WAS THE GLE ON MAY 17, 2012 LINKED WITH THE M5.1-CLASS FLARE THE FIRST IN THE 24TH SOLAR CYCLE?

C. R. A. Augusto, V. Kopenkin and C. E. Navia
Instituto de Fisica, Universidade Federal Fluminense, 24210-346, Niteroi, Rio de Janeiro, Brazil

A. C. S. Felicio, F. Freire, A. C. S. Pinto, B. Pimentel, M. Paulista and J. Vianna
Departamento de Fisica, Universidade Federal Fluminense, 24210-346, Niteroi, Rio de Janeiro, Brazil

A. C. Fauth
Instituto de Fisica Gleb Wataghin, Universidade Estadual de Campinas, 13083-859, Campinas, São Paulo, Brazil

AND

T. Sinzi
Rikkyo University, Toshima-ku, Tokyo 171, Japan

ABSTRACT

On May 17, 2012 an M5.1-class flare exploded from the sun. An O-type coronal mass ejection (CME) was also associated with this flare. There was an instant increase in proton flux with peak at \( \geq 100 \text{ MeV} \), leading to S2 solar radiation storm level. In about 20 minutes after the X-ray emission, the solar particles reached the Earth. It was the source of the first (since December 2006) ground level enhancement (GLE) of the current solar cycle 24. The GLE was detected by neutron monitors (NM) and other ground based detectors. Here we present an observation by the Tupi muon telescopes (Niteroi, Brazil, 22\(^\circ\).9S, 43\(^\circ\).2W, 3 m above sea level) of the enhancement of muons at ground level associated with this M5.1-class solar flare. The Tupi telescopes registered a muon excess over background \( \sim 20\% \) in the 5-min binning time profile. The Tupi signal is studied in correlation with data obtained by space-borne detectors (GOES, ACE), ground based neutron monitors (Oulu) and air shower detectors (the IceTop surface component of the IceCube neutrino observatory). We also report the observation of the muon signal possibly associated with the CME/sheath striking the Earth magnetosphere on May 20, 2012. We show that the observed temporal correlation of the muon excess observed by the Tupi muon telescopes with solar transient events suggests a real physical connection between them. Our observation indicates that combination of two factors, the low energy threshold of the Tupi muon telescopes and the location of the Tupi experiment in the South Atlantic Anomaly region, can be favorable in the study and detection of the solar transient events. Our experiment provides new data complementary to other techniques (space and ground based) in the study of solar physics.

Subject headings: solar physics: interplanetary shocks, solar physics, astrophysics and astronomy (flares and mass ejections), geomagnetic storms, atmospheric effects

1. INTRODUCTION

Ground-level enhancements (GLEs), typically in the GeV energy range, are sudden increases in cosmic ray intensities registered by neutron monitors (NMs), which are ground based instruments that detect the secondary neutrons produced by the primary protons penetrating the Earth’s atmosphere (Gopalswamy et al. 2010). These enhancements can be registered by other types of ground detectors, such as air shower detectors and muon telescopes (Nitta et al. 2012). In most cases GLEs take place during the intense X-class solar flares as well as the fast (above \( \sim 1000 \text{ km s}^{-1} \)) Coronal Mass Ejections (CMEs) (Gopalswamy et al. 2010, 2011a). There are some GLEs cases associated with weaker flares and slower CMEs (Cliver 2006)

GLE events are solar energetic particle (SEP) events. SEP are one population of particles in the interplanetary space from the Sun to 1 AU, that are classified according to particle origin or acceleration region (Kallenrode 2001, 2003; Tsurutani et al. 2009). SEP have intermediate energies from \( \sim 10 \text{ keV/nucleon} \) to the GeV range and occur in events that last from some hours to a few days. SEP are much more frequent at times of solar maximum than during solar minima, the occurrence of SEP events is directly related to flares and CMEs (Kallenrode 2003). There are recognized two distinct classes of SEP events, impulsive (accelerated in flares) and gradual (accelerated at CME driven shocks) (Cane et al. 1986; Kallenrode 2003).

A number of individual GLEs has been studied in details in literature, nevertheless the exact conditions and processes that are responsible for these extreme SEP
events are not understood yet (Nitta et al. 2012).

