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Geomagnetic storm's precursors observed from 2001 to 2007 with the Global Muon Detector Network (GMDN)

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[1] We use complementary observations from the prototype and expanded Global Muon Detector Network (GMDN) and the Advanced Composition Explorer (ACE) satellite to identify precursors of geomagnetic storm events. The GMDN was completed and started operation in March 2006 with the addition of the Kuwait detector, complementing the detectors at Nagoya, Hobart, and São Martinho da Serra. Analyzed geomagnetic storms sorted by their intensity as measured by the Disturbance storm-time (Dst) index. Between March 2001 and December 2007, 122 Moderate Storms (MS), 51 Intense Storms (IS), and 8 Super Storms (SS) were monitored by the GMDN. The major conclusions are (i) the percentage of the events accompanied by the precursors prior to the Sudden Storm Commencement (SSC) increases with increasing peak Dst, (ii) 15% of MSs, 30% of ISs, and 86% of SSs are accompanied by cosmic ray precursors observed on average 7.2 hours in advance of the SSC. **Citation:** Rockenbach, M., et al. (2011), Geomagnetic storm's precursors observed from 2001 to 2007 with the Global Muon Detector Network (GMDN), *Geophys. Res. Lett.*, *38*, L16108, doi:10.1029/2011GL048556.

1. Introduction

[2] Interplanetary structures ejected by the Sun occasionally hit Earth's magnetosphere, causing great disturbances called Geomagnetic Storms (see the review by *Schwenn et al.* [2005]). During these disturbances, solar wind energy and energetic particles transferred into the magnetosphere [*Gonzalez et al.*, 1994]. Using the Disturbance Storm Time (Dst) index, geomagnetic storms can be classified by their intensity as Super Storms (SS): Dst < −250 nT; Intense Storms (IS): −250 nT < Dst < −100 nT; and Moderate Storms (MS): −100 nT < Dst < −50 nT [*Gonzalez et al.*, 1999].

[3] *Munakata et al.* [2000] showed that decreases and/or increases of cosmic rays can be observed prior to the geomagnetic disturbances. Since March 2006, data was collected from the expanded Global Muon Detector Network (GMDN), making possible cosmic ray observations with a total coverage around the interplanetary magnetic field lines that connect the observation site to the interplanetary structure coming from the sun [*Okazaki et al.*, 2008].

[4] This work uses a new methodology, in which the 12-hour trailing average of the best-fit parameters is subtracted from the cosmic ray observations, in order to remove the contribution of the diurnal anisotropy and thus improve the precursor observations [*Fushishita et al.*, 2010].

2. Methodology

[5] This work analyzes the cosmic ray precursors of geomagnetic storms observed by the expanded GMDN, in full operation since March 2006, when the Kuwait City detector (installed in Kuwait University, Kuwait) was added to the prototype network, which has been in operation since March 2001. The prototype network was composed of detectors located at Nagoya University, Japan; the Australian Antarctic Division, Hobart, Tasmania; and the Southern Space Observatory (SSO/CRS/CCR/INPE-MCT), São Martinho da Serra, Brazil. Each of these detectors is multidirectional, allowing cosmic ray intensities in various viewing directions to be recorded simultaneously [*Da Silva et al.*, 2004]. The prototype (pre-March, 2006) network had 39 viewing directions. Following the December, 2005 upgrade of the São Martinho da Serra detector from a 2 × 2 × 2 to a 2 × 4 × 7 configuration, and the installation of the Kuwait detector, the GMDN has 60 viewing directions available.

[6] The diurnal anisotropy, when observed by a detector on the Earth, produces a diurnal variation in which the muon rate in each directional channel varies as a sinusoidal function of local time [*Okazaki, et al.* 2008]. This diurnal variation is generally different in different directional channels, and need to be corrected. The contribution from the diurnal anisotropy to the pressure corrected count rate recorded at universal time *t*, in the *j*-th directional channel of the *i*-th muon detector in the GMDN is given as

$$I_{i,j}^{DA}(t) = I_{i,j}^{-0}(t) + \xi_x^{-GEO}(t)\left(c_{1i,j}^{1}\cos(\omega t_i) - s_{1i,j}^{1}\sin(\omega t_i)\right) + \xi_y^{-GEO}(t)\left(s_{1i,j}^{1}\cos(\omega t_i) + c_{1i,j}^{1}\sin(\omega t_i)\right) + \xi_z^{-GEO}(t)c_{1i,j}^{0}, \tag{1}$$

