Muon excess at sea level from solar flares in association with the Fermi GBM spacecraft detector

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Abstract

This paper presents results of an ongoing survey on the associations between muon excesses at ground level registered by the Tupi telescopes and transient solar events, two solar flares whose gamma-ray and X-ray emissions were reported by, respectively, the Fermi GBM and the GOES 14. We show that solar flares of small scale, those with prompt X-ray emission classified by GOES as C-Class (power $10^{-6}$ to $10^{-5}$ W m$^{-2}$ at 1 AU) may give rise to muon excess probably associated with solar protons and ions emitted by the flare and arriving at the Earth as a coherent particle pulse. The Tupi telescopes are within the central region of the South Atlantic Anomaly (SAA), which allows particle detectors to achieve a low rigidity of response to primary and secondary charged particles ($\geq 0.1$ GV). Here we argue for the possibility of a “scale-free” energy distribution of particles accelerated by solar flares. Large and small scale flares have the same energy spectrum up to energies exceeding the pion production, the difference between them is only the intensity. If this hypothesis is correct, the Tupi telescope is registering muons produced by protons (ions)
whose energy corresponds to the tail of the spectrum. Consequently
the energy distribution of the emitted protons has to be a power law
spectrum, since power law distributions are characterized as scale free
distributions. The Tupi events give support to this conjecture . . .

1 Introduction

The last solar cycle 24 started at the beginning of 2008 [1]. Even so, in
this second semester of 2010, we are still at a low level of activity, in an anom-
alous extended period of minimal solar activity. But sunspots are starting to
appear again, and spots are the manifestation of the magnetic field poking
through the surface of the Sun.

This Sun cycle anomaly is the first in the spatial era, i.e., where the Sun
is monitored by spacecraft detectors, but there are such registered from 107
years ago, of a similar pattern. That happened during the transition between
cycles 13 and 14.

Solar flares are among the most powerful astrophysical phenomena in the
solar system. Initially the observation and the study of these solar flares
used detectors on the surface of the Earth, mainly by neutron monitor ex-
periments. A lot has been obtained with these observations, such as the
anti-correlation between solar activity and the flow of galactic cosmic rays.
The existence of a prompt and late emission in flares and their correlations
with Coronal Mass Emission (CME), Forbuch events, a fall in the cosmic ray
intensity, due to a solar disturbance crossing the Earth, and so forth. .

However, in most cases, the observations are restricted to flares with high
intensity, those with an X-ray flux at 1 UA is classified by GOES as X-Class
and M-Class flares, flux above $10^{-4}$ and $10^{-5}$ W m$^2$ respectively. Recently the
Tupi experiment has reported experimental evidence of muon excess in asso-
ciation with high energy particles (protons and ions) with energies above the
pion production threshold (because they produce muons in the atmosphere),
emitted by flares of small scale, those with an X-ray flux below $10^{-5}$ W m$^2$
or C-Class flares [2, 3].

Even in events observed at ground level in association with large solar
flares, the acceleration mechanism producing particles (protons, ions) up to
several tens of GeV is not well understood. The situation becomes still more
critical in the case of ground events associated with solar flares of small scale.
Here we argue for the possibility of a “scale-free” energy distribution of par-
ticles accelerated by solar flares. This mean that high and low fluxes of solar particles, associated to big and small flares, have the same energy spectrum, up to energies exceeding the pion production. The difference between them is only the intensity.

This hypothesis is corroborated by new observations of two solar flares of small scale observed by Tupi telescopes, in association with energetic gamma-rays detected by Fermi GBM (designed to observe gamma-ray bursts) and with X-ray flux detected by GOES 14; both are spacecraft detectors orbiting the Earth.