Since 1950th the observation and the study of the powerful solar flares has been done exclusively with NMs all around the world, especially in the polar regions (Meyer et al. 1956, Simpson 2003, Moraal et al. 2000). Observation with NMs yield a lot of new information. For instance, the anti-correlation between solar activity and the flow of galactic cosmic rays, the existence of a prompt and late emission in flares, correlations of the cosmic ray intensity with CMEs and other solar disturbances crossing the Earth, etc. (Chupp 1987, Moraal et al. 2000). Nowadays, particles accelerated near the Sun can be detected by space-borne instruments. The measurement of high energy protons in space is achieved by the High Energy Proton and Alpha Detector (HEPAD) (Onsager et al. 1990) on the Geostationary Operations Environmental Satellite (GOES), which provides data on differential fluxes in three channels in the energy region between 350 MeV and 700 MeV, integral flux above 700 MeV, and the X-ray flux in two wavelengths (http://www.oso.noaa.gov/goes/index.htm).

Solar flares that can be measured at the Earth’s surface are rare events. Not all of the solar explosions observed by satellites can be measured at the Earth’s surface. For instance, there can be dissipation of the radiation by the interplanetary magnetic field (IMF), particles can be deflected or captured by the Earth’s magnetic field or absorbed by the Earth’s atmosphere.

GLEs are quite rare events. Fewer than 100 events have been observed by NMs in the last 70 years (http://www.nasa.gov/mission_awesome/sunearth/news/particlesspace/). It is important to note that ground detectors do not observe GLEs simultaneously. For instance, the NMs which observed the GLEs in solar cycle 23 were located at regions with the geomagnetic rigidity cutoff ∼ 1 GeV or less (Shea & Smart 2011). Solar flares and CMEs occur whenever there is a rapid large-scale change in the Sun’s magnetic field. Solar flare detection at ground level depends on 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 (Reames 1999). At least two more factors may contribute to GLEs: the presence of prior CMEs and the magnetic field connection of the acceleration region to Earth. The time profiles of the observed SEP events depend on the original solar active region longitude (heliolatitude). For example, those from the western source active regions tend to rise more quickly to the peak than those from the eastern source regions (Cane et al. 1988, 2003, Nitta et al. 2012, Reames 1999). The solar active areas are distributed in much broader longitudes than those of impulsive SEP events in flares (Reames 1999).

Among 16 GLEs observed in the previous solar cycle 23, 14 GLEs were linked with X-class flare, one with an M7.1-class flare and one with a C2.2-class flare. It was reported that in 15 GLE the associated blast has also emitted a CME (Kahler 2001; Cliver 1983, 2006). Usually the CMEs provide conditions for the seed particles to be re-accelerated. These shock driven CMEs lead to GLEs that can be observed by ground based detectors. The last GLE from the previous solar cycle 23 was originated by the X3.4 class flare at (02:14 Universal Time (UT)) on December 13, 2006, at the active solar spot region with heliospheric coordinates (S06,W23). There was also a CME associated with this X3.4 solar blast.

On the other hand, the first GLE observed in the current solar cycle 24 has been linked with an M5.1-class solar flare on May 17, 2012. An O-type (type O stands for “occasional”) CME was also launched during this event (http://cdaw.gsfc.nasa.gov/), and a category S2 solar radiation storm was observed.

Here we present new data on the observation of muon excess in association with the M5.1-class flare. In this study we include data obtained by other ground based observations, such as Oulu NM (Usoskin et al. 2011) and the IceTop air shower detectors (Tamburro 2012), as well as observations obtained by space-borne detectors. In addition, we also analyze the Earth passage of the magnetic disturbance linked with the CME originated in the solar eruption on May 17, 2012. The Tupi observations are studied in correlation with observations reported by the Advanced Composition Explorer (ACE) located in the L1 Lagrangian point (http://www.swpc.noaa.gov/). We also used the estimated 3 hr planetary Kp index considering that it reflects the mean magnetospheric activity (http://www.swpc.noaa.gov/rtsslots/kpdl.html). Based on the Tupi data, we obtained the time delay and the signal significance of the flare and the CME ejeta, as well as the earth passage time of the ejecta.

