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Precursory Signs of Large Forbush Decreases

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Abstract
The study of space-weather effects and more specifically Forbush decreases of the cosmic-ray intensity depends on space and ground measurements. Very often Forbush decreases and geomagnetic storms are accompanied by pre-increases and/or pre-decreases manifested in cosmic-ray behavior, known as precursory signs. These cosmic-ray intensity variations do not coincide with the shock arrival but begin well before (up to 24 hours) the onset of the main event. In this study a group of large Forbush decreases with amplitude $\geq 4\%$ was examined for precursors. According to the helio-longitude of the solar source, the events were separated into three categories: western ($21^\circ \leq$ helio-longitude $\leq 60^\circ$), eastern ($-60^\circ \leq$ helio-longitude $\leq -21^\circ$), and central ($-20^\circ \leq$ helio-longitude $\leq 20^\circ$). The selected events cover 1967 – 2017. The analysis of the Forbush decreases and the plotting of the asymptotic longitudinal cosmic-ray distribution diagrams were based on the "Global Survey Method" and the "Ring of Stations" method, respectively. Data on solar flares, solar-wind speed, interplanetary magnetic field, and geomagnetic indices (Kp and Dst) were also used. The results show the clear signs of precursors in a significant number of events.

Keywords Forbush decreases · Precursors · Solar sources · Pre-increases · Pre-decreases

1. Introduction

As is well known, cosmic rays can be considered as isotropic and stable on a galactic scale (Calisto et al., 2011). However, while moving toward the Earth, cosmic rays can be affected by the Sun and interplanetary space (Belov et al., 1995). As a result, the cosmic-ray intensity shows anisotropies and variations. One of the most important variations in galactic cosmic rays, and moreover an important manifestation of space weather, is the phenomenon of Forbush decreases (FDs).

The result of the effect of coronal mass ejections (CMEs and ICMEs) and/or high-speed solar-wind streams originating from coronal holes on cosmic rays (Lockwood, 1971; Cane,

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2000; Belov, 2008; Papaioannou et al., 2010; Belov et al., 2014; Kryakunova et al., 2015) can be defined as a FD. FDs usually are characterized by a sharp decrease and a slow recovery. The main phase of the decrease is completed, as a rule, within 12 – 24 hours, whereas the recovery phase can last up to several days (e.g. Mavromichalaki, 2012; Belov et al., 2014).

The study of FDs results in a wide variety of such events (Cane, 2000). FDs are distinguished in relation to various factors that can be differentiated between events. For example, FDs can be categorized not only as small or large (according to their amplitude) or long- or short-lasting (according to their duration), but they can also be characterized regarding their recovery characteristics (complete recovery or absence of recovery phase), their temporal profile (simple or complicated) and their completion phase (one or two steps), etc. The variety of solar sources and their combination, the different conditions existing in interplanetary space before and during the event, and finally the nature of the observations result in different types of FDs (Belov, 2008).

Precursor effects of FDs (pre-decreases and/or pre-increases of the cosmic-ray intensity) can forewarn of an imminent manifestation of such events from some hours up until one day before (Nagashima et al., 1990; Nagashima, Fujimoto, and Morishita, 1994; Belov et al., 1995, 2001; Papailiou et al., 2012a, 2012b) and therefore contribute to space-weather prediction (Badruddin et al., 2019). The kinetic interactions of the CR particles with the approaching shock are responsible for the precursory signs (Ruffolo et al., 1999; Leerungnavarat, Ruffolo, and Bieber, 2003; Asipenka et al., 2009). Specifically, the “loss cone” effect, in which the Earth is magnetically connected to the CR-depleted region behind the shock front and a part of the cosmic rays can exit the FD zone along the magnetic-field lines, is responsible for the precursor decreases (Belov et al., 1995; Leerungnavarat, Ruffolo, and Bieber, 2003; Abunina et al., 2020). Furthermore, the acceleration of galactic cosmic rays at the front of the approaching interplanetary disturbance, as the particles are being reflected from the approaching shock, causes the precursor increases (Kuzmicheva, Dorman, and Kaminer, 1972; Kaminer, Kuzmicheva, and Mymrina, 1981; Belov et al., 1995; Kudela and Storini, 2006). It should be clarified that the area in front of the shock wave is where both types of precursors are created simultaneously (Abunina et al., 2020).

However, as already mentioned, each FD is a unique event evolving under specific interplanetary conditions. Therefore, the manifestation of precursors may differ during each event, because of differences in the shape and the characteristics of the interplanetary shock wave. For example, the precursory sign can be determined by the speed of the interplanetary shock wave and the position of the shock in regard to the observation point (Abunina et al., 2020). Consequently, either pre-decreases or pre-increases, or neither or both can be observed. Nevertheless, it is clear that common features of FDs can affect the type, duration, and location of the precursors. This study, which extends over a long period of time, has shown that precursory signals can be recognized, classified, and maybe in the future even predicted.

