# Precursor signatures of the storm sudden commencement in 2008

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**Abstract:** Plasma structures ejected from solar eruptions travel in interplanetary space with speed of hundreds of kilometers per second and may hit the Earth. Signatures preceding the arrival of such plasma structures can be detected in the high-energy cosmic ray intensity observed with four multidirectional muon telescopes in the Global Muon Detector Network (GMDN) on the Earth. A typical signature is a “loss cone” effect which is observed as a systematic intensity decrease of cosmic rays with small pitch angles measured from the sunward interplanetary magnetic field direction. Corrections for the atmospheric pressure and temperature effects are applied to the muon data before examining the pitch angle distributions in the two-days-period preceding a moderate geomagnetic storms observed in November 24$^{th}$ 2008. The contribution of the first order anisotropy, which is not of primary interest when searching for the “loss cone” effect, is also subtracted from the observed intensity.

**Keywords:** geomagnetic storms, muon detectors, solar related phenomena.

## 1 Introduction

The passage of a solar wind disturbance at the Earth may produce significant variation in the intensity of galactic cosmic rays (GCRs) with energies up to ~100 GeV. By the interaction of > 1 GeV primary galactic cosmic rays with Earth’s atmosphere, secondary cosmic rays are created and can be observed by ground-based detectors, such as muons detectors and neutron monitors [1]. Due to the high speed and parallel mean free path of cosmic rays anisotropies, inhomogenities in the interplanetary magnetic field (IMF), are transmitted fast to remote locations [2].

Cosmic ray intensity increases or decreases appearing before the Forbush decreases have been observed for a long time [3]. More recently, the existence of local time dependent precursory decrease of cosmic ray (muon) intensity in front of a shock during the morning (6-12h) and post-shock increase during the evening (18-24h) was suggested [4]. It was concluded that the precursory decrease is produced by the IMF-collimated outward flow of the low-density cosmic rays from the region behind the shock. Cosmic ray precursors of 39 geomagnetic storms with the peak $Kp \geq 7_-$ occurred in the period from 1992 to 1998 were examined previously [5]. In that work, analysis of the pitch angle distribution of high-energy cosmic ray intensity measured by the Nagoya and Hobart muon detectors was done and 15 of 22 storms were found as associated with precursors.

Part of the precursors observed by [5] show a decrease confined in small pitch angles around the sunward IMF direction and are called “loss cone” because the decrease is confined in a cone centered in the sunward IMF direction. Other precursors observed by [4] consists of pre-increases of cosmic ray intensity with pitch angles up to 90 degrees, approaching the shock from the upstream region and reflecting from it [6]. Similar analysis was performed for severe geomagnetic storms using a network of neutron monitor [7]. All these studies are related to strong geomagnetic storms associated with strong interplanetary shocks. There is no systematic study for moderate and weak geomagnetic storms in terms of their relation to muon observations so far.

## 2 Objective and Methodology

The aim of this paper is to study the possibility of observing a cosmic ray precursors of a weak geomagnetic storm registered in November 24th 2008 at 23:51 UT. We analyze the spatial and temporal variations of high-energy GCR intensity using data from the Global Muon Detector Network (GMDN) formed by 4 detectors installed in Nagoya (Japan), Hobart (Australia), São Martinho da Serra (Brazil) and Kuwait City (Kuwait). The GMDN has a response to the secondary muons related to the primary GCRs with median rigidities ranging from ~50 to ~110 GV. These high-energy GCRs have large Larmor radii in the IMF (~0.2 to ~0.5 AU at 5 nT) and are less sensitive to small-scale irregular structures in the solar wind. More details about the GMDN are described elsewhere [8].