This article is organized as follows. In Section 2 we discuss favorable conditions to detect the impulsive SEP, especially those linked with GLEs. In addition to those already recognized in literature, we highlight the specific location of the Tupi muon telescopes near the South Atlantic Anomaly (SAA) central region. Section 3 explains experimental setup. Section 4 presents methodology and the results of the association between the Tupi muon excess and an M5.1-class flare on May 17, 2012, registered by satellites and ground based detectors. Section 5 describes the Tupi observation of the muon excess on May 20, 2012 possibly associated with the Earth passage of the CME ejeta originated in the solar events on May 17, 2012. Section 6 presents other examples on the association between muon excesses at ground level and transient solar events in the current solar cycle 24, registered by spacecrafts. In Section 7 we present summary and our conclusions.

2. CONDITIONS TO “HUNT” FOR SOLAR ENERGETIC PARTICLES AT EARTH

Large solar flares are often associated with CMEs. Under favorable conditions, such as a good magnetic connection between Sun and Earth, a blast of high-energy particles with energies above several hundred of MeV, can reach the upper atmosphere and produce secondary particles detected by ground based detectors. The energetic charged particles emitted by a flare, move into the interplanetary medium, following the solar magnetic field lines (Parker spiral), which defines the sunward magnetic field direction. In general, solar flares originated in active areas located in the western sector of the Sun (in the heliolongitude) have a good magnetic connection with the Earth. The best condition happens when the
emitted particles have very small pitch angles, relative to the footpoint spiral field that connects the Earth to longitude 55° West of the central meridian of the Sun (as viewed from the Earth) (Shea & Smart 1996; Smart & Shea 2003). Under this condition the energetic particles travel essentially along the interplanetary magnetic field lines, and their diffusion in the interplanetary medium is negligible.

This minimum scattering condition is usually called a "scatter free" propagation. In general, MeV solar particles appear to have an average mean free path length of the order of ~0.1−0.3 AU and the time delay between the X-ray emission (observed at 1 AU) and the onset of the GLE is several dozens of minutes. On the other hand, long time delays indicates a diffusive propagation.

For solar flares from active regions located at the East of the helilongitude, the time delay (between emission and the GLE onset) can be from several hours up to days. Almost all diffusion models involving solar particle transport in the interplanetary medium show that the maximum time delay is proportional to the square of the distance traveled. Using the heliographic coordinate system (Wibberenz 1974), the onset time delay of the GLE is given by (Barouch et al. 1971; Smart & Shea 1985)

\[ T_d (\text{in hours}) = \frac{0.133 \, D}{\beta} + 4 \theta^2, \]  

where \( \beta = v/c \), \( v \) is the particle speed, \( \theta \) is the heliolongitude, and \( D \) is the Archimedean spiral path length (measured in AU). The minimum in the curve corresponds to zero pitch angle condition, that is a flare at the "foot point" of the Archimedean spiral path between the Earth and the Sun (this is about \( \theta = 57.2^\circ \)). Figure 1 shows the time delay as a function of the heliolongitude, where the solid line indicates is the expected delay time according to Wibberenz’s model (Wibberenz 1974).

On the other hand, both the intensity and the spectrum of SEP observed by ground based detectors also depend on the relative locations of these detectors on Earth, as well as at the time of the occurrence of solar flares. For instance, ground based detectors positioned near the geomagnetic equator are not able to register SEP from solar flares due to high geomagnetic cutoff rigidity. Thus, the polar regions with low geomagnetic cutoff rigidity are the most favorable locations to detect solar transient events.

However, there is one more place on Earth, where the Earth magnetic field is weakened considerably. This is the South Atlantic Anomaly (SAA), the area at mid-South latitudes, off the coast of Brazil (see Figure 2). It covers almost 7.8 million km² and currently continues to grow.

Geographical distribution of proton flux measured by the HEPAD ICARE instrument on-board the Argentinian satellite SAC-C showed an excess (up to 10 times) of protons with \( E > 850 \text{MeV} \) in the SAA central region in comparison with the region outside of the SAA. These high energy protons are hard to be considered as Van Allen trapped protons, because the SAA models such as AP8 and several measurements of the trapped protons showed that their energies do not exceed 300 MeV (Boatella et al. 2010). In addition, the PAMELA Collaboration introduced a subcutoff in the rigidity that is below the nominal Stormer rigidity cutoff in the SAA area (Casolino et al. 1987). Downward going protons with energies above 200 MeV are also clearly seen at the latitudes between 40°S and 20°S (the SAA area). These are so-called “quasi-trapped particles”. This geomagnetic subcutoff is about 10 times smaller than the nominal geomagnetic cutoff rigidity. At the Tupi experiment location (22°S, 43°W) that is close to the

