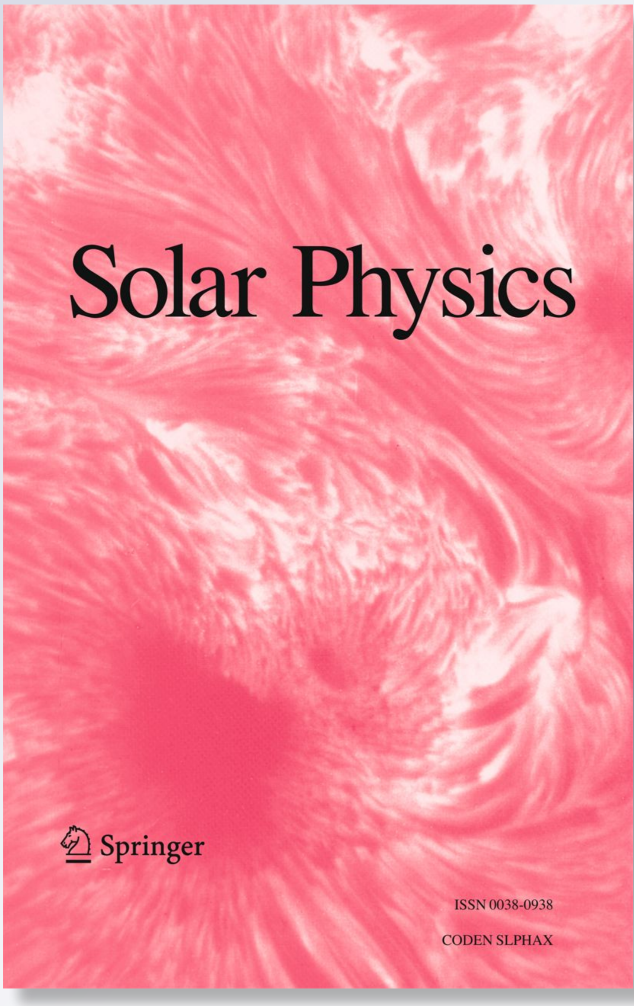
Precursor Effects in Different Cases of Forbush Decreases

M. Papailiou, H. Mavromichalaki, A. Belov, E. Eroshenko & V. Yanke

Solar Physics
A Journal for Solar and Solar-Stellar Research and the Study of Solar Terrestrial Physics

ISSN 0038-0938
Volume 276
Combined 1-2

Sol Phys (2012) 276:337-350
DOI 10.1007/s11207-011-9888-1



Springer

Solar Phys (2012) 276:337–350
DOI 10.1007/s11207-011-9888-1

Precursor Effects in Different Cases of Forbush Decreases

M. Papailiou · H. Mavromichalaki · A. Belov · E. Eroshenko · V. Yanke

Received: 19 September 2011 / Accepted: 20 October 2011 / Published online: 30 November 2011

Abstract Over the last few years, the pre-decreases or pre-increases of the cosmic-ray intensity observed before a Forbush decrease, called the precursor effect and registered by the worldwide neutron monitor network, have been investigated for different cases of intense events. The Forbush decreases presented in this particular study were chosen from a list of events that occurred in the time period 1967 – 2006 and were characterized by an enhanced first harmonic of cosmic-ray anisotropy prior to the interplanetary disturbance arrival. The asymptotic longitudinal cosmic-ray distribution diagrams for the events under consideration were studied using the "Ring of Stations" method, and data on solar flares, solar-wind speed, geomagnetic indices, and interplanetary magnetic field were analyzed in detail. The results revealed that the use of this method allowed the selection of a large number of events with well-defined precursors, which could be separated into at least three categories, according to duration and longitudinal zone. Finally, this analysis showed that the first harmonic of cosmic-ray anisotropy could serve as an adequate tool in the search for precursors and could also be evidence for them.

Keywords Cosmic rays · Forbush decreases · Neutron monitors · Precursors

1. Introduction

Galactic cosmic rays (CRs) interact with transient disturbances moving from the Sun, and in this way they transfer information about the oncoming disturbance before it reaches the Earth. These disturbances, especially those associated with sporadic sources (solar flares or filament disappearance), create perturbations in the magnetosphere which can cause a storm

M. Papailiou · H. Mavromichalaki (✉)
Nuclear and Particle Physics Section, Physics Department, National and Kapodistrian University of Athens, Zografos, 15771 Athens, Greece
e-mail: emavromi@phys.uoa.gr

A. Belov · E. Eroshenko · V. Yanke
Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation RAS (IZMIRAN), Troitsk, Moscow region, Russia

in the geomagnetic field. Geomagnetic storms are often followed by CR-intensity decreases, known as Forbush effects (FEs), which are created by this disturbance in the heliosphere (Forbush, 1958; Lockwood, 1971; Cane, 2000).

Unlike in quiet periods, before the Forbush decrease (FD) anomalies in the CR intensity distribution, such as pre-increases or pre-decreases, along with changes in the anisotropy are noticed. These anomalies in the CR variations were recognized a long time ago (Fenton *et al.*, 1959; Blokh, Dorman, and Kaminer, 1959), but over the last few years this particular subject has been intensively investigated (Nagashima *et al.*, 1993; Belov *et al.*, 1995; Belov *et al.*, 2001; Leerungnavarat, Ruffolo, and Bieber, 2003; Munakata *et al.*, 2005; Asipenka *et al.*, 2009). The above-mentioned changes in the behavior of the galactic CRs are observed from one hour up to 20 hours before the shock arrival (Belov *et al.* 1995, 2001) and can be used to forecast the oncoming disturbance and the geomagnetic storm.

Although precursors have been investigated for a long time and intensively, their discrimination remains a complex issue. As a result, clear and convincing examples of such phenomena are not often published, and the most characteristic of them appear repeatedly in many articles. One of the goals of this work is to determine a method for analyzing the data of neutron monitors in order to study new events with obvious CR precursors and thus increase the number of the aforementioned examples.

