A study of Forbush decrease events with ground-based muon observations

Natural Resources Canada / Ressources naturelles Canada

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Introduction

Ground-based muon detectors are able to observe changes in intensities of cosmic rays when they are subject to modulation effects by solar disturbances. Such changes can be interpreted as precursors for geomagnetic storms (Fig. 1) and can be used to improve warnings for extreme space weather conditions.

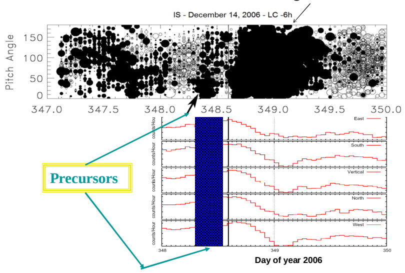

Figure 1 shows muon data measured for different view directions by the muon telescope in São Martinho da Serra (Brazil) for event occurred on December 14, 2006. The dark circles indicate a deficit of intensity of muons and can serve as storm precursors. One can see in Fig. 5 that the precursor first were observed in the eastward viewing channel, then in the vertical and westward, as expected for an anisotropic depression of the cosmic ray intensity.

Fig. 1 Observations of precursors with a GMDN telescope in São Martinho da Serra (Brazil)

An identification of the precursors requires accurate, reliable and complete data, which can be obtained by providing full-sky coverage. GMDN is continually developing and expanding to perform a real-time monitoring system of high-energy cosmic rays for space weather forecasting but there is a data gap over Canada (Fig. 2). The gap could be filled by a detector located in Ottawa (Fig.3). Both figures were presented by Dr. K. Munakata in Canadian Muon Workshop, 2011, Oct 17-19, St-Émile-de-Suffolk, Québec, Canada.

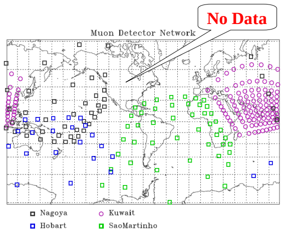

Fig. 2 Current GMDN has a gap over Canada

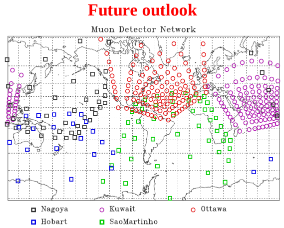

Fig. 3 A suggested muon detector in Ottawa eliminates the gap in GMDN

Carleton muon detector. A test muon detector has been developed at Carleton University, Ottawa in the beginning of 2012 (Fig. 4). The detector has demonstrated the possibility of measuring muon fluxes (Fig. 5) but its detection area is too small to provide good statistics of these measurements and be comparable with GMDN telescopes. Options for building a large detector (5 x 5 m²) located in Ottawa are currently being investigated.

Fig. 4 Test muon detector (1×1 m²) in Carleton is currently taking data shown in Fig. 5.

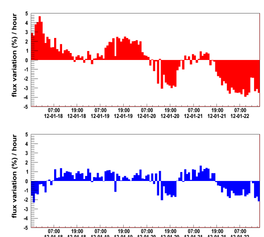

Fig. 5 Relative flux variation in time: raw data (red) and pressure corrected data (blue)

Objectives: The main goal of the project is to study possible precursors of Coronal Mass Ejections (CMEs) by looking at their signatures in Cosmic-Ray (CR) muons. The study will determine the feasibility of obtaining timely warning of extreme space weather conditions using ground-based muon detectors to impact on advanced capability for forecast of geomagnetic storms. The project has two parts. One of them is to develop a Canadian muon telescope to fill the gap existing over North America in current Global Muon Detector Network (GMDN); the other is to clarify the signatures of the interplanetary CMEs in CR muon variations.

Data Analysis

1. Selection of extreme events based on 14-year GMDN data

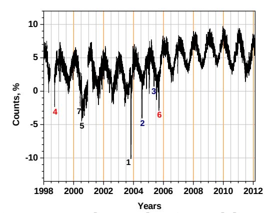

Fig. 6 Nagoya telescope data (vertical direction view); numbers indicate events listed in Table 1

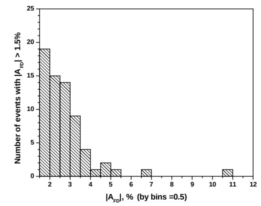

Fig. 7 The more magnitude of Forbush Decrease (FD) the less frequency of occurrence of such an event