We use hourly muon count rates in 13 directional channels for each station after correcting for the pressure and temperature effect. The statistical error ranges from 0.06% to 0.49%. The stations of Nagoya and São Martinho da Serra have 17 directional channels but we decided not to use the 4 directions with high zenith angle due to bigger statistical errors. To correct the atmospheric pressure effect in the observed muon count rate, a linear regression is done [9,10]:

$$\Delta N_P = \overline{N} \cdot \beta_P \cdot \Delta P \quad (1)$$

$$N_{PRESSURECORRECTED} = N_{NOTCORRECTED} - \Delta N_P \quad (2)$$

where $\overline{N}$ is the average of the count rate in a given directional channel calculated in a long period after removing data affected by any other sources. For simplicity, generally one year of data is used. It is very difficult to remove all the variations associated with other causes but major transient variations which are known a priori to be not atmospheric. For example, it is common to observe decreases in the count rate associated to geomagnetic storms. For these reasons periods where geomagnetic storms are observed should be removed from the dataset before calculating any regression coefficient to prevent possible bias. $\Delta P$ is the difference between the mean value of the pressure and the hourly average pressure at the site where the detector is located. Once beta is calculated, it is assumed as constant for a given directional channel of a given station. All the $\beta_P$ coefficients found are negative, indicating an anti-correlation between the pressure and the observed muon count rate.

We also attempt to correct the temperature effect, which has a negative atmospheric temperature effect on muon intensity measured with the surface-level detectors. This predominantly arises from the increase of muon decays due to the atmospheric expansion. According to first explanation given, the path of muons from the higher atmospheric level (where they are generated) to the ground becomes longer, and more muons decay, leading to decreasing of muon intensity [11].

A significant negative correlation, therefore, is expected between the altitude of a given equi-pressure surface and the muon intensity, i.e., the muon intensity decreases with increasing the altitude due to the expansion.

There is a more complex temperature correction methodology [12] but the temperature variation for each atmospheric depth is required. As it is seldom to have for all muon detectors it is decided to use the simplest methodology in a similar way done for data observed in 2006 by the GMDN [8]. The formulas used are:

$$\Delta N_T = \overline{N} \cdot \beta_T \cdot \Delta H \quad (3)$$

$$N_{TEMPERATURECORRECTED} = N_{NOTCORRECTED} - \Delta N_T \quad (4)$$

where $\Delta H$ is the deviation of the altitude of 100 hPa to its annual average. This equi-pressure was chosen since it is expected to be the one with maximum production of muons.

Measurements of the altitude of 100hPa equi-pressure surface (henceforth called the "the altitude of 100hPa") are made continuously by radiosonde by the British Natural Environment Research Council (NERC), once every 12 hours (close to midday and midnight), in several sites in the world, generally close to airports. Among the data available, we selected the measurements sites closer to the muon detectors. For correcting data of the Nagoya muon detector, we used the mean value of radiosonde data of three stations (Shionomisaki, Tateno and Wajina) whose locations form a triangle whose center is close to the detector. For the remaining muon detectors we used data from only one high-altitude measurement site for each detector. In case of Kuwait and Hobart, the radiosonde sites are very close to the respective detectors. On the other side, for the detector in São Martinho da Serra the radiosonde site is more distant than the previous case. Other sites with approximately the same distance where available only for part of the period analyzed and we decided not to include them. More details about the temperature measurements sites are shown in Table 1.

The hourly count rates were subtracted and divided by mean value (calculated in an arbitrary period selected between 24 hours to 72 hours before the SSC) to obtain the hourly deviation $I_{i,j}(t)$ at given station $i$ and directional channel $j$.

To avoid the spurious diurnal variations in the pressure and temperature corrected muon deviation $I_{i,j}(t)$, we performed a normalization by using a 24 hours trailing moving average (TMA) of hourly deviation of each station $r_{i,j}(t)$ and a reference station $r_{1,1}(t)$ according to the expression:

$$J_{i,j}(t) = I_{i,j}(t) \cdot \frac{r_{1,1}(t)}{r_{i,j}(t)} \quad (5)$$

where $J_{i,j}(t)$ is the normalized deviation. The vertical direction of Nagoya ($r_{1,1}(t)$) was adopted as reference since it has the highest count rate and, for this reason, the lowest statistical error. This normalization is based on previous works [8,13] and efficiently removes the spurious diurnal variation and works well for deriving the temporal variation over a period shorter than 24 hours.

| High-altitude pressure measurements sites | | Muon station | Approx. distance (km) |
|---|---|---|---|
| Name | Geographic coordinates (degrees) | | |
| Shionomisaki | 33.5 N; 140.1 E | Nagoya | 200 |
| Tateno | 36.0 N;140.1 E | Nagoya | 400 |
| Wajina | 37.4 N; 136.9 E | Nagoya | 300 |
| Porto Alegre | 30.0 S; 308.8 E | São Martinho da Serra | 260 |
| Kuwait | 29.2 N; 48.0 E | Kuwait | 10 |
| Hobart | 42.8 N; 147.5 E | Hobart | 30 |

Table 1. Sites and corresponding detectors used for temperature correction.

