Interplanetary coronal mass ejection effect on the muon flux at sea level

C. E. Navia, C. R. A. Augusto, and M. B. Robba
Instituto de Física Universidade Federal Fluminense, 24210-130, Niterói, RJ, Brazil

(Dated: January 14, 2019)

We present the results of 720 hours of observations of transient solar events at ground level, during the summer season 2005 (Souther Hemisphere). Data were taken with the TUPI muon telescope, working at a high counting rate (up to 100 KHz) and always pointing on the IMF lines (45 degrees of pitch angle). An anti-correlation among the arrival of keV protons (observed by EPAM detector aboard the ACE spacecraft) and sudden depressions in the muon flux at sea level have been observed. The phenomena is discussed in the context that they can be considered as mini-Forbush, caused by a shielding effect of the passage of a disturbance (shock and plasma) and may be a signature of interplanetary manifestations of coronal mass ejections.

Direct measurements of solar energetic particles have been made successfully using satellite-borne observatories. However, these measurements are limits to the 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. The detection of solar neutrons and charged particles at ground level using the neutron monitor world-wide network starting from 1954 by Simpson [1] have shown an excellent performance, because the intensities are recorder to several geomagnetic cut-offs and the geomagnetic dependence, anisotropies and other characteristics may be better known. Transient depressions reaching a minimum value in approximately one day in the galactic cosmic ray intensity following for a gradual recovery in up to several days have been observed in neutron monitors data. These phenomena, called "Forbush events" [2] have been known over the past 6 decades. It is now known that they are associated with the passage of an interplanetary disturbance (shock and plasma enveloping the Earth) [3] and in most cases they are considered as an interplanetary manifestations of coronal mass ejections.

On the other hand, in the framework of a study of a possible "photo-muon" excess from galactic center, several ground level enhancements (GLEs) in the muon flux have been found. 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 [4]. 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 (∼ 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, 4].

We present here the results of a experiment dedicated to the investigation of transient solar events such as solar flares and their influence on the galactic cosmic rays at 1 AU. The 720 hours of observation during the summer season 2005 (Souther Hemisphere) correspond to 60 raster scans with a duration of 12 hours each, across parallel lines in declination (Sun’s declination) and an hour angle of 3 hours early in relation to the Sun’s hour angle, under this conditions the pitch angle is always 45° (where 0° pitch angle represent sun-ward direction). Figure 2 from the ref. [4], summarizes the situation. In this summer session we have identified several sudden depressions (already observed previously) in the muon counting rate and we show here that these muon intensity depressions and the arrival of solar protons in the keV energy region at the ACE spacecraft [7] may be a good indicator of the passage of a small interplanetary disturbance (shock and plasma). This is because sudden and/or gradual increases of keV protons (above the proton flux background flux) in the ACE spacecraft coincide with the beginning of the depressions in the TUPI muon intensity at ground level.

