

Precursors of the forrush decrease on December 14, 2006 observed with the Global Muon Detector Network (GMDN)

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Abstract. We analyze the precursory anisotropy of a Forbush decrease observed with the multi-directional muon detector at São Martinho in Brazil on December 14, 2006. By subtracting contribution from the diurnal anisotropy precisely determined by the Global Muon Detector Network (GMDN), we succeed in extracting clear signatures of the precursor. The precursor first appeared ten hours prior to the onset of the Storm Sudden Commencement (SSC) as an increase of muon rate at the pitch angle of $\sim 60^\circ$ around the IMF. This increase is consistent with the measurement of galactic cosmic rays reflected and accelerated by an interplanetary shock approaching toward the Earth with a radial speed of ~ 1160 km/sec. This intensity increase is observed for four hours and then followed by an intensity deficit known as a loss cone (LC) around $\sim 0^\circ$ pitch angle during the next four hours before the SSC onset. Weak signature of LC is also observed with São Martinho one day earlier on December 13, at the similar local time as December 14. This suggests that the LC appeared only 6.6 hours after the CME eruption on the sun, when the interplanetary shock was expected to be located 0.2 AU from the sun.

Keywords: Coronal Mass Ejection, Loss Cone precursor, cosmic ray anisotropy

I. INTRODUCTION

A solar disturbance propagating away from the Sun affects the pre-existing population of galactic cosmic rays (GCRs) in a number of ways. Most well-known is the ‘‘Forbush decrease’’, a region of suppressed cosmic ray density located downstream of a Coronal Mass Ejection (CME) shock. Some particles from this region of suppressed density leak into the upstream region and, traveling nearly at the speed of light, they race ahead of the approaching shock and are observable as a precursory loss cone (LC) anisotropy far into the

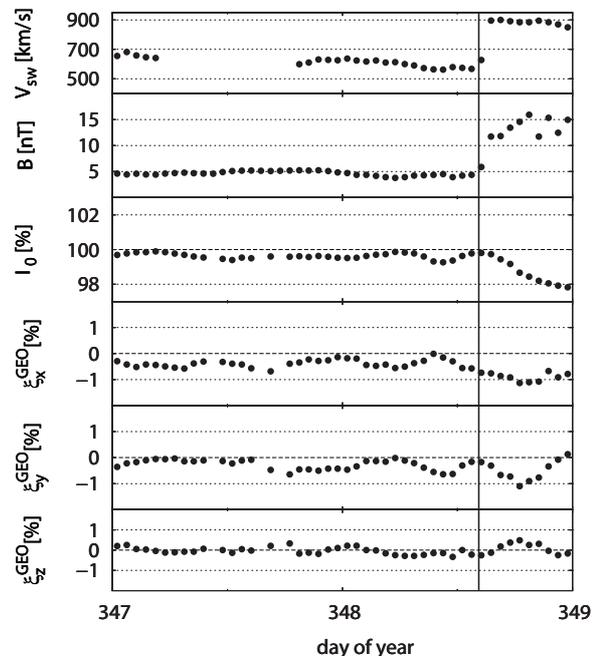


Fig. 1. Hourly mean solar wind and cosmic ray data observed over two days of 13 and 14 December, 2006. Each panel from the top shows the solar wind velocity, IMF magnitude, measured by ACE, the best-fit GCR density and three components of the GCR anisotropy in the GEO coordinate system, observed by the GMDN, as a function of time in the day of year (DOY) on the horizontal axis. The SSC onset time is indicated by a vertical solid line. The influence of LC on the cosmic ray data is seen in $I_0(t)$, $\xi_x^{GEO}(t)$ and $\xi_y^{GEO}(t)$ at \sim DOY 348.4 (see text).

upstream region. LCs are characterized by intensity deficits confined to a narrow pitch angle region around the sunward Interplanetary Magnetic Field (IMF) and are typically visible 4-8 hours ahead of shock arrival for shocks associated with major geomagnetic storms [1]. The precise measurement of LCs became possible only recently, when the Global Muon Detector Network (GMDN) capable for continuously monitoring the