The pre-increases and pre-decreases can be explained as kinetic interactions of the CR particles with the approaching shock and ejecta or the region behind the shock (Ruffolo *et al.*, 1999; Leerungnavarat, Ruffolo, and Bieber, 2003; Asipenka *et al.*, 2009). Moreover, precursor decreases apparently result from a "loss cone" effect, in which the neutron monitor station is magnetically connected to the CR-depleted region downstream of the shock (Belov *et al.*, 1995; Leerungnavarat, Ruffolo, and Bieber, 2003). On the other hand, precursor increases are caused by galactic-CR acceleration at the front of the advancing disturbance, as the particles are being reflected from the approaching shock (Belov *et al.*, 1995; Dorman, Iucci, and Villoresi, 1995).

Most of the predictors have a peculiar longitude (or pitch angle) dependence of CR intensity with the abrupt transfer from minimum to maximum of CR variations which cannot be fitted by the sum of only the first two harmonics. These sharp changes probably occur within the $140° - 180°$ and $270° - 310°$ longitude regions, near the usual direction of the interplanetary magnetic field (IMF) line (sunward and anti-sunward). These anomalies are usually observed in the last hours before the shock arrival, typically within four hours; however, they sometimes cover a longer period. The neutron-monitor network is a good tool for detecting such anomalies in the pitch angle or longitudinal distribution of CR variations. In recent years, searching for predictors by muon-telescope data has also been developed rather successfully (Munakata *et al.* 2000, 2005, 2006; Kudela and Storini, 2006).

One approach to display the possible precursor effects is the "Ring of Stations" method based on the asymptotic angle distribution of the CR variations which has been used in many studies. In particular, it has been used to describe the bright example of the precursor for the event in September 1992, which is mentioned in many research papers (Belov *et al.*, 1995; Munakata *et al.*, 2000; Belov *et al.*, 2003; Asipenka *et al.*, 2009). It is also used as an application in the high-resolution Real-Time Neutron Monitor Database (NMDB) for real-time construction of the CR angle distribution (see http://www.nmdb.eu/?q=node/19 or http://cr0.izmiran.ru/PrecursorMonitoring/index.htm).

At the Bartol Research Institute, the system of real-time monitoring of the precursors is created on the basis of pitch-angle CR distribution (http://neutronm.bartol.udel.edu/spaceweather/). A limited number of stations are used and are homogeneously distributed according to longitude (Spaceship Earth). The efficiency of the system is satisfactory, but it depends on the operational reliability of the station (a break at one station creates a gap in the scanning of $\approx 50°$ of the celestial sphere) and on the constant flow of the IMF data which are used for the pitch angle calculations.

As was shown by Belov *et al.* (2003), the observed longitudinal distribution of the CR variations before the shock cannot be described by the changes of low-order harmonics. Nevertheless, it is clear that changes of these harmonics during this time period should also exist. In a recent work, Belov *et al.* (2008) calculated the average value of the first harmonic of the CR anisotropy using 1529 FEs and clearly showed that it increases before the shock arrival. For this reason, the cases which were analyzed in this work were chosen from a large list of events where the essential increase of the equatorial component of the first harmonic of CR anisotropy [A_{xy}] was observed for at least one hour before the shock arrival.

In this study, different FDs that occurred in the time period 1967 – 2006 and presented similar precursor effects have been analyzed. The article consists of a description of the data and the applied method (Section 2) and a discussion on the results obtained for three groups of FE precursors: clear pre-decrease for almost 24 hours before the shock arrival; pre-increase of about 12 hours; and pre-decrease lasting sometimes less than 12 hours until the shock arrival is observed (Section 3). The conclusions are presented in Section 4.

2. Data and Method

Hourly values of the CR density and anisotropy, obtained from the neutron-monitor network, were combined with solar, interplanetary, and geomagnetic parameters in the database of the interplanetary disturbances and FEs created at the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation RAS (IZMIRAN: Belov, 2008). This database of FEs currently includes about 6000 events over the period 1957 – 2010 and allows the selection of events with regard to different parameters and various statistical estimations.

Using the global survey method (GSM), the density and first harmonic of anisotropy for the CR of rigidity 10 GV have been calculated (Belov *et al.*, 2005; Asipenka *et al.*, 2009) and entered into this database. Solar-wind parameters and geomagnetic indices were obtained from the OMNI database (http://omniweb.gsfc.nasa.gov).

For studying the precursor effects in different Forbush events, the "Ring of Stations" (RS) method has been applied (Belov *et al.*, 1995, 2003; Asipenka *et al.*, 2009) to the hourly data of CR intensity recorded by the neutron-monitor stations of the worldwide network with cutoff rigidity $R_c < 4$ GV and latitudes $< 70°$. A list of the stations used in the RS method is presented in Table 1.

This method calculates the hourly values of CR-intensity variations at each station relative to a fixed period and then plots it according to the asymptotic longitude of the station at that moment. The precursor effect is very anisotropic; thus, the sky coverage in the asymptotic directions of the stations used should be as full as possible. Using as many neutron monitors as possible, temporal variations of CR intensity distributed in space by asymptotic directions are depicted.

The pitch-angle distribution method is more tightly connected to the model of pre-decreases caused by the "loss cone," but the asymptotic longitudinal dependence method has its own advantages: *i*) it provides the real longitudinal distribution of CR intensity, *ii*) it depends less on the uncertainties of the model of the isotropic and anisotropic variations, and *iii*) it does not depend on the IMF measurements (Belov *et al.*, 1995; Asipenka *et al.*, 2009). In addition, the IMF measurements have a local character, whereas CRs reflect an influence of space.

Table 1 List of the neutron monitor stations used in the "Ring of Stations" method.

