COSMIC RAY MUON OBSERVATION AT SOUTHERN SPACE OBSERVATORY – SSO (29°S, 53°W)

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Abstract. Under an agreement on scientific cooperation between Brazil and Japan, a prototype detector of cosmic ray muons has been operating since March 2001 at Southern Space Observatory (SSO) located at São Martinho da Serra (29°S, 53°W), Brazil, in order to observe cosmic ray precursors of geomagnetic storms. This detector plays a key roll in the prototype network of muon observations together with two larger detectors operating in Japan and Australia. The planned extension of the detector in its size will complete the global coverage of our muon detector network. The prototype network has already discovered cosmic ray precursors of several magnetic storms, as reported by Munakata et al. (Munakata, K. et al.: 2000, *J Geophys Res.* 105, A12, pp. 27, 457–27, 468; Munakata K. et al.: 2001, Proceedings of ICRC.) We have also observed the Forbush Decreases (FDs), as well as the precursory enhancements of cosmic ray anisotropy preceding the onsets of geomagnetic storms. This report presents the description of the network and some results obtained since the prototype detector implementation.

Keywords: cosmic rays, muon detector network, forbush decreases, space weather forecasting, magnetic storm prediction

1. Introduction

Cosmic rays have been studied as a natural phenomenon that can tell us much about both the Earth's environment in space and distant astrophysical processes (Suess et al., 2000). A solar disturbance propagating away from the Sun affects the pre-existing population of galactic cosmic rays in a number of ways. For instance, analysis of cosmic ray anisotropy ($\vec{B} \times \vec{\nabla}$ n) with the IMF ($\vec{B}$) data measured by space probe yields the cosmic ray gradient vector ($\vec{\nabla}$ n), which contains valuable information about the large-scale structure and geometry of the CME (Bieber and Everson, 1998).

The ground-based measurements using neutron monitors (Simpson et al., 1953) and muon detectors (Fujimoto et al., 1976, 1984) are preferred for measuring anisotropies of primary cosmic rays with energy greater than 1 GeV because a detector with large volume can be deployed on the ground. These energetic particles are of great interest from a space-weather perspective for several reasons. First, these particles travel nearly at the speed of light. Such particles, which interact with a shock or CME, get out of the downstream region and race ahead of the

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much slower shock, can provide advance warning of a disturbance approaching the earth. Second, they have large mean free paths of the pitch-angle scattering. This is important because precursory signatures of an approaching disturbance are wiped out by the scattering after the particles traveled beyond a mean free path. Third, the Larmor radii of these particles in the IMF are larger than the size of the Earth's magnetosphere, but smaller than the typical scale size of disturbances. The typical energy of cosmic rays measured by a muon detector is 50 GeV, which corresponds to a Larmor radius of $\sim$0.2 AU. This is significant because it implies that the kinetic anisotropy and gradient mainly reflect the structure of the disturbance of this scale.

In March 2001, a prototype muon detector was installed at São Martinho da Serra (29°26′24″S, 53°48′38″W, 500 m above sea level) in the main building of the SSO of the National Institute for Space Research (INPE), Brazil. It has been operating since then in order to get basic information on the performance of the full-scale network with a planned large muon detector in Brazil.

2. Instrumentation

Since the detectors with large volume can be installed at ground-based stations, neutron monitor (Simpson et al., 1953) and muon detectors (Fujimoto et al., 1976, 1984) are the preferred instruments for measuring anisotropies of $>$1 GeV cosmic rays. Typical neutron monitor has maximum response to $\sim$10 GeV primary cosmic rays, while muon detector responds to $\sim$50 GeV cosmic rays. As high energy muons travel straight in the atmosphere keeping the information of the incident direction of primary cosmic rays, we can make the directional measurement of cosmic ray intensity by installing multidirectional muon telescopes at a single station. However, the current muon detector network is hampered by a lack of station(s) in the western hemisphere. The symbols (squares, triangles and diamonds) in Figure 1 show the asymptotic viewing directions (after correction for geomagnetic bending) of cosmic ray particles incident to each directional telescope (Munakata et al., 2000), in the network before installing the prototype detector in Brazil. The thin lines through the symbols encompass the central 80% of the energy response of each directional channel (Bieber et al., 2001b). This illustration demonstrates the need for a new muon detector for filling the big gap over the European and Atlantic area.

