Mini-Forbush events on the muon flux at sea level

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The results of 720 hours of observation of transient solar events at ground level during the summer season of 2005 in the southern hemisphere are presented. Data were taken with the TUPI muon telescope working at a high counting rate of up to 100 KHz and always pointing to the IMF lines at 45 degrees of pitch angle. An anticorrelation between the arrival of the KeV protons observed by EPAM detector aboard the ACE spacecraft and sudden depressions in the muon flux at sea level has been observed. The phenomenon is discussed in the context that it can be considered as mini-Forbush, caused by a shielding effect of the passage of a disturbance (shock and plasma). It may be regarded as a signature of interplanetary manifestations of coronal mass ejections, as well as corotating high speed streams.

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I. INTRODUCTION

Direct measurements of solar energetic particles have been made successfully using satellite-borne observatories. However, these measurements are limited to below the MeV energy region by 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. Interactions of the primary cosmic rays with the atmosphere produce, among other things, a lower energy secondary nucleons, in particular, neutrons that are not slowed by ionization loss. These secondaries fall in the energy range of a few hundred MeV up to about 1 GeV. These nucleons in turn produce further nuclear interactions, either in the atmosphere or in lead target materials surrounding the neutron monitors (NM) used as detectors. The interaction rate may be measured most conveniently and reliably by detecting the reaction products in neutrons rather than by detecting the charged fragments directly. In addition, neutron monitors have also the capacity to see neutron enhancements due to the solar flares and coronal mass ejection.

The neutron monitor worldwide network starting from 1954 by Simpson [1], has shown excellent performances because the intensities are recorded to several geomagnetic cutoffs and the geomagnetic dependence and anisotropies and other characteristics are better known. Transient depressions reaching a minimum value in approximately 1 d in the galactic cosmic ray intensity followed by a gradual recovery of several days to one week have been observed in NM data. These phenomena, called ‘‘Forbush events’’ [2], were known over the past six decades. It is now clear that they are associated with the passage of an interplanetary disturbance of shock and plasma enveloping Earth [3], and in most cases they are considered as interplanetary manifestations of coronal mass ejections (CMEs).

Our original objective of this TUPI telescope in observing ground level enhancements in the muon flux was actually to investigate the possible ‘‘photo-muon’’ excess from galactic center. It was not intended to investigate the Forbush events. 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 small scale solar flares [4]. The high performance of the TUPI muon telescope in detecting a muon cluster, generated by the arrival in the upper atmosphere of a small bundle of protons and/or ions with energies exceeding the pion production level and above the local geomagnetic cutoff of 9.8 GV, arises mainly from two factors. The first is its high counting rate of up to 100 kHz and second is its tracking system which guides the telescope looking always near the direction of the interplanetary magnetic field (IMF) lines. From January 2005 onward, the TUPI muon telescope has been collecting data pointing to the direction of the IMF lines. In this paper, we will show that, with the detector magnetically well connected to the Sun through the IMF lines and working with a high counting rate, it is possible to observe a new category of Forbush events called here as mini-Forbush. In order to understand the origin of these mini-Forbush events, a straightforward analysis is made.

This paper is organized as follows. In Sec. II, we present the experimental setup of the TUPI telescope. The results of seven Forbush events and the analysis of these events are presented in Sec. III. In Sec. IV, the Forbush event rate is discussed, and our conclusions are presented in Sec. V.

II. EXPERIMENTAL SETUP

The TUPI muon telescope is located at sea level in the city of Niteroi at the southeast part of Brazil with latitude $S22^0 54' 33''$ and longitude $W43^0 08' 39''$. The telescope consists of four plastic scintillator panels each with 50 cm

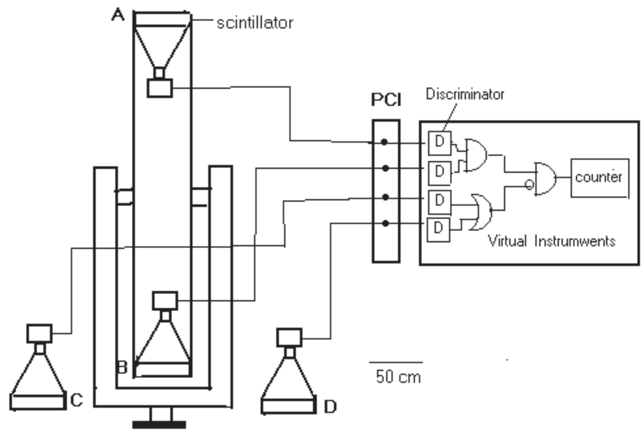

FIG. 1. Experimental setup of the TUPI telescope including the data acquisition system.

