Forbush Decreases Associated with Western Solar Sources and Geomagnetic Storms: A Study on Precursors

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Abstract As suggested in many studies the pre-increases or pre-decreases of the cosmic ray intensity (known as precursors), which usually precede a Forbush decrease, could serve as a useful tool for studying space weather effects. The events in this study were chosen based on two criteria. Firstly, the heliolongitude of the solar flare associated with each cosmic ray intensity decrease was in the 50°–70°W sector and, secondly, the values of the geomagnetic activity index, Kp_{max}, were ≥ 5. Twenty five events were selected from 1967 to 2006. We have used data on solar flares, solar wind speed, geomagnetic indices (Kp and Dst), and interplanetary magnetic field in our detailed analysis. The asymptotic longitudinal cosmic ray distribution diagrams were plotted using the "Ring of Stations" method for all the events. The results reveal clear signs of precursors in 60 % of selected events.

Keywords Forbush decreases · Geomagnetic storms · Pre-decreases · Pre-increases · Neutron monitors

1. Introduction

The study of precursors (pre-decreases or pre-increases) in the cosmic ray intensity (CRI) usually preceding Forbush decreases (FDs) has been the main subject in many investigations (Belov *et al.*, 1995; Leerungnavarat, Ruffolo, and Bieber, 2003; Dorman, 2005; Kudela and Storini, 2006). Pre-decreases apparently result from a "loss cone" effect in which the

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neutron monitor station is magnetically connected to the cosmic ray depleted region down-stream of the shock (Belov *et al.*, 1995; Leerungnavarat, Ruffolo, and Bieber, 2003), while pre-increases are caused by galactic cosmic ray acceleration at the front of the advancing disturbance, as the particles are being reflected from the approaching shock (Belov *et al.*, 1995; Kudela and Storini, 2006).

Recent investigations (Papailiou *et al.* 2012a, 2012b) indicate that the enhanced equatorial component of the first harmonic of the cosmic ray anisotropy, A_{xy}, observed for at least one hour before the shock arrival, can be considered as a satisfactory criterion for precursors.

In this study the events under examination were chosen based on the heliolongitude of the solar flare associated with each CRI decrease ($50° - 70°$W) and the values of the geomagnetic index Kp (≥ 5). Thus, 25 events were selected; some are described in more detail below. Although events related to western solar sources are not so big and do not show as well-marked cosmic ray variations near Earth as those related to eastern or central sources, they were chosen because they are characterized by a larger anisotropy before the shock arrival.

2. Data and Method

Asymptotic longitudinal cosmic ray distribution diagrams were plotted using the "Ring of Stations" (RS) method. This method uses hourly data of CRI variations recorded by the neutron monitor stations. In this study stations with cut-off rigidity $R_c < 4$ GV and latitudes $< 70°$ were used (Belov *et al.*, 1995; Asipenka *et al.*, 2009). The asymptotic longitudinal cosmic ray distribution diagrams were obtained using data from 31 neutron monitors. A detailed list of the neutron monitor stations used by the RS method was included in Papailiou *et al.* (2012a). The density and first harmonic of the anisotropy for cosmic rays of rigidity 10 GV, as calculated by the global survey method (Belov *et al.*, 2005), and solar wind parameters and geomagnetic indices, as obtained from the OMNI database (http://omniweb.gsfc.nasa.gov), have been used for the analysis of each event.

3. Results

The events under study correspond to the time period $1967 - 2006$, which covers the 21st ($1976 - 1986$), 22nd ($1986 - 1996$) and 23rd ($1996 - 2008$) Solar Cycles (http://www.ngdc. noaa.gov/stp/solar/ssndata.html). The yearly distribution of the 25 FDs, connected to western solar sources and geomagnetic storms, along with the yearly distribution of 15 of them, which revealed signs of precursors, are shown in Figure 1 (upper and bottom panels, respectively). In these figures solar activity (through sunspot number) is also depicted for the same time period. As is seen, the frequency of observed FDs is highest around the maximum of the solar cycles.

A certain correlation exists between the size of the Forbush effect and a precursor, though for the western sources this rule is often broken; it is possible to see a big precursor with a small Forbush effect since the main part of solar wind disturbances goes to the West and is not visible at Earth.

