.

Keywords: Gamma ray burst, Gamma ray Astrophysics, Ground level enhancement

1. INTRODUCTION

The Tupi experiment [1] is a small, Earth-based muon apparatus, devoted to the study of cosmic rays and located in Niteroi City, Rio de Janeiro, Brazil (22S, 43W), inside the so-called South Atlantic Anomaly (SAA) region. The apparatus is constituted of two telescopes, one of them has a vertical orientation and the other is oriented at 45 degrees to the vertical (zenith) pointing to the west. The telescopes are capable of detecting muons (“photo-muons”) with an energy threshold above 0.1 GeV, induced in the atmosphere by cosmic rays including gamma rays with primary energies above the pion production threshold (~ 10 GeV). 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. Therefore, only muons with trajectories close to the telescope axis are registered.

Moreover, the SAA is a region close to the west coast of Brazil in which the shielding effect of the magnetosphere is not perfectly spherical and shows a "dip" 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 azimuthal drifting of energetic particles, bouncing between hemispheres and coming deeper down into the atmosphere owing to the low field intensity over the SAA. They thereby interact with the dense atmosphere which results in ionization production and increased electrical conductivity, which propitiate the precipitation of charged particles. This characteristic offers the muon telescopes the possibility of achieving a low rigidity of response to primary and secondary charged particles (> 0.4 GV).

The SAA magnetic depression is a very low magnetic field region at the ground. In the IGRF95 data [2], the magnetic field strength in the SAA region (26S, 53W) is 24000 nT, around two times lower than the magnetic field in the Antarctic high region (70S, 140E) which is 60000 nT. The geomagnetic isointensity lines over the globe is shown in Fig.1.

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 in the telescope’s sensitivity. This means that the sensitivity of particle telescopes is highest in the SAA region, because in this region the transverse magnetic field is very small, and even smaller than the average value for the polar regions. In addition, on Earth the ionization peak due to cosmic rays occurs at approximately 10 km. However, at SAA region due to particles precipitation, this peak occurs near the Earth’s surface and the ionization (pair production) rate is higher. Consequently, the atmospheric conductivity is also higher. This facilitates the propagation of the charged particles (pions and muons) produced in the photoproduction process (for instance, increase their mean free path). Thus, we have estimated the number of muons on Earth’s surface per photon is at least 15 times greater than

![Fig. 1: The geomagnetic total field intensity distribution, represented by isointensity lines (in nT) over the Globe. The lowest value of magnetic intensity situated in southern Brazil defines the position of SAA region.](image-url)
Fig. 2: Time profile rates observed in the vertical (upper) and inclined (lower) Tupi Telescopes on 2009/03/15. They represent the muon counting rate at every 10 seconds (raw data). The vertical arrow represents the Konus-Wind trigger occurrence.

Fig. 3: IPN triangulation for the GRB trigger 090315, showing the coordinates for this event inside the field of view (FoV) of the inclined Tupi telescope.

II. OBSERVATIONS

The search for transient events such as burst signals in the Tupi telescopes follows the following procedures: the Tupi light curves around the time of the satellite GRB triggers is examined both with a semi-automatic routine and by hand, if a muon excess with a confidence level above $4\sigma$ in temporal coincidence with the trigger time is found, it is verified if the trigger coordinates are inside of the field of view (FoV) of the telescope. However, this second procedure is not always possible to accomplished since the trigger coordinates are not always known. This happens, for instance, with the GRB triggers 090315 of the Konus-Wind detector, and it is described below:

1) **Temporal coincidence** The main characteristic is the occurrence of a muon enhancements (sharp peak) with an high confidence level ($10.8\sigma$) in the inclined muon counting rate, in temporal coincidence with the GRB trigger 090315. Fig. 1 summarizes the situation. It can be noticed that the muon enhancement does not appear in the vertical telescope. The vertical arrows in the lower figure represent the Konus-Wind trigger occurrence [4]. We want to highlight that the day 2009/03/15 was characterized by precipitation during 24 hours. The peak in temporal coincidence with the satellite event trigger 090315 was the highest peak observed on that day in the inclined telescope.

2) **IPN triangulation** When the observation of the temporal coincidence between the Konus-Wind event trigger 090315 and the increase of muons in the inclined Tupi telescope was established, the coordinates of the event trigger 090315 still had not been determined. The determination of these coordinates was requested to the IPN (Interplanetary Network) team. The IPN triangulation through the Konus-WAM annulus, Konus-MESSENGER annulus, Konus-MO annulus and the Konus-BAT annulus, had confirmed that the coordinates of the event trigger 090315 were inside of field of view (FoV) of the inclined Tupi Telescope.
summarizes the situation.