Outline  This paper is organized as follows: In Section 2 a brief description of the Tupi experiment is presented and includes a comment on the location of the Tupi telescopes. In Section 3, we argue why the telescopes have a high sensitivity. Section 4 contains a brief description of micro and mini solar flares. A brief study on muon excess and solar flare association is presented in Section 5 Section 6 is devoted to showing the results of the association between muon excesses at ground level and two solar mini flares, registered by GOES-14 (X-ray flux) and Fermi GBM (gamma-ray counting rate). Section 7 contains an analysis of the pitch angle and muon excess intensity, and Section 8 contains conclusions and remarks.

2  The Tupi experiment

The Tupi experiment [4] is an Earth-based muon apparatus, devoted to the study of cosmic rays, located in Niteroi City, Rio de Janeiro, Brazil (22.88S, 43.16W), consequently near the SAA central region. The apparatus has two telescopes. Each telescope was constructed on the basis of two detectors, plastic scintillators, 0.5 m × 0.5 × 35 cm, placed perpendicularly to the axis of the telescope. The distance between the plastic scintillators is 3.0 m.

The general layout of the vertical telescope, including the data acquisition, is shown in Fig.1. The data acquisition system is made on the basis of a USB card, with a counting rate of up to 100 kHz per channel. All steps from signal discrimination to the coincidence and anti-coincidence are made via software, using the virtual instrument technique. The application programs were written using the Lab-View tools.

The main task of the first level trigger is a coincidence between the two detectors. The second-level trigger is a veto for air shower coming from
other directions, and contains a third detector placed off the telescope axis. Thus the directionality of each muon telescope is guaranteed by a veto or anti-coincidence guard, using a third detector. Therefore, only muons with trajectories close to the telescope axis are registered.

One of the two telescopes has a vertical orientation, and the other is oriented near 45 degrees to the vertical (zenith) pointing to the west. Both telescopes have an effective aperture of 65.6 cm$^2$ sr, projecting to the space a cone with an open angle of 9.5$^\circ$ in relation of the telescope axis.

At sea level and in the sub-GeV to GeV energy region, the muon flux is $\sim 70$ times higher than the nucleon flux, and $\sim 800$ times higher than the electron flux. Consequently, the telescopes are capable of detecting mainly muons induced in the atmosphere by cosmic rays (mostly protons). The minimum proton energy $E_{\text{p\_th}}$ needed to produce muons of energy $E_{\mu}$ in the atmosphere is $E_{\text{p\_th}} \sim 10 \times E_{\mu}$. In the case of the Tupi experiment, the muon energy threshold is $E_{\mu} \sim 0.1$ GeV. This means that the minimum proton energy is $E_{\text{p\_th}} \sim 1.0$ GeV.

The telescopes are inside a building and there are two flagstones on the telescopes and only muons with an energy higher than 0.1 GeV are detected. This muon energy threshold is that required to penetrate the two flagstones. The flagstone reduces the noise due to other non-muon particles, for example, it is opaque to electrons.

The Tupi experiment has a fully independent power supply, with an autonomy of up to six hours to safeguard against local power failures. As a result, the data acquisition is carried out 24 hours a day, giving a duty cycle greater than 90%.

### 2.1 Location of the Tupi telescopes

The Earth is surrounded by the magnetosphere which protects us from cosmic rays with energies less than several GeV by deflecting or capturing them in the Van Allen radiation belts. Even so, there is an additional factor that may locally enhance the cosmic ray intensity at middle latitudes. This is the so-called South Atlantic Anomaly (SAA), which is an area of anomalously weak geomagnetic field strength.

In the IGRF95 data [5], the magnetic field strength in the central SAA region (26S, 53W) is 24,000 nT. This area coincides with the Atlantic coast to the south-west of Brazil, while the total SAA area covers a great part of South America’s central region. The boundary region is defined as that
where the magnetic field strength is less than 28,000 nT, as shown in Fig.2 (top panel).

The SAA is a result of the eccentric displacement of the magnetic field centre from the geographical centre of the Earth (by about 400 km) as well as the displacement between the magnetic and geographic poles of the Earth. This behaviour permits the inner Van Allen belt to impart highly energetic particles (mostly protons), penetrating deeper into the atmosphere owing to the low field intensity over the SAA, and thereby interacting with the dense lower atmosphere, resulting in higher ionization and increased electrical conductivity [6].