![Fig. 1.— Expected time delay (onset at Earth) of 800 to 1300 MeV solar protons as a function of solar longitude (solid line). The May 17, 2012 solar flare was associated with a active region AR1476 located at (N07W88), so the expected time delay is about 1.8 h. The time delay observed by NMs is ~0.49 h and the time delay for the Tupi detector is ~0.2 h.](image1)

![Fig. 2.— Left panel: Sketch of the geomagnetic hole in the South Atlantic area. The magnetic field intensity in this area is about three times lower than the intensity of the magnetic field at the SAA boundary. Right panel: Geographical distribution (latitude vs longitude) of proton flux (\( E > 850 \text{MeV} \)) measured by the HEPAD ICARE detector (Boatella et al. 2010). The color scale is logarithmic. The dark color (red) represents 10 times higher proton flux than the one with the light color (blue).](image2)
SAA central region, this subcutoff is around 800-1000 MV (equivalent to 800-1000 MeV for protons.)

Thus, the primary and secondary charged cosmic ray particles can penetrate deep into the atmosphere owing to the low geomagnetic field intensity over the SAA. Consequently, in the SAA region cosmic ray fluxes at lower energies are even higher than world averages at comparable altitudes. This is reflected as an enhancement in the counting rate of the incoming primary cosmic ray flux.

3. EXPERIMENTAL SETUP

The Tupi experiment has two muon telescopes (Augusto et al. 2011). 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 telescope has a vertical orientation, and the other one is oriented near 45 degrees to the vertical (zenith), pointing to the west. Each telescope counts the number of coincident signals in the upper and lower detector. The output raw data consists of counting rate versus universal time (UT). The Tupi telescopes are placed inside a building, under two flagstones of concrete (150g/cm²). The flagstones increase the detection muon energy threshold up to \( \sim 0.2 - 0.3 \text{ GeV} \) required to penetrate the two flagstones. The Tupi telescopes have an effective field of view 0.37sr. The effective solid angle of each detector can be roughly obtained from the following relation:

\[
\Omega = 2\pi(1 - \cos\theta_z), \text{ where } \theta_z \text{ is the maximum zenith angle.}
\]

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 application programs were written using the LAB-VIEW tools. The Tupi experiment has a fully independent power supply, with an autonomy of up to 3 h to safeguard against local power failures. As a result, the data acquisition is basically carried out 24 h a day.

The Tupi experiment is in the process of constant expansion and upgrade. There is work in progress on additional new telescopes in Campinas (Brazil) and La Paz (Bolivia).

4. OBSERVATION OF THE GLE ON MAY 17, 2012 BY THE TUPI MUON TELESCOPE

Here, we present the muon excess associated with the May 17, 2012 M5.1-class solar flare observed by the Tupi muon telescopes. We compare our data with observations made by spacecraft detectors, such as GOES satellites. The timeline of the solar flare (onset; peak; end) is as follows: (01:25 UT; 01:47 UT; 02:14 UT) (Augusto et al. 2011). 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 telescope has a vertical orientation, and the other one is oriented near 45 degrees to the vertical (zenith), pointing to the west. Each telescope counts the number of coincident signals in the upper and lower detector. The output raw data consists of counting rate versus universal time (UT). The Tupi telescopes are placed inside a building, under two flagstones of concrete (150g/cm²). The flagstones increase the detection muon energy threshold up to \( \sim 0.2 - 0.3 \text{ GeV} \) required to penetrate the two flagstones. The Tupi telescopes have an effective field of view 0.37sr. The effective solid angle of each detector can be roughly obtained from the following relation:

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The X-ray energy flow measured by the GOES in the wave length 0.8-4 A is used to classify the solar flare. For the May 17, 2012 event the X-ray energy flow peak went up to \( 5.1 \times 10^{-5} \text{ Watts m}^{-2} \), and represents an M5.1-class flare. In general, M-class flares are ten times smaller (in X-ray flow) than the X-class flares (the most powerful). The May 17, 2012 solar eruption consisted of an M5.1 soft X-ray solar flare and a fast CME. In addition, the GOES registered increase in the proton flux. There was observed a S2 radiation storm. Figure 3 summarizes the situation.