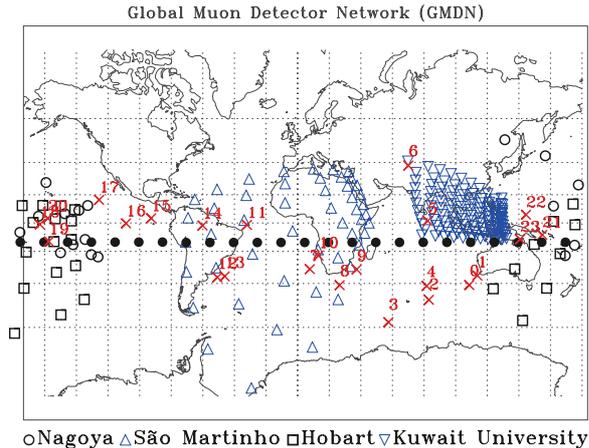


Fig. 2. Asymptotic viewing directions along the sunward IMF in 24 hours prior to the SSC onset on December 14. Each cross displays the direction along the IMF by *ACE* for each hour (UT) indicated by the attached number, while solid circles display the directions along the nominal Parker field. Open triangles are viewing directions of São Martinho and Kuwait University with the new recording system, while open circles and squares are viewing directions of Nagoya and Hobart, respectively (see section III in text). Viewing directions in this figure are all corrected for geomagnetic bending.

sunward IMF direction was completed in March 2006 [2]. For accurate analyses of LC, it is also necessary to properly remove the contribution from the diurnal anisotropy, which always exists in space with an amplitude comparable to the intensity deficit in LC. In this paper, we analyze a LC precursor observed with the Global Muon Detector Network (GMDN) in December 2006 by applying new analysis methods for removing the influence of the diurnal anisotropy and also for better visualizing LC signature.

II. EVENT OVERVIEW

An X3.4 flare commenced at 02:14UT on December 13, 2006 and was followed by a halo CME eruption shortly after at 02:54UT. This CME was accompanied by a strong interplanetary (IP) shock, which traveled interplanetary space with an average velocity of 1160 km/s and arrived at the Earth causing the Storm Sudden Commencement (SSC) onset at 14:14UT on December 14 [3]. An intense geomagnetic storm followed the SSC with peak Kp index of 8+. There was no other full-halo CME recorded between 02:14UT on December 13 and 14:14UT on December 14. Fig. 1 shows hourly data over two days of December 13 and 14. Together with the solar wind velocity and the IMF magnitude in top and second panels, this figure shows the cosmic ray density and three components of the diurnal anisotropy in the local geographical coordinate system (GEO) derived from the best-fitting to the GMDN data [2], each as a function of time in the day of year (DOY) on the horizontal axis. A $\sim 3\%$ decrease of the cosmic ray density is observed following the onset of the SSC indicated by the vertical solid line. Fig. 2 displays asymptotic viewing directions along the sunward IMF in 24 hours prior to the SSC onset on December 14, together with viewing directions

(after correction for geomagnetic bending) available in the GMDN. Although a large fluctuation in the IMF orientation observed by *ACE* is evident, the majority of the orientation is in the southern hemisphere, as expected for the sunward direction along the IMF in the ecliptic plane viewed from the Earth in December. It is clear from this figure that the LC precursor is expected to be observed in the directional channels viewing around the equator or a little south of the equator. In the following analyses, we use the nominal Parker field instead of the IMF observed by *ACE* for calculating the pitch angle of each direction of viewing in the GMDN to avoid effects of the large fluctuation. The anisotropy of ~ 50 GeV GCR intensity observed with muon detectors is rather stable, changing only gradually even when the IMF observed by *ACE* shows a large fluctuation.

III. ANALYSIS METHOD

The number of viewing directions available from the GMDN was drastically increased from the conventional one by installing a new recording system using the Field Programmable Gate Arrays (FPGAs), with which we can count muons for all possible coincidences between a pair of unit detectors on the upper and lower layers [4]. If we have a square $N \times N$ array of unit detectors aligned to the north-south (or east-west) direction in the i -th muon detector, it is possible to analyze the pressure corrected muon rates $I_{k,l}^i(t)$ ($k, l = -N + 1, \dots, 0, \dots, N - 1$) in total $(2N - 1) \times (2N - 1)$ directional channels at the time t , where positive (negative) k and l represent eastern (western) and northern (southern) incidence, respectively, with $k = l = 0$ corresponding to the vertical incident. In order to visualize the directional distribution of GCR intensity, we plot $I_{k,l}^i(t)$ as a function of k and l in a color-coded format, which we call the “2D map” (two dimensional map of the cosmic ray intensity). The number of directional channels used in this paper is 25 (5×5) from Hobart, 121 (11×11) from Kuwait and 49 (7×7) from São Martinho, respectively (see Fig. 2). We cannot apply this technique to Nagoya data in this paper, as the FPGA recording system was not installed in the Nagoya detector until May, 2007.