Thus, cosmic rays with an energy around several dozens of MeV to GeV including solar particles can reach the north and south polar regions, but it is difficult for them to reach low latitude regions due to a high rigidity cut-off (above 9 GV). Nevertheless, in the SAA area, the anomalously weak geomagnetic field strength gives the muon telescopes the lowest rigidity of response to cosmic protons and ions, ($\geq 0.1$ GV).

According to satellite data, such as from the MOPPIT space instrument [7], the geographical distribution of single events (particles reaching the Earth) presents a great anisotropy with a much higher event density in the SAA region. The background events not connected to the SAA or Polar regions (20%) are due to galactic cosmic rays. Single events due to particle precipitation contribute 54% in the SAA (Van Allen background) and 26% in the Polar regions. Most of the single particle events observed by satellite instruments are in the keV to MeV energy range. The MOPPIT result of the geographical distribution of single events is summarized in Fig.2 (bottom panel).

It has been shown that the SAA region [8] also favours the precipitation of high energy particles (Van Allen background), with energies above the pion production threshold, because they produce air showers in the Earth's atmosphere and the hard component (muons) is able to reach sea level [8]. Even so, the Van Allen background has an enhancement only at daytime, beginning three hours after sunrise until around one hour after sunset. Because the focus effect of the interplanetary magnetic field (IMF) lines become dominant, in this schedule, they point for the Earth surface.
3 Particle telescope sensitivity

The Earth’s magnetic field deflects the charged particles of the shower initiated by a primary particle. This deflection is caused by the perpendicular component of the Earth’s magnetic field to the particle trajectory. This effect results in a decrease in the number of collected particles and therefore in telescope sensitivity. This means that the sensitivity of particle telescopes depends on the transverse component of the magnetic field intensity of the Earth.

The radius of curvature, $R$, of a positive muon travelling down the atmosphere with momentum $p$ perpendicular to the Earth’s transverse magnetic field, $B_\perp$, is $R = p/(eB_\perp)$. As the muon travels, it will be shifted horizontally by a distance $\delta x$ in the direction perpendicular to $B_\perp$. A formula for $\delta x$, to first order in $z/R$ where $z$ is the height of the atmosphere where the muon is generated, can be obtained as $\delta x \sim z^2/R = z^2ceB_\perp/p$. Thus the muons are shifted by a quantity that depends on the distance $z$ but also on the momentum $p$ of the muon. The $\Delta x$ in the SAA area is at least 50% smaller than the $\Delta x$ outside the SAA area. Fig.3 summarizes the situation. This means that the sensitivity of the telescopes is up to three times higher in the SAA region because the transverse magnetic field is very small, even smaller than the average value for the polar regions. This offers the Tupi muon telescopes the opportunity to observe small scale transient events.

On the other hand, in the Earth’s upper atmosphere, there is a layer called the ionosphere (100 km above sea level) which is characterized by a larger ion concentration. According to Chapman’s hypothesis [9] regarding the different origins of the ionosphere, the F ionospheric layer is attributed to the action of the ultra-violet rays of the sun and the E layer is attributed to the action of neutral solar corpuscles. However, in the stratosphere at low and middle latitudes and starting from 12 km above sea level there is a residual ion concentration [10]. The ionization in this region is mainly due to cosmic rays and the effect is an increase in the electric conductivity of the stratosphere, which is given by

$$\sigma = -\frac{e^2}{\nu} \sum \left( \frac{n_i}{m_i} \right),$$

where $e$ is the electron charge, $\nu$ is the collision frequency, $n_i$ is the ion density and $m_i$ is the ion mass.
In the SAA region, due to the influence of the lower Van Allen belt, which imparts highly energetic particles (mostly protons) coming deeper down into the atmosphere, there is an enhancement of the ionization production and increasing electric conductivity, and it embraces great atmospheric depths. A consequence of this behaviour is the change in the value of the coefficient that describes the energy loss of a charged particle such as a muon for ionization. The result is an increase in the range of charged particles. For instance, in the SAA region, cosmic ray fluxes are even higher than world averages at comparable altitudes, reflecting an enhancement of incoming primary cosmic rays.