The next step is determining the pitch angle, that is, the angle between the IMF direction and the arrival direction of a primary cosmic ray particle which produces the secondary observed by the a given directional channel. The IMF direction is determined using *in situ* magnetic field data measurements made at Lagrangian Point L1 by the ACE spacecraft. As we are working with hourly muon data, hourly averages of the IMF are used. The arrival directions of the primary cosmic ray (including a correction by geomagnetic bending) were derived previously considering the median rigidity of each channel [8]. Once the direction of the IMF and the arrival direction of a particle are calculated, the pitch angle can be computed simply as the difference between both. A zero degree pitch angle means that a given particle reached the Earth's atmosphere in the direction of the interplanetary magnetic field toward the Sun, while a 180 degree pitch angle means the anti-Sunward direction.

As only two measurements in a day were available for the correction of the temperature effect in muon data, hourly muon data corrected by the temperature effect using radiosonde data can still be affected by this effect. In this way, the first order anisotropy was derived to remove any local effect (regarded, for example, to the temperature effect) possibly associated with a given detector but not present in the others.

As the angular separation between two directional channels in a detector is about 120 degrees at most, the horizontal separation of paths along two directions is only 350 km even at the top (~100 km above the sea level) of the atmosphere and is smaller at low altitudes. The temperature variation in the atmosphere and the temperature effect, therefore, can be regarded to be almost constant within such a small region in the atmosphere covered by a single station. This is true particularly hourly mean values of muon count rates analyzed in this work. For this reason, the following best fit calculation for the pitch angle distribution $J_{i,j}^{cal}(t)$ to the observed normalized deviation ($J_{i,j}^{obs}(t)$) in the station (subscript $i$) and directional channel (subscript $j$) at a time $t$

$$J_{i,j}^{cal}(t) = J_i^0(t) + J^1(t)\cos(\chi_{i,j}(t)), \quad (6)$$

where $\chi_{i,j}(t)$ is the pitch angle calculated. One of the best fit parameters, $J_i^0(t)$, in Eq. 6 represents effects, including the temperature effect, which are common for all directional channels but different from one station to the other, while $J^1(t)$ is the best fit parameter representing the first-order anisotropy. By subtracting $J_i^0(t)$ from $J_{i,j}^{obs}(t)$ we expect to have the station-specific effects (like temperature and others) removed, remaining only the anisotropic component of $J_{i,j}^{obs}(t)$ which is the object of primary interest here.

In order to correct the temperature effect, previous works [4,5,7,13] used only the first order anisotropy. This paper is probably the first attempt to look for precursors a moderate geomagnetic storms using high atmosphere temperature data combined with the first order anisotropy.

# 3 Results

The best fit parameters $J_i^0(t)$ and $J^1(t)$ are shown in Figure 1, as well as the sum of the deviations of the 52 directional channels. By observing the muon intensity it is clear that no significant Forbush decrease was observed by the GMDN.

The pitch angle distribution plot is shown in Figure 2 as a function of time from two days before the SSC until one day after. Each normalized deviation of each directional channel is represented by a circle whose diameter is proportional to its magnitude. Decreases are represented by the black circles while increases are represented by the white ones. A systematic decrease can be observed from about 5 hours before the SSC in small pitch angles. This can be a candidate for a loss cone.

A similar signature can be observed in Figure 3, where the average comic ray deviation (AD) before the SSC is plotted as a function of the pitch angle. The cosmic ray deviations were grouped in 10-degree pitch angles ranges and were averaged in 5-hours periods. Each panel shows a different time period (specified in each panel in universal time of November 24th 2008). The statistical errors are indicated by the vertical bars. We can notice that in the three upper panels no significant AD (neither a decrease nor increase) has its error bar completely above or below the zero AD line and, thus, there is not significant cosmic ray anisotropy observed in the period from 3h until 18h UT. On the other hand, in the lower panel of Figure 3 there is a clear decrease for pitch angles smaller than 40 degrees, indicating cosmic ray anisotropy and also a loss cone effect.