As stated in section I, we need to accurately remove the contribution from the diurnal anisotropy for precise analyses of the LC precursor. This was not possible before the GMDN with which we can precisely measure the diurnal anisotropy utilizing the global sky coverage of the network [2]. By using the 12 hour trailing moving averages (TMAs) of the best-fit cosmic ray density, $I_0(t)$, and three components of the observed diurnal anisotropy, $\xi_x^{GEO}(t)$, $\xi_y^{GEO}(t)$, $\xi_z^{GEO}(t)$, we calculate the contribution from the diurnal anisotropy to $I_{k,l}^i(t)$ at a universal time t as

$$\begin{aligned} \bar{I}_{k,l}^i(t) = & \bar{I}_{k,l}^{0i}(t) + \bar{\xi}_x^{GEO}(t)(c_{1k,l}^{1i} \cos \omega t_i - s_{1k,l}^{1i} \sin \omega t_i) \\ & + \bar{\xi}_y^{GEO}(t)(s_{1k,l}^{1i} \cos \omega t_i + c_{1k,l}^{1i} \sin \omega t_i) \\ & + \bar{\xi}_z^{GEO}(t)c_{1k,l}^{0i} \end{aligned} \quad (1)$$

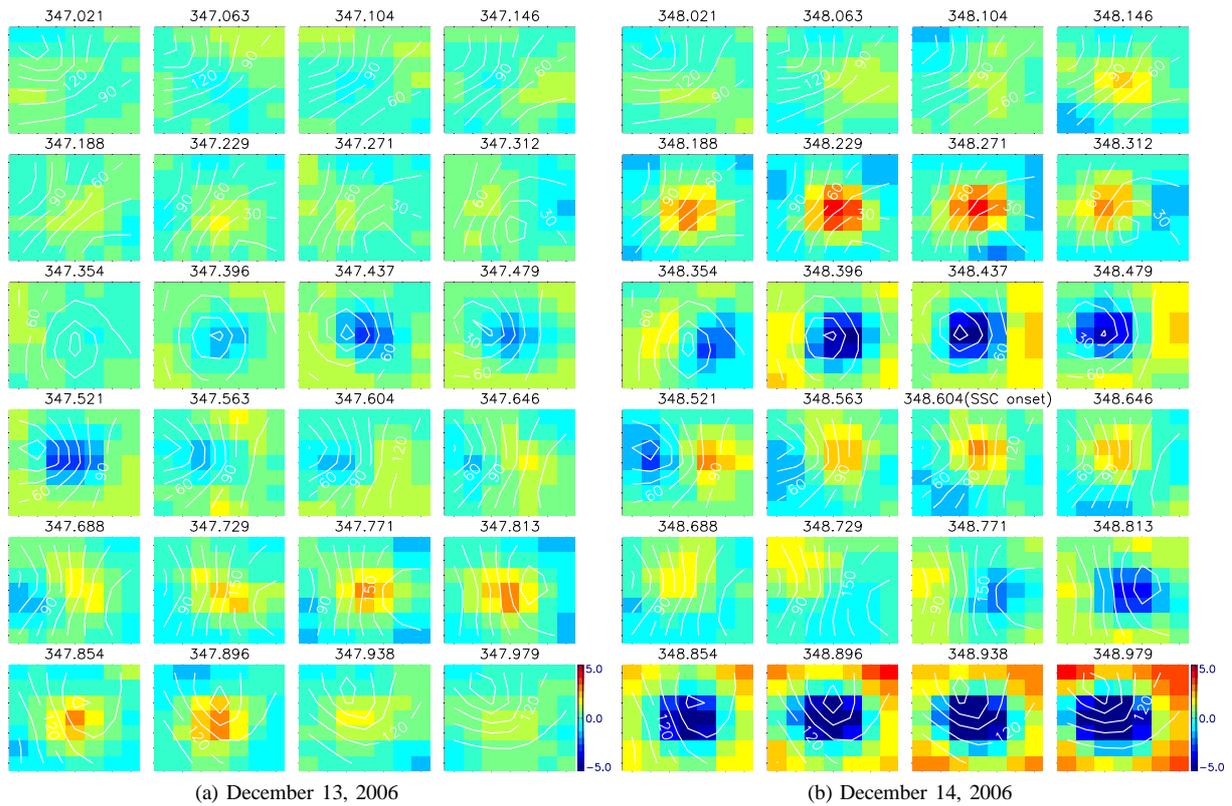


Fig. 3. 2D-maps of $sI_{k,l}^i(t)$ observed by São Martinho on December 13 (a) and 14 (b) in a color-coded format. Each small panel in (a) and (b) shows $sI_{k,l}^i(t)$ in 49 (7×7) viewing directions in one hour indicated by the day of year (DOY) at the top. The average over an entire field of view is subtracted every hour to demonstrate the relative deficit and excess of the intensity. The vertical axis in each panel denotes the latitude of incident direction spanning from the north (upper) and south (lower) directions in the field of view denoted by l , while the horizontal axis represents the longitude from the east (right) and west (left) directions denoted by k . Also shown by the white curve in each panel is the contour line of the pitch angle measured from the sunward direction along the nominal Parker field and calculated for cosmic rays incident to each directional channel with the median primary energy appropriate to that channel (we assume $1/P$ rigidity spectrum for the anisotropy). In these figures, we set the color scale ranging ± 5 as indicated by a color bar at the bottom right corner.