4 Solar flares of small scale

A solar flare is defined as a sudden, rapid, and intense variation in brightness. A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. Radiation is emitted across virtually the entire electromagnetic spectrum. In solar flares, the interaction of the energetic electrons with thermal protons provides the deceleration, and X-ray photons with energies less than or nearly equal to the electron energy are produced. These X-ray photons are the emitted radiation signatures detected by scientific instruments such as GOES and SOHO. The frequency of flares coincides with the eleven year solar cycle. When the solar cycle is at a minimum, active regions are small and rare and few solar flares are detected. Their occurrence increases in number as the Sun approaches the maximum of its cycle. However, the period around the solar minimum is useful for the observation of small transient events, such as micro and mini flares, whose flux is less than $10^{-5}$ Watts m$^{-2}$.

Harder X rays with energies greater than 10 keV are also believed to be electron-ion bremsstrahlung. Spectral measurements of such hard X rays follow a power-law rather than an exponential shape.

However, the gamma radiation observed in a solar flare has several origins. The bremsstrahlung spectrum can extend up into the gamma-ray range. Indeed, in some of the biggest flares, the spectrum is seen to extend to energies in excess of 100 MeV. Proton and heavy ion interactions also produce gamma-rays through $\pi^0$ decay, resulting in a spectrum that has a maximum at 68 MeV.

At higher energies, there are gamma-rays produced, not from the flare
electrons, but from nuclear interactions of the protons and heavier ions accelerated in the flare, or in other words, released by a flare driven shocks. These high energy particles interact with the nuclei of the different elements in the ambient solar atmosphere to produce a far more complicated emission spectrum. A continuous spectrum and many individual gamma-ray lines have been identified, and they result from the decay of elements in the solar atmosphere as carbon, nitrogen, etc., that are excited to high energy states in various nuclear interactions.

5 Association between muon excess and solar flare

Energetic particles from solar flares, moving along solar magnetic field-lines, undergo pitch angle scattering caused by magnetic field fluctuations. This process is often assumed to be the basic physical process behind diffusive propagation of solar particles in interplanetary space, and they are also subjected to adiabatic losses. Fig.4 summarizes the situation, where the diffusive transport between the Sun and the Earth of solar charged particles emitted in a flare is shown. They are the two equi-density curves, they open up (they diffuse) when they spread sun away. Consequently, in most cases, only particles produced in very intense flares will give some signal (bigger than the background produced by the cosmic rays) in detectors located on the Earth’s surface.

The association between an X-ray flare and a muon excess requires taking into account the delay between the flare start and the time of flight between the Sun and the Earth of energetic particles. The time of flight is estimated from results of simulation under the assumption of which the propagation of energetic particles released by a flare driven shocks are injected to the planetary medium in coherent pulses of energetic particles and a realist Archimedean spiral field lines around the Sun [11]. Here, we summarize simulation results for a typical arc length along the magnetic field (garden hose direction). \(< z > (= 1.3 \text{ AU})\), as a function of the distance travelled, \(S\), which can be expressed as

\[
< z > = \alpha(\lambda)S. \tag{2}
\]

The constant \(\alpha(\lambda)\), depending on the scattering mean free path, \(\lambda\), and satisfying the constraint condition \(\alpha(\lambda) = 1\) for \(\lambda = 1.0 \text{ AU}\), sometimes called
the ‘scatter-free’ condition, implies that particles freely stream along the field at their maximum speed like a coherent particle pulse. In other words, the focus effect of the interplanetary magnetic field (IMF) lines become dominant and the propagation of the energetic particles is like coherent pulses, following trajectories around the field lines of the IMF.