	NM Station	Abbrev.	Latitude [deg.]	Longitude [deg.]	R_c [GV]	Altitude [m]
1	Apatity	APTY	67.55	33.33	0.65	177
2	Calgary	CALG	51.08	−114.13	1.08	1128
3	Cape Schmidt	CAPS	68.92	−179.47	0.45	0
4	Climax	CLMX	39.37	−106.18	2.93	3400
5	Deep River	DPRV	46.10	−77.50	1.25	145
6	Durham	DRHM	43.10	−70.83	1.76	0
7	Fort Smith	FRSM	60.02	−112.00	0.30	0
8	Goose Bay	GSBY	53.27	−60.40	0.74	46
9	Inuvik	INVK	68.35	−133.72	0.14	21
10	Irkutsk	IRKT	52.47	104.02	3.66	433
11	Kerguelen	KERG	−49.35	70.25	1.14	33
12	Kiel	KIEL	54.33	10.11	2.29	54
13	Kiev	KIEV	50.72	30.30	3.39	120
14	Kingston	KGSN	−42.99	147.29	1.82	65
15	Larc	LARC	−62.20	−58.96	3.01	40
16	Lomnicky Stit	LMKS	49.20	20.22	4.00	2634
17	Magadan	MGDN	60.12	151.02	2.10	0
18	Mawson	MWSN	−67.60	62.88	0.15	0
19	Moscow	MOSC	55.47	37.32	2.46	200
20	Mt. Washington	MTWS	44.30	288.70	1.58	1909
21	Mt. Wellington	MTWL	−42.92	147.24	1.83	725
22	Nain	NAIN	56.55	−61.68	0.40	0
23	Newark	NWRK	39.68	−75.75	1.97	50
24	Norilsk	NRLK	69.26	88.05	0.63	0
25	Novosibirsk	NVBK	54.80	83.00	2.91	163
26	Oulu	OULU	65.02	25.50	0.81	15
27	Peawanuck	PWNK	54.98	−85.44	0.50	0
28	Sanae	SNAE	−71.67	−2.85	0.86	856
29	Terre Adelie	TERA	−66.65	140.00	0.00	32
30	Tixie Bay	TXBY	71.60	128.90	0.53	0
31	Yakutsk	YKTK	62.02	129.73	1.70	105

For this particular work, Forbush decreases (FDs) through the time period 1967 – 2006 with anisotropy $A_{xy} > 1.2\%$ were selected (93 events in total). Usually this anisotropy has a value $< 0.6\%$. The chosen anisotropy can be considered as anomalous, since it exceeds the mean statistical value significantly. As was shown by Belov *et al.* (2008), the events with A_{xy} before the shock greater than 1.1% are distinguished by deeper FDs and higher values of anisotropy. In this study, 27 different FDs, from the group of 93 events, were chosen to be analyzed and are presented on the basis of their common behavior in the asymptotic longitudinal CR distribution diagrams.

Table 2 Main interplanetary parameters for the events of the first group.

Events	Solar flares	Heliographic Latitude/longitude	Kp_{max}	Dst_{min} [nT]	IMF_{max} [nT]	Solar wind speed max [km s^{-1}]	FD amplitude [%]	$A_{xy\ min}$ [%]
24 June 1980	M2.3	S12E17	3.7	−18	14.0	453	> 3	2.62
28 October 2000	C4.0	N10W66	6.0	−113	18.8	415	8	3.49
17 August 2001	C2.3	N26W10	7.0	−105	32.1	599	6	4.41
23 April 2002	X1.5	S14W84	6.0	−56	15.1	593	2	1.49
10 May 2002	M1.4	S08E28	4.0	−11	10.8	421	2	1.96

3. Results

After the analysis and a careful study of the asymptotic longitudinal diagrams were performed, the aforementioned events were distributed into three categories: The first group, for which a pre-decrease in the longitudinal zone 90° – 180° was noticed almost 24 hours before the shock arrival, includes five events (24 June 1980, 28 October 2000, 17 August 2001, 23 April 2002, and 10 May 2002). The second group, for which the precursor effect is a pre-increase in the longitudinal zone around and above 180° and lasts almost 12 hours until the FD, includes 14 events (3 January 1978, 13 July 1978, 11 January 1980, 30 March 1980, 25 July 1980, 11 December 1980, 2 October 1981, 10 October 1988, 9 September 1992, 26 August 1998, 20 February 2000, 25 September 2001, 7 September 2002, 9 July 2006), and the third group, for which a pre-decrease in different longitudes and of different duration in every case is observed, includes eight events (8 September 1981, 16 April 1982, 4 March 1995, 10 August 1998, 18 October 1998, 15 September 2000, 3 August 2001, 25 August 2002).

A short description of the relevant interplanetary disturbances and the longitude–time distribution of CR variations for some of the aforementioned events are presented below.

3.1. Forbush Decreases with a Long Pre-decrease in a Narrow Longitudinal Zone

The values of the geomagnetic indices Kp and Dst connected to the FDs of this group, along with other interplanetary parameters, are presented in Table 2. A firm conclusion about the sources cannot yet be drawn because of the limited number of events analyzed (two events are connected to western sources, two with eastern, and only one with a solar flare that belongs to the central heliolongitudinal sector). However, it is safe to say that, for the majority of the events, an increase of the IMF intensity and the solar-wind speed is observed. Moreover, moderate or strong geomagnetic storms seem to precede the aforementioned FDs.

In particular, for the event on 17 August 2001, a strong increase of the IMF intensity (23.6 nT) and of the solar-wind speed (≈ 600 km s^{-1}) resulted in the strong sudden storm commencement (SSC) that was recorded on 17 August 2001 at 11:03 UT (Figure 1, upper panel). The two-step FD recorded on 17 – 18 August 2001 (Figure 1, middle panel) was almost 6% and was followed by a significant increase of CR solar diurnal anisotropy. The associated C2.3 flare (N26W10) was recorded on 14 August 2001 at 11:30 UT and belongs to the central heliolongitudinal sector. Geomagnetic indices Kp and Dst during this event were 7 and −107 nT respectively (strong magnetic storm) as can be seen in Figure 1 (bottom panel).