On the other hand, ref. [8] has reported Forbush events in 30 years of neutron monitor data. Forbush events was observed also in spacecraft experiments [6], in air shower arrays [10], as well as in muon telescopes at ground level [11]. The magnitudes of the Forbush depression depend of several factors such as the energy threshold of the detected particles, the geomagnetic cut-off of the observation location, as well as how the data are presented. For instance hourly averages present bigger magnitudes than the daily averages. In the TUPI experiment the Forbush events have been observed as a drastic change in the muon count rate (raw data). The muons detected ($E_{\mu} > 0.1$ GeV) are produced by primary charged particles (protons and/or ions) with an energy above the geomagnetic cut-off (9.8 GV) and the data is presented in bins of 15 minutes. Figures from 1 to 5 presents five samples of events observed during the summer season 2005. In all cases, in the lower panels, the TUPI muon relative intensity (pressure corrected) is presented, and in the upper panels the solar proton flux (EPAM protons) as observed by ACE spacecraft in the keV energy band is
shown. From these figures it is possible to extract some special characteristics of Forbush events observed by a narrow angle (9.5° of aperture) muon telescope at sea level, with a geomagnetic cut-off of 9.8 GV and always pointing to the IMF lines (45 degrees of pitch angle). These can be summarized by the following: (a) In most cases the sudden depression coincide with the arrival at the Earth of solar protons (EPAM protons) in the keV energy band. In the event on 2005/02/24 the arrival of keV protons is around 40 minutes before the depression and in the event on 2005/04/26 the arrival of keV protons is ∼ 2 hours before the depression. (b) In all cases the duration of the depression exceed the 23 hours UT when the telescope tracking run is off, and we do not have the duration of the depressions, we have only some evidence indicating a recovery time shorter than 24 hours. However, in order to obtain this information we include in the analysis two events observed out of the summer season 2005, in two consecutive days. Figure 6 summarize the situation. All the characteristics (as above mentioned) of Forbush events observed in the TUPI muon flux are valid for these two events. In addition the recovery time can be obtained as 21 hours. This short recovery time contrast with the recovery time (several days to week) observed in Forbush events in NM data. (c) In some cases before the sudden depression a pre-Forbush increase in the muon flux is observed, probably caused by the galactic cosmic ray acceleration at the front of the advancing disturbance. A clear pre-Forbush increases can be observed for instance in the event on 2005/03/03 (see Fig.4) and specially on 2005/04/25 (see Fig.6 right). A big pre-Forbush as shown in Fig.6 may be also a signature of the presence of GV protons (above the geomagnetic cut-off) associated with the interplanetary disturbance [12]. However this type of signature (GV associated protons) can be observed better in the polar regions where the geomagnetic cut-off is smaller. (d) In contrast with Forbush decrease events as observed in neutron monitor (NM) data, characterized with a sudden depression lasting 10 hours to one day to reach a minimum intensity, the Forbush events observed in the TUPI muon flux have a sudden remarkable depression reaching a minimum intensity around one hour. (e) In the case of the event on 2005/03/15 (Fig.5) there is also the arrival the very high energy proton flux in the MeV energy band (ACE SIS-protons) around 1.5 hours before the beginning of the depression. The prompt high energy solar particles observed inside or immediately before of keV solar proton (ejecta) suggest that the ejecta field lines are connected to the Sun. (f) The event on 2005/04/25 (see Fig.6) is possible to see the two step signature of the Forbush depression, the first decrease occurs due to the passage of the turbulent field (shock) followed by the passage of the ejecta (plasma). It is possible to see also which the magnetic cloud is not uniform during its passage to the earth, because anisotropies can be observed in the depressions (see figures 5 and 6 right).

On the other hand, if Forbush were the interplanetary manifestation of CMEs a 1 : 1 correspondence will be expected. However, if we take into account only those cloud (shock and ejecta) crossing the vicinity on Earth a correspondence between CMEs and Forbush of 7 : 1 would be expected [13]. The occurrence rates of CMEs at solar minimum is ∼ 0.7 per day, meaning that the occurrence rates of Forbush on Earth is 0.1 per day or 3 per month. A preliminary result from the present experiment it indicates a Forbush rates of 9 per month, three times larger than the expected value. This results suggest a second cause or mechanism for the origin of the Forbush events, such as co-rotating high speed streams [14], because, the solar wind can be followed by a fast moving stream, the faster moving material will catch-up to the slower material and this interaction produces shock waves that can accelerate particles. One might question also the ability of ground-based experiments to detect all Forbush events, because only a fraction of Forbush (22 events) [16] were identified in 57 ICME-CME pairs [17]. However, any conclusion with respect to Forbush rates is premature. Our result need further confirmation because the present ongoing experiment will deliver much better statistics in the coming years.