long, 50 cm wide, and 3 cm thick. Each scintillator is viewed with a 7 cm Hamamatsu photomultiplier. The main part of the telescope is built with two detectors A and B mounted telescopically and connected in coincidence according to the scheme shown in Fig. 1. The separation between these two detectors is 3 m, and with this geometry it is possible to obtain an effective aperture of 65.5 cm^2 sr. Two veto detectors C and D are installed off the axis, and are connected in anticoincidence with A and B. The objective of these off-axis detectors is to eliminate events such as air showers that reach the telescope in a direction different from that of the axis. The analogical signal output of each detector is preamplified, and the preamplifier signal has a rise time of 1.0 μs. These analogical pulses are connected to a ADVANTAGE PCI47-11 card inside a PC-computer with 16 analogical input channels working with a counting rate of up to 100 kHz. All the steps, such as discrimination of the signals as well as coincidences and anticoincidences, are made via software using the virtual instrument technique. The right part of Fig. 1 summarizes the data acquisition system. The telescope is triggered by events leading to signals in A and B detectors and simultaneously no signal in C and D detectors. More details of the experimental setup and results of the TUPI telescope have been reported elsewhere [5,6].

III. RESULTS

We present here the results of an 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 of 2005 in the southern hemisphere corresponds to 60 raster scans, with a duration of 12 hours each, across parallel lines in declination approximately equals to that of the Sun's declination and a right ascension that also approximately coincides with the Sun's right ascension plus 3 h. In Table I, the coordinates of declination and right ascension of the Sun and the observed point for seven raster scans are presented. Under these conditions, due to the angular aperture of 9.5 degrees of the telescope, the IMF lines are inside of the field of view of the telescope. In other words, the pitch angle, defined as the angle between Sunward zero degree reference direction and the telescope's axis, is approximately 45 degrees during a raster scan. Figure 2 summarizes this basic configuration.

The magnitude of the Forbush depression depends on several factors, such as the energy threshold of the detected particles, the geomagnetic cutoff of the observation location, as well as the way data are presented. For instance, hourly averages present bigger magnitudes than daily averages. In the TUPI experiment, the Forbush events have been observed as a drastic change in the raw data muon count rate. The detected muons with $E_\mu > 0.1$ GeV are produced by primary charged particles of protons and/or ions with an energy above the local geomagnetic cutoff of 9.8 GV, and the data are presented in bins of 15 minutes. In this summer, we have identified the beginning of these sudden depressions in the TUPI muon intensity coinciding with gradual and/or sudden increases of KeV protons above the background proton flux in the EPAM detector aboard of the ACE spacecraft [7]. This may be a good indicator of the passage of a small interplanetary disturbance of shock and plasma in Earth vicinity. Figures 3–8 present seven sample events. In the lower panel, the TUPI muon pressure corrected relative intensity is presented, and in the upper panel, the solar EPAM proton flux in the KeV energy band is shown. In order to see the fluctuations during a raster scan, a central panel is included in Fig. 3

TABLE I. Coordinates of declination and right ascension of the Sun and the TUPI telescope axis during the seven raster scans here presented.

Sun coordinates			TUPI telescope coordinates	
Date	Declination	Right ascension	Declination	Right ascension
2005/02/16	$-12^0 9' 13''$	22h0m52s	-12^0	23.1 h
2005/02/17	$-11^0 48' 12''$	22h4m44s	-12^0	23.3 h
2005/02/24	$-9^0 16' 21''$	22h31m30s	-12^0	23.2 h
2005/03/03	$-6^0 37' 40''$	22h57m49s	-8^0	23.3 h
2005/03/15	$-1^0 56' 7''$	23h42m7s	-8^0	0.4 h
2005/04/25	$+13^0 21' 25''$	2h12m48s	$+8^0$	3.1 h
2005/04/26	$+13^0 40' 44''$	2h16m34s	$+8^0$	3.2 h