In contrast, in the other extreme case, when the scattering mean free path is small compared to the scale length of the IMF (i.e., $\lambda \leq 0.2$ AU), particle propagation follows helical trajectories around the IMF. Fluctuations of small scale in the IMF act as scattering centres of the particles and the propagation is dominantly diffusive.

A muon excess, detected at sea level by a directional telescope, is the signature of primary particles arriving at the top of the atmosphere with a strong anisotropic pitch angle distribution: ‘an almost coherent pulse’. The rise time in the profile time of the muon excess can be used to infer the coherency of a pulse: for instance a very short rise time suggests a non-diffusive coherent particle pulse transport. Thus an almost coherent pulse has a value of $\lambda \geq 0.2$ UA and corresponds to a time of flight of energetic particles with a mean rigidity of 1 GV of up to 35 minutes. This delay correspond to up to $\sim 27$ minutes in relation to the X-ray signal at 1AU.

Ground-level solar flares are usually observed by high latitude neutron monitors at relatively low rigidities ($\sim 1–3$ GV), and in most cases the ground-level events are linked to solar flares of high intensity whose prompt X-ray emission is catalogued as X-class (above $10^{-4}$ Wm$^{-2}$). Evidently, solar flare detection at ground level depends on several aspects, such as a good magnetic connection between the Sun and Earth. Most solar flares associated with GLEs are located on the western sector of the Sun where the IMF is well connected to the Earth. An example of a good magnetic field connection between the Sun and Earth is shown in Fig.5. Flares located near the foot-point of the “garden hose” field line between the Sun and Earth reach the Earth with a pitch angle close to $45^0$, because protons (ions) travel toward the Earth in a spiral trajectory, following the garden hose field line.

6 Results

The GOES14 Ion Chamber Detectors provide whole-sun X-ray fluxes for the 0.5–4.0 and 1.0–8.0 $\AA$ wavelength bands. In most cases the GOES X-ray fluxes of solar flare are used as a reference for other types of detection, such
as ground level detectors and the Fermi GBM.

In addition, the Fermi GBM detector is designed to observe gamma-ray bursts (GRBs) in the FOV (field of view) of the GBM instrument, that is, if the GRB is bright enough to be localized, and in the energy range 10 keV to 30 MeV.

Here we will begin analysing the time profiles of the muon counting rate of these two muon excesses observed on 4 October 2010 and 3 November 2010 and compare them with the time profiles of, respectively, the GOES14 X-ray fluxes and Fermi GBM gamma-ray counting rate.

6.1 The event on 4 October 2010

The muon enhancement on 4 October 2010 is a sharp peak in the muon counting rate \( (E_\mu > 0.1 \text{ GeV}) \) observed in the vertical muon telescope. The onset in time correlation has great statistical significance (7.1\( \sigma \)) when the counting rate is 5 minutes binning, the muon arrival excess is 12.42 minutes late in relationship with the arrival of an X-ray excess flux on GOES14. This is a mini flare whose X-ray prompt emission is classified as 1.9C-class (a flux of \( 1.9 \times 10^{-6} \text{ Watt/cm}^2 \)). Fig.6 summarizes the situation, where the GOES14 X-ray prompt emission on 4 October 2010 for two wave lengths is shown in the top panel, and the corresponding (vertical) Tupi muon counting rate (5 minutes binning) is shown in the bottom panel. There is no signal in the inclined telescope.

The time delay between the X-ray detection and muon excess detection is 12 minutes. This means that the time of flight from the Sun to the Earth of the energetic particles was 20 minutes. According to the criteria established in the last section, the muon excess was formed by primary particles arriving at the top of the atmosphere with an anisotropic pitch angle distribution, ‘an almost coherent pulse’, and with a rigidity above 1 GV (1 GV corresponds to 1 GeV for protons).