The identification and analysis of precursors has been studied by the Athens Cosmic Ray Group of the National and Kapodistrian University of Athens and the Cosmic Ray Group of the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) of the Russian Academy of Sciences over the last few years. Moreover, the Cosmic Ray Group of IZMIRAN has created a Forbush Effects and Interplanetary Disturbances database (FEID: spaceweather.izmiran.ru/eng/dbs.html; Belov, 2008; Abunin et al., 2013), i.e. a database of all FDs, which occurred from the beginning of the neutron monitors' operation until today. These events were recorded by the global *Neutron Monitor Network*, which consists of at least 50 stations, distributed all over the Earth (Belov et al., 2015). In this database, FDs characteristics, such as amplitude, time of minimum, sources, anisotropies, etc., have been identified and described (Belov, 2008; Abunina et al., 2013; Belov et al., 2014). The data refer to ≈ 7000 events, which took place 1957 – 2017 (Belov et al., 2018). It can be argued that events from six complete solar cycles (19 – 24) are included, therefore providing the largest time series of data.

Studies on the manifestation of precursors have been conducted in the past using different criteria. From the aforementioned database up until today 118 different FD events have been chosen and studied for precursory signs for the time period 1967 – 2006. These events meet two criteria: i) the criterion of anisotropy, value of A_{xy} anisotropy greater than 1.2 % (Papailiou et al., 2012a), ii) the criterion of western solar sources and geomagnetic storms, value of the helio-longitude of solar flares and the geomagnetic index $\mathrm{Kp}_{\mathrm{max}}$ ranging from 50° to 70° W and from 5.0 to 9.0, respectively. (Papailiou et al., 2013). In conclusion, 27 out of 93 events meeting the first criterion (Papailiou et al., 2012a) and 15 out of 25 events meeting the second criterion (Papailiou et al., 2013) present precursors as depicted in the diagrams of asymptotic longitudinal cosmic-ray distribution.

Moreover, 34 different events of FDs have been chosen and studied for precursors over the period 2008 – 2016. The selected events have amplitude equal to or greater than 2 %, are associated with a sudden storm commencement (SSC), and have a value of anisotropy [A_{xy}] greater than 0.8% (Lingri et al., 2019). In total, 16 FDs (47 %) presented precursory signs, i.e. decreases (in asymptotic longitudes ≈ 70° – 190° about 18 hours before the SSC) and/or increases (in asymptotic longitudes ≈ 190° – 300° about 10 hours before the start of the event) of the cosmic-ray intensity before the main event (Lingri et al., 2019).

The research on precursors of FDs is being continued in the present work using a fourth criterion, that of large FDs with amplitude ≥ 4%. The classification of large FDs regarding the helio-longitude of their solar sources and the description of their features was included by Papailiou et al. (2020). Taking these results into account, the asymptotic longitudinal cosmic-ray distribution diagrams presented herein provide interesting information in regard to the precursory signals of large FDs. In total 87 events were studied, from which 61 manifested apparent signs of pre-increases and/or pre-decreases.

2. Data and Method

Cosmic-ray intensity variations, and FDs in particular, are studied through cosmic-ray intensity data provided by neutron monitors (Belov et al., 2014). Neutron monitors are modern and reliable ground particle detectors located in different locations on Earth (Agarwal and Mishra, 2008), creating a global network, and they are used for the detection of the nucleonic component of the cosmic rays in the spectrum range 0.5 to 20 GeV (Simpson, 2000).

The IZMIRAN FEID contributes significantly to the investigation of the different phenomena of space environment, since hourly values of the cosmic-ray density and anisotropy are studied in combination with solar, interplanetary, and geomagnetic parameters (Belov, 2008) allowing a detailed and thorough analysis of every event. More specifically, the data from the neutron-monitor network (Belov et al., 2018) is being entered into the FEID and using the global-survey method for particles with rigidity of 10 GV, the cosmic-ray density variations and first harmonic of anisotropy for cosmic rays is calculated. The OMNI database (omniweb.gsfc.nasa.gov) provides data on solar-wind parameters and geomagnetic indices.