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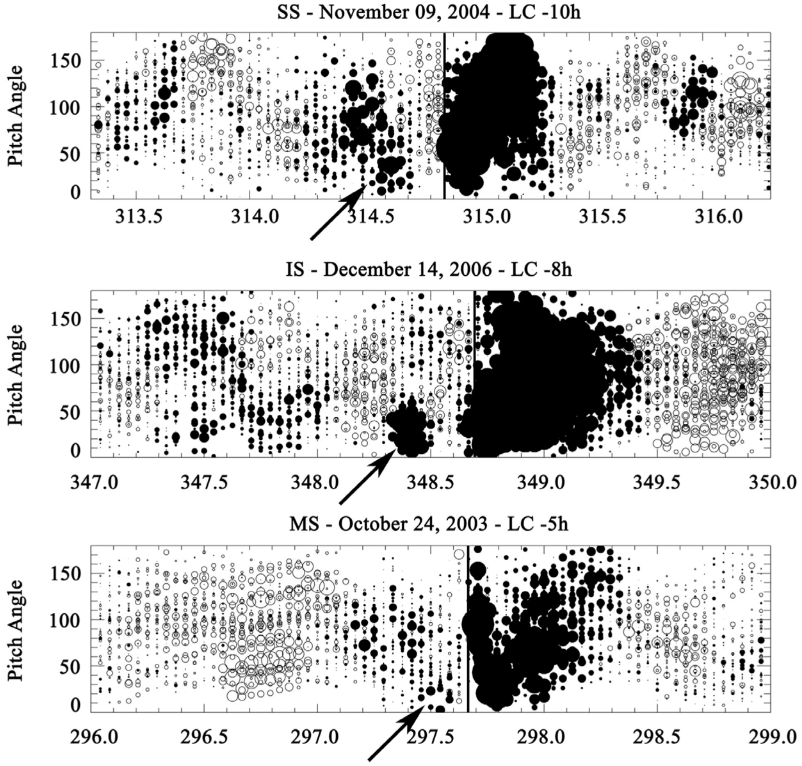

Figure 1. Pitch angle distribution in function of time for the three geomagnetic storm's precursors examples observed by the GMDN (top) on November 9, 2004 showing a loss cone (LC), 10 hours prior to the SSC, (middle) on December 14, 2006 showing a loss cone (LC), 8 hours prior to the SSC, and (bottom) on October 24, 2003 showing a loss cone (LC), 5 hours prior to the SSC. Each circle represents an hourly measurement by a single telescope plotted at the appropriate time (abscissa) and pitch angle (ordinate) of the telescope's viewing direction. A pitch angle of 0° corresponds to the sunward IMF direction. Open and solid circles represent, respectively, an excess and deficit of cosmic ray intensity relative to the average, and the diameter of each circle is proportional to the magnitude of deficit or excess.

where, $c^1_{1i,j}$, $s^1_{1i,j}$, and $c^0_{1i,j}$ 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 and $\omega = \pi/12$ [*Fushishita et al.*, 2010]. $\overline{I}^{0}_{i,j}(t)$, $\overline{\xi}^{GEO}_x(t)$, $\overline{\xi}^{GEO}_y(t)$, and $\overline{\xi}^{GEO}_z(t)$ are the 12-hour trailing averages of the best-fit parameters calculated as

$$\overline{X}_{i,j}(t) = \sum\nolimits_{t-11}^{t} X(t)/12 \qquad (2)$$

where X indicates one of best-fit parameters in Equation (1). Comparing the 24-hours and the 12-hours trailing averages of the best-fit parameter, with the second we could observe the loss-cone effect, better than the first one.

[7] To obtain the directional intensity distribution free from the diurnal anisotropy, $I^{DA}_{i,j}(t)$, in Equation (1) is subtracted from the observed $I^{obs}_{i,j}(t)$, as

$$\Delta I^{cal}_{i,j}(t) = I^{obs}_{i,j}(t) - I^{DA}_{i,j}(t). \qquad (3)$$

This new methodology can improve the GMDN system for cosmic ray real-time monitoring [*Kuwabara et al.*, 2004, 2006], since $\Delta I^{cal}_{i,j}(t)$, in Equation (3), is derived using the "trailing" average and is not affected by variations occurring after time t, which is an important issue for space weather forecasting and makes possible almost real time predictions [*Fushishita et al.*, 2010].

[8] We use the "significance" $s^{cal}_{i,j}(t)$ instead of $\Delta I^{cal}_{i,j}(t)$, defined as

$$s^{cal}_{i,j}(t) = \Delta I^{cal}_{i,j}(t)/\sigma_{i,j}, \qquad (4)$$

where $\sigma_{i,j}$ is the count rate error for the (i,j) directional channel in the network, in order to visualize the precursor signatures clearer by suppressing the statistical fluctuations.