where $c_{1k,l}^i$, $s_{1k,l}^i$, and $c_{1k,l}^{0i}$ are the coupling coefficients calculated by assuming a rigidity-independent anisotropy, t_i is the local time at the location of the i -th detector, $\omega = \pi/12$, $\bar{I}_{k,l}^{0i}(t)$ is the contribution from the cosmic ray density $I_0(t)$ [2] and $\bar{I}_0(t)$, $\bar{\xi}_x^{GEO}(t)$, $\bar{\xi}_y^{GEO}(t)$ and $\bar{\xi}_z^{GEO}(t)$ are the 12 hour TMAs of the best-fit parameters calculated as

$$\bar{I}_0(t) = \sum_{t-11}^t I_0(t) / 12, \quad (2)$$

$$\bar{\xi}_x^{GEO}(t) = \sum_{t-11}^t \xi_x^{GEO}(t) / 12, \quad (3)$$

$$\bar{\xi}_y^{GEO}(t) = \sum_{t-11}^t \xi_y^{GEO}(t) / 12, \quad (4)$$

$$\bar{\xi}_z^{GEO}(t) = \sum_{t-11}^t \xi_z^{GEO}(t) / 12. \quad (5)$$

By subtracting $\bar{I}_{k,l}^i(t)$ in eq. (1) from the observed $I_{k,l}^i(t)$, we get the directional intensity distribution $\Delta I_{k,l}^i(t)$ free from the diurnal anisotropy as

$$\Delta I_{k,l}^i(t) = I_{k,l}^i(t) - \bar{I}_{k,l}^i(t). \quad (6)$$

We cannot use $I_0(t)$, $\xi_x^{GEO}(t)$, $\xi_y^{GEO}(t)$, $\xi_z^{GEO}(t)$ in eq. (1) instead of $\bar{I}_0(t)$, $\bar{\xi}_x^{GEO}(t)$, $\bar{\xi}_y^{GEO}(t)$, $\bar{\xi}_z^{GEO}(t)$, respectively, because the LC signature recorded in a large detector like São Martinho makes the best-fit $I_{k,l}^i(t)$ too close to the observed value and consequently

leads to too small $\Delta I_{k,l}^i(t)$ in eq. (6). This is actually seen in $I_0(t)$, $\xi_x^{GEO}(t)$, $\xi_y^{GEO}(t)$, $\xi_z^{GEO}(t)$ in Fig. 1 showing all these parameters changing in response to the LC signature recorded in São Martinho at \sim DOY 348.4. This is why we use TMAs in our subtraction technique. We also calculated with 6 hour and 24 hour TMAs instead of 12 hour TMA and confirmed the results remain essentially unchanged. Note that $\Delta I_{k,l}^i(t)$ in eq. (6) is derived using the “trailing” average and is not affected by the variation occurring after t . This is an important issue for possible real time forecasting.

In order to demonstrate the relative deficit and excess of the intensity, we subtract from $\Delta I_{k,l}^i(t)$ the average over an entire field of view in every hour. To visualize the LC signature clearer by suppressing the fluctuation, we also use instead of $\Delta I_{k,l}^i(t)$ the “significance” $sI_{k,l}^i(t)$ defined as

$$sI_{k,l}^i(t) = \Delta I_{k,l}^i(t) / \sigma_{k,l}^i, \quad (7)$$

where $\sigma_{k,l}^i$ is the count rate error for the (k, l) directional channel in the i -th detector.