A necessary step for investigating precursor effects in different FDs is the plotting of the asymptotic longitude–time diagram for each event based on the "Ring of Stations" (RS) method (Belov et al., 2003; Asipenka et al., 2009; Abunina et al., 2020). This method processes hourly values of cosmic-ray intensity as it is recorded by stations of the worldwide neutron-monitor network with geomagnetic cut-off rigidity $R_i < 4$ GV (Papailiou et al., 2012a, 2012b), altitude $h_i < 1200$ m, and coupling coefficient for the North–South component of the cosmic-ray anisotropy $\left|C_{10}^i\right| < 0.55$ (Abunina et al., 2020). It demonstrates hourly values of the cosmic-ray intensity variations at each station in relation to a quiet period and then plots according to the asymptotic longitude of the particles that are recorded by the neutron monitor at that exact time. By using as many neutron monitors as possible, the depiction of the temporal variations of the cosmic-ray intensity distributed in asymptotic directions is achieved (e.g. Papailiou et al., 2012a).

The RS-method was used in many investigations with the aim of depicting the behavior of the asymptotic distribution of cosmic-ray variations in a clear way. Specifically, it was applied for the analysis of the precursors for the FD on 9 September 1992, which is referred to in a number of scientific articles and studies related to space-weather prediction (Munakata et al., 2000; Belov et al., 2003; Dorman et al., 2003; Dorman, 2005; Asipenka et al., 2009) and is also included in the present investigation. Another recent example of the application of the RS-method is the description of the non-standard cosmic-ray behavior inside an interplanetary disturbance given by Abunin et al. (2020). Here we present an investigation of the unusual cosmic-ray behavior during the FD on 20 – 26 August 2018 and the causes of the relatively large cosmic-ray anisotropy combined with a comparatively small FD amplitude. Moreover, the remarkable solar eruptions and geospace disturbances during the minimum of Solar Cycle 24 are evidence that powerful and peculiar events may occur in the minimum of the solar cycle. On 26 August 2018, an unexpectedly strong geomagnetic storm suddenly occurred. The peculiar FD, which was also recorded, had a magnitude that was about 1.5%, which is rather small for the observed G3-class geomagnetic storm. The main unusual feature of the event is that large positive bursts with an enhancement up to 3% above the pre-event level were recorded on the FD background. These bursts were mainly caused by an unusually large and variable cosmic-ray anisotropy combined with lowering of the geomagnetic cut-off rigidity in the perturbed Earth's magnetosphere under conditions of the solar cycle minimum (Abunin et al., 2020).

3. Large Forbush Decreases

3.1. Classification

The FEID of IZMIRAN was used as a tool for selecting and organizing the large FDs (Papailiou et al., 2020). The parameters that were considered for this study were: i) the amplitude of the FDs ($\geq 4\%$), ii) the quiet background (48 hours and 18 hours difference between the previous and next events, respectively), iii) the presence of SSC, and iv) the existence of an identified solar source (solar flare).

In total 87 events were analyzed for the period 1967 – 2017. Based on the heliographic longitude of the solar flares, there are three categories of FDs: i) western sources ($21° \leq$ helio-longitude $\leq 60°$), which include 23 events, ii) eastern sources ($-60° \leq$ helio-longitude $\leq -21°$), which include 28 events, and iii) central sources ($-20° \leq$ helio-longitude $\leq 20°$), which include 36 events.

The FDs for each of the above-mentioned categories, along with some parameters that characterize the cosmic-ray event (amplitude, anisotropy before the shock arrival, maximum anisotropy during the FD), the conditions of the interplanetary space (solar-wind speed and interplanetary magnetic field) and the geomagnetic activity (geomagnetic indices Dst and Kp) for the group of western, eastern, and central solar flares have been analyzed in detail

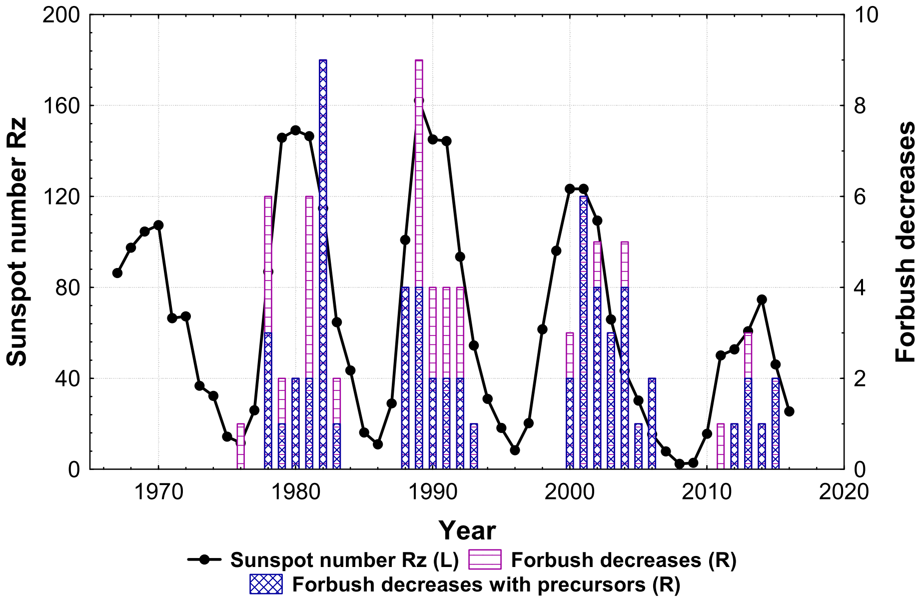

Figure 1 Yearly distribution of the number of solar sunspots Rz (black curve), of the 87 Forbush decreases (purple horizontal hatching), and of the 61 of them with precursors (blue crosshatching) for the criteria under investigation.