![Image](http://www.lmsal.com/solarsoft/latestventsarchive.html)

**Fig. 3.** Observation of the May 17, 2012 solar flare. The x-ray prompt emission of the solar flare at the onset time (01:25 UT) is classified as M5.1 class by the GOES satellite (top panel). Proton flux time profile observed by the GOES satellite (central panel). For comparison, there is time profile of the 5-min muon counting rate observed by the inclined Tupi muon telescope (bottom panel).

On May 17, 2012, there have been observed a significant increase in the counting rate of the IceTop air shower detector\(^5\), a neutron monitors at the South Pole NM and Oulu NM (close to the North Pole) in association with the M5.1-class flare. This observation constitute the first GLE in the current solar cycle 24.

A comparison between the GLE observation made by the IceTop air shower detector at the South Pole and

\(^5\) The IceTop surface component of the IceCube neutrino observatory.
the muon counting rate in the inclined Tupi telescope is shown in Figure 4. The IceTop has two discriminators rates: SPE (Single Photo Electron) and MPE (Multi Photo Electron). The counting rates (for both SPE and MPE) are in the range from 1 to 10 kHz. On the other hand, the counting rate of the Tupi telescopes is 100 kHz. In Figure 4 we show the time profiles of the vertical and inclined Tupi telescopes on May 17, 2012. The muon excess over background in the vertical Tupi telescope is $\sim 10\%$, and in the inclined Tupi telescope - 20\%.

The GLE event observed by the Oulu NM (located in the region near the North Pole) on May 17, 2012 is presented in Figure 5. For comparison we show the time profile of the 5-min muon counting rate in the inclined Tupi telescopes on May 17, 2012.

These ground based observations show large extension and anisotropy of the SEP linked with the M5.1 solar flare. Usually the counting rate of secondary particles produced by vertically incident projectiles is in reverse correlation with the atmospheric pressure. The variation of the barometric coefficient observed by NM detectors is around 1\% per mbar. However, the variation of the barometric coefficient for muons at sea level is $\sim 10$ times lower, i.e. 0.1\% – 0.2\% per mbar.

We would like to point out some differences between the Tupi observations and the IceTop-Oulu observations. The Tupi telescopes observe the muon excess as a narrow peak. As one can see from Figures 4 and 5, the width of the GLE signal observed by IceTop-Oulu is $\sim 3$ times wider than the Tupi peak. This difference can be attributed to the small field of view of the Tupi telescopes. The effective field of view of NMs and air shower detectors is higher, $\sim 3.14$ sr. The muon telescope detects only those particles whose direction of propagation is close to the axis of the telescope, by other words, when the particle flux is contained within the telescope field of view.

Comparison of the May 17, 2012 GLE signal significance as a function of the onset time and the peak time is summarized in Figure 6. From this figure we can see that Tupi observed the peak of the signal before the solar flare maximum (detected by GOES), and the IceTop and Oulu experiments observe the GLE peak after the solar flare maximum. For 1.2 AU Parker spiral length, the solar particle release time has been reported as (01:40 UT), normalized to electromagnetic emissions (Gopalswamy et al. 2012).

5. TUPI OBSERVATION OF THE O-TYPE CME ON MAY 20, 2012

Recently the Tupi experiment has reported the results of an ongoing survey on the association between the muon flux variation at ground level and the Earth-directed transient disturbances in the interplanetary medium propagating from the Sun (such as CME and corotating interaction regions (CIRs)) (Augusto et al. 2012b). In present work we apply the same method for the analysis of the geomagnetic disturbance linked with the CME associated with an M5.1 solar flare on
May 17, 2012. According to the SOHO LASCO/C2 (http://sohowww.nascom.nasa.gov), the CME first appearance was at (01:48 UT).