[9] Complementary observations of interplanetary magnetic field (IMF) observed by the Advanced Composition Explorer (ACE) satellite are used for calculating the pitch angle of each GMDN viewing direction, which is defined as the angle between the sunward IMF direction and the viewing direction of the j-th directional telescope in the i-th muon detector of the GMDN [*Munakata et al.*, 2000]. This pitch angle is measured from the direction toward the Sun along the IMF, that is, 0° corresponds to the sunward IMF direction.

[10] The geomagnetic storms distributions observed in the analysis period (2001–2007) include: 8 Super Storms (SS), 51 Intense Storms (IS), and 122 Moderate Storms (MS). In

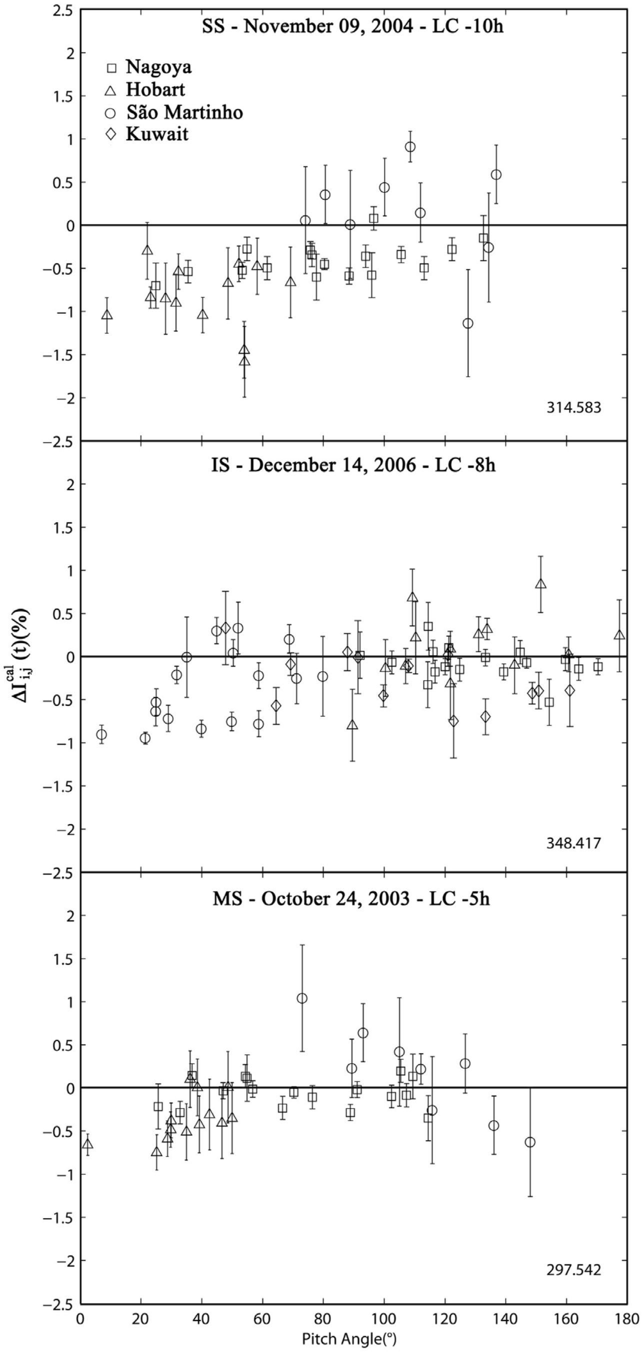

Figure 2. Cosmic ray intensity distributions ($(\Delta I_{i,j}^{cal}(t)(\%))$, in function of pitch angle observed (top) on November 9, 2004 showing a loss cone (LC), 10 hours prior to the SSC, observed by Hobart, (middle) on December 14, 2006 showing a loss cone (LC), 8 hours prior to the SSC, observed by São Martinho da Serra, and (bottom) on October 24, 2003 showing a loss cone (LC), 5 hours prior to the SSC, observed by Hobart. The numbers in the bottom right corner indicate the specific time of each observation, corresponding to the arrows in Figure 1.

some of these events, however, the sunward IMF direction was not well monitored by the GMDN and/or there were no IMF data available from the *ACE* satellite. When these are removed, 7 SS, 37 IS, and 89 MS are left for analysis. A list of storms can be seen in work by *Echer et al.* [2008a, 2008b] and *Zhang et al.* [2007].