(Papailiou et al., 2020). In general it can be argued that the majority of disturbances reaching the Earth are directed from central longitudinal zones and only a few disturbances are connected to other longitudinal zones (Abunina et al., 2013). Therefore, primarily central and secondarily eastern solar sources are more likely to be associated with FDs with large amplitude. On the other hand, FDs related to western solar sources, even though they are less likely to have large amplitudes or to be clearly expressed in cosmic-ray variations near the Earth, present an increased anisotropy before the shock arrival (Papailiou et al., 2013, 2020).

3.2. FDs and Solar Activity

The events presented in this study refer to the years 1967 – 2017, covering Solar Cycles (SC) 21 (1976 – 1986), 22 (1986 – 1996), 23 (1996 – 2008), and almost all of Solar Cycle 24 (2008 – 2019) (Prince et al., 2013). Solar activity and cosmic-ray intensity are two anticorrelated parameters (Dorman, 1974; Agarwal and Mishra, 2008; Hathaway, 2015; Mavromichalaki, 2012; Melkumyan et al., 2018).

In Figure 1, yearly distributions of the 87 FDs under examination along with the 61 of them that presented precursory signals are shown. The events under investigation cover two odd (SC21 and SC23) and two even (SC22 and SC24) solar cycles. Differences and similarities of these odd and even solar cycles are described by Mavromichalaki et al. (1997). In the same figure, the solar-activity variation (sunspot number: Rz) is also presented for the interval under study (www.ngdc.noaa.gov/stp/solar/ssndata.html). As is seen, the greater number of events (in total, but also those with precursors) is recorded near solar maximum (Alania and Wawrzynczak, 2008; Melkumyan et al., 2019). More particularly, for the maxima of Solar Cycles 21, 22, 23, and 24, solar maxima are recorded on the years 1979, 1989, 2001, and 2014, respectively. Therefore, large FDs are more frequently recorded in the period 1981 – 1982 (for SC 21), 1989 (for SC 22), the period 2001 – 2002 (for SC 23), and 2013 (for SC 24).

4. Precursors of FDs

The analysis concerning the large FDs that were selected from the FEID for the time period 1967 – 2017 is presented below.

In total, 87 events were analyzed and 61 of them showed precursory signs. The events that provided precursors after a detailed analysis and careful study are organized as follows: the western sources group includes 18 events (out of 23), the eastern group includes 19 events (out of 28), and the central group includes 24 events (out of 36).

In the following, and before continuing with the description of precursory signs for the three groups of FDs, it is worth discussing the connection of Forbush effects to the solar source. As was already mentioned, FDs are related to interplanetary disturbances coming to the Earth caused by CMEs (western, eastern, or central). These CMEs are usually connected to a solar flare, sometimes to non-AR eruptions. The majority of the CMEs associated with solar flares, which occur far beyond the central sector, usually do not cause FDs near the Earth, and if they do, these FDs are very small. Nevertheless, this rule can often be broken and FDs, which are related to extremely large and strong CMEs, can be observed near the Earth (Belov, 2008).

A more detailed analysis is provided for one of the FDs under study, the FD on 15 May 2005 related to a central source. This event is provided and analytically displayed as an example of how all the events were analyzed and examined in regard to some significant parameters.

On 13 May 2005 at 16:13 UT, a flare of GOES Class M8.0 (N12E11) was recorded in the central zone of the solar disk in AR 10759. The associated halo CME had a speed of 1689 $\mathrm{km\,s^{-1}}$ according to the coronagraph data, and the velocity of propagation towards the Earth was estimated at 2171 $\mathrm{km s^{-1}}$ (cdaw.gsfc.nasa.gov/CME_list/halo/halo.html). The SSC for the event under consideration was recorded on 15 May 2005 at 2:38 UT. During this FD the maximum values of the IMF intensity and solar-wind speed were 54.2 nT and 959 $\mathrm{km\,s^{-1}}$, respectively (Figure 2, upper panel). The cosmic-ray intensity decrease for this event was almost 9.5% and was followed by a significant increase of cosmic-ray solar diurnal anisotropy (2.53%) (Figure 2, middle panel). The geomagnetic $\mathrm{Kp_{max}}$ and $\mathrm{Dst_{min}}$ indices during this event were 8.3 and −263 nT, respectively (severe magnetic storm) as can be seen in Figure 2 (bottom panel).