On the other hand, solar flare events have been searched for since 2008 by the Fermi GBM. So far, even in this minimum solar activity period, the Fermi GBM has found evidence of a high energy photon emissions (gamma-rays) from solar flares. From 27 October 2009 to 3 November 2010, 22 solar flares have been registered by the Fermi GBM. Solar activity is expected to rise in the next months, reaching a maximum in 2012, and the number of flares observed by the GBM must increment by a factor of up to ten for the same period.
For the first flare here analyzed and observed on 4 October 2010, the Fermi GBM trigger was at 16:32:31.443 and it was classified as a solar flare with a reliability of 0.8. The Fermi GBM light curve is shown in Fig.7 (top panel), it has a very fast rise time, even a faster rise time than the emission of X-rays observed by GOES 14 (see Fig.6, top panel). In contrast the rise time observed in the time profiles of the muon counting rate is not so fast as is shown in Fig.7 (bottom panel), this shows a certain degree of diffusion of the energy particles emitted by the flare during its transport.

However, the flare duration (gamma-ray emission) in the Fermi GBM is very short when compared with the X-ray emission and the muon counting rate. The gamma-ray emission as observed by Fermi does not exceed 467 seconds, while the X-ray emission and the muon excess has a duration bigger than 2000 seconds. In addition, it is possible to infer up to three peaks (or at least two with high confidence) in the Fermi GBM light curve. These peaks seem to have a correlation with the three peaks observed in the muon counting rate. Even so, they have a temporal shift.

6.2 The event on 3 November 2010

The muon enhancement on 3 November 2010 has two sharp peaks in the muon counting rate observed in the vertical muon telescope. The onset in time correlation has great statistical significance of up to 20.0σ when the counting rate is 5 minutes binning, the arrival of the muon excess is also 12 minutes late in relationship with the arrival of an X-ray excess flux at GOES14 as is shown in Fig.8. This mean that the muon excess was formed by primary particles arriving at the top of the atmosphere as a coherent pulse, and with a rigidity above 1 GV. We see again that no signal exists in the inclined telescope.

This flare is more intense than the previous one, it is of 5.0C-class. In addition, it is possible to see the same structure in both the time profiles (X-ray flux and muon counting rate): two serial peaks. The time interval between these two serial peaks in both GOES 14 X-ray flux and Tupi muon excess is \(~38\) minutes. That is a signature of there being little diffusion of the particles during their transport from the Sun to the Earth following IMF lines.

For this second flare, observed on 3 November 2010, the Fermi GBM trigger was at 12:13:10.916 and it was classified as a solar flare with a reliability of 0.92. The Fermi GBM light curve is shown in Fig.9 (top panel) and in
the same figure are (bottom panel) the time profiles (raw data) of the muon counting rate. In this case both the muon excess and the GOES 14 X-ray flux have a faster rise time than the rise time observed in the Fermi GBM light curve. The gamma-ray emission duration as observed by Fermi GBM is short (1295 seconds) in relation with the muon excess duration of around 1 hour. This contrasts with the long duration of the X-ray emission as observed by GOES 14, because after a fast rise time, it falls off slowly. However the two peaks observed in the muon counting rate, during the first 500 seconds as is shown in Fig.9, are in excellent correlation with the two peaks observed in the Fermi GBM.

In addition, the time delay of the muon excess in relation with the gamma-ray detection by Fermi (at 1 AU) is less than 33 seconds. Again, this is a signature indicating a non-diffuse transport of the charged particles emitted by the solar flare.

7 Pitch angle and muon excess intensity

Fig.10 shows the Sun location, at Fermi trigger time, and the muon excess location during the sky scanner by the vertical telescope due to the rotation of the Earth, for the case of the two flares here analysed. The size (diameter) of the open circles is proportional to the logarithm of the muon counting rate. In both, the difference between the Sun and telescope axis declination is small, \( \Delta \delta = 17.2 \) and \( \Delta \delta = 7.5 \), respectively. Thus the pitch angle defined as the Sun-ward direction and the telescope axis is approximately equal to the difference between the right ascension of the Sun and of the axis of the telescope. Here a zero degree pitch angle represents the telescope pointing in the Sun-ward direction. We would like to point out that one hour in right ascension corresponds to 15 degrees.