All the events under study, along with the main interplanetary parameters, are shown in Table 1. In this work the events on 21 January 2005, 24 August 2005, 26 May 1990, and 4 October 1983, are analyzed for the first time. Below follows a detailed description of the relevant interplanetary disturbances during the aforementioned decreases along with the longitude-time distribution of cosmic ray variation diagrams.
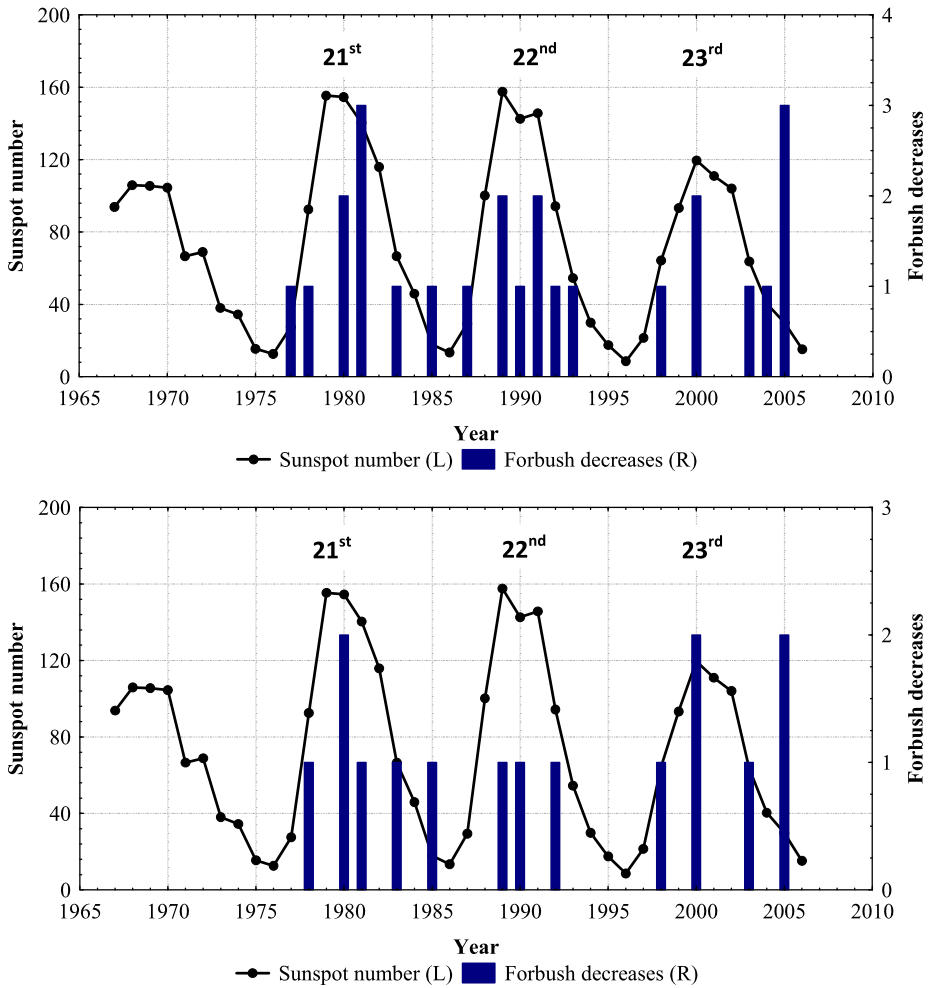
Figure 1 Yearly distribution of the sunspot number and the number of Forbush decreases associated with western solar sources and geomagnetic storms (upper panel) and of those with precursors (bottom panel).

The asymptotic longitude distribution of cosmic ray variations observed by different stations is presented in Figures 2, 3, 4, and 6. In these figures the vertical axis corresponds to the asymptotic longitude of the stations and the horizontal axis refers to the time as DD.HH in UT. The CRI decreases, as measured by all neutron monitor stations used by the RS method, are depicted with red circles, while yellow circles refer to CRI increases, relative to a quiet fixed period. The size of the circles is proportional to the size of the variation. The vertical line denotes the time when the sudden storm commencement (SSC) was registered.