A sudden increase in the density, speed, and temperature of the solar wind and in the IMF intensity registered by a satellite, indicates the arrival of a shock wave. If the origin of the disturbance is the CME ejecta, then the disturbance crosses the Lagrange point L1 first, and after several hours it arrives at Earth. If CME has significant southward component (Bs) of the interplanetary magnetic field (IMF) in either the sheath behind the shock or in the driver gas (magnetic cloud), then after reaching the Earths magnetosphere, it may lead to geomagnetic storms (Tsurutani et al., 1988; Gonzalez et al., 1994; Tsurutani et al., 1997a, 2006a,b). In addition, the ground-based detectors can observe depressions of cosmic-ray intensity (so called Forbush events) (Cane 2000; Cane et al., 1996) due to the shadow effect by the passage of the disturbance on the Earth. Several indices were developed to reflect global information about current magnetospheric activity based on different inputs at different locations around the globe, Kp and Dst are the most widely used indicators (Bartels 1963, Sugiura 1964, Rostoker 1972, Mayaud 1980, Gonzalez et al., 1994).

According to the Stereo A spacecraft, the speed of the O-type CME on May 17, 2012 was \(\sim 1500 \text{ km s}^{-1}\). The preliminary analysis indicated that the CME was not entirely directed to the Earth. However, according to the SWEPAM solar wind detector on board the ACE spacecraft, on May 20, 2012 at (01:44 UT) there was a solar flare at the onset time (01:25 UT) is classified as an M5.1 class by the GOES satellite. The solar flare peak time determined by GOES is (01:47 UT). The Tupi signal significance in the period (0 − 9h UT) is estimated using the 5-min binning time profile. The Oulu NM onset time was reported as (01 : 43 UT) (when the intensity is 2% of the peak). We made estimations of the signal significance for the IceTop experiment using the SPE-MPE counting rate in Figure 4.

The signal (with significance 4\(h \text{UT}\)) in association with a \(Kp = 4\) (see the first arrow in Figure 7). The second arrow at \(\sim 13h \text{UT}\) indicates a 10% increase in the Tupi muon counting rate, the corresponding \(Kp = 3\) at (12-15 h UT). Possible explanation of this observation is that the travel duration of the magnetic disturbance through the Earth was around 9 hours. After the passage, the \(Kp\) index falls to \(Kp = 1\). In Figure 7 we show comparison between the solar wind parameters (temperature and speed) observed by the ACE satellite (two panels from the top), the \(Kp\) index (bottom panel) on May 20, 2012 and the muon counting rate in the vertical Tupi telescope (third panel). The Tupi counting rate is 5 min binning here. The arrows in the third panel indicates the begin and the end of the disturbance signal on Tupi data.

registered an interplanetary shock. A possible origin of this shock was the O-type CME of May 17, 2012. The shock signal at Earth was very soft, with the Kp index \(Kp = 4\) at (3-6 h UT). This means that the disturbances in the geomagnetic field caused by the CME eject was of minor scale.

The signal (with significance 4.1%) in the vertical Tupi telescope is observed at \(\sim 4h \text{UT}\) in association with a \(Kp = 4\) (see the first arrow in Figure 7). The second arrow at \(\sim 13h \text{UT}\) indicates a 10% increase in the Tupi muon counting rate, the corresponding \(Kp = 3\) at (12-15 h UT). Possible explanation of this observation is that the travel duration of the magnetic disturbance through the Earth was around 9 hours. After the passage, the \(Kp\) index falls to \(Kp = 1\). In Figure 7 we show comparison between the solar wind parameters (temperature and speed) observed by the SWEPAM solar wind detector on board the ACE satellite, the \(Kp\) index and the muon counting rate in the vertical Tupi telescope on May 20, 2012.