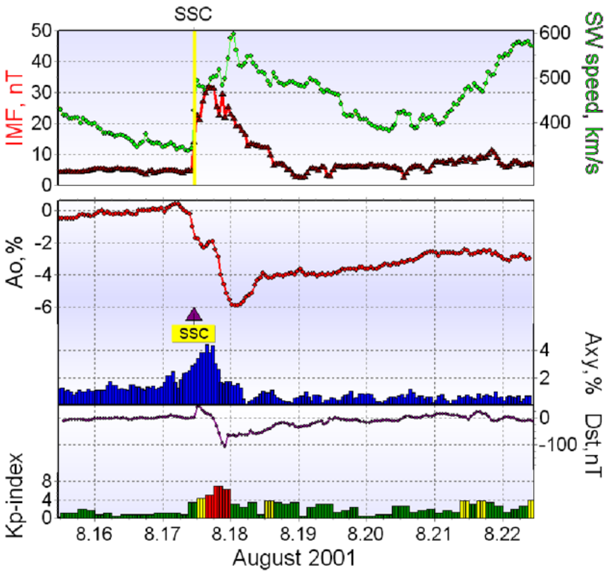


Figure 1 Variations of the interplanetary magnetic field and solar-wind speed (upper panel), cosmic ray intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 17 August 2001. The horizontal axis refers to MM.DD.

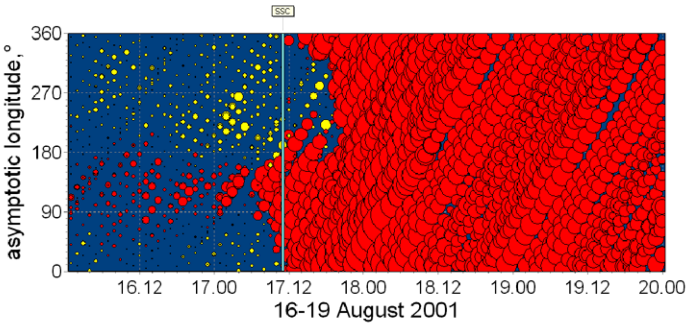


Figure 2 The longitude–time distribution of the event on 17 August 2001. The horizontal axis refers to DD.HH.

The CR event described above was also depicted using the asymptotic longitudinal CR distribution in order to examine and determine the existence of precursors for the event (Figure 2).

The asymptotic longitudinal CR distribution diagrams were obtained using 31 neutron-monitor stations. This number of stations covers essentially all of the asymptotic longitudes and guarantees that data from as many longitudes of arrival as possible are obtained at every moment. Each station rotates with the Earth and thus scans a complete circle of longitudes during a day. Clearly, a more complete picture of the whole celestial sphere is obtained when at any moment a sufficient number of stations looking toward different asymptotic directions is used.

An example of a longitude–time distribution of CR variations as measured by different neutron monitors for a specific event is shown in Figure 2. In this figure the red circles stand for decreases of CR intensity, while yellow circles depict increases of CR intensity, relative to a quiet fixed period, as measured for all neutron-monitor stations used in the RS method. The size of the circle is proportional to the size of the variation. The vertical line denotes the

Table 3 Main interplanetary parameters for the events of the second group.

Events	Solar flares	Heliographic Latitude/longitude	Kp_{max}	Dst_{min} [nT]	IMF_{max} [nT]	Solar wind speed max [$km\,s^{-1}$]	FD amplitude [%]	A_{xy} min [%]
03 January 1978	M3.0	S18E05	7.3	−121	17.9	756	4	2.97
13 July 1978	X3.0	N18E58	4.3	−11	13.4	442	> 4	2.62
11 January 1980	X1.0	S11E29	3.0	−20	11.1	442	2	1.51
30 March 1980	C6.0	N14E52	4.0	−39	11.9	397	< 2	2.25
25 July 1980	M8.9	S17E13	7.0	−88	16.0	503	> 4	1.97
11 December 1980	C3.0	N50W08	4.7	−27	18.0	640	4	3.30
02 October 1981	C7.6	S16E47	6.3	−50	19.4	710	> 3	2.65
10 October 1988	M3.3	S23W36	7.7	−156	27.4	–	> 2	2.17
09 September 1992	M1.3	S13W32	7.3	−135	25.0	589	> 4	4.10
26 August 1998	X1.0	N35E09	8.0	−188	18.9	847	8	4.85
20 February 2000	M1.3	S29E07	4.7	−20	16.9	455	2	2.45
25 September 2001	X2.6	S16E23	7.3	−102	26.1	677	8	1.84
07 September 2002	C5.2	N09E28	7.3	−170	22.9	550	5	1.64
09 July 2006	M2.5	S09W34	3.3	0	9.7	433	4	1.95

time at which the shock was registered, which is usually the onset of the FDs, when the CR intensity is reduced at all neutron-monitor stations, as is shown in Figure 2.

Interestingly, for the first group of events, a long and narrow pre-decrease is noticed for all stations with asymptotic longitudes from 90° until 180° (Figure 2). In reality, the pre-decrease of these events seems to be about 20° – 30° narrower in space. This happens because neutron monitors record particles within a wide enough range of longitudes so that the observed effect appears wider than it really is. As can be seen in Figure 2, the pre-decrease appears up to 24 hours before the events (Papailiou *et al.*, 2011). However, a pre-increase is also noticed for eastern directions, from 180° until 360° (Figure 2).

3.2. Forbush Decreases with a Pre-increase Above 180°

The heliographic coordinates of the solar flares connected to these FDs along with other interplanetary parameters are presented in Table 3. Clearly, the events under examination are mostly connected to central or eastern sources and in most cases are associated with geomagnetic storms (moderate, strong, or severe). Moreover, for some events of this group an increase of the IMF intensity was measured.