A SSC was registered on 21 January 2005, at 17:11 UT. The source of the event was an X7.1 flare on 20 January 2005, at 18:36 UT in active region (AR) 10720 with coordinates N14W61. Even though a ground level enhancement (GLE) on January 20 preceded this event, it is a good example of precursor. The geomagnetic conditions were also quiet before the FD. During this event the maximum interplanetary magnetic field (IMF) intensity was 29.5 nT and the maximum solar speed velocity was 950 km s^{-1}. The CRI decrease was about

**Table 1** Main interplanetary parameters for the events under study.

Event	Flare	Heliographic latitude/longitude	Kp_{max}	Dst_{min} (nT)	FD amplitude (%)
10 May 1978	X2.0	N22W68	6.0	−78	0.7
28 Jan. 1980	M7.0	S19W51	5.3	−69	2.5
30 Oct. 1980	C4.0	S19W60	5.3	−58	3.6
23 Jul. 1981	X2.7	S37W56	5.7	−89	3.9
4 Oct. 1983	M1.1	S18W53	6.7	−71	1.1
12 Aug. 1985	C5.4	S11W69	6.3	−51	1.1
19 Mar. 1989	X6.5	N33W60	6.7	−106	2.2
26 May 1990	M8.7	N33W55	7.3	−87	0.8
27 Jun. 1992	X3.9	N09W67	6.7	−98	0.6
29 May 1998	C7.5	N18W58	6.7	−58	1.8
6 Apr. 2000	C2.1	N16W66	8.7	−288	2.8
28 Oct. 2000	C4.0	N10W66	6.0	−127	7.7
4 Nov. 2003	X8.3	S14W56	7.0	−89	2.6
21 Jan. 2005	X7.1	N14W61	8.0	−105	9.0
24 Aug. 2005	M2.6	S11W54	8.7	−216	6.4
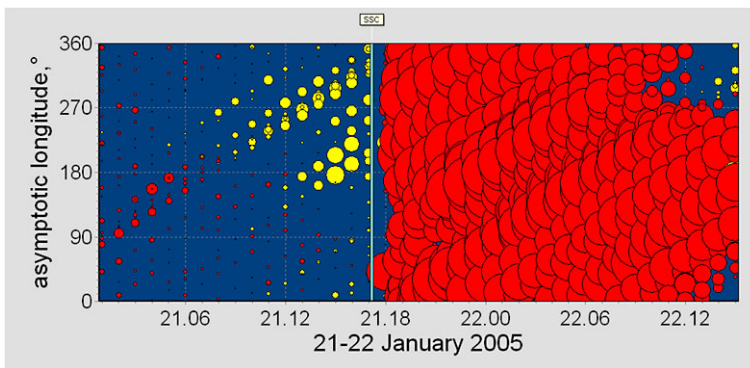
**Figure 2** The event on 21 January 2005, presented as a longitude-time distribution. For explanation see text.

9 % and the maximum anisotropy was 5.26 %. The registered geomagnetic storm was severe (*Kp* and *Dst* indices were 8 and − 105 nT, respectively). As seen in Figure 2 a pre-increase above 180° was visible before the shock.

Concerning the event on 24 August 2005, the SSC was registered on 24 August 2005, at 6:13 UT. This event was the result of a combination of an M2.6 flare registered on 22 August at 00:44 UT in AR10798 with coordinates S11W54 and the coronal hole 183. During this event the maximum IMF intensity was 52.2 nT and the maximum solar wind speed was 720 km s^{-1}. The CRI decrease was about 6.4 % and the maximum anisotropy was 2.66 %. In addition to this, a severe storm with *Kp* index 8.7 and *Dst* index − 216 nT was registered. As seen in Figure 3 a pre-decrease at around 90°, was visible before the shock.