6. OTHER OBSERVATIONS OF MUON EXCESS IN ASSOCIATION WITH SOLAR FLARES IN THE CURRENT SOLAR CYCLE 24

Solar flares are characterized by their brightness in x-ray flux. In most cases, only flares of X-class and M-class (flux above \(10^{-4}\) and \(10^{-3}\)Watts m\(^{-2}\) respectively) are observed by ground detectors. Since 2005 (Augusto et al., 2003; Navia et al., 2005) the experiment with the Tupi muon telescopes have reported observation of signals from small solar transient events, including association with gamma-ray emission by C-class flares observed by the Fermi GBM detector (Augusto et al., 2011), as well as simultaneous observa-
tions between Tupi muon excess and the Pierre Auger observatory (SD in scaler mode) counting rate enhancements in association with X-ray emission from solar flares detected by GOES satellites (Augusto et al. 2012). It means that small-scale solar flares, those with prompt X-ray emission in excess of $10^{-6} \text{Watts m}^{-2}$ at 1 AU (classified as C class) may give rise to GLEs, probably associated with solar protons and ions arriving to the Earth as a coherent particle pulse. In general, significance of the signal from a solar flare observed by the Tupi telescopes depend on several factors. For instance, solar flares originated in active areas with a good magnetic connection with the Earth, during the time interval ($\sim 12 - 22 UT$), with practically nondiffusive transport of the particles emitted by Sun, are favorable for the Tupi experiment observation. In Figures 8,9,10 we show new examples on possible association between muon enhancements at ground observed by the TUPI telescopes and the Sun’s X-ray activity, a X2.1-class flare on September 6, 2011, a M6.9-class flare on July 8, 2012 and a C2.3-class flare on November 5, 2012 respectively. Consequently, all observed in the current 24-th solar cycle. Currently the Tupi experiment is focused on systematic collection of the solar flare events.

It is usually assumed that a solar flare must be very powerful, in order to be a candidate for an association with a GLE. However, there are at least three factors favorable for high sensitivity attained by the Tupi telescopes to solar transient events. First, this is the physical location of the Tupi experiment within the SAA region, where the shielding effect of the magnetosphere has "dip" due to the anomalously weak geomagnetic field strength. Despite the Stormer geomagnetic rigidity cutoff of 8-9 GV at the Tupi location, the SAA introduces a subcut-off in the geomagnetic rigidity with a low value $\sim 0.8 - 1.0$ GV. This means that the SAA works as a "funnel" for SEP. The second factor is the low energy threshold ($E_{th} \sim 0.2 - 0.3$ GeV) in the Tupi experiment. The minimum proton energy $E_{p}$ needed to produce muons of energy $E_{\mu}$ in the atmosphere is $E_{p} \sim 10 \times E_{\mu}$. Some experiments on study of solar modulation of galactic cosmic rays use lead plates of up to 5 cm of thickness, that significantly increase the energy threshold (up to several dozens GeV). For the purpose, the Tupi experiment does not use the lead plates. Third, the Tupi data acquisition is made on the basis of a Universal Serial Bus card, with a counting rate of up to 100 kHz per channel. Since October 2012 the sampled rate of the vertical and inclined telescopes works at 30 MHz.

7. CONCLUSIONS

Here we described an observation by the Tupi muon telescopes of the muon excess at ground level associated with an M5.1 class solar flare on May 17, 2012. This means that the particles, producing muons in the Earth’s atmosphere, were emitted by the Sun, and their transport to Earth was practically nondiffusive. This first GLE event of solar cycle 24 was registered by neutron monitors all over the world.

We have reported a description and an analysis of the time evolution of the muon flux variation at ground level in temporal correlation with the May 20, 2012 CME linked with the M5.1 solar flare.

The Tupi muon telescopes are sensitive to primary particles (including photons) with energies above the pion production threshold. The Tupi telescope can detect muons at sea level with energies greater than $\sim 0.2 - 0.3$ GeV. The Tupi telescopes are located at sea level and within the 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. In this area the primary and secondary charged cosmic ray particles can penetrate deep into the atmosphere owing to the low magnetic field intensity over the SAA. In this region the solar flare induced particles will come down to very low altitudes. Consequently, in the SAA region cosmic ray fluxes at lower energies are higher than world averages at comparable altitudes. This feature is reflected as an enhancement in the counting rate of the incoming primary cosmic rays flux.

We have also shown at least three experimental evidence of the association between the different types of solar flares and GLEs detected by the Tupi telescopes, already in the current 24-th solar cycle. Our experimental data show that the Tupi experiment is able to add new information and can be complementary to other techniques designed to study solar transient events. It is obvious that further experimental observations of experimental events in association with solar transient events are necessary to get better statistical constraints in the study of space weather conditions in Earth’s environment.

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Fig. 9.— Top panel: Time profile of the x-ray flux on July 8, 2011, according to GOES 15, for two wavelengths. Central and bottom panel: The 5-min muon counting rate in the vertical Tupi telescope. There was an M6.9 solar flare from active area 1515 (S14W86). The flare timeline (onset;peak:end): (16:23 UT; 16:32 UT; 16:42 UT).