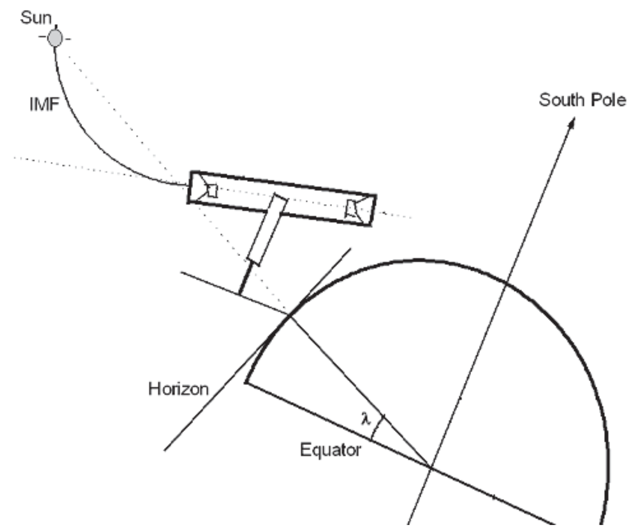

FIG. 2. Tracking system of the TUPI telescope with an equatorial assemble. The scheme has a pitch angle of 45 degrees such that the telescope axis is always well-connected to the IMF lines (garden hose lines) between the Sun and Earth.

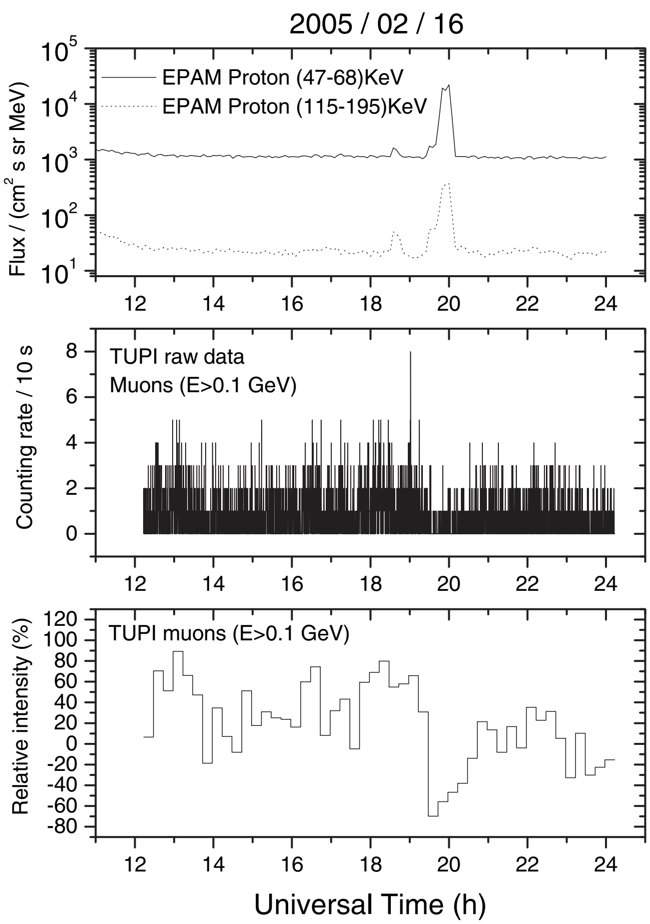

FIG. 3. Upper panel: Time profiles of the EPAM protons in two different energy bands. Central panel: TUPI raw data with count rate at every 10 seconds. Lower panel: TUPI muon relative intensity after pressure correction for the 2005/02/16 raster scan.

