Global Muon Detector Network Observing Geomagnetic Storm's Precursor Since March 2001

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***Abstract*. We use complementary observations from the prototype Global Muon Detector Network (GMDN) and the Advanced Composition Explorer satellite to identify precursors of geomagnetic storm events. The GMDN was completed in March 2006 with the installation of the Kuwait detector, in addition to detectors at Nagoya, Hobart and São Martinho da Serra. In this work, we analyze geomagnetic storms sorted by their intensity as measured by the Disturbance storm-time (Dst) index. Between March 2001 and December 2007,** 89 **Moderate Storms (MS),** 38 **Intense Storms (IS) and** 7 **Super Storms (SS) were monitored by the muon detector network. We find that the percentage of the events accompanied by the precursors prior to the Sudden Storm Commencement (SSC) increases with increasing peak Dst. We also find that** 15% **of MSs,** 30% **of ISs and** 86% **of MSs are accompanied by cosmic ray precursors observed on average** 7.2 **hours in advance of the SSC. We discuss the interplanetary structure responsible for these storms and examine the possibility of forecasting them using cosmic ray precursors.**

***Keywords*: Geomagnetic storms, cosmic ray precursors, space weather forecasting**

I. INTRODUCTION

Interplanetary structures ejected by the Sun occasionally hit Earth's magnetosphere, causing great disturbances called Geomagnetic Storms (see the review by Schwenn et al. [1]). During these disturbances, solar wind energy and energetic particles transfer into the magnetosphere [2]. Using the Disturbance Storm Time (Dst) index we can classify geomagnetic storms by their intensity as Super Storms (SS): Dst < -250 nT; Intense Storms (IS): -250 nT $<$ Dst < -100nT; and Moderate Storms (MS): -100 nT<Dst < -50 nT [3].

Munakata et al. [4] showed that precursory cosmic ray decreases and/or increases can be observed prior to geomagnetic disturbances. Since March 2006 we have data from the 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 [5].

In this work, we use a new methodology, in which we subtract the 12-hour trailing average of the best-fit parameters from the cosmic ray observations, in order to remove the contribution of the diurnal anisotropy and thus improve the precursor observations. This methodology will be further discussed in [6].

II. METHODOLOGY

We analyze the cosmic ray precursors of geomagnetic storms observed by the GMDN, in full operation since March 2006 when the Kuwait City detector (installed in Kuwait University, Kuwait) was added to the prototype network that had operated 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/INPE-MCT), São Martinho da Serra, Brazil. Each of these detectors is multidirectional, allowing us to simultaneously record the intensities in various viewing directions [7]. The prototype network had 39 directional telescopes. In December 2005 the São Martinho da Serra detector was upgraded from a $2\times2\times2$ confguration to $2 \times 4 \times 7$. The Kuwait detector was installed three month later, since when 60 directional telescopes have been available.

We derive the contribution to the diurnal anisotropy from the pressure corrected count rate recorded in each directional channel by fitting the function $\bar{I}^{fit}_{i,j}(t)$ at universal time t, in the j-th directional channel of the i-th muon detector in the GMDN [6], as

$$\begin{aligned}\bar{I}^{fit}_{i,j}(t) = \bar{I}^{0}_{i,j}(t) \quad &+\bar{\xi}^{GEO}_{x}(t)\left(c^{1}_{1i,j}cos(\omega t_i) - s^{1}_{1i,j}sin(\omega t_i)\right)\\ &+\bar{\xi}^{GEO}_{y}(t)\left(s^{1}_{1i,j}cos(\omega t_i) + c^{1}_{1i,j}sin(\omega t_i)\right)\\ &+\bar{\xi}^{GEO}_{z}(t)c^{0}_{1i,j}, \qquad (1)\end{aligned}$$

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 $\omega = \pi/12$. $\bar{I}^0_{i,j}(t)$, $\bar{\xi}^{GEO}_x(t)$, $\bar{\xi}^{GEO}_y(t)$ and $\bar{\xi}^{GEO}_z(t)$ are the 12-hour trailing averages of the best-fit parameters calculated as

$$\bar{X}_{i,j}(t) = \sum_{t-11}^{t} X(t)/12 \tag{2}$$

where the symbol X indicates any best-fit parameter.

To obtain the directional intensity distribution free from the diurnal anisotropy, we subtracted $\bar{I}^{fit}_{i,j}(t)$ in eq. (2) from the observed $I^{obs}_{i,j}(t)$, as

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

We use the complementary observations of interplanetary magnetic field (IMF) by Advanced Composition Explorer (ACE) for calculating the pitch angle of each direction of viewing, 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 [4]. This pitch angle is measured from the direction toward the Sun along the IMF, that is, 0^o corresponds to the sunward IMF direction.

Geomagnetic storms accrued in our analysis period include 8 Super Storms, 51 Intense Storms, and 122 Moderate Storms. Some of these events, however, were not well monitored by the muon detector network and/or by the ACE satellite. Removing these left 7 SS, 37 IS and 89 MS available for analysis.