Table 1. List of FD events

No.	Year Day (DOY)	Shock (ACE)					Forbush Decrease (Nagoya, vert.)			
		t_1	t_2	v_1, km/s	v_2, km/s	$(v_1+v_2)/2$, km/s	t_{start}	t_{min}	A_{FD}, %	Δ/A_{FD}, %
1	2003 Oct 29 (302)	1:00 (302)	7:05 (302)	716	1810	1263	6:29 (302)	12:12 (302)	11.02	7.0
2	2004 Jul 26 (209)	22:24 (208)	22:28 (208)	597	931	764	0:53 (209)	6:10 (209)	6.01	10.7
3	2005 May 15 (135)	2:10 (135)	3:49 (135)	510	776	643	3:29 (135)	6:02 (135)	4.09	10.3
4	1998 Sep 24 (267)	23:13 (267)	23:19 (267)	436	617	526.5	3:27 (268)	10:01 (268)	3.85	22.3
5	2000 Jul 13 (195)	9:00 (195)	9:37 (195)	507	694	600.5	9:00 (195)	15:02 (195)	3.22	0
6	2005 Sep 10 (253)	15:59 (253)	0:59 (254)	688	1070	879	3:02 (254)	14:32 (254)	3.76	28.7
7	2000 Jun 8 (160)	8:39 (160)	8:43 (160)	504	759	631.5	8:39 (160)	15:09 (160)	2.98	0
8	2004 Jan 22 (22)	1:03 (22)	1: 07 (22)	470	662	566	4:03 (22)	13:57 (22)	3.30	19.1
9	2005 Jan 21 (21)	16:42 (21)	16:54 (21)	589	924	756.5	18:14 (21)	20:54 (21)	3.03	8.9
10	1999 Jan 22 (22)	19:45 (22)	19:49 (22)	530	621	575.5	5:02 (23)	13:30 (23)	2.95	6.4
11	2001 Nov 5 (309)	21:52 (309)	1:52 (310)	412	734	573	5:39 (310)	11:15 (310)	2.68	5.6
12	2001 Mar 27 (86)	1:16 (86)	1:18 (86)	418	519	468.5	6:33 (86)	16:03 (86)	2.67	19.8
13	2001 Sep 25 (268)	18:20 (268)	21:20 (268)	366	694	530	20:20 (268)	6:32 (269)	2.64	6.1
14	2004 Jul 24 (206)	5:36 (206)	5:39 (206)	489	582	535.5	7:60 (206)	14:00 (206)	2.62	1.9
15	2001 Aug 17 (229)	10:15 (229)	10:18 (229)	346	481	413.49	10:48 (229)	14:51 (229)	2.54	33.1
16	2001 Sep 29 (272)	9: 03 (272)	9: 09 (272)	546	644	595	19:12 (272)	0:09 (273)	2.52	20.6
17	2011 Jun 17 (168)	1:59 (168)	2:04 (168)	478	552	515	4:01 (168)	14:48 (168)	2.07	21.7
18	1998 Nov 8 (312)	4:18 (312)	4:23 (312)	475	618	546.5	6:14 (312)	15:58 (312)	1.90	53.7
19	2000 Sep 17 (261)	16:55 (261)	16:59 (261)	592	734	663	17:02 (261)	9:40 (262)	0.73 (1.92)	0
20	2001 Apr 11 (101)	13:07 (101)	13:15 (101)	504	602	553	0:30 (102)	12:50 (102)	1.64	20.7
21	2001 Apr 28 (118)	4:29 (118)	4:32 (118)	468	777	622.5	8:20 (118)	16:54 (118)	1.38	50.7
22	2006 Dec 14 (348)	13:52 (348)	14:02 (348)	602	925	763.5	14:02 (348)	5:53 (349)	1.30	0
23	2001 Apr 4 (94)	14:20 (94)	14:27 (94)	468	641	554.5	14:31 (94)	22:00 (94)	0.70	0

The listed in Table 1 FD events were selected by visual inspection of hourly CR intensity recorded with Nagoya muon telescope in the vertical view direction (cut-off rigidity is 11.09 GV) since 1998 to 2011 includingly (Fig. 6) by two criteria: (a) event should not be a part of a chain of events unless only it is the first one in it; (b) event occurs at McMurdo neutron station. Table 1 includes all such events with FD magnitude AFD exceeding 2.5%, the rest events are given for illustrative purposes. In the table, v_1 and v_2 are solar wind speed values immediately in front of and behind shock respectively, registered at ACE at time moments t_1 and t_2 (see Fig. 8); t_{start} and t_{min} are moments when FD starts and reaches minimum in muon counts, A_{FD} is the magnitude of the FD and Δ is its uncertainty, their measurements are shown in Fig. 9-11 (see also Sec. 3).