A strong increase in the solar-wind speed of up to 710 $km\,s^{-1}$ and in the IMF intensity of up to 19.4 nT was observed, and a strong shock was recorded on 2 October 1981 at 20:22 UT (Figure 3, upper panel). The steep CR intensity decrease was almost 3% (Figure 3, middle panel) and was associated with an eastern C7.6 flare recorded on 30 September 1981 at 05:11 UT. During this event a moderate geomagnetic storm was recorded ($Kp_{max} = 6.3$ and $Dst_{min} = -50$ nT), as can be seen from Figure 3 (bottom panel).

Another example is the FD on 25 September 2001. A strong increase of the IMF intensity and of the solar-wind speed (26.1 nT and 677 $km\,s^{-1}$ respectively) caused the strong SSC which was recorded on 25 September 2001 at 20:25 UT (Figure 4, upper panel). The FD recorded on 25 – 26 September 2001 (Figure 4, middle panel) was almost 8%. The associated X2.6 flare (S16E23) was recorded on 24 September 2001 at 09:32 UT. Geomagnetic indices

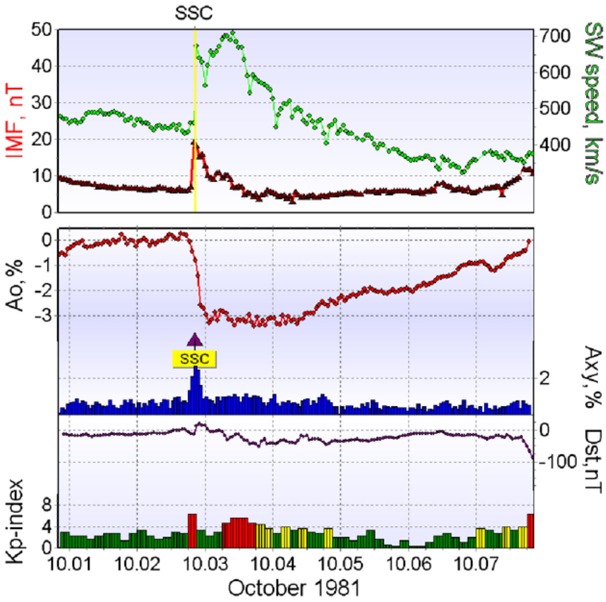


Figure 3 Variations of the interplanetary magnetic field and solar-wind speed (upper panel), cosmic ray intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 2 October 1981. The horizontal axis refers to MM.DD.

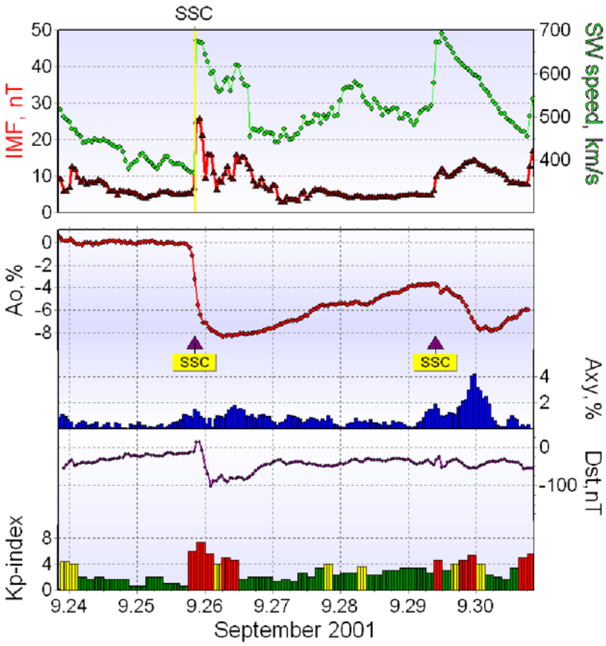
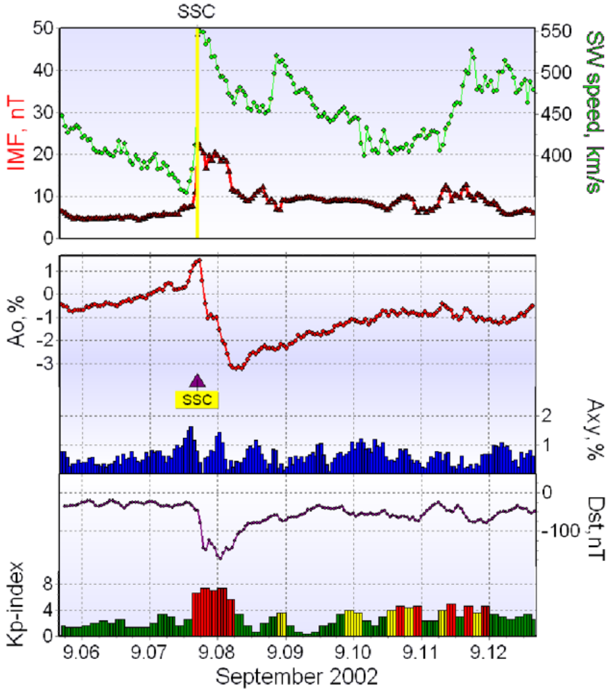


Figure 4 Variations of the interplanetary magnetic field and solar-wind speed (upper panel), cosmic ray intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 25 September 2001.The horizontal axis refers to MM.DD.

Kp and Dst during this event were 7.3 and −102 nT respectively (strong magnetic storm), as can be seen in Figure 4 (bottom panel).

Finally, for the event on 7 September 2002, a jump in the IMF intensity (22.9 nT) and the solar-wind speed (550 km s^{-1}) resulted in a strong SSC registered on 7 September 2002 at 16:36 UT (Figure 5, upper panel). As is shown in Figure 5 (middle panel), CR intensity

Figure 5 Variations of the interplanetary magnetic field and solar-wind speed (upper panel), cosmic-ray intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 7 September 2002. The horizontal axis refers to MM.DD.



decreased ≈5%, and a strong magnetic storm (geomagnetic indices Dst and Kp reached the values of −170 nT and 7.3 respectively) occurred (Figure 5, bottom panel). The flare connected with this event was eastern (N09E28) of class C5.2 and occurred on 5 September 2002 at 16:18 UT.