III. RESULTS AND DISCUSSIONS

Fig. 1 shows the geomagnetic storms observed in the entire period from March 2001 to December 2007, sorted by year. In each year we have three columns indicating the total number of storms in that year (T), storms for which there was good data coverage (G), and the storms in which we could detect some kind of precursor (P). The different colors indicate the kind of storms.

Following the analysis method used by Munakata et al. [4], we considered two kinds of precursor, a "Loss Cone" (LC), which is displayed as an intensity deficit localized around 0^o pitch angle, and an "Enhanced Variation" (EV), which is characterized by an increase or decrease of intensity that cannot be described as a systematic function of pitch angle. The top panel in Fig. 2a shows an EV observed before the SS that occurred on April 11, 2001. The precursor was observed 4 hours prior to the storm sudden commencement (SSC), as indicated by the vertical line in the figure. The top panel of Fig. 2b shows the pitch angle distribution of cosmic rays for the fourth hour prior to the SSC, in which one can see that this precursor was observed by São Martinho da Serra's detector. The middle panel of Fig. 2a shows the LC observed by São Martinho da Serra's detector six hours before the SSC of the magnetic storm that occurred on December 14, 2006. The pitch angle distribution of the sixth hour for this event is shown in the middle panel of Fig. 2b. This was the first magnetic storm observed by the full GMDN, after its completion in March 2006. We note that there are no gaps in directional pitch angle coverage in this event. Unfortunately, this is the only intense magnetic storm observed since the GMDN was completed. Detailed analyzes on this event are presented by Fushishita et al. [6]. The bottom panel of Fig. 2a shows the LC observed by São Martinho da Serra's detector, approximately 7 hours before the SSC of the magnetic storm that occurred on April 28, 2003. The bottom panel of Fig. 2b shows the pitch angle distribution of cosmic ray of the 7th hour prior to the SSC.

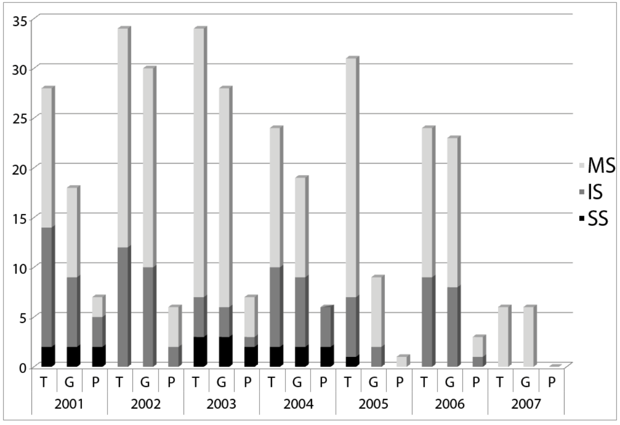
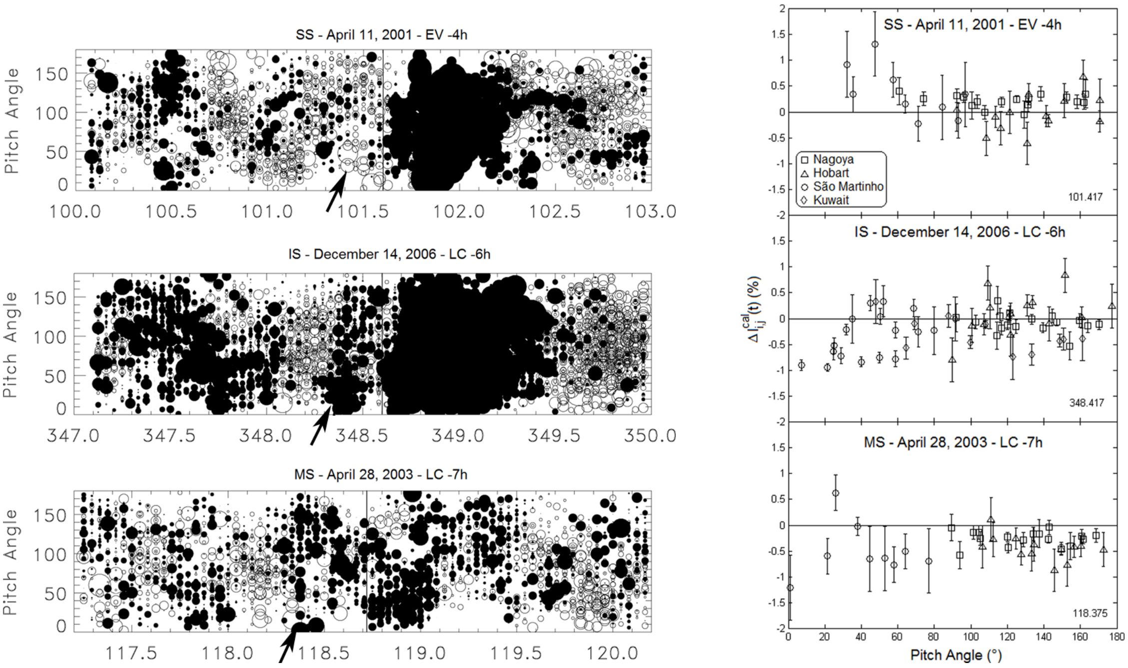