A precursor signal (pre-increase) was recorded seven hours before the shock wave at longitudes 120° – 250° (from 14 May 20 UT to 15 May 02 UT) in the neutron-monitor data (Figure 5, upper panel).

In Table 1 the events with pronounced signs of precursors are presented for the western, eastern, and central sources, respectively. The precursory signal for the majority of the FDs is a pre-increase in longitudes around or above 180°, which lasts for a few hours. However, in some cases a pre-decrease in the longitudinal zone 90° – 180° is also visible.

The longitude–time distribution diagrams for the above-mentioned events were plotted and some of them are presented below. In these figures, decreases of the cosmic-ray intensity are depicted by red circles, while increases of cosmic-ray intensity are represented by yellow circles. These variations refer to a quiet previous period, as recorded by all neutron-monitor stations used in the RS-method. The size of the circle corresponds to the size of the variation.

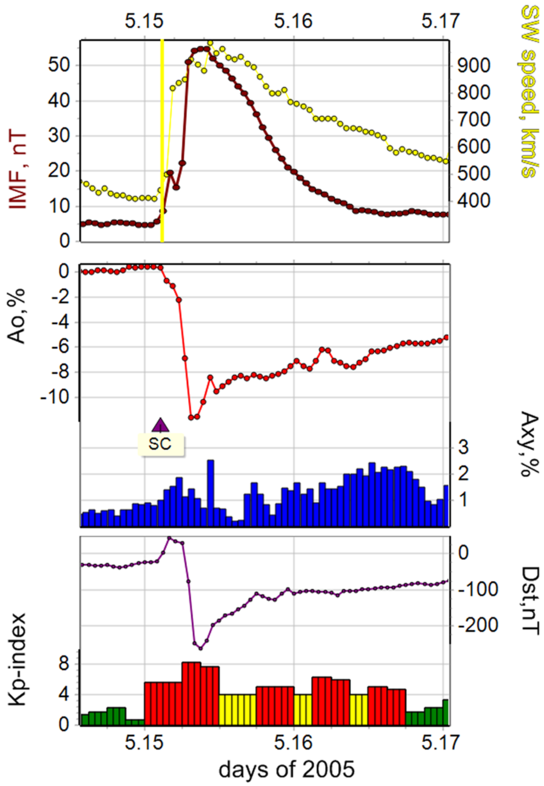

Figure 2 Variations of the interplanetary magnetic field and solar-wind speed (upper panel), cosmic-ray intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 15 May 2005. The horizontal axis refers to MM.DD. The yellow line and SC indicate when the SSC was recorded.

The time at which the SSC is recorded is marked with a vertical-blue line. Usually, it also denotes the onset of the FDs, when the cosmic-ray intensity is reduced at all neutron-monitor stations.

For the group of western sources an obvious pre-increase a few hours before the main event on 4 November 2003 is observed in asymptotic longitudes greater than 180° (Figure 3, upper panel). A pre-increase for asymptotic longitudes above 180° and duration of about seven hours is also recorded for the FD on 26 July 2004 (Figure 3, middle panel), whereas for the event on 17 March 2015 (Figure 3, bottom panel) there is a clear pre-decrease around the asymptotic longitudinal zone 90 – 180° lasting for several hours.

From the longitude–time distribution diagrams for the events on 6 June 1979 (Figure 4, upper panel), 2 October 1981 (Figure 4, middle panel), and 1 October 1991 (Figure 4, bottom panel) from the eastern sources group, a pre-increase for asymptotic longitudes above 180°, which lasted more than ten hours before the main event, is noticed. However, it is interesting to mention that on 6 June 1979 (Figure 4, upper panel) a small pre-increase is also recorded in asymptotic longitudes below 90°, and on 1 October 1991 (Figure 4, bottom panel) a significant pre-decrease in asymptotic longitudes 90° – 180° lasting for almost six hours until the main event was recorded.

In Figure 5 the precursory signals for three events of the central sources group are presented. More specifically, for the FD on 15 May 2005 (Figure 5, upper panel) a pre-increase, which lasted almost seven hours until the SSC arrival and covers an area of asymptotic longitudes from 120° to 250°, is recorded. For the FD on 13 April 2013 (Figure 5, middle panel) a rather small pre-increase, which spreads through the whole range of asymptotic longitudes,

Table 1 Classification of Forbush decreases, revealing precursory signals according to their solar sources.