For this second group of events, a pre-increase was registered at the stations with asymptotic longitudes above 180° until 360°. As is seen in Figure 6, the pre-increase is recorded a few hours and up to almost 12 hours before the shock arrival. However, for the event on 25 July 1980 the pre-increase lasts for almost 24 hours. In most cases the pre-increase is accompanied by a pre-decrease in lower longitudes (below 180°), lasting only a few hours before the event.

3.3. Forbush Decreases with a Pre-decrease of Varying Duration

The most important parameters describing the interplanetary conditions for the events of this category are presented in Table 4. As is shown, these decreases are not connected to strong geomagnetic activity.

Specifically for the event on 8 September 1981, the SSC was registered on 8 September 1981 at 21:46 UT after a small increase of the IMF intensity (≈14.7 nT) and of the solar wind speed (≈450 km s^{-1}), as is shown in Figure 7 (upper panel). The CR intensity decreased ≈2% (Figure 7, middle panel), and the geomagnetic activity was not that high, since the geomagnetic indices Kp and Dst were 4.3 and −12 nT respectively (Figure 7, bottom panel). The solar flare associated with this event was central (S13E16) and of class M7.4, which occurred on 3 September 1981 at 10:57 UT.

During the event on 25 August 2002, the CR intensity decrease did not exceed 2% (Figure 8, upper panel). The shock registered on 25 August 2002 at 22:00 UT was weak, and

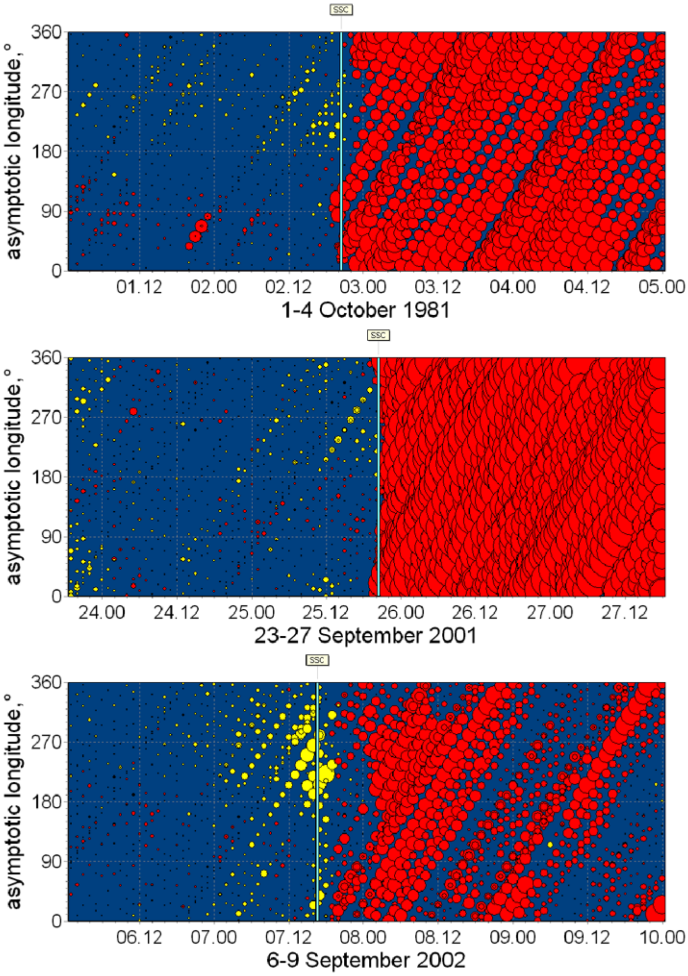


Figure 6 The longitude–time distribution of the events on 2 October 1981, 25 September 2001, and 7 September 2002. The horizontal axis refers to DD.HH.

the values of the solar-wind speed and the IMF intensity were low (336 km s^{-1} and 9.4 nT respectively). Moreover, the geomagnetic activity was also low (maximum Kp index was 3.3 and minimum Dst index was −7 nT), as is shown in Figure 8 (bottom panel).

Figure 9 is an example of the asymptotic longitudinal distribution for the FDs mentioned above. As already mentioned, in this category the precursor effect is a pre-decrease in different longitudes, sometimes above 180° and with different duration. For example, the pre-decrease for the FDs on 8 September 1981 (Figure 9, upper panel), 18 October 1998, and 3 August 2001 lasts almost 24 hours until the shock arrival, whereas the pre-decrease for the decrease on 25 August 2002 (Figure 9, bottom panel) lasts 12 hours until the SSC, and that for the event on 15 September 2000 even less.

As was shown by Belov *et al.* (2008), the magnitude of the CR anisotropy is statistically connected to the magnitude of the evolving FEs and the anisotropy inside these FEs, as is seen in Tables 2, 3, and 4 for the events under consideration.

Table 4 Main interplanetary parameters for the events of the third group.