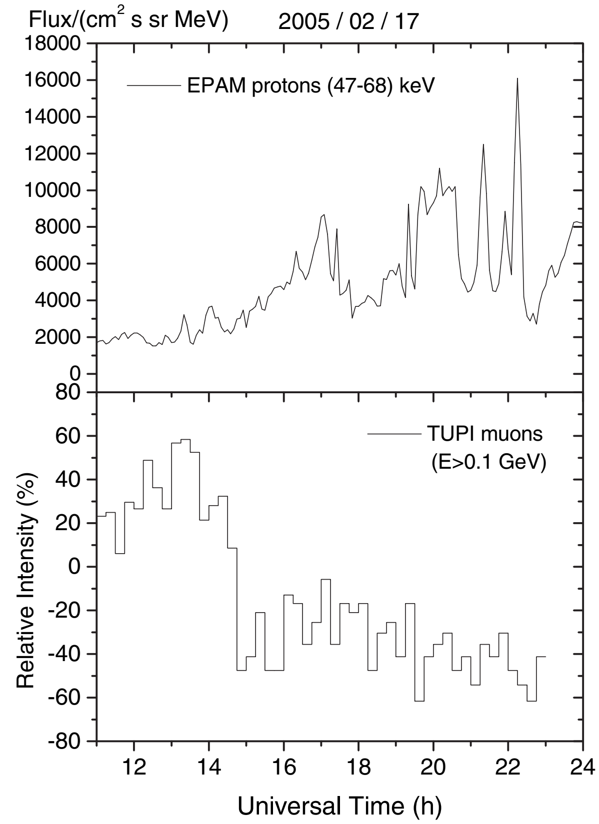

FIG. 4. Upper panel: Time profiles of the EPAM protons in two different energy bands. Lower panel: TUPI muon relative intensity after pressure correction for the 2005/02/17 raster scan.

where the raw counting rate is shown. From these figures, it is possible to extract the following special characteristics of Forbush events observed by a 9.5° narrow aperture IMF aligned muon telescope.

(a) In most cases, the sudden depression coincides with arrival of solar EPAM protons in the KeV energy band. For the event on 2005/02/24, the arrival of KeV protons is around 40 minutes before the depression, and for the event on 2005/04/26, the arrival of KeV protons is about two hours before the depression.

(b) In all cases, the duration of the depression exceeds the 23rd hour UT when the IMF lines are out of reach of the telescope tracking system. In order to estimate the recovery time, we include two events in two consecutive days, as shown in Fig. 8, giving a recovery time of about 21 hours. All the above mentioned characteristics of Forbush events of this TUPI muon flux are valid for these two events. This short recovery time contrasts with the recovery time of several days to one week observed in NM Forbush data.

(c) In some cases, a pre-Forbush increase in the muon flux is observed before the sudden depression, probably caused by the galactic cosmic ray accel-

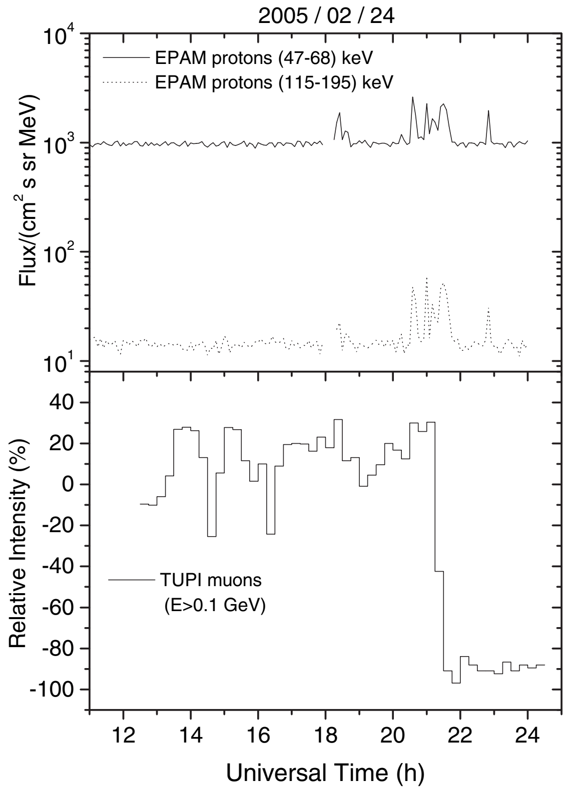

FIG. 5. The same as Fig. 4, only for the raster scan on 2005/02/24.