3) **Confidence analysis** All the time bins of the Tupi data are tested by the bin selection criteria (BSC). The signal in the i-th bin is defined as: \( \sigma_i = \frac{(C^{(i)} - B^{(i)})}{\sqrt{B^{(i)}}} \), where \( C^{(i)} \) is the measured number of counts, and \( B^{(i)} \) is the number of background counts. In the absence of any signal, the \( \sigma_i \) function follows a Gaussian distribution. The significance test (BSC) is shown in Fig.4, where we have obtained the \( \sigma_i \) distribution (in unit of standard deviation), in the time window of \( \Delta t = 10\,\text{s} \), obtained by shifting the window to inside one hour before and one hour after the Konus-Wind trigger. From this confidence analysis, it is possible to see three categories of particles; the muon background following a Gaussian distribution, the muons due to particle precipitation in the SAA, with a confidence level up to \( 8\sigma \), the highest confidence level so far registered, indicated by a vertical arrow and corresponding to the sharp muon peak, in temporal coincidence with the event trigger 090315.

III. **Contamination due to particle precipitation in the SAA**

According to the AP-8 Satellite measurements, due to particle precipitation in the SAA, the proton flux in the 10.0 MeV energy band is around 1000 times higher than the proton flux out the SAA region. However in the GeV region (above the pion energy production threshold) the Tupi measurements have shown that the proton (muon) flux in the SAA is up to 15 times higher than proton (muon) flux, out of the SAA region. This happens in the interval of precipitation (three hours after the sunrise and until one hour after the sunset), and it is when the solar magnetic field lines overtake the Earth’s surface. The particle precipitation is subject to seasonal variations. Out of this interval, the particle precipitation is smaller, showing a random temporal behavior. However, there are days when the precipitation occurs during 24 hours.

On the other hand, the signals of particle precipitation have a high confidence level (see Fig.4). Even if the muon excess in temporal coincidence with the event trigger 090315 has a confidence level above \( 10\sigma \), a probable contamination could still appear. That is, the signal could be due to particle precipitations. In other
words, over a long random period of time, not coincident with GRB triggers, how often can a muon excess in the telescope exceed 10σ?

The answer is summarizes in Fig.5 where an analysis on the basis of collected data over a period of 30 days (March 2009) is presented. In the upper figure, the average hourly variation of the muon counting rate is presented. From this figure, it is possible to see that there are two levels in the muon counting rate. The higher level is due to particle precipitations 3 hours after the sunrise (12 h UT), and it stays on until one hour after the sunset. Thus the contamination due to particle precipitation is less between the 0h UT until the 12h UT.

As the muon excess in temporal coincidence with the event trigger 090315 happened at the 04:13:00 UT, the confidence analysis was made taking into account the SAA conditions.

In the inclined telescope is only 0.016% in the first 12 hours. In the lower figure the daily values of the highest average hourly variation of the muon counting rate is presented. From this figure, it is possible to see that there are two levels in the muon counting rate. The higher level is due to particle precipitations 3 hours after the sunrise (12 h UT), and it stays on until one hour after the sunset. Thus the contamination due to particle precipitation is less between the 0h UT until the 12h UT.

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As the muon excess in temporal coincidence with the event trigger 090315 happened at the 04:13:00 UT, the confidence analysis was made taking into account only the data of the first 12 hours. In the central figure, the distribution of the fluctuations of the Tupi inclined telescope counting rates, in a time window of \(t = 10\sigma\), over a period of 30 days (March 2009) is presented. We can see that the probability of obtain a muon excess with a confidence level above 10σ due to particle precipitation in the inclined telescope is only 0.016% in the first 12 hours. In the lower figure the daily values of the highest standard deviation for March 2009 and considering also only the first 12 hours is shown.

IV. ENERGY SPECTRUM

Finally, a preliminary analysis on the primary photon energy spectrum is presented in Fig.6. Despite the fact that gamma rays in the energy band around 10 GeV have only a small chance (\(\sim 10^{-5}\) muons per photon) of undergoing interactions in the atmosphere that yield pions, the photons are more efficient in producing energetic, forward-directed pions. The result comes from the FLUKA Monte Carlo simulation [6]. In addition, the height distribution of muons above sea level has a peak at \(\sim 17 - 20\) km for proton showers [7] and at \(\sim 12\) km for photon showers [8]. This means that “photomuons” have a good chance of reaching ground level. Considering that only 10% of these muons reached the detector, the Tupi photon energy spectrum was estimated by point 1 of Fig.6. However, taking into account the SAA conditions, such as the high conductivity of the atmospheric layers and considering that in the SAA the magnetic field is the smallest, a preliminary analysis indicates that the muon flux in the SAA region is at least 15 times higher than muon flux out the SAA region which gives point 2 of Fig.6. We have included in the figure the Suzaku-WAM spectrum [9] for comparison.

V. CONCLUSIONS

We have reported a description and an analysis of a muon excess (10.8σ) observed in the inclined Tupi telescope. The event is in temporal coincidence with the GRB trigger 090315. The GRB coordinates for this burst were obtained firstly by the Tupi telescope and later confirmed by the IPN triangulation. Thus this GRB is the first observed at ground and confirmed by satellites. In addition the chances of this muon excess to be produced by particle precipitation in the SAA is only 0.016%.

The Tupi experiment is now under expansion, and in the next two months there will be eight more telescopes.

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