In early March 2001, a small prototype muon detector was installed at São Martinho da Serra (29°26′24″S, 53°48′38″W, above 500 m sea level), at the SSO of INPE, Brazil, to fill the gap in Figure 1.

The detector consists of two horizontal layers of plastic scintillators separated by 1.73 m, with an intermediate 5 cm thick layer of lead to absorb the soft component in cosmic rays in the atmosphere. Each layer comprises a 2 $\times$ 2 array of 1 m^2 unit detectors (1 m $\times$ 1 m $\times$ 0.1 m plastic scintillator viewed by a photomultiplier tube

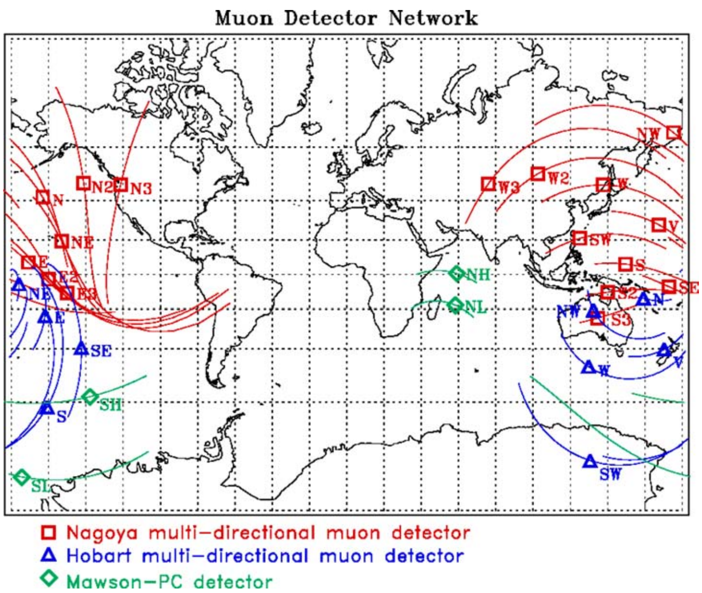

Figure 1. The big gap before the installation of the prototype muon detector at SSO.

Figure 2. The prototype muon detector installed at SSO.

of 12.7 cm diameter) giving a total detection area of 4 m^2 (Figure 2). The observed count rate in the vertical channel is 390 000 count per hour (cph). The detector is identical to that operating in Nagoya, Japan, except for its smaller detection area (Nagoya muon detector has a total detection area of 36 m^2 and a vertical count rate of 2 760 000 cph).

TABLE I
Characteristics of the prototype muon detector at SSO

São Martinho (29.4° S, 306.2° E)			
Telescope name	Hourly count (10^4 cph)	Count error %	P_m GV
V	39	0.16	53
N	11	0.30	58
S	11	0.30	57
E	11	0.30	59
W	11	0.30	56
NE	4.7	0.46	64
NW	5.4	0.43	61
SE	5.3	0.43	63
SW	5.5	0.43	60

The muon detector is multidirectional, that is, it detects the muon intensity in every channel of incident direction of muons. The detector at São Martinho da Serra has nine directional channels: Vertical, North, South, East, West, North-East, North-West, South-East and South-West respectively represented by the symbols: V, N, S, E, W, NE, NW, SE, SW. Table I summarizes characteristics of directional telescopes in São Martinho da Serra, including the median rigidity (P_m) of primary cosmic rays (Munakata et al., 2000).

We have been planning to expand the 2 × 2 array of 1 m^2 detectors at São Martinho da Serra to a 6 × 6 array. This expansion will increase the number of directional channels of cosmic ray intensity to 17 (from nine at present), as well as the count rate in each channel (the vertical count rate, for instance, is expected to be 2 860 000 cph).

Figure 3 shows the directional coverage of the full-scale network with the expanded detector at São Martinho da Serra, in the same manner as in Figure 1. The open circles show the viewing directions of the present prototype detector at São Martinho da Serra, while the solid circles show new directions to be added by the proposed expansion. The count rates in all directional channels at São Martinho da Serra would also increase dramatically.