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Fig. 10.— Top panel: Time profile of the x-ray flux on November 5, 2012, according to GOES 15, for two wavelengths. Central and bottom panel: The 5-min muon counting rate in the vertical Tupi telescope. The numbers 1 and 2 correspond to the 1st and second peaks in association with the GOES data. Peak 1: a B4.0 solar flare from active area (S14E88). The flare timeline (onset;peak:end): (10:00 UT; 10:06 UT; 10:15 UT). Peak 2: a C2.3 solar flare from active area (S14E88). The flare timeline (onset;peak:end): (18:30 UT; 18:39 UT; 18:47 UT). There is an increase in the counting rate after (∼ 10 h UT). This seasonal variation of the intensity is due to day-night asymmetry (Augusto et al. 2010).

REFERENCES

Augusto, C. R. A., et al. 2005, Phys. Rev. D, 71, 103011.
Augusto, C. R. A., et al. 2010, Astroparticle Physics, 34, 40.
Augusto, C. R. A., et al. 2011, Phys. Rev. D, 84, 042002.
Augusto, C. R. A., et al. 2012, Phys. Rev. D, 86, 022001.
Augusto, C. R. A., et al. 2012, ApJ, 759, 143.
Barouch, E., M. Gros & P. Masse 1971, Sol. Phys., 19, 1971.
Bartels, J. 1963, Ann. Geophys., 19, 1.
Boatella, C., Hubert, G., Ecoffet, R. and S. Duzellier 2010, IEEE Trans. Nucl. Sci. 57, 2000.
Cane, H. V., McGuire, R. E. & von Rosenvinge, T. T. 1986, ApJ, 301, 448.
Cane, H. V., Reames, D. V. & von Rosenvinge, T. T. 1988, J. Geophys. Res., 93, 9555.
Cane, H. V., von Rosenvinge, T. T., Cohen, C. M. S., & Mewaldt, R. A. 2003, J. Geophys. Res. Let., 30, 8017.
Cane, H. V. 2000, Space Sci. Rev., 93, 55.
Cane, H. V., Richardson, I. G., & von Rosenvinge, T. T. 1996, J. Geophys. Res., 101, 21561.
Cane, H. V., Reames, D. V. & von Rosenvinge, T. T. 1988, J. Geophys. Res., 93, 9555.
Cane, H. V., von Rosenvinge, T. T., Cohen, C. M. S., & Mewaldt, R. A. 2003, J. Geophys. Res. Let., 30, 8017.
Cane, H. V. 2000, Space Sci. Rev., 93, 55.
Cane, H. V., Richardson, I. G., & von Rosenvinge, T. T. 1996, J. Geophys. Res., 101, 21561.
Casolino, M. et al. (PAMELA Collaboration) 2007, in Proceedings of the 30th International Cosmic Ray Conference, Mexico City, 2007, edited by R. Caballero et al. (Universidad Nacional Autonoma de Mexico, Mexico City, 2008), Vol. 1, pp. 709-712.
Chupp, E., L., et al. 1987, ApJ, 318, 913.
Cliver, E., W. 1982, Sol. Phys. 75, 341.
Cliver, E. W. 2006, ApJ, 639, 1206.
Cliver, E. W., Kahler, S. W., Shea, M. A., & Smart, D. F. 1982, ApJ, 260, 362.
Cliver, E. W., Kahler, S. W., H.V. Cane, M.J. Koomen, D.J. Michels, R.A. Howard, N.R. Sheeley, Jr. 1983, Sol. Phys., 89, 181.
Cliver, E. W., Kahler, S. W., H.V. Cane, M.J. Koomen, D.J. Michels, R.A. Howard, N.R. Sheeley, Jr. 1983, Sol. Phys., 89, 181.
Fletcher, L., et al. 2011, Space Sci. Rev., Space Sci. Rev., 159, 19.
Gonzalez, W. D. et.al. 1994 J. Geophys. Res., 99(A4), 5771.
Gopalswamy, N., Xie, H., & Usoskin, I. 2010, Indian J. Radio & Space Physics 39, 240.
Gopalswamy, N., Xie, H., Yashiro, S., & Usoskin, I. 2011, Space Sci. Rev. (submitted).
Gopalswamy, N., and S. Yashiro, S. 2011, ApJ, 736, L17.