Events	Solar flares	Heliographic Latitude/longitude	Kp_{max}	Dst_{min} [nT]	IMF_{max} [nT]	Solar wind speed max [km s^{-1}]	FD amplitude [%]	A_{xy} min [%]
08 September 1981	M7.4	S13E16	4.3	−12	14.7	444	2	3.06
16 April 1982	M1.8	S27W03	5.0	−60	17.1	518	> 2	1.97
04 March 1995	–	–	2.7	−27	–	–	1	1.33
10 August 1998	C2.9	N18E52	3.7	−37	10.7	498	< 2	1.91
18 October 1998	C1.0	N16E03	6.7	−139	26.2	430	< 2	1.24
15 September 2000	M1.6	N07W67	2.7	−10	–	–	4	3.30
03 August 2001	–	–	4.3	−18	13.7	477	> 1	3.00
25 August 2002	–	–	3.3	−7	9.4	336	2	2.35

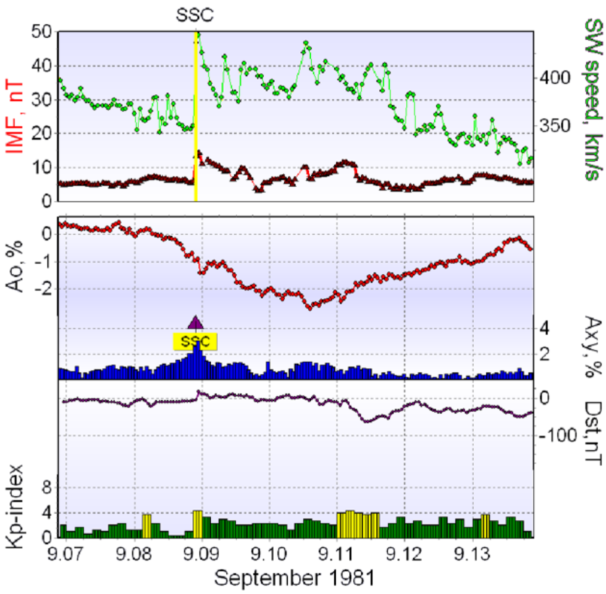


Figure 7 Variations of the interplanetary magnetic field and solar-wind speed (upper panel), cosmic ray intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 8 September 1981. The horizontal axis refers to MM.DD.

To summarize, in this study all of the FDs with anisotropy $A_{xy} > 1.2\%$ before the shock (93 events) for the time period 1967 – 2006 were analyzed with regard to the presence of predictors before the FD onset. It turned out that 27 events revealed clearly pronounced precursors. These events can be separated into three categories according to the precursor effect presented in their longitude–time distribution. For the first group, the precursor is a pre-decrease in the longitudinal zone 90° – 180° lasting for 20 – 24 hours until the shock arrival. An increase of the IMF and the solar-wind speed is measured for the majority of these events. Moreover, the specific decreases were connected to high or strong geomagnetic activity. A pre-increase which appears at longitudes above 180° and lasts almost 12 hours is the precursor effect for the second group of events. These FDs usually follow geomagnetic storms (moderate, strong, or severe) and are connected mainly to central or eastern sources. Finally, the precursor for the third group is a pre-decrease that appears in different longitudes

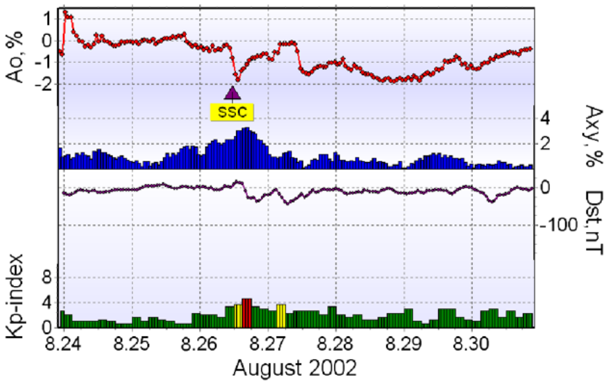


Figure 8 Variations of the cosmic-ray intensity A_0 and A_{xy} anisotropy (upper panel) and Dst- and Kp-indices (bottom panel) for the event on 25 August 2002. The horizontal axis refers to MM.DD.

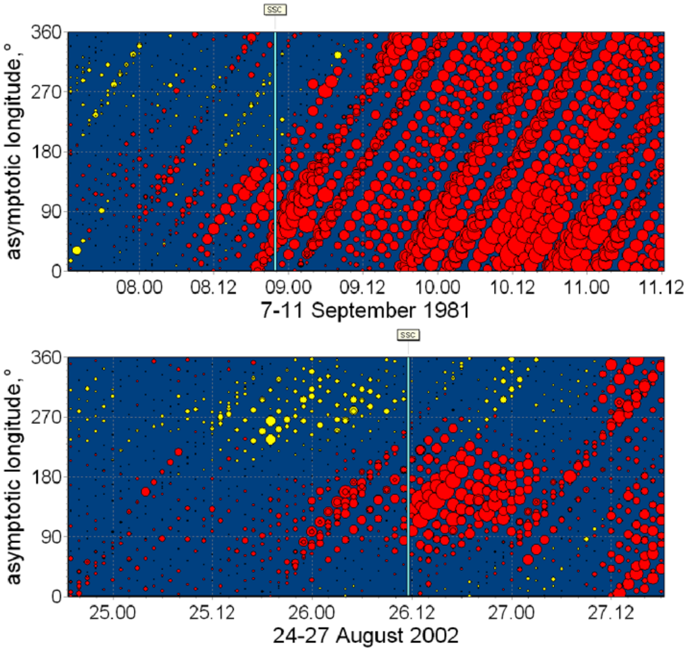


Figure 9 The longitude–time distribution of the events on 8 September 1981 and 25 August 2002. The horizontal axis refers to DD.HH.

each time and has a duration of several hours up to 24 hours. The geomagnetic activity preceding these events is low.

4. Conclusions

From our analysis we conclude the following: In order to study the precursor effect of FDs, a specific group of events was selected from the FE database of IZMIRAN, namely the events for which the increase of the CR vector anisotropy was already observed before the SSC arrival. Among these events, many FEs were found with obvious predictors.

The analysis shows that the increase in the first harmonic of CR anisotropy before the shock arrival is a good tool in searching for predictors of FDs and magnetic storms and can also serve as one of the indices that characterize the occurrence of precursors. Certainly, it is advisable to look for precursors at smaller increases of anisotropy as well.

This research indicates that the precursors of a magnetic storm are determined by frequent phenomena in CR variations. From this analysis the conception about precursors that was developed earlier is confirmed. That is, precursors constitute a complicated combination of pre-increases and pre-decreases in CR variations which have a different physical nature that assumes specific angular distribution of CR intensity.