Besides the high rate of Forbush events observed in the TUPI experiment, the change in the temporal scale when compared with NM events is other characteristic observed in TUPI events. The beginning of the TUPI Forbush events correspond, in a straightforward way, to local minima in the hourly average flux observed by the Moscow Neutron Monitor [18]. However, during the TUPI Forbush events the kp scale [19] is smaller than 5. The kp index of 0 to 4 is below magnetic storm, consequently there is not storm notification (or storm level G0) at least according to the NOAA Space Weather Scale. Consequently, we are probably in the front of a new category of Forbush events, and we called mini-Forbush events. They happen in the high energy region and in anti-coincidence with the arrival on the Earth of keV protons and this characteristic can be used as a signature of an interplanetary ”thin” disturbance crossing the vicinity of Earth.

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 and to Dr. M. Olsen for reading the manuscript. We are also grateful to the various catalogs available on the internet and to their open data police, especially to the ACE Real-Time Solar Wind (RTSW) Data.

[1] J. . Simpson, Phys. Rev. 94, 426 (1954).

[2] S. C. Forbush, Phys. Rev. 51, 1108 (1937).
[3] E. N. Parker, Interplanetary Dynamical Processes, Monographs and Texts in Phys. and Astro., 8, Interscience Publishers: New York, New York (1963).
[4] C. R. A. Augusto, C. E. Navia and M. B. Robba, to appear in PRD., preprint (astro-ph/0504644 v1).
[5] C. R. Augusto, C. E. Navia and M. Robba, Nucl. Instrum. Methods Phys. Res. 503, 554 (2003).
[6] C. E. Navia, C. R. A. Augusto, M. B. Robba, M. Malheiro and H. Shigueoka, Astrophys. Journal. 621, 1137 (2005).
[7] ACE Real-Time Solar Wind Data Website, World Wide Wide: [http://www.sec.noaa.gov/ace/](http://www.sec.noaa.gov/ace/)
[8] H. V Cane, I. G. Richardson, and T. T. von Rosenvinge, J. Geophys. Res., 101(A10), 21561 (1996).
[9] H. V. Cane, I. G. Richardson, and G. Wibberenz, J. Geophys. Res., 102(A4), 7075 (1997).
[10] A. Mahrous et al., in 27th ICRC, Hamburg, 3477 (2001).
[11] K. Fujimoto, I. Okada, T. Aoki, K. Mitsui, H. Kojima and Y. Ohasi, in 27th ICRC, Hamburg, 3525 (2001).
[12] J.E Humble, M. L Dulding, M. A. Shea, D. F. Smart and H. Sauer, in 24th ICRC, Rome, 4, 900 (1995).
[13] H. Cane, Space Science Review 93:55 (2000).
[14] N. Iucci, M. Parise, M. Storine and G. Villoresi, Il Nuovo Cimento, 2C, 1 (1979).
[15] Oulu spaceweb textbook, available in [http://www.oulu.fi/textbook/solarwind.html](http://www.oulu.fi/textbook/solarwind.html)
[16] R. F. Penna and A. C. Quillen, preprint (astro-ph/0411588 v2).
[17] N. Gopalswamy, A. Lara, S. Yashiro, M. L. Kaiser and R. A. Howard, J. Geophys. Res., 106(A12),29207 (2001).
[18] Moscow Neutron Monitor data: available in [http://helios.izmiran.rssi.ru/cosray/main.htm](http://helios.izmiran.rssi.ru/cosray/main.htm)
[19] The K index: available in [http://www.sec.noaa.gov/info/Kindex.html](http://www.sec.noaa.gov/info/Kindex.html)
FIG. 1: Upper panel: Time profiles of the EPAM protons in two different energy bands. Lower panel: TUPI muon relative intensity after pressure correction for the 2005/02/16 raster scan.
FIG. 2: The same as figure 2, only for the raster scan on 2005/02/17.
FIG. 3: The same as figure 2, only for the raster scan on 2005/02/24.
FIG. 4: The same as figure 2, only for the raster scan on 2005/03/03.
FIG. 5: The same as figure 2, only for the raster scan on 2005/03/15.
FIG. 6: The same as figure 2, only for the raster scan on 2005/04/25 and 2005/04/26.