29th International Cosmic Ray Conference Pune (2005) **00**, 101–104

Muons enhancements at sea level from solar flares of small scale

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The TUPI experiment is a tracking telescope on the basis of plastic scintillators located at sea level (Niteroi city Brazil), has successfully observed muon enhancements associated to solar flares of small scale. The previous results are confirmed and more events (muon enhancements) are reported. We show that small scale solar flares, those with prompt X-ray emission classified as C class (power above 10^{-6} Watts m^{-2} at 1 AU) may give rise to GLEs, probably associated with solar protons and ions arriving to the Earth as a coherent particle pulse. The TUPI telescope's high performance with these energetic solar particles arises mainly from: (1) its high counting rate (up to 100 KHz). This value in most cases is around 100 times higher than other detectors at ground and (2) due to its tracking system. The telescope is always looking near the direction of the IMF lines. The GLE's delay in relation of the X-ray prompt emission suggest that shock driven by corona mass ejection (CME) is an essential requirement for the particle acceleration efficiency.

1. Introduction

It is commonly accept that a solar flare must be powerful to be a candidate for association with a GLE. Because, in most cases, we have found reports of the detection at ground level of GLEs associated to solar powerful flares of large scale, those with a X-ray prompt emission classified as X-class (above $10^{-4}W\ m^{-2}$). Our previous paper was devoted to cross-correlation analysis between the sudden commencements in the muon counting rate at sea level and the X-ray prompt emission of solar flares of small scale [1]. The high performance of the TUPI muon telescope with respect to a muon cluster whose origin is the arrival in the upper atmosphere of a small bundle of protons and/or ions with energies exceeding the pion production and above the local geomagnetic cut-off (9.8 GV) arises mainly from: (1) its high counting rate ($\sim$ 100 kHz) and (2) its tracking system. The telescope is always looking near to the direction of the IMF lines. Details of the experimental setup of the TUPI telescope have been reported in [2, 3].

Observations in satellites and at ground of solar flares [4] have led to the identification of two classes of acceleration events: impulsive (prompt) and gradual (post-eruptive or delayed). The impulsive events require selective acceleration such as the gyroresonant interaction with plasma waves. The energetic particles from these events arrive very quickly, around 15-25 minutes after a flare. In contrast, the gradual events have a strong association with coronal mass ejection (CME) and suggest that the particles in these events are accelerated by CME driven shocks. The energetic particles from these events are observed up to several hours after a flare.

The GLEs as observed by the TUPI telescope at sea level are characterized by an impulsive peak with a fast rise time . This is a signature indicating that they are constituted by a bundle of muons produced in the atmosphere by the arrival of a coherent particle pulse, probably from the sun. This mean that the particles from the pulse front arrive at the earth almost simultaneously. In order to discriminate (to count) a small coherent particle pulse, a detector working with a rather fast response time, better than milliseconds, is necessary in order to reduce the dead time, during which the detector may not respond to the incident radiation. The TUPI telescope has a counting rate up to $\sim$ 100 KHz. This value in most cases is around 100 times higher than other detectors at ground, and at this frequency it is possible to obtain a response time as short as $\Delta T \sim 10\ \mu s$.

Due to the TUPI telescope's tracking system, the pitch angle defined as the angle between the sun-ward direction and the telescope axis direction, is always the same (constant) during a raster scan. This characteristic probably also helps to increases the sensitivity because the energetic solar charged particle propagation follows the interplanetary magnetic field lines (IMF), the rotation of the Sun gives the magnetic field a spiral form (garden hose effect) the pitch angle of the IMF at 1 AU is $\sim 45^0$ (this value doesn't include the magnetic field of the Earth). If the telescope axis is oriented near or close to the direction of these IMF lines, as is schematized in Fig.1, the solar particle sources will be magnetically well connected to the direction of the telescope axis and the detection efficiency will be close to maximum. This favorable situation increases the telescope's sensitivity.

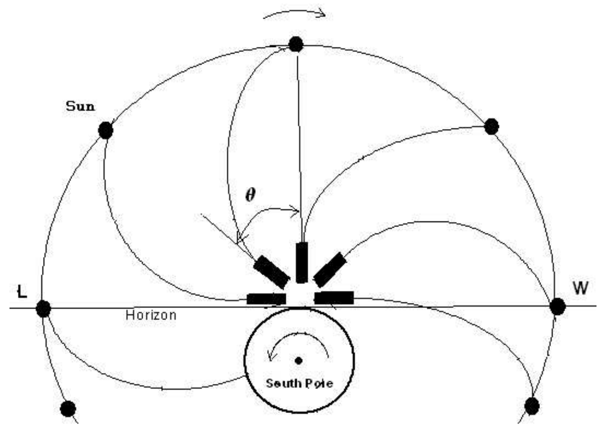

Figure 1. Schematic representation in the South hemisphere of the IMF "garden hose" lines connecting the Sun and the Earth during a raster scan. Due to its tracking system the TUPI telescope axis is always close to the direction of the IMF lines. The scheme is for the best condition, 45^0 of pitch angle

2. Results

In figures 2 and 3 the time profiles of the GOES12 X-ray in the band-width $1.0-8.0$ A and $0.5-4.0$ A [5] (upper panels), the TUPI raw data (central panels) and the TUPI relative intensity after pressure corrected (lower panels) are shown for four raster scans respectively. When a GLE has been correlated with a solar flare, the X-ray peak (in the $1.0-8.0$ A band-width) of the flare is marked by a flare index. For example, C1.3 means $1.3\times10^{-6}Wm^{-2}$.

