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The Asymptotic Longitudinal Cosmic Ray Intensity Distribution as a Precursor of Forbush Decreases

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Abstract Identifying the precursors (pre-increases or pre-decreases) of a geomagnetic storm or a Forbush decrease is of great importance since they can forecast and warn of oncoming space weather effects. A wide investigation using 93 events which occurred in the period from 1967 to 2006 with an anisotropy $A_{xy} > 1.2\%$ has been conducted. Twenty-seven of the events revealed clear signs of precursors and were classified into three categories. Here we present one of the aforementioned groups, including five Forbush decreases (24 June 1980, 28 October 2000, 17 August 2001, 23 April 2002, and 10 May 2002). Apart from hourly cosmic ray intensity data, provided by the worldwide network of neutron monitor stations, data on solar flares, solar wind speed, geomagnetic indices (Kp and Dst), and interplanetary magnetic field were used for the analysis of the examined cosmic ray intensity decreases. The asymptotic longitudinal cosmic ray distribution diagrams were plotted using the "ring of stations" method. Results reveal a long pre-decrease up to 24 hours before the shock arrival in a narrow longitudinal zone from 90° to 180°.

Keywords Forbush decreases · Geomagnetic activity · Loss cone effect · Pre-decreases

1. Introduction

The influence of coronal and consequent interplanetary coronal mass ejections (CMEs and ICMEs) and/or high-speed streams of the solar wind from coronal holes on background

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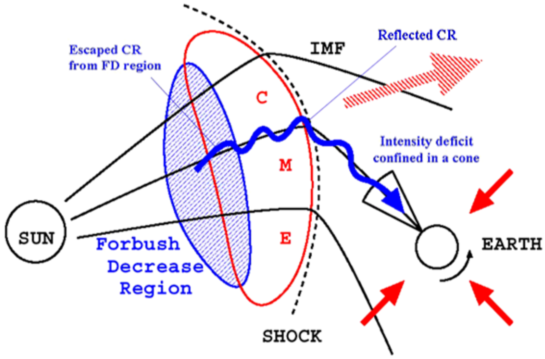


Figure 1 The "loss cone" effect (Asipenka *et al.*, 2009a).

cosmic rays (CRs) can result in CR intensity decreases, known as Forbush decreases (FDs). These events are characterized by a relatively fast depression of CR intensity followed by a slower recovery on a time scale of several days (Forbush, 1958; Lockwood, 1971; Cane, 2000; Belov, 2008). Interplanetary shock waves, high-speed solar wind streams, and magnetic clouds all can be responsible for the registered variations of the CR intensity (Papaioannou *et al.*, 2010).

The changes in CR intensity behavior begin well before the arrival of the interplanetary shock or solar wind disturbance at Earth. The effect of an approaching shock (precursor) is a complicated combination of pre-increases and pre-decreases in CR variations and assumes a specific angular distribution of CR intensity (Belov, 2008). As mentioned in Kudela and Storini (2006), particles with large pitch angles approaching the shock from the upstream region and reflecting from it are usually seen as pre-increases. Pre-decreases correspond to relatively small pitch angles and apparently result from a "loss cone" effect. As shown in Figure 1, the neutron monitor station is magnetically connected to the CR-depleted region downstream of the shock (Asipenka *et al.*, 2009a).

Over the last few years an increasing number of studies concerning precursor effects in CR intensity have been carried out (Nagashima *et al.*, 1993; Belov *et al.*, 1995; Dorman, Iucci, and Villoresi, 1995; Ruffolo *et al.*, 1999; Leerungnavarat, Ruffolo, and Bieber, 2003; Dorman, 2005 and references therein; Kudela and Storini, 2006; Mavromichalaki *et al.*, 2011). A series of strong FDs have been studied separately in order to reach some well-established conclusions on the types of precursor effects.

According to Asipenka *et al.* (2009a), a pre-decrease within the narrow longitudinal sector along the average direction of the interplanetary magnetic field (IMF) is observed 11 hours before the shock for the FD on 29 August 1979. Another example presented by Asipenka *et al.* (2009a) is the event on 15 September 2005, where low CR intensity in the narrow region of longitudes 90 – 180° stands out against the background of increases in CR variations.

Moreover, a clear pre-decrease for longitudes 75 – 180° lasting for almost 20 hours until the FD onset is noticed for the FD on 25 – 26 January 1968 (Belov *et al.*, 1995; Kudela *et al.*, 2000). A similar behavior is observed for the FDs on 11 – 12 July 1991 and 24 – 25 June 1978. All these events are associated with western and central solar flares. However, for the event on 4 April 1991, which is connected to an eastern flare, a pre-increase is noticed within the sector 165 – 270° (Belov *et al.*, 1995).

In a recent work (Papailiou *et al.*, 2012) 93 events with an equatorial component of the first harmonic of CR anisotropy A_{xy} greater than 1.2% for the time period 1967 – 2006 were analyzed, and 27 of them ($\sim$ 29%) revealed clear signs of a precursor. According to the nature of the precursors these events were separated into three categories: i) pre-decrease in the longitudinal zone 90 – 180° almost 24 hours before the shock arrival (five events), ii) pre-increase in the longitudinal zone around and above 180° almost 12 hours before the FD (14 events), and iii) pre-decrease at different longitudes and of different durations (eight events). Examples from all three groups have been presented in detail.

In this study five different FDs, corresponding to the first of the aforementioned categories, have been analyzed and presented on the basis of their common behavior in asymptotic longitudinal CR distribution diagrams. The chosen value of anisotropy can be considered as anomalous, since it significantly exceeds the mean statistical value, which is usually less than 0.6%.

2. Data and Methods of Analysis

The "ring of stations" (RS) method makes it possible to study these anomalies in CR intensity by using data from the worldwide network of neutron monitor stations (Belov *et al.*, 1995; Belov *et al.*, 2003; Asipenka *et al.*, 2009a). Specifically, hourly CR intensity data recorded by the neutron monitor stations with cut-off rigidity $R_c < 4$ GV and latitudes $< 70°$ are used. A detailed list of the neutron monitor stations used by the RS method is included in Papailiou *et al.* (2012).

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 complete as possible. Using as many neutron monitors as possible, we have depicted temporal variations of CR intensity distributed in space by asymptotic directions.

The asymptotic longitudinal CR distribution diagrams were obtained using 31 neutron monitor stations. This number of stations basically covers 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, thus scanning 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 at different asymptotic directions is used (http://www.nmdb.eu/?q=node/19).

Apart from the asymptotic angle distribution of the CR variations, the CR pitch angle distribution (http://neutronm.bartol.udel.edu/spaceweather/) can also be used to display the potential precursor effects. Even though this method is more tightly connected to the model of pre-decreases caused by the loss cone, the asymptotic longitude dependence method has its own advantages (Papailiou *et al.*, 2012).

The database of the interplanetary disturbances and Forbush effects created at IZMIRAN (Belov, 2008) combines hourly values of the CR density and anisotropy, obtained from the neutron monitor network, with solar, interplanetary, and geomagnetic parameters. The database, which currently includes about 6000 events over the period 1957 – 2010, allows the selection of events with regard to different parameters and various statistical estimations. Moreover, using the global survey method (GSM), the density and first harmonic of anisotropy for CRs of rigidity 10 GV have been calculated (Belov *et al.*, 2005; Asipenka *et al.*, 2009b) and entered into the database. Solar wind parameters and geomagnetic indices were obtained from the OMNI database (http://omniweb.gsfc.nasa.gov).

3. Results

In this work the events on 24 June 1980, 28 October 2000, 17 August 2001, 23 April 2002, and 10 May 2002 are presented. What follows is a detailed description of the relevant interplanetary disturbances during the aforementioned decreases along with the longitude–time distribution of CR variation diagrams of these events.

Forbush Effect on 24 June 1980 This event was related to a disturbance registered on 24 June 1980 after an M2.3 flare (S12E17) on 21 June 1980 at 00:03 UT. The associated shock arrival (Figure 2, upper panel) was registered on 24 June 1980 at 2:48 UT. No strong changes in the interplanetary space parameters (maximum values for IMF intensity and solar wind speed were 14 nT and 453 km s^{-1}, respectively) or in the geomagnetic activity (maximum Kp index was 3.67 and minimum Dst index was -18 nT) were noticed, as is seen in Figure 2 (bottom panel). However, a significant CR intensity decrease ($\approx 4\%$) was registered (Figure 2, upper panel). Forbush decreases usually can be related to high geomagnetic activity (Dorman, 2005). However, it is possible that a CR intensity decrease is not accompanied by a Dst depression; vice versa a large Dst depres-

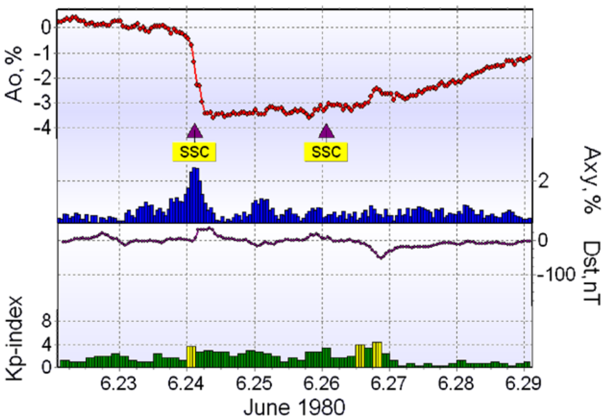


Figure 2 Variations of CR intensity A_0 and A_{xy} anisotropy (upper panel), and Dst- and Kp-indices (bottom panel) for the event on 24 June 1980 (the horizontal axis refers to MM.DD).

