Solar transient events: The connection among measures obtained at sea level and space

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Abstract: We report a survey on transient events measured at sea level using a new technique on the basis of a muon telescope with a tracking system and working with a high counting rate ($\sim$ 100 kHz). Results during the solar events on 2005/05/13 are presented. Although we have only the data in the last 12 hours under ideal condition (telescope always oriented to the IMF lines), it is possible to see with a high confidence level the association between two solar $flares$ (whose X-ray prompt emissions are classified by GOES Group as C1.5 and M8.0) and sudden increases in the muon flux, as well as the beginning of a pre-Forbush increase in the muon flux due to the arrival of a big solar disturbance of MeV protons observed in the ACE spacecraft. These ground level enhancements (GLEs) suggest that the solar energetic particles extend in energies to well above 10 GeV, because they produce muons in the Earth's atmosphere, even when the GLE is associated to solar $flares$ of small scale.

Introduction

Charged primary cosmic rays impacting in the Earth with a magnetic rigidity bigger than the local geomagnetic cut-off value can penetrate deeper in the atmosphere, and if their energies are above the pion production they can produce muons, through the charged pion decay process ($\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$). The muon background at sea level is produced by galactic cosmic ray (mainly protons). Most of the particles (95% at $E > 1GeV$) observed at sea level are muons and the mean muon energy is ~ 4 GeV and their energy spectrum is almost flat below 1 GeV, steepens gradually to reflect the primary spectrum. The muon angular (zenith) distribution is close to $\cos^n \theta$ (with $n \sim$ 2.0) and this dependence is obtained when the azimuth angle is constant. However, if the muon flux is measured by a telescope in regime of raster scan, which follows a celestial source with zenith and azimuth angles simultaneously changing, the zenith angular distribution is distorted. Because of the geomagnetic effect, this change brings an excess of muons from the west direction.

On the other hand, the neutron monitor worldwide network, starting from 1954 by Simpson [4], has shown excellent performance to detection of solar particles, because the intensities are recorded to several geomagnetic cutoffs. The pitch angle distribution and other characteristic of a GLE due to a transient solar event, such as a flare or CME, can be better monitored. However, in most cases only powerful flares or CMEs can be associated by ground observations.

This survey is a continuation on ground level enhancements (GLEs) reported earlier on different subjects [2],[1]. In this paper we report three ground level enhancements (GLEs) detected in the last twelve hours on May 13, 2005, under ideal condition with the telescope axis oriented to the IMF lines. This characteristic is probably one of the reasons for the increase of the sensibility of the telescope and that it allowed the association, with a high confidence level, between the satellite observed solar flares (whose X-ray prompt emissions are classified by GOES satellite as C1.5 and M8.0) and the sudden increases in the muon flux, as well as the beginning of a pre-Forbush increase in the muon flux due to the arrival of a big solar disturbance of MeV protons observed in the ACE spacecraft.

Experimental setup

The TUPI muon telescope consisted of four plastic scintillator panels each 50 cm long, 50 cm wid and 3.0 cm thick. Each scintillator is viewed by a 7.0 cm Hamamatsu photomultiplier according to the scheme shown in Fig.xx. The main part o the telescope is built with two detectors A and B mounted telescopically and connected in coincidence as is shown in Fig.1. The separation among these two detectors is of 3 meters, and with this geometry it is possible to obtain an effective aperture of 65.5 $cm^2 sr$. An equatorial assembly allows the axis of the telescope always pointing to a pre-established direction. The telescope has two other detectors C and D (veto detectors) installed off the axis of the telescope, and are connected in anti-coincidence with the other two A and B detectors. The purpose of these detectors is to eliminate events, such as air showers, that reach the telescope in directions different from the direction o the telescope's axis.

The analogical signal output of each detector is pre-amplified and these analogical pulses are connected to a ADVANTAGE PCI47-11 card (inside a PC-computer) with 16 analogical input channel working with a counting rate of up to 100 kHz All the steps such as discrimination of the signals as well as coincidences and anti-coincidence are made via software using the virtual instrumen technique. Figure 1 summarizes the acquisition data here presented and the trigger of the telescope (signal in the A and B detectors and simultaneously no signal in the C and D detectors).

At the city of Niteroi where the TUPI muon telescope is located, the geomagnetic cut-off is 9.8 GV. The position is $22^0 54' 33''$ S and $43^0 08' 39''$ W at sea level. The telescope is inside a building and under two floors of concrete ($150 g cm^{-2}$, on average), as shown in Fig.1. The telescope can detect muons with energies greater than the $\sim 0.1 GeV$ required to penetrate the two floors.