The event on 26 May 1990, is an example of a very peculiar precursor. The SSC was registered on 26 May 1990, at 20:37 UT. The source of the event was an M8.7 flare, which
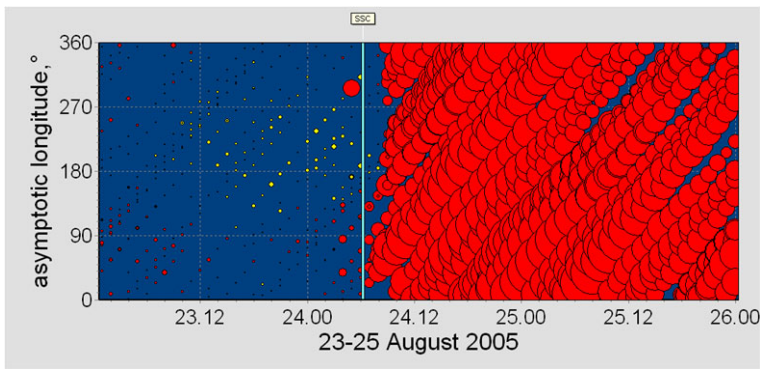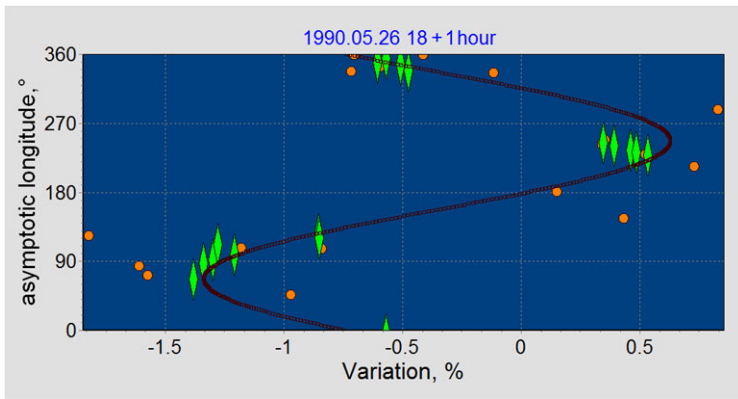
Figure 3 The event on 24 August 2005, presented as a longitude-time distribution.
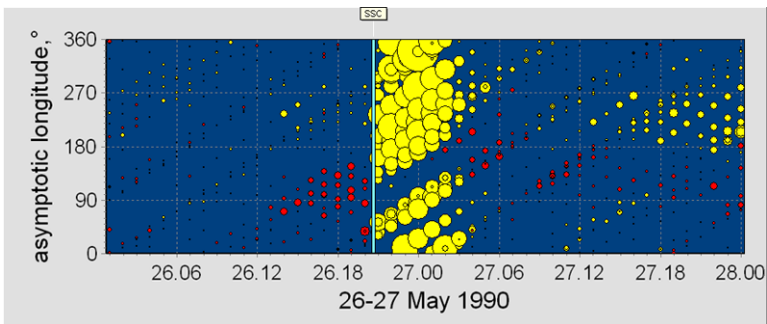

Figure 4 The event on 26 May 1990, presented as a longitude-time distribution.

occurred on 23 May at 4:01 UT in AR6063 with coordinates N33W55. Even though there is no obvious CRI decrease, this is a good example of precursor. Almost 6 hours prior to the shock arrival a very characteristic CRI decrease at longitudes around 90° was recorded. This variation is expected to be a precursor of a FD, which however was not registered by neutron monitors due to the GLE on 26 May; nevertheless, it was a precursor of the geomagnetic storm which started simultaneously with the shock arrival. Cosmic rays underwent this decrease in the interplanetary medium and brought this information to Earth. Thus, this event is unusual and has no analog. During this event the observable CRI decrease was about 0.8 % but the maximum anisotropy was 2.61 %. The registered geomagnetic storm was strong (*Kp* and *Dst* indices were 7.3 and −87 nT, respectively). The asymptotic longitudinal cosmic ray distribution diagram for this event is presented in Figure 4.

In previous studies (Belov *et al.*, 2001) it was shown that during precursors a specific longitudinal angle distribution of the cosmic ray variations appears when maximum and minimum are very close and, then, the CRI changes sharply around certain longitudes. In Figure 5 such a longitudinal angle distribution of the cosmic ray variations is plotted for the event on 26 May 1990, from 18:00 to 19:00 UT, two hours before the shock arrival. The figure clearly shows the close position of the minimum and maximum of cosmic ray variations in a narrow strip of longitudes, around 90°. As is clearly seen, this distribution cannot be described by the simple harmonic of the first order.