3. Data Observation and Results

Large geomagnetic storms are primarily caused by interplanetary disturbances associated with the coronal mass ejections (CMEs) (Gosling et al., 1990; Gosling, 1993). The population of energetic particles observed by ground level detectors is also modulated by the interplanetary disturbances like shocks and ejecta (shock drivers) associated with CMEs (Lockwood, 1971). The intensity of cosmic rays

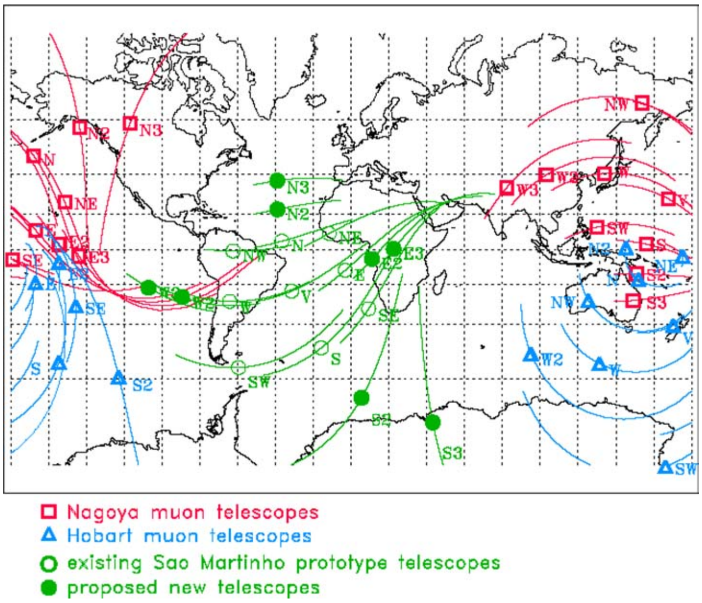

Figure 3. Proposed expanded muon detector network.

with energy above 1 GeV is normally suppressed by 1–10%, downstream of the shock and within ejecta following the shock. Munakata et al. (2000) have previously identified cosmic ray precursors with lead times ranging from six to nine hours prior to the storm sudden commencement (SSC) and demonstrated that the muon detector network may provide useful information for space weather forecasting.

The nine directional telescopes installed at the SSO started operating on March 8, 2001 with a vertical count rate of 390 000 counts per hour. The real time data can be exchanged between three stations in Brazil, Japan and Australia through the internet. Cosmic ray precursors of geomagnetic storms have been observed by the prototype network and previously reported by Munakata et al. (2001). The Brazilian team has also been analyzing the data and studying the muon response to geomagnetic storms. Some sample events observed with muon detector network are displayed in Figure 4, which shows (on the top panel) the percentile variation of muon hourly count.

Also shown in the figure are the Dst index data (the second panel from the top), the IMF components, B_z and B_t, (the third panel) and the solar wind speed (the last panel) measured by the ACE satellite. The Dst index is used to identify the occurrence of geomagnetic storms, while the IMF and solar wind data are used to identify the shock arrival at the earth. In Figure 4 we can see the immediate decreases of the cosmic ray intensity, signatures of the Forbush decreases (FDs). The FD was first discovered at the beginning of cosmic ray studies and has been studied for more than 60 years (Forbush, 1937). This phenomenon is primarily