Method

Direct measurements of solar energetic particles has been made successfully using satellite-borne observatories. However, these measurements are limits to MeV energy region by the small active areas in space. The high energy solar particles in the MeV to GeV energy region or above can be obtained using only indirect methods such as ground-based detectors. The ground-based detectors can infer information about the primary solar particles only from the showers originating from their interaction with air nuclei. This makes such observations extremely dependent on the knowledge of the shower development in the atmosphere.

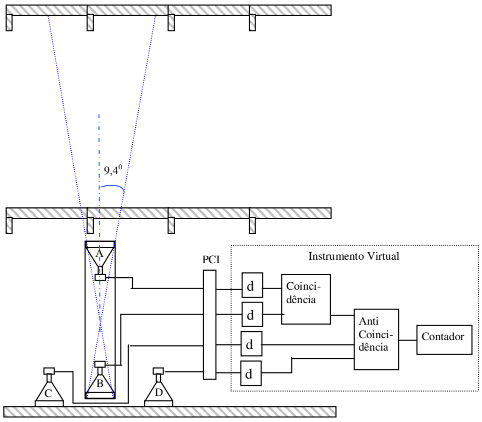

Figure 1: Scheme of the Tupi muon telescope and the data acquisition system.

The energetic solar charged particles follow the interplanetary magnetic field lines (IMF). The rotation of the Sun gives the magnetic field lines a spiral form with the pitch angle of the IMF at 1 AU about 45^0. If the telescope axis is oriented near or close to the direction of these IMF lines, as is shown in Fig.2, the solar particle sources will always be magnetically well connected to the telescope axis. This characteristics increases the sensitivity of the gound detector to the solar particle. Here we present some events obtained during a raster scan of an IMF line following the same Sun's declination plus a right ascension that equals the Sun's right ascension plus 3 h to give a pitch angle of 45^0. Figure 2 summarizes the configuration.

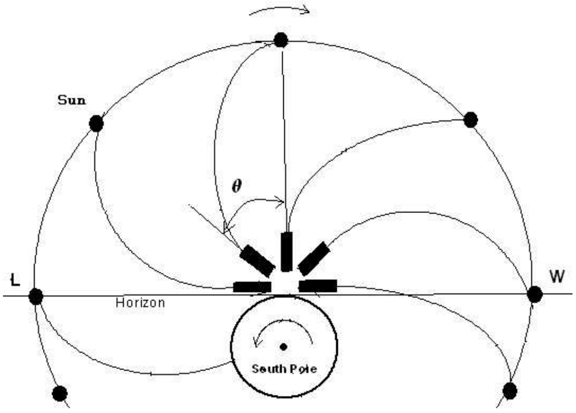

Figure 2: The raster scan of the Sun by the Tupi telescope. The scheme is for the best condition, $\theta = 45^0$ of pitch angle.

Transient solar events

Recent observations by using both spacecrafts and ground level detectors have shown three types of sources for solar energetic particle events.

(a) The first one is the impulsive events associated with the X-ray prompt emission of flares. In this case, the acceleration of the charged particles is by the shock wave of the flare. They are electron-rich and have a short duration. Consequently their observation at ground level requires powerful flares. The delay observed between the X-ray prompt emission and the energetic particles (above MeV energies) both at 1 AU is around 15 to 30 minutes.

(b) The second one is the gradual events associated with coronal mass ejection (CME). CMEs may and may not be associated with flares. In most cases, after around 30 minutes from the emission of a flare there is a CME. In this case, the particle acceleration occurs by CME driven shocks in the high solar corona. These events are called gradual events and are proton-rich, because their composition reflect the ionization states of the high corona. They are also of long duration, because as the shock wave spreads for the heliosphere it is able to accelerate particles of the ambient heliosphere plasma, as long as the strength of the shock is high enough.

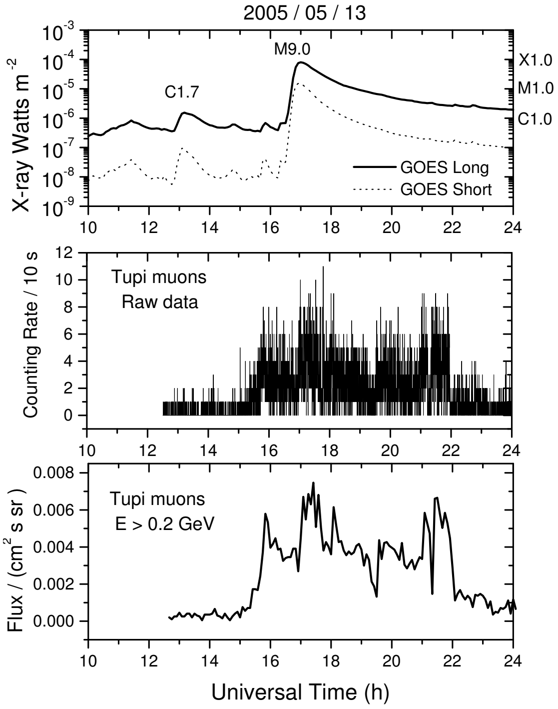

Figure 3: Time profiles of the solar X-ray emission, the Tupi raw data and the 5 minutes list of the muon intensity, for the 13/05/2005 raster scan.