Fig. 1: Distribution of the analyzed geomagnetic storms separated by year. "MS", "IS" and "SS" represent, respectively, "Moderate Storms", "Intense Storms" and "Super Storms". "T" indicate the total number of storms in that year, "G" are storms for which there was good data coverage, and "P" indicate the storms in which we could detect some kind of precursor.

IV. SUMMARY AND DISCUSSIONS

In this work, we analyzed geomagnetic storms that occurred between March 2001 and December 2007 in terms of their cosmic ray modulation, using both the prototype and complete Global Muon Detector Network (GMDN), together with the Advanced Composition Explorer (ACE) satellite data. From the total number of events, 133 (73.5%) have good data coverage and could be analyzed. In general, we found that for 103 (77%) of these 133 storms no cosmic ray precursor (NP) was observed. Analyzing in more detail, the left panel in Fig. 3 shows that 76 of these storms with NP were MS, 26 were IS, and 1 was SS, indicating the number of NP events decreasing with increasing the magnetic storm intensity. That is reasonable since the solar structure that cause SS have stronger magnetic field intensity than that which cause IS or MS. This means that, as one goes to more intense events, and consequently more intense



(a) Pitch angle distribution for geomagnetic storms.

(b) Pitch angle distribution of cosmic ray.

Fig. 2: Three examples of precursors observed on April 11, 2001 (top panel), December 14, 2006 (middle panel), and April 28, 2003 (bottom panel).

magnetic field intensity, cosmic ray precursors are more visible, because magnetic fields present in these intense structures reduce the gyroradii of the particles, causing a consequent decrease of the transport and in the diffusion coefficient, resulting in an increase in the modulation of the cosmic rays [8]. The only SS storm before which we did not observe any precursor occurred in October 30, 2003, the second of the "Halloween events" [9]. It is important to point out that this event occurred only one day after another SS storm (the first of the "Halloween events"). After the passage of the interplanetary CME by Earth, the local interplanetary medium became very disturbed. We suggest that this background condition suppressed the observation of any precursor.
In terms of prediction capability, we can see, in the right panel in Fig. 3, that LC precursors were observed more frequently between 9 and 12 hours before the SSC, and EV between 3 and 6 hours before it. Remarkably, precursors were observed as early as 18 hours prior to the SSC. On average, geomagnetic storms were accompanied by cosmic ray precursors observed 7.2 hours in advance of the SSC.

Comparing with Munakata et al.'s results [4], we conclude that the complete GMDN, after the December 2005 additions to the São Martinho detector and the inclusion of the Kuwait detector in March 2006, together with the use of the new methodology of calculating the 12-hour trailing average of the best-fit parameters, substantially improved the lead time observation of cosmic ray precursors of geomagnetic storms. 86% of the SS, 30% of the IS, and 15% of the MS were observed by the GMDN. This new methodology can improve the real-time cosmic ray monitoring system [10], since $\Delta I^{cal}_{i,j}(t)$ in eq. (3) is derived using the "trailing" average and is not affected by variations occurring after time t. This is an important issue for possible real time prediction [6].

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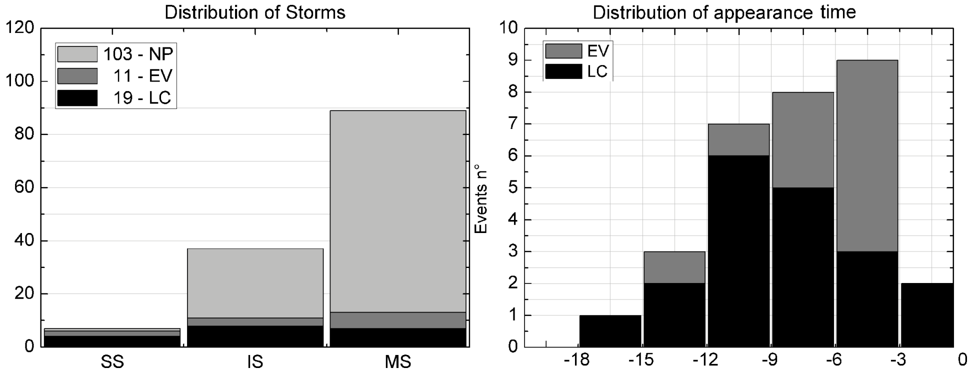

Fig. 3: Histograms of magnetic storms intensity and the appearance time of precursors. "NP" , "EV" and "LC" represent, respectively, "no-precursor" , "enhanced variation" and "loss cone" precursors.