# 4 Summary and conclusions

This article described a methodology for visualization of loss cones signatures using simultaneous observation of 13 directional channels for each of the four muon detectors of the GMDN. Cosmic ray intensity was corrected for both the atmospheric temperature and pressure effect. Spurious diurnal variations were removed using a 24-hours trailing moving average and local effects associated with each detector where removed using the first order anisotropy.

The methodology was tested for a moderate geomagnetic storm observed in November 24th 2008 and a loss cone signature was identified. Although is this signature systematically been observed for intense geomagnetic storm, a publication, its observation during small and moderate storms is limited. As a future work, the same methodology will be tested in other small and moderate storms in order to test whether precursors with be observed or not.

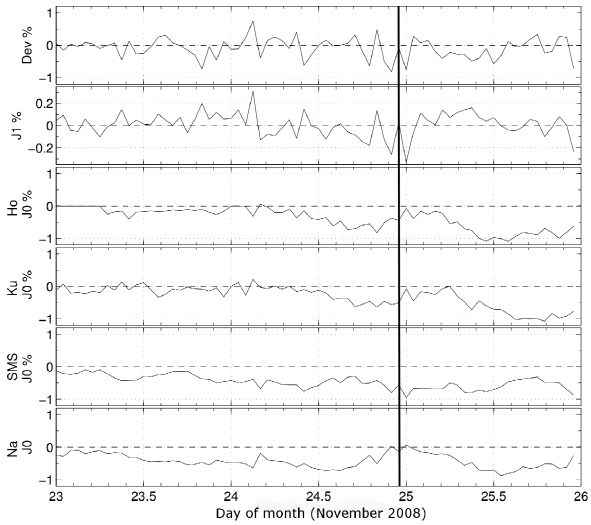


Figure 1. General parameters analyzed for the SSC is in 2008/11/24 at 23:51UT. In the panels, from top to bottom, the sum of the deviation of all the 52 directional channels used in this paper, the $J^1(t)$ parameter which is station independent, and $J_i^0(t)$ parameter of Hobart, Kuwait, São Martinho da Serra and Nagoya, respectively.

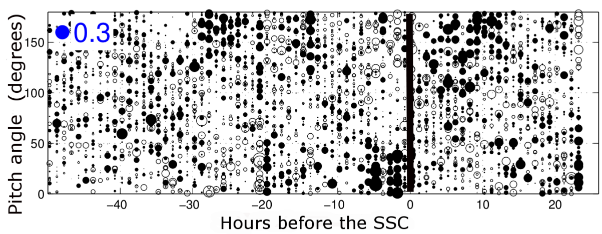


Figure 2. The pitch angle distribution derived from two days before until one day after the SSC. A systematic decrease can be observed a few hours before the SSC close to zero degree pitch angle. Close to the in the upper left corner a circle indicates a sample diameter of a 0.3% deviation.

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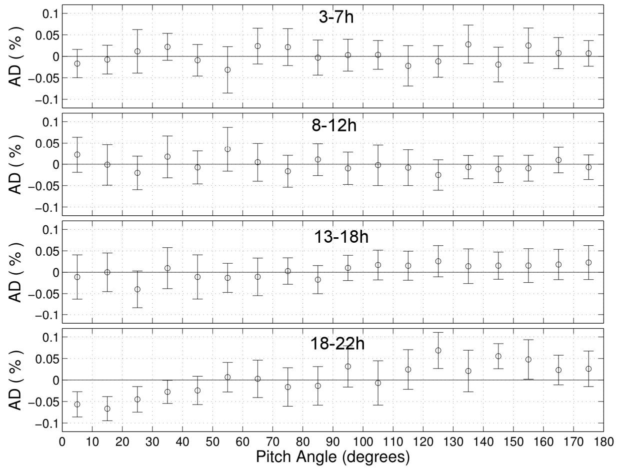


Figure 3. Average cosmic ray deviation (AD, in %) as a function of the pitch angle (degrees). The different panels show data from different 5-hour periods in November 24th 2008 (as indicated in the upper center, in universal time). All periods plotted show data before the SSC. Only in the lower panel a clear decrease for small pitch angles can be observed. This is a clear signature of a loss cone precursor.

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