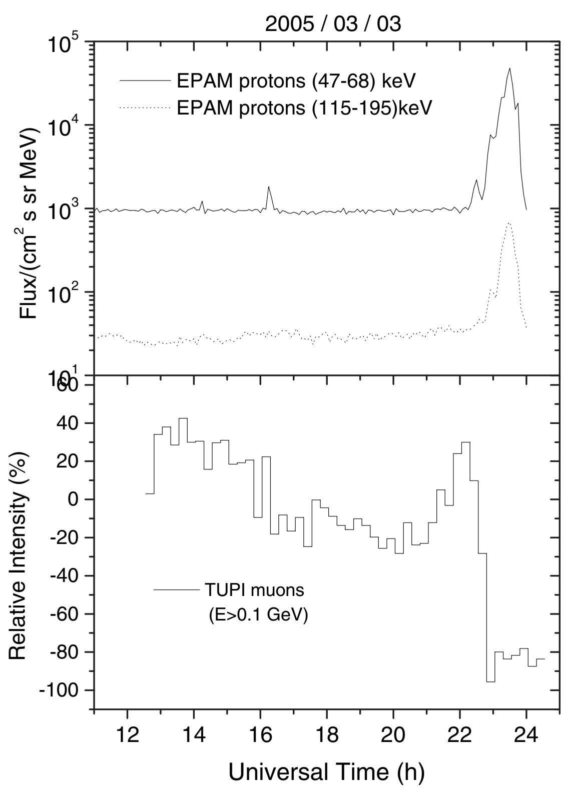

FIG. 6. The same as Fig. 4, only for the raster scan on 2005/03/03.

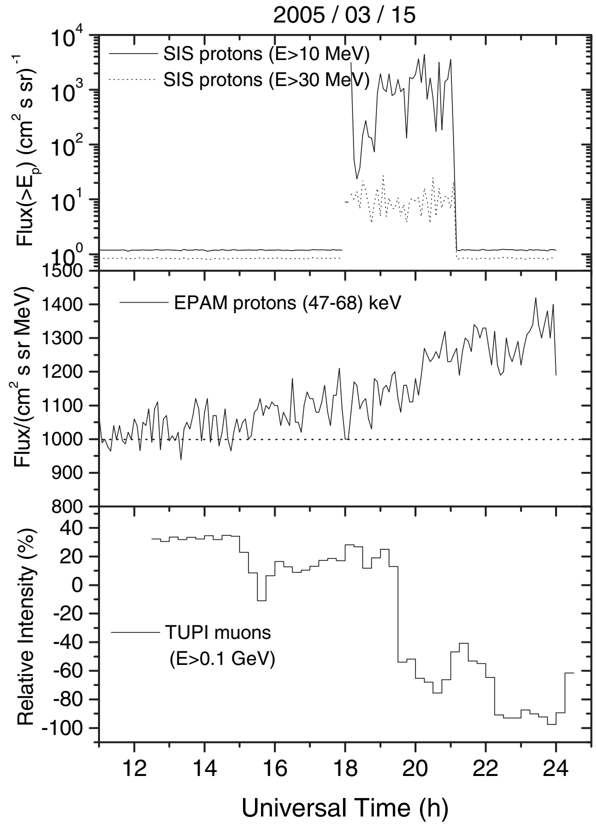

FIG. 7. The same as Fig. 4, only for the raster scan on 2005/03/15.

eration at the front of the advancing disturbance by mirror effect. A clear pre-Forbush increase can be observed for instance in the events on 2005/03/03 (see Fig. 6) and especially on 2005/04/25 (see Fig. 8 left). A big pre-Forbush shown in these figures may also be a signature of the presence of GV protons above the geomagnetic cutoff associated with the interplanetary disturbance [8], called as "energetic storm particles." However this type of GV associated proton signature can be observed better in the polar regions where the geomagnetic cutoff is smaller.

(d) In contrast to Forbush events as observed in NM data, characterized by a depression that takes 10 hours to 1 d to reach the minimum intensity, the Forbush events observed in the TUPI muon flux have a remarkable sudden depression that reaches the minimum intensity in about 1 h.

(e) In the case of the event on 2005/03/15 (Fig. 7), there is also the arrival of 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 the KeV solar proton ejecta suggest that the ejecta field lines are connected to the Sun.