Figure 5 Dependence of cosmic ray variations on the asymptotic longitude of neutron monitors in the event on 26 May 1990. For explanation see text.
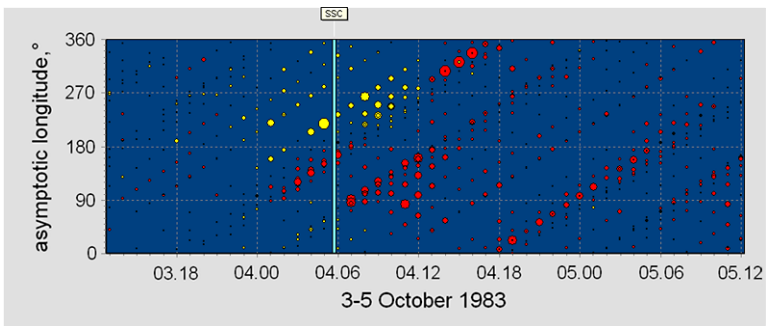

Figure 6 The event on 4 October 1983, presented as a longitude-time distribution.

In Figures 5 and 7, orange dots are hourly cosmic ray variations, green diamonds depict cosmic ray variations averaged within the sector $\pm 20°$ for Figure 5 and $\pm 10°$ for Figure 7, while the curve is the fitted first harmonic of the anisotropy (solar–diurnal variation) for the data under consideration.

The event on 4 October 1983 (see Figure 6), demonstrates that such a characteristic precursor distribution can persist. The SSC for this event was registered on 4 October 1983, at 5:41 UT. The source of the event was an M1.1 flare on 2 October 1983, at 6:12 UT in AR4324 with coordinates S18W53. During this event the maximum IMF intensity was 23.6 nT and the maximum solar wind speed was 533 km s^{-1}. The CRI decrease was about 1.1 % and the maximum anisotropy was 1.91 %. The registered geomagnetic storm was moderate (*Kp* index was 6.7 and *Dst* index was -71 nT). In Figure 7 the data are plotted along four hours, from 1:00 to 5:00 UT on 4 October 1983. It is seen that the first harmonic does not completely describe the distribution of the variations. It is obvious that similar variations are grouped at a certain longitude, the minimum being within a narrow strip of longitudes – around 90°.

It should be mentioned that there is one FD on 28 October 2000, which is included not only in the group of events connected to western solar sources and geomagnetic storms, discussed in this study, but also in the group of events with an equatorial component of the first harmonic of the cosmic ray anisotropy, A_{xy}, greater than 1.2 % (Papailiou *et al.*, 2012b).
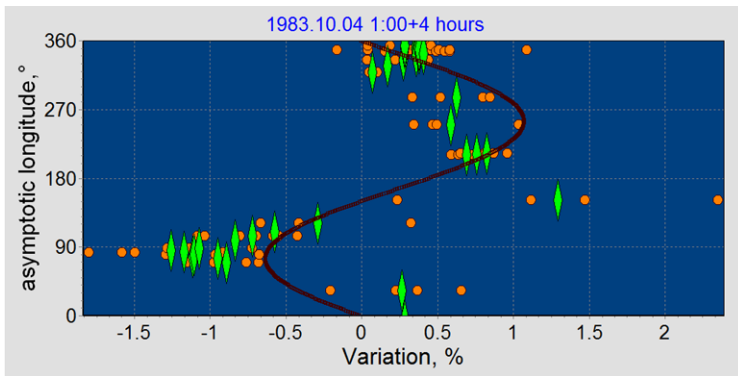
Figure 7 Dependence of cosmic ray variations on the asymptotic longitude of neutron monitors in the event on 4 October 1983.

4. Conclusions

Twenty five Forbush decreases, which were associated to western-hemispheric solar flares and followed by geomagnetic storms, were chosen from a list of events throughout the period 1967 – 2006. We conclude that before geomagnetic storms and Forbush effects, which are caused by CMEs with a source in the western portion of the solar disk, precursors can be seen in galactic cosmic rays very often as a CRI pre-increase and pre-decrease in certain longitudes. The growing amplitude of the first harmonic of the cosmic ray anisotropy, which is determined by neutron monitor network data, is connected, as a rule, with the appearance of the precursor.

Sometimes the size of the precursor is so big and the CRI distribution is so unusual and specific that this precursor may serve to forecast a significant interplanetary disturbance arriving to Earth, even in the absence of other data.

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