The association between SOHO/LASCO CMEs and GOES-8 X-ray flares is $30 \pm 43.3\ min$ in average to CMEs no metric type II [3] and requires also taking into account the time of flight between the Sun and the Earth of highly energetic particles. The total delay is estimated from simulations and experimental data as 1.08 ± 1.57 hours for flares linked with CME (no metric type II). In this case, most of the flares are classifies as small scale.

(c) A third category of events specially observed at ground level is the so called Forbush events. They are transient depressions in the cosmic ray flux, reaching a minimum value in approximately one day followed by a gradual recovery in up to several days. They are associated with the shielding effect due to the passage of an interplanetary disturbance in the Earth's vicinity. This interplanetary disturbance is often a manifestation of CME shock and plasma envelope, or co-rotating high speed streams caused by fast moving materials catching up to the slow moving materials in the solar wind generating shocks.

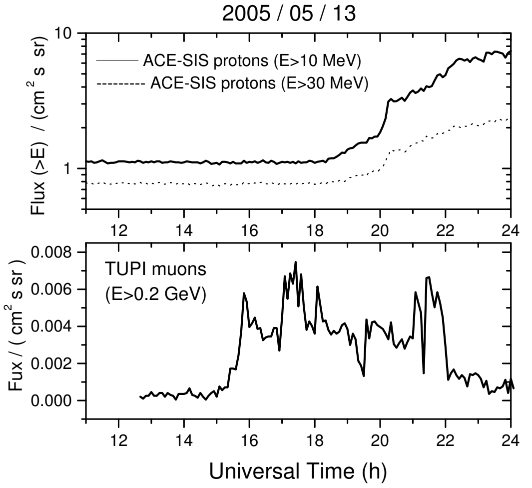

Figure 4: Time profiles of the solar SIS proton (ACE data) and the 5 minutes list of the Tupi muon intensity, for the 2003/05/13 raster scan.

Results

(a) The first TUPI muon enhancement can be associated to the solar flare of small scale whose prompt X-ray emission is classified as C1.5 class (see Fig.3). The flare starts at 12:49 UT, reaching a maximum at 13:04 UT according to the GOES data. After about 3 hours, a sudden increase of the TUPI muon flux reaching a maximum at 15:52 UT is observed. This delay suggests a gradual association between the flare and the GLE. In this case, the solar energetic particles are accelerated by shock waves driven by CMEs, because solar flare and CME often occur together. Usually CMEs have a delay in relation to the (C class) associated flare of 30 ± 43 minutes.

(b) The second TUPI muon enhancement may be associated to the powerful solar flare whose prompt X-ray emission is classified as M8.0 class (see Fig.3). The flare starts at 16:36 UT reaching a maximum at 17:28 UT. It is practically in coincidence with a sudden increase of the TUPI muon flux, which suggests an impulsive association between the flare and the GLE. In this case, the solar energetic particles are accelerated locally in the solar coronal by the solar flare itself.

(c) The third TUPI muon enhancement starts at about 21 UT. In contrast with the two previous enhancements, in this case there is no notification of solar flare by the GOES spacecraft. However, the TUPI muon sudden increase coincides with the arrival of protons (SIS protons) in the MeV energy band at the ACE spacecraft (see Fig.4). We call this as disturbance. This muon enhancement can be caused by the cosmic ray acceleration at the front of the advancing disturbance, and can be a signature of GV protons (above the geomagnetic cut-off) associated with the interplanetary disturbance and traveling at the front of it. The disturbance provokes a Forbush event only $\sim$ 27 hours after, on 15/05/2005, and it has been observed in all Neutron Monitors.

Conclusions

We have shown experimental evidences of the association between solar transient events observed by spacecraft and GLEs at ground level, obtained with a scintillator telescope always oriented to the IMF lines. A small scale flare, a large scale flare, and a disturbance were observed in a period of 12 hours. In all cases, there are energetic particles with energies beyond the local geomagnetic cut-off of 10 GeV, because they produce muons in the Earth's atmosphere. The acceleration mechanism in solar flares to extreme energies remains open, specially for flares of small scale and continued observations and further investigations are called for.

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