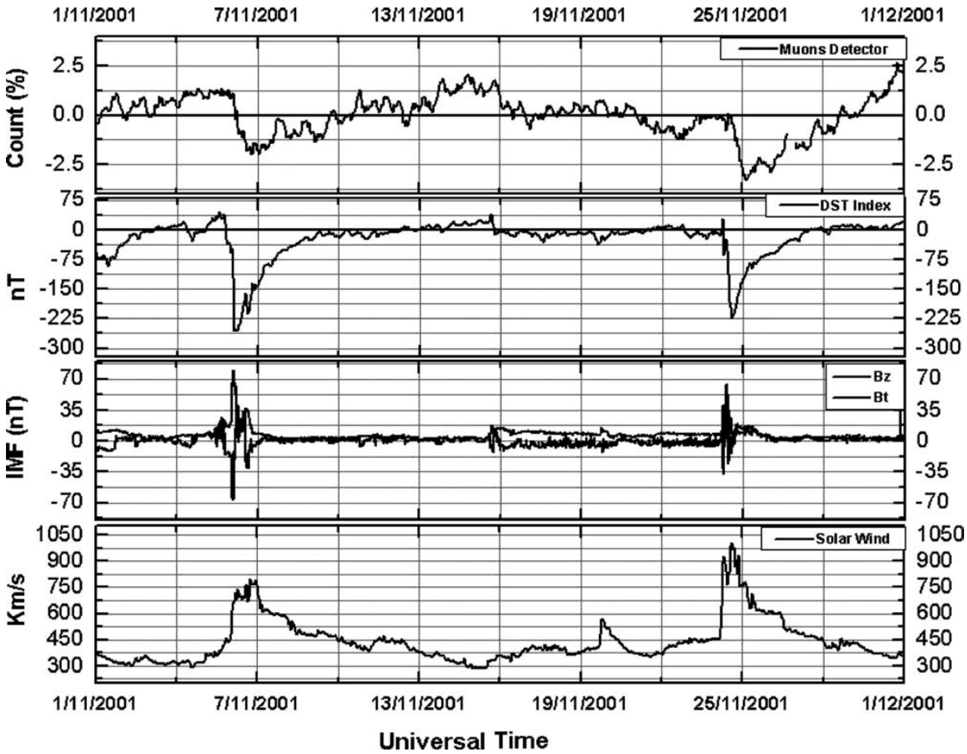

Figure 4. Example of cosmic ray data recorded by São Martinho da Serra prototype muon detector. The top panel indicates the muon count rate in November 2001. Dst index data (second panel), IMF components (third panel) and solar wind speed (last panel) have been collected through the internet and used to identify the onset of geomagnetic storm and the shock arrival at the earth. Two Forbush decreases identified by accentuated decreases in the cosmic ray count can be seen.

defined as a decrease of cosmic ray intensity during geomagnetic storm (Dorman, 1963). However it is also known that the FDs are often observed under the quiet geomagnetic conditions as well. Figure 5 shows an example of FDs observed by our network during quiet geomagnetic activity.

Munakata et al. have analyzed the cosmic ray precursors of geomagnetic storms and the pitch angle distributions recorded by a network of ground level muon detectors in Nagoya (Japan), Hobart (Australia), Mawson (Antarctica) and a prototype muon detector in São Martinho da Serra (Brazil) (Munakata et al., 2000). Figure 6 shows a cosmic ray precursor of a large geomagnetic storm with the maximum Kp index of 7.3 reported by Munakata et al. (2000). Shown in this figure are the temporal variations of the hourly count rates in three vertical muon telescopes at Nagoya, Misato and Sakashita. Misato and Sakashita are Japanese underground muon detectors at vertical depths of, respectively, 34 and 80 m of water equivalent. The median primary energies of vertical telescopes at Misato and Sakashita are,