3. Results and Discussion

[11] Following the analysis method used by *Munakata et al.* [2000], two kinds of precursors were considered: a "Loss Cone" (LC), which is observed as an intensity deficit localized around 0° pitch angle, and an "Enhanced Variance" (EV), which is characterized by an increase or decrease of intensity that cannot be described as a systematic function of pitch angle. Figure 1 shows the significance, $s_{i,j}^{cal}(t)$, as a function of time measured from the storm sudden commencement (SSC) (abscissa) and the pitch angle (ordinate). Each circle in the pitch angle plot represents an hourly measurement by a single telescope, with relative deficit (solid circles) or excess (open circles). Figure 1 (top) shows an LC observed before the SS that occurred on November 9, 2004. This precursor was observed 10 hours prior to the SSC indicated by the black vertical line in Figure 1. Figure 2 (top) shows the pitch angle distribution of the cosmic ray intensity ten hours prior to the SSC. This precursor was observed by the Hobart muon detector. Figure 1 (middle) shows the LC observed by the São Martinho da Serra detector eight hours before the SSC of the December 14, 2006 magnetic storm (IS). The pitch angle distribution in this precursor is shown in Figure 2 (middle). This was the first magnetic storm observed by the GMDN, which was completed in March 2006. There are no gaps in pitch angle directional coverage for this event. Unfortunately, because of this long solar minimum activity the December 14, 2006 geomagnetic storm is the unique intense magnetic storm observed since the GMDN was completed. Figure 1 (bottom) shows the LC observed by the Hobart detector, approximately 5 hours before the SSC of the October 24, 2003 magnetic storm (MS). Figure 2 (bottom) shows the distribution of the cosmic ray pitch angle five hours prior to the SSC.

4. Summary and Conclusions

[12] Out of a total of 181 storm events, 133 (73.5%) events had good data and could be analyzed. Of these 133 storms, 103 (77%) storms had no cosmic ray precursor (NP) observed. It is due to a poor coverage of pitch angle around the IMF before the GMDN expansion in 2006. Careful analysis shows in Figure 3 (left) that these storms without precursor include - 76 moderate storms – (MS), 26 intense storms – (IS), and 1 was a super storm – (SS), indicating that the percentage of NP events decreases with increasing magnetic storm intensity. This is reasonable because the solar structure that causes SS has stronger magnetic field intensity than that which causes IS or MS. This means that as events become more intense, and consequently have stronger magnetic field intensity, cosmic ray precursors became more visible, because the magnetic fields in these intense structures reduce the particles gyroradii, consequently causing a decrease of the transport and the diffusion coefficient, resulting in a modulation increase of the cosmic rays [*Belov et al.*, 2001]. The October 30, 2003 storm (the second of the "Halloween" events) is the only SS storm for which the GMDN did not observe any precursor [*Gopalswamy et al.*, 2005]. It is important to point out that the October 30, 2003 event occurred only one day after another SS storm (the

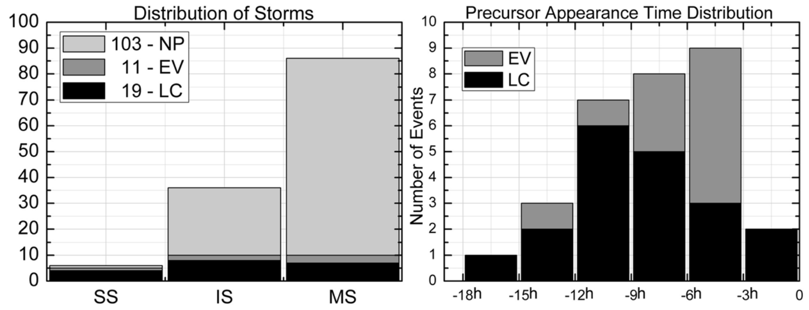

Figure 3. Magnetic storms intensity and the appearance time distribution histograms of the precursors. NP, no-precursor; EV, enhanced variance; LC, loss cone precursors; SS, super storms; IS, intense storms; and MS, moderate storms.

first of the "Halloween events"). The local interplanetary medium is known to become very disturbed after the passage of the interplanetary CME by Earth and this may have suppressed the production of precursor with long lead time for the October 30, 2003 event.

[13] As shown in Figure 3 (right), the loss-cone (LC) precursors were more frequently observed 9 to 12 hours before the SSC, and for the enhanced variance (EV) 3 to 6 hours before the SSC. Remarkably, the LC precursor of a super storm (SS) is observed as early as 15 hours prior to the SSC. On average, the lead time of the precursor is 7.2 hours before the SSC.

[14] Comparing the conclusions of this work – with the new data from the expanded GMDN, after the December 2005 upgrade at the São Martinho da Serra detector and the inclusion of the Kuwait detector in March 2006, combined with the developed new methodology for the 12-hour trailing average calculation of the best-fit parameters – with the results of *Munakata et al.* [2000], there is no doubt that exists a substantially improvement of the cosmic ray precursors for lead time observations of geomagnetic storms. In conclusion, 86% of the SS, 30% of the IS, and 15% of the MS were observed with precursor by the GMDN.

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