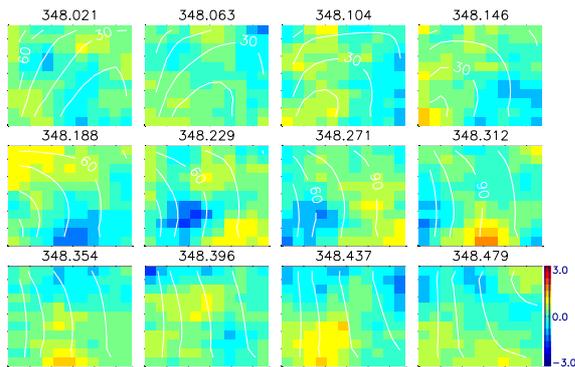


Fig. 4. 2D-maps of $sI_{k,l}^i(t)$ observed by Kuwait on December 14. Each small panel shows $sI_{k,l}^i(t)$ in 121 (11×11) viewing directions in one hour. Same as Fig. 3 except the color scale ranging ± 3 .

IV. RESULTS AND DISCUSSIONS

Figs. 3a and 3b show the 2D maps of $sI_{k,l}^i(t)$ in eq. (7) for São Martinho on December 13 and 14, respectively, while Fig. 4 shows $sI_{k,l}^i(t)$ for Kuwait on December 14. Also shown by the white curve in each panel is the contour line of the pitch angle measured from the sunward direction along the nominal Parker field and calculated for cosmic rays incident to each directional channel with the median primary energy appropriate to that channel (we assume $1/P$ rigidity spectrum for the anisotropy throughout this paper). In these figures, we set color scales ranging ± 5 for São Martinho and ± 3 for Kuwait. In Fig. 3b for São Martinho, there is a clear LC precursor seen with an intensity deficit at around 0° pitch angle in DOYs 348.354~348.479 (08:00~12:00UT on December 14, hereafter referred as period I) with the minimum intensity about -0.6% .

There is also a clear intensity excess seen at $30^\circ \sim 90^\circ$ pitch angle during a preceding period DOYs 348.188~348.312 (04:00~08:00UT on December 14) with the maximum intensity about $+0.2\%$. Such an intensity excess is expected from the ground based measurement of GCRs reflected by the IP shock approaching the Earth. The numerical model for GCR transport across the shock also predicts the pitch angle distribution with such an intensity excess superposed on the LC distribution [5]. The fractional energy gain for a GCR traveling along the IMF with an energy E after the reflection by the IP shock approaching with a velocity V is calculated as

$$\Delta E/E \approx 2V \cos \theta_{Bn}/c, \quad (8)$$

where θ_{Bn} is the angle between the shock normal and the IMF and c is the speed of light. The intensity excess expected from this energy gain is estimated as

$$\Delta I/I = \gamma \Delta E/E \approx 2\gamma V \cos \theta_{Bn}/c, \quad (9)$$

where γ is the power-law index of the GCR energy spectrum, which we set to 2.7. By using the observed average velocity (1160 km/s) of the IP shock for V

and by tentatively assuming $\theta_{Bn} = 60^\circ$, we get $+1.0\%$ for $\Delta I/I$. This value is five times the observed maximum intensity, but seems to be consistent with the observations if the superposed intensity depression due to LC is taken into account. It is concluded therefore that the intensity excess recorded at São Martinho is consistent with the measurement of GCRs reflected by the IP shock. This is the first clear observation of the shock reflected GCRs with the muon detector, although we need to confirm this further by more quantitative comparisons between the observation and the model.

In Fig. 3a for São Martinho, a weak LC signature is also seen one day earlier in DOYs 347.396~347.521 (09:00~13:00UT on December 13, hereafter referred as period II), during the similar local times as the period I when the signature is seen on December 14. This suggests that the LC precursor appeared only 6.6 hours after the CME eruption at 02:54UT, when the IP shock was expected to be located 0.2 AU from the sun. If this is the case, then the signature also should have been observed prior to period I on December 14 by other detectors viewing the eastern sky neighboring the field of view of São Martinho. It is actually seen in Fig. 4 for Kuwait in DOYs 348.188~348.312 (04:00~08:00UT on December 14) even with such a small detector (thanks to a better directional resolution of the Kuwait muon hodoscope using the proportional counter tubes!). The signature was also seen in Hobart, but less evident probably due to the large counting rate error and poor directional resolution of this small detector. We add to note that a large muon hodoscope GRAPES III in operation at Ooty in southern India also recorded a clear LC precursor on $\sim 09:00$ LT (03:30UT) on December 14, just before the signature recorded in Kuwait in Fig. 4 (Dr. H. Kojima, private communication). This gives further observational support for that the LC signature already existing as early as at 09:00~13:00UT on December 13. We confirmed that there is almost no notable excess or deficit intensity except the periods discussed above.

V. ACKNOWLEDGMENTS

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