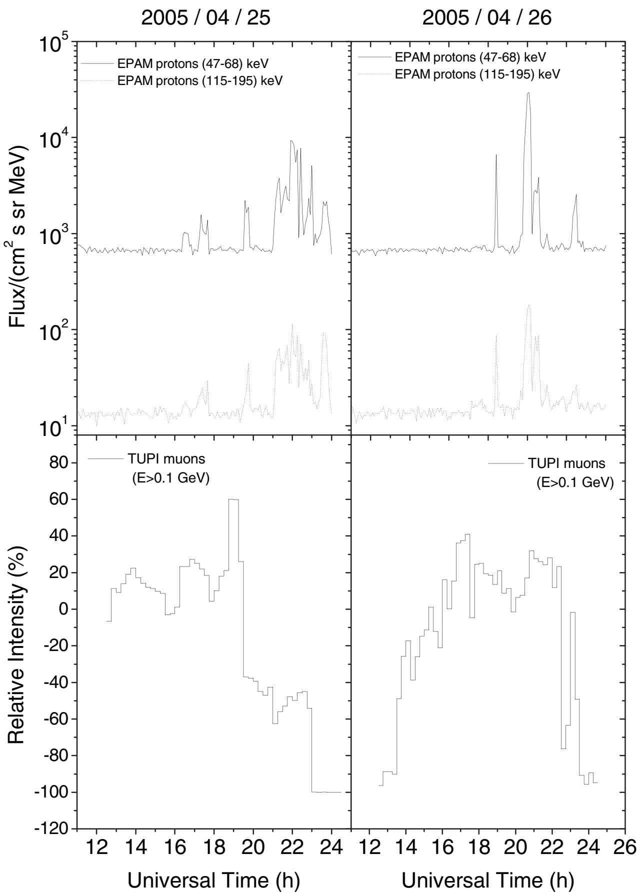

FIG. 8. The same as Fig. 4, only for the raster scan on 2005/04/25 and 2005/04/26.

(f) As for the event on 2005/04/25 (Fig. 8), it shows clearly the two step signature of the Forbush depression. The first decrease occurs due to the passage of the turbulent shock field followed by the passage of the ejecta plasma. It is also possible to see that the magnetic cloud is not uniform during its passage through Earth, because anisotropies can be observed in the depressions, for instance, in Figs. 7 and 8 right.

IV. FORBUSH EVENT RATES

Forbush events have been reported in the last 30 years of NM data [9]. Forbush events are also observed in spacecraft experiments [10], in air shower arrays [11], as well as in muon telescopes at ground level [12]. On the other hand, if Forbush were the interplanetary manifestation of CMEs, a one to one correspondence would be expected. The occurrence rate of CMEs at solar minimum is about 0.7 per day on the Sun. Taking into account that only one in every seven magnetic clouds (shock and ejecta) crosses Earth [13], the occurrence rates of Forbush on Earth is 0.1 per day or 3 per month. Preliminary result of the present experiment indicates a Forbush rate of 10 per month which is 3 times larger than the expected value. This result suggests a second cause or mechanism for the origin of the Forbush events, such as corotating high speed streams [14]. These streams are generated by fast moving jets, originating from coronal holes, catching up on the solar wind in the spiral of the IMF lines. The corotating interaction produces shock waves creating pressure variations. Since only a fraction of Forbush (22 events) [15] was identified in 57 ICME-CME pairs [16], one might also question the ability of ground-based experiments in detecting all Forbush events. In any case, any conclusion with respect to the Forbush rate at this time is premature. Our results will need further confirmation because the present ongoing experiment will deliver much better statistics in the coming years.

V. CONCLUSIONS

In this paper, we have presented experimental evidences of sudden depressions observed in the TUPI muon flux at sea level in coincidence with the arrival of KeV protons observed by the EPAM detector aboard the ACE spacecraft. The detected muons have energies above 0.1 GeV and they are produced by charged primaries, mainly protons, with energies compatible with the local geomagnetic cutoff of 9.8 GV. The analysis corresponds to observations during the summer season of 2005. Besides the high rate of Forbush events observed in this TUPI experiment, the time scale of these events is very different comparing with NM events. On the other hand, the beginning of the TUPI Forbush events corresponds, in a straight forward way, to local minimum in the hourly average flux observed by the Moscow Neutron Monitor [17]. However, during the TUPI Forbush events, the k_p scale [18] is smaller than 5. Since the k_p index of 0 to 4 is below magnetic storm level, consequently there is no storm notification (or storm level G0) at least according to the NOAA Space Weather Scale. Consequently, we are probably facing a new category of Forbush events, and we called them mini-Forbush events. They happen in the high energy region and in anticoincidence with the arrival of KeV protons. This characteristic can be used as a signature of an interplanetary ‘‘thin’’ disturbance crossing the vicinity of Earth.

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