The complexity of mechanisms of the precursor formation, the variety of the interplanetary coronal mass ejecta, and the different conditions in interplanetary space result in a variety of CR behaviors before the shock arrival.

In general, we can say that every case of FD is unique and that each evolves under specific interplanetary conditions. The result is that the precursors are revealed in different ways every time. Thus it is of great importance to analyze more events in detail before reaching a safe conclusion useful for monitoring space weather effects.

Acknowledgements This work is partly supported by Russian FBR grants 11-02-01478, Program No 6 BR of the Presidium RAS "Neutrino Physics and Neutrino Astrophysics," State contract MN No 14.740.11.0609. We are grateful to the teams of the CR stations for providing the neutron-monitor data available for this study (see http://cr0.izmiran.ru/ThankYou). The authors of the University of Athens thank the Special Research Account for supporting the Cosmic Ray Research. The authors would also like to thank the anonymous referee for useful comments.

References

Asipenka, A., Belov, A.V., Eroshenko, E., Mavromihalaki, H., Papailiou, M., Papaioannou, A., Oleneva, V., Yanke, V.G.: 2009, In: *Proc. 31st ICRC*, *Lodz, Poland*, icrc1109 (http://www.nmdb.eu/?q=node/109).

Belov, A.V.: 2008, In: Gopalswamy, N., Webb, D.F. (eds.) *Universal Heliophysical Processes*, *Proc. IAU Symp.*, **257**, Cambridge Univ. Press, Cambridge, 439. doi:10.1017/S1743921309029676.

Belov, A.V., Dorman, L.I., Eroshenko, E.A., Iucci, N., Villoresi, G., Yanke, V.G.: 1995, In: Iucci, N., Lamanna, E. (eds.) *Proc. 24th ICRC*, *Rome, Italy*, Internat. Union Pure Appl. Phys. **4**, 888.

Belov, A.V., Bieber, J.W., Eroshenko, E.A., Evenson, P., Pyle, R., Yanke, V.G.: 2001, In: Droege, W., Kunow, H., Scholer, M. (eds.) *Proc. 27th ICRC*, *Hamburg, Germany*, Internat. Union Pure Appl. Phys. **9**, 3507.

Belov, A.V., Bieber, J.W., Eroshenko, E.A., Evenson, P., Pyle, R., Yanke, V.G.: 2003, *Adv. Space Res.* **31**, 919.

Belov, A., Baisultanova, L., Eroshenko, E., Mavromichalaki, H., Yanke, V., Pchelkin, V., Plainaki, C., Mariatos, G.: 2005, *J. Geophys. Res.* **110**, A09S20. doi:10.1029/2005JA011067.

Belov, A.V., Dryn, E., Eroshenko, E.A., Kryakunova, O., Oleneva, V., Yanke, V.G., Papailiou, M.: 2008, In: Kiraly, P., Kudela, K., Stehlik, M., Wolfendale, A.W. (eds.) *Proc. 21st ECRS*, *Kosice, Slovakia*, Inst. Exp. Phys., Slovak Academy of Sciences, 347.

Blokh, Ya.L., Dorman, L.I., Kaminer, N.S.: 1959, In: *Proc. 6th ICRC*, *Moscow, Russia*, **4**, 77.

Cane, H.V.: 2000, *Space Sci. Rev.* **93**, 55.

Dorman, L.I., Iucci, N., Villoresi, G.: 1995, In: Iucci, N., Lamanna, E. (eds.) *Proc. 24th ICRC*, *Rome, Italy*, Internat. Union Pure Appl. Phys. **4**, 892.

Fenton, A.G., McCracken, R.G., Rose, D.C., Wilson, B.G.: 1959, *Can. J. Phys.* **37**, 970.

Forbush, S.E.: 1958, *J. Geophys. Res.* **61**, 93.

Kudela, K., Storini, M.: 2006, *Adv. Space Res.* **37**, 1443.

Leerungnavarat, K., Ruffolo, D., Bieber, J.W.: 2003, *Astrophys. J.* **593**, 587.

Lockwood, J.A.: 1971, *Space Sci. Rev.* **12**, 658.

Munakata, K., Bieber, J.W., Yasue, S., Kato, C., Koyama, M., Akahane, S., Fujimoto, K., Fujii, Z., Humble, J.E., Duldig, M.L.: 2000, *J. Geophys. Res.* **105**, 27457.

Munakata, K., Kuwabara, T., Yasue, S., Kato, C., Akahane, S., Koyama, M., Ohashi, Y., Okada, A., Aoki, T., Mitsui, K., Kojima, H., Bieber, J.W.: 2005, *Geophys. Res. Lett.* **32**, L03S04. doi:10.1029/2004GL021469.

Munakata, K., Yasue, S., Kato, C., Kota, J., Tokumaru, M., Kojima, M., Darwish, A.A., Kuwabara, T., Bieber, J.W.: 2006, WSPC/SPI-B368 *Adv. Geosci.* **2**, Chapter 09.

Nagashima, K., Sakakibara, S., Fujimoto, K., Fujji, Z., Ueno, H.: 1993, In: Leahy, D.A., Hickws, R.B., Venkatesan, D. (eds.) *Proc. 23rd ICRC, Invited, Rapporteur, and Highlight Papers*, *Calgary, Canada* **3**, World Scientific, Singapore, 711.

Papailiou, M., Mavromichalaki, H., Belov, A., Eroshenko, E., Yanke, V.: 2011, In: *13th ESPM*, *Rhodes, Greece* **P9.7**, 163. http://astro.academyofathens.gr/espm13/documents/ESPM13_abstract_programme_book.pdf.

Ruffolo, D., Bieber, J.W., Evenson, P., Pyle, R.: 1999, In: Kieda, D., Salamon, M., Dingus, B. (eds.) *Proc. 26th ICRC, Salt Lake City, USA* **6**, Internat. Union Pure Appl. Phys., 440.