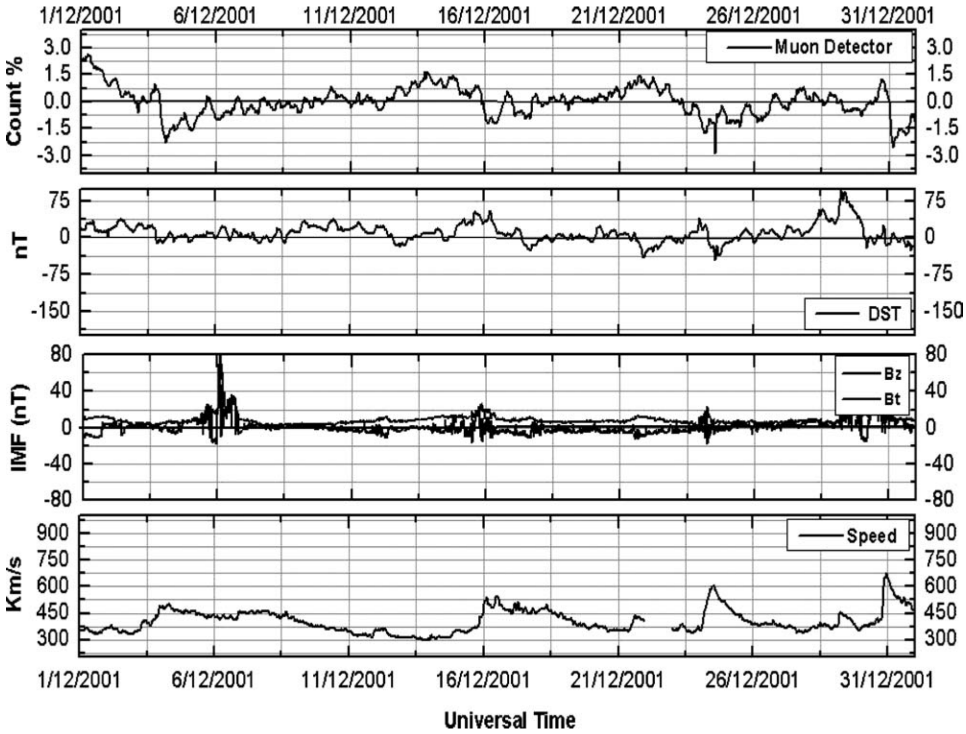

Figure 5. Example of Forbush decrease occurred during quiet geomagnetic conditions. A Forbush decrease of ∼2% associated with a Dst decrease of about –10 nT is observed on December 3.

respectively, 145 and 331 GeV. The sharp intensity decreases preceding the SSC indicated by a vertical line are clearly seen in the count rates recorded at Nagoya and Misato on day 251 and 252. It is visible even in Sakashita data, but less prominent than in other data at shallower depths. These decreases are the manifestation of the "loss-cone" intensity distribution observed by a single telescope as its viewing direction sweeps across the sunward IMF. The presence of the "loss-cone" effect in Misato and Sakashita data indicates that the "loss-cone" precursor of this storm is a high-energy phenomenon.

4. Summary

We have studied the cosmic ray response to geomagnetic storms by analyzing the data recorded by a ground level prototype muon detector installed at the SSO. Monitoring energetic cosmic ray intensity is of wide importance since it can provide good parameters reflecting the nature of interplanetary disturbances. Munakata et al. (2000) have previously demonstrated that the muon detector network can be

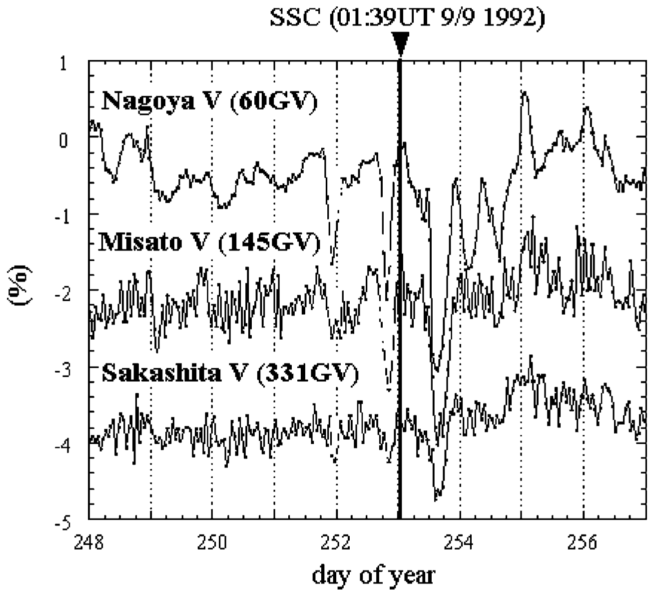

Figure 6. Temporal variations of cosmic ray intensity observed for a storm on September 9, 1992. Relative counting rate of cosmic ray muons recorded by three vertical telescopes at Nagoya, Misato and Sakashita are plotted as functions of time (day of year). The data plotted in this figure are corrected for atmospheric pressure variation, but uncorrected for temperature variation.

a good tool for space-weather forecasting as it can observe cosmic ray precursors from six to nine hours prior to the storm onset. It can also be used to predict the arrival of CME at the earth and the consequent development of the magnetic storm. Energetic particles associated with a CME can produce serious damages in spacecraft systems, and the enhanced electromagnetic emission from the sun, mainly in X-ray band, leads to failures in radio communications due to the anomalous increase of ionization in ionospheric layers. A great part of these failures could be avoided with an efficient system, which can predict with hours of antecedence the arrival of energetic particles and allow the satellites and electronic systems to be turned off in advance. The present muon detector network, however, still has a big gap in directional coverage over the Atlantic and European regions. This gap disabled us from precisely evaluating the appearance time of long-lasting precursors. As illustrated in Figure 3 (open circles), even a single prototype muon detector installed in southern Brazil provided a large improvement in the sky coverage over the Atlantic region. The expansion of the detector in its size is therefore required for both better understanding of the cosmic ray precursors and space weather forecasting. A new muon detector (6×6 array) will be installed in the southern region of Brazil, at SSO, to complete the full-scale network without the gap over European and Atlantic regions.

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