Western sources	Eastern sources	Central sources
30 October 1980	13 July 1978	3 January 1978
5 March 1981	6 June 1979	10 April 1978
23 July 1981	10 May 1981	25 July 1980
12 June 1982	2 October 1981	6 August 1982
10 October 1988	24 April 1982	23 November 1982
7 May 1989	9 June 1982	4 February 1983
30 March 1990	13 July 1982	4 January 1988
9 September 1992	27 December 1982	13 January1988
23 March 1993	30 November 1988	12 June 1990
28 April 2001	11 January 1989	8 July 1991
17 August 2001	11 April 1989	8 June 2000
24 November 2001	4 September 1989	11 October 2001
20 March 2002	1 October 1991	17 April 2002
4 November 2003	26 February 1992	18 August 2002
26 July 2004	19 July 2000	29 May 2003
9 July 2006	27 August 2001	20 November 2003
14 December 2006	25 September 2001	22 January 2004
17 March 2015	7 September 2002	5 December 2004
	13 September 2004	15 May 2005
		14 July 2012
		13 April 2013
		17 March 2013
		15 February 2014
		6 November 2015

is recorded for more than ten hours before the onset of the main event. For the event on 6 November 2015 (Figure 5, bottom panel) the pre-increase is visible in asymptotic longitudes greater than 180°. This event has an unusual behavior of cosmic-ray variations inside an interplanetary disturbance; similar behavior was also described by Abunin et al. (2020) for the event of 26 August 2018. However, in this study such features are not considered.

5. Results

This study makes an effort to recognize and record precursory signals in FDs, which were obtained from the IZMIRAN Forbush-Effects and Interplanetary Disturbances Database. The events under study cover the period from 1967 – 2017 and meet the criterion of large FDs. Based on the helio-longitude of the solar sources these events were grouped into three categories.

The results from this investigation are outlined as follows:

i) Large FDs are mostly observed during solar maximum.
ii) In total 87 events were analyzed and 61 (70%) of them provided precursors.
iii) FDs related to western solar sources are more likely to show precursory signals, than those related to eastern or central sources.

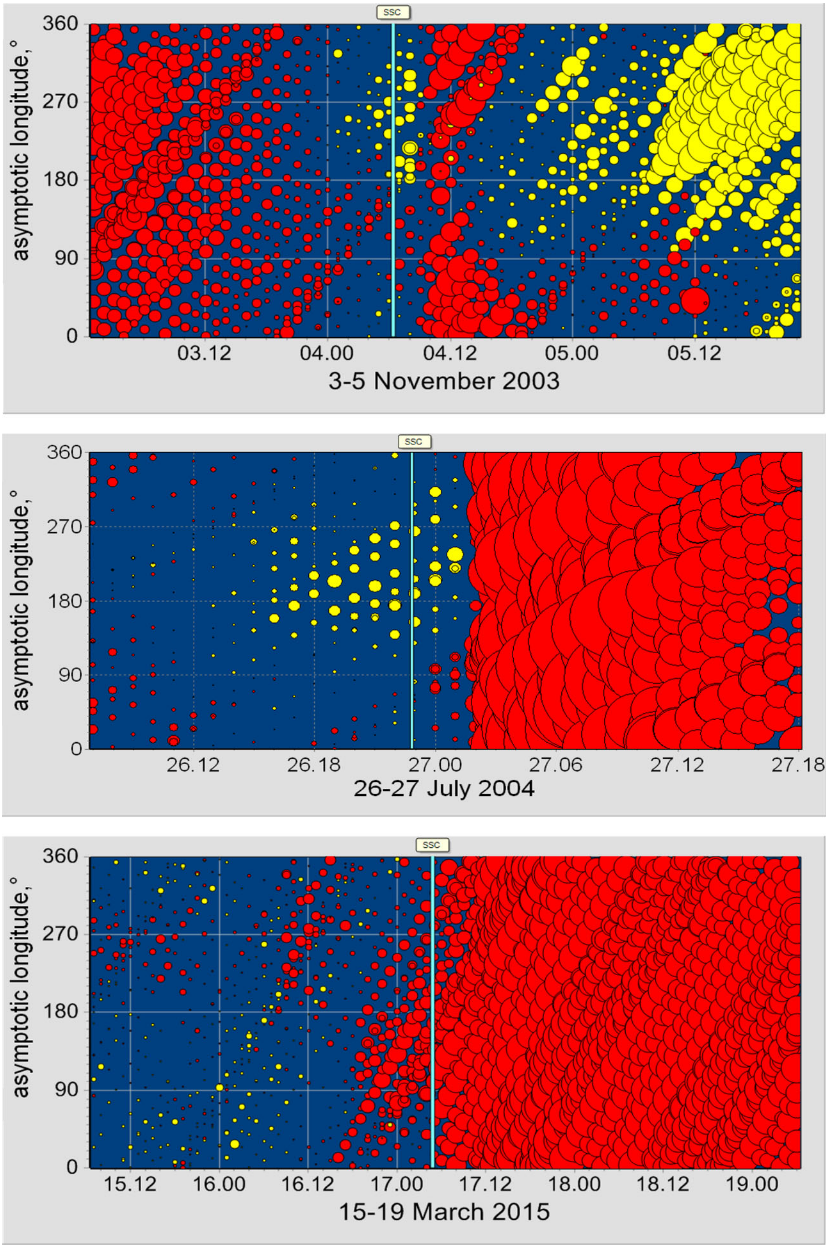

Figure 3 Asymptotic longitude–time distributions of the western events on 4 November 2003 (upper panel), 26 July 2004 (middle panel), and 17 March 2015 (bottom panel).

iv) More specifically 18 out of 23 FDs (78%) connected to western solar sources, 19 out of 28 FDs (68%) connected to eastern solar sources and 24 out of 36 FDs (67%) connected to central solar sources revealed clear signs of precursors some hours before the onset of the event.

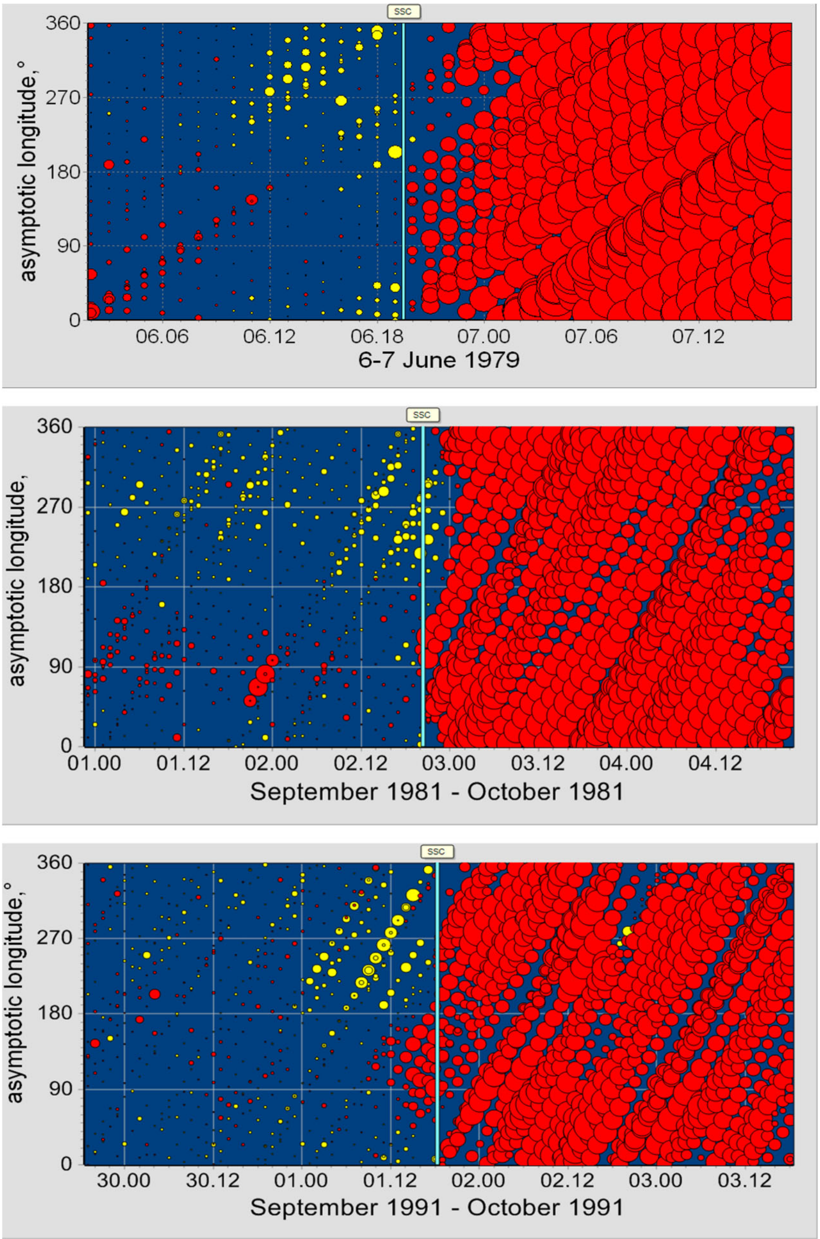

Figure 4 Asymptotic longitude–time distributions of the eastern events on 6 June 1979 (upper panel), 2 October 1981 (middle panel), and 1 October 1991 (bottom panel).

v) The precursory signal is mainly a pre-increase in asymptotic longitudes around or above 180°.

The categorization of FDs according to the helio-longitude of the solar source provides the investigation of precursors with a new perspective. A FD is a heliospheric phenomenon

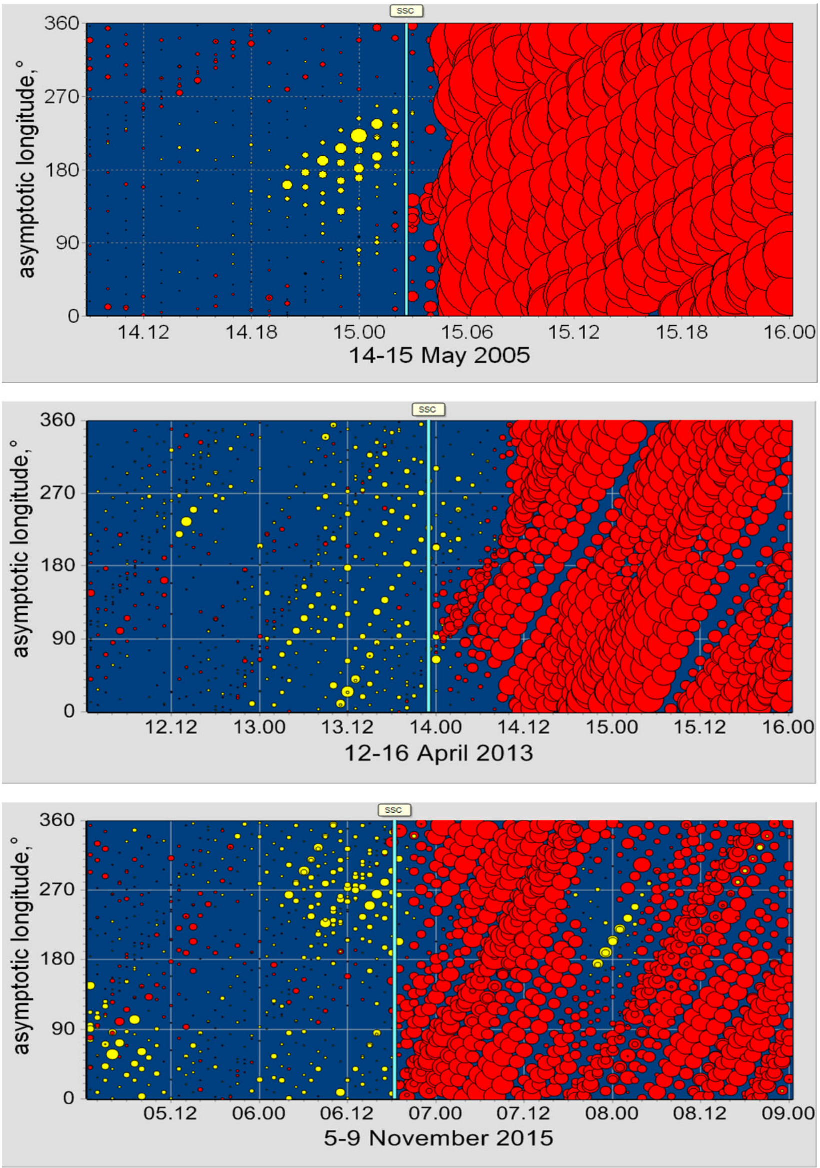

Figure 5 Asymptotic longitude–time distribution of the central events on 15 May 2005 (upper panel), 13 April 2013 (middle panel), and 6 November 2015 (bottom panel).

that begins long before the interplanetary disturbance reaches the Earth, when the disturbance is still forming near the Sun (Belov, 2008). This being the case, it is clear that events related to western solar sources are not so large and do not show as well-marked cosmic-ray variations near the Earth as those related to eastern or central sources; however, they are characterized by an increased anisotropy before the shock arrival, one of the typical precursors of FDs. Interplanetary disturbances from western sources affect the IMF force lines near the Earth earlier. Therefore, precursory signs for FDs connected to western solar sources are clearer and are more often observable up to one day before the onset of the FD.

The aim of this investigation is to identify and describe the precursory signals that precede a FD and are detected by ground-based neutron monitors. Apart from the four criteria that have already been tested and have provided impressive results, in the future other criteria, which are possibly related to the precursory signals, have to be applied, examined, and analyzed. The ultimate goal is to create a complete and reliable database of FDs precursors and eventually formulate valid and accurate criteria that will lead to the developing and implementing of a geomagnetic-disturbances alert system and finally to the monitoring of space-weather phenomena. The "Ring of Stations" method, which uses data from the global *Neutron Monitor Network*, is the most suitable and reliable tool for this research.

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Declarations

Disclosure of Potential Conflicts of Interest The authors declare that there is no conflict of interest.

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