Summary. To evaluate models of propagation of solar disturbances and develop models for magnetic storm precursors the existing muon data from GMDN and solar disturbance data measured on satellites are used and analysed. Some results of a statistical analysis of Forbush decrease events which are often associated with the interplanetary CMEs are presented. Using muon data from the Nagoya telescope, distributions of the muon intensity for each year were obtained and few large events in CRs were identified. By analysing the distribution function, parameters of extreme events were found and a list of extreme events was composed. Analysis of these events was undertaken to look for correlations between the magnitude of the Forbush decrease and both the solar wind parameters and the interplanetary magnetic field with a view to using them in further modeling of extreme space weather events.

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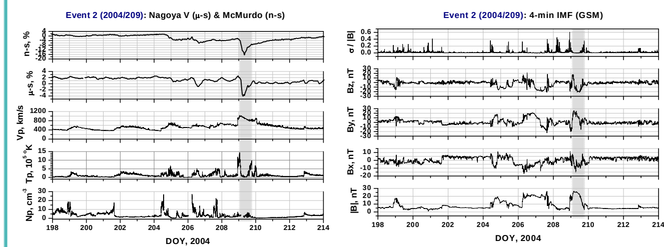
2. Analysis of muon and solar data

Time-distributions for counts of muons and neutrons together with density, temperature and velocity for protons in the solar wind plasma as well as the interplanetary magnetic field were taken for each event using data from Nagoya muon telescope (http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon/), McMurdo neutron station (http://neutronm.bartol.udel.edu/~pyle/bri_table.html) and ACE Level 2 data (http://www.srl.caltech.edu/ACE/ASC/level2/). As an example, these distributions are shown below for event 2. The shadowed stripe shows a time period during a geomagnetic storm defined by values of index Kp exceeding +6 (http://www-app3.gfz-potsdam.de/kp_index/quicklook.html). One can see that for the event 2 shock, FD and storm has in fact the same commencement.



3. Estimate of magnitude of Forbush decrease (see Table 1)

In attempt to find a correlation between AFD, measured with using muon telescope data, and parameters of solar wind, a ratio of uncertainty Δ in the value of AFD, resulting from diurnal variations, to AFD was introduced. Then the events listed in Table 1 were conditionally broken into three groups depending on the ratio: events with the ratio less than 7% (small variations), between 7% and 22% (medium variations) and larger than 22% (large variations).

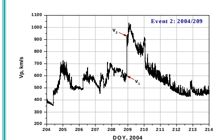


Fig. 8 Sample of shock front

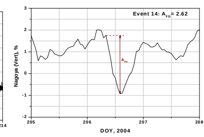


Fig. 9 Sample of FD with small variations

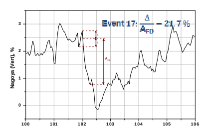


Fig. 10 Sample of FD with medium variations

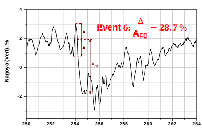


Fig. 11 Sample of FD with large variations

Examples for calculating AFD and the ratio for events from different groups are shown in Fig. 9-10. In case when an event has a many-step decrease (as e.g. in Fig. 10 and 11), only the first step is taken into account. In Fig. 12 we represent each event by its value of AFD (Δ is shown as an error bar) and average v of values v1 and v2 from Table 1; dashed lines show AFD with taking a total decrease (also shown in brackets in Table 1). The quantity v = v1 + (v2 - v1)/2 is chosen as it depends both on background for a shock (v1) and a jump at the front (v2-v1). Although the figure shows no correlation between AFD and v, the idea of grouping events by some criteria and introducing interplanetary magnetic field with other parameters looks reasonable to continue the analysis of events under study.

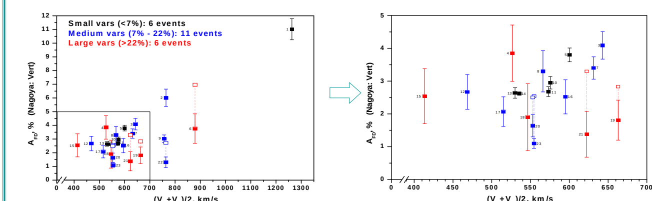


Fig. 12 The fragment marked by rectangle in the left figure is zoomed-in at the right.

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