Due to virtual instrument technique used in the data acquisition system, it is possible to examine the time profile of a GLE for other off-line (higher) pulse-height amplitude discrimination, chosen via software [2]. Using this "noise filter" we have verified that the six GLEs here presented are not mere background fluctuations.

3. Conclusions

In most of cases only the impulsive emission of powerful flares (such as those of X class) is accompanied by observations at ground level by the network neutron monitors at ground. However, in this paper, the TUPI telescope's previous result about muon enhancements in association with small scale flares (power above 10^{-6} Watts m^{-2} at 1 AU) is confirmed and other four events are here reported. The high counting rate (up to 100 kHz) together with the tracking system make of the TUPI telescope very sensitive to the a bundle of muons produced by a coherent particle pulse coming from the sun

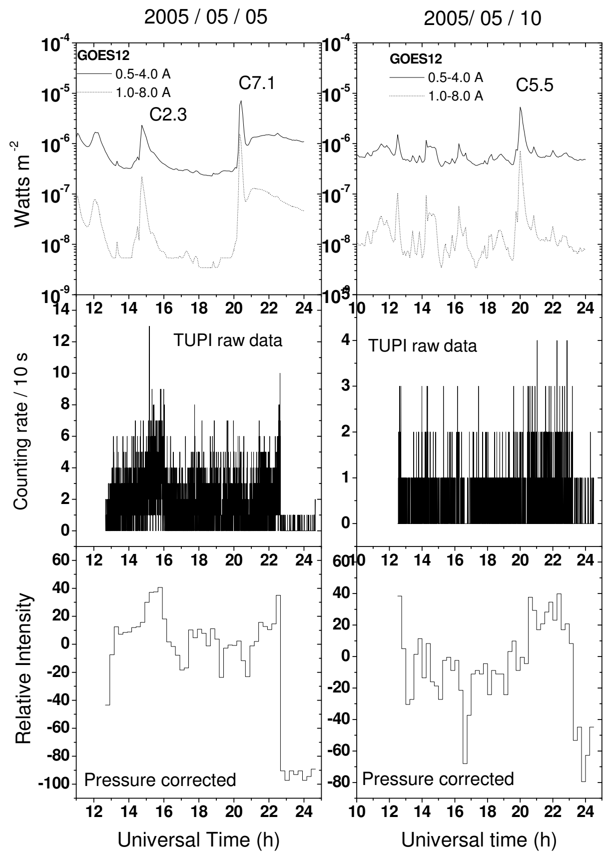

Figure 2. Upper panels: Time profiles of the GOES12 X-ray prompt emission in two different energy bands. Middle panels: TUPI raw data. Lower panels: TUPI muon relative intensity after pressure correction for the 2005/05/05 and 2005/05/10 raster scans respectively.

The delay between the flare emissions and the GLEs of up to several hours suggest an association with gradual or post-eruptive acceleration processes. Consequently, the shock driven by CME is an essential requirement for the particle acceleration efficiency.

4. Acknowledgements

This work was partially supported by FAPERJ (Research foundation of the State of Rio de Janeiro) in Brazil. The authors wish to express their thanks to Dr. A. Ohsawa from Tokyo University for help in the first stage of the experiment. We are also grateful to the various catalogs available on the internet and to their open data police, especially to the NOAA's Space Environment Center (SEC).

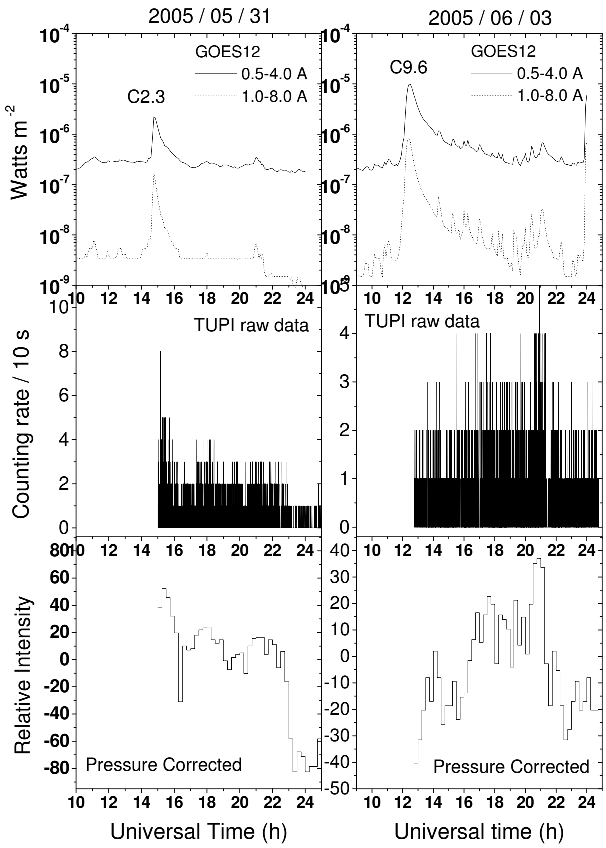

Figure 3. Upper panels: Time profiles of the GOES12 X-ray prompt emission in two different energy bands. Middle panels: TUPI raw data. Lower panels: TUPI muon relative intensity after pressure correction for the 2005/05/31 and 2005/06/03 raster scans respectively.

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