Following Fig.10, we can observe a pitch angle around 18 degrees for the first event and 51 degrees for the second event. Flares located near the footpoint of the ‘garden hose’ field line between the Sun and Earth reach the Earth with a pitch angle close to 45°, as is shown in Fig. 5 (that is, a good magnetic connection between the Sun and Earth). Consequently, the charged particle transport is along an IMF line: under this condition, the particles will be subject to only small fluctuations of the IMF and the transport will be practically non-diffuse.

This means that the diffusion of the particles carried during their trans-
port between the Sun and the Earth is smaller for the second event. In fact, the rise time in the time profiles of the muon counting rate is smaller for the second event. In addition, for the second event the interval among the peaks observed basically is the same of that observed in GOES 14 and Fermi GBM. Consequently, a coherent pulse of particles arriving in the top of the atmosphere was responsible for the excess of muons observed in the vertical telescope.

On the other hand, a more prolonged rise time, as observed in the time profiles of the muon excess of the first event, means a more accentuated diffusion of the particles: this happens because the particles were ejected in space by the Sun off of the direction of an IMF line crossing the Earth, and they have a pitch angle around 18 degrees. Even so, a good correlation exists among the excess of muons observed in the vertical telescope and the emission of X-rays observed by the GOES 14 and the emission of gamma-rays as observed by the Fermi GBM.

8 Conclusions and remarks

Solar flares release energy in many forms—electro-magnetic (gamma-rays and X-rays), particles (protons, ions and electrons), and mass flows. Flares are characterized by their brightness in X-ray flux. The biggest flares are X-Class flares (flux between $10^{-4}$ and $10^{-3}$ Watt m$^2$). M-Class flares have one tenth the energy and C-Class flares have one tenth of the X-ray flux seen in M-Class flares.

In most cases only flares of X-class and M-class are observed by ground detectors. However, we report here two C-class flares observed as muon excesses by the vertical Tupi telescope located at sea level and within the South Atlantic Anomaly (SAA) region. We argue here that the high sensitivity attained by the Tupi telescopes is a consequence of its location, as in the SAA region the shielding effect of the magnetosphere is not perfect and shows a ‘dip’. The SAA is an area of anomalously weak geomagnetic field strength. This characteristic offers muon telescopes (inside the SAA region) the possibility of achieving a low rigidity of response to primary and secondary charged particles ($\geq 0.1$ GV).

We have shown that both events (muon excess) are in excellent correlation with the X-ray emission observed by GOES 14, as well as in excellent correlation with the gamma-ray emission observed by Fermi GBM. In ad-
dition, from an analysis on the basis of a Monte Carlo study, rise time in the muon time profiles, and their pitch angle, we conclude that the second event on 03 November 2010 is constituted at least by two extremely coherent muon pulses, which means that the particles producing muons in the Earth atmosphere were emitted by the Sun in the same direction as an IMF line crossing the Earth and their transport was practically non-diffuse.

Already for the first event analysed, and registered on 4 November 2010, the transport conditions between the Sun and the Earth were not very favourable. Even so it has a good correlation with both the Goes 14 X-ray flux and the Fermi GBM gamma-ray counting rate.

If muons are detected at sea level with energies above 0.1 GeV, this means primary (protons) with energies above the threshold of pion production (∼1 GeV). Even so, what is the mechanism in the flare that accelerates protons to these energies? Especially for flares of small scale, such as those of C-Class, is this a question.

Here we have argued for the possibility of a ‘scale-free’ energy distribution of particles accelerated by solar flares. Large and small scale flares have the same energy spectrum, up to energies exceeding the pion production, they differ only in their intensity.

If this hypothesis is correct, the vertical telescope is registering muons produced by protons (ions) whose energy corresponds to the tail of the spectrum. Consequently, the energy distribution of the emitted protons has to be a power law spectrum, as power law distributions are characterized as scale free distributions.

Finally, we would like to point out that solar flare events also have been searched for in the first year of Fermi LAT data (August 2008-August 2009). Up until now there has been no evidence of high energy emission from solar flares detected by the LAT [12].

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Figure 1: General layout of the vertical telescope including the logic implemented in the data acquisition system using LabVIEW software.
Figure 2: Top panel: Geographic distribution of geomagnetic field intensity. The SAA boundary is around $B = 28000 \text{ nT}$. The triangle and the square indicate the localizations of the Tupi facility. Bottom panel: Geographic distribution of single events (particles reaching the Earth) according to MOPPIT space instrument. In the MeV region the background events not connected to the SAA or Polar regions (20%) are due galactic cosmic rays. Due to particle precipitation, the particle events are 54% in the SAA and 26% in the Polar regions. The SAA is the region with the largest event density.
Figure 3: Comparison between the lateral shift of a vertical (born) positive muon traveling downward in the atmosphere with momentum $p$, due to the Earth’s transverse magnetic field, $B_\perp$, inside and outside the SAA region.

Figure 4: Diffusive transport between the Sun and the Earth of solar charged particles emitted in a solar flare. The effect is due to interplanetary magnetic field fluctuations, since ions (protons) have a pitch angle different from zero. Consequently, in most cases, only particles produced in very intense flares will give some signal (bigger than the background produced by the cosmic rays) in the detectors located on the Earth’s surface.
Figure 5: Example of a good magnetic field connection between the Sun and Earth. Flares located near to the foot-point of the “garden hose” field line between the Sun and Earth reach the Earth with a pitch angle close to 45°, because, protons (ions) travel toward the Earth in a spiral trajectory, following the garden hose line and have very sharp onsets.
Figure 6: Top panel: The X-ray flux on July 14, 2010 according to GOES 14, for two wave lengths. Bottom panel: The 5-minute muon counting rate in the vertical Tupi telescope. A prompt association around the 21h UT between a sharp peak registered by the Tupi telescope and a sudden increases in the X-ray emission (mini flare) registered by the Goes 14 can be observed.
Figure 7: Top panel: The gamma-ray counting rate on 4 October 2010, starting at 16:32:31.443 UT and according to Fermi GBM (Trigger bn101004689). Bottom panel: The 5-minutes muon counting rate in the vertical Tupi telescope, expressed in term of the significance level.
Figure 8: Top panel: The X-ray flux on 3 November 2010 according to GOES 14, for two wavelengths. Bottom panel: The 5-minute muon counting rate in the vertical Tupi telescope. A prompt association around the 21h UT between a sharp peak registered by the Tupi telescope and a sudden increase in the X-ray emission (mini flare) registered by the Goes 14 can be observed, only in the vertical Tupi telescope.
Figure 9: Top panel: The gamma-ray counting rate on 3 November 2010, starting at 12:13:19.916 UT and according to Fermi GBM (Trigger bn101103509). Bottom panel: The 1-second muon counting rate in the vertical Tupi telescope.
Figure 10: Sun location, at Fermi trigger time and the muon excess location during the sky scanner by the vertical telescope due to the Earth rotation, for the case of the two flares here analyzed. The size (diameter) of the open circles is proportional to the logarithm of the muon counting rate. In both, the difference between the Sun and telescope axis declination is small, $\Delta \delta = 17.2$ and $\Delta \delta = 7.5$ respectively. Thus the pitch angle defined as the Sun-ward direction and the telescope axis is approximately equal to the difference between the right ascension of the Sun and of the axis of the telescope. As one hour in right ascension corresponds to 15 degrees, we observe a pitch angle around 18 degrees for the first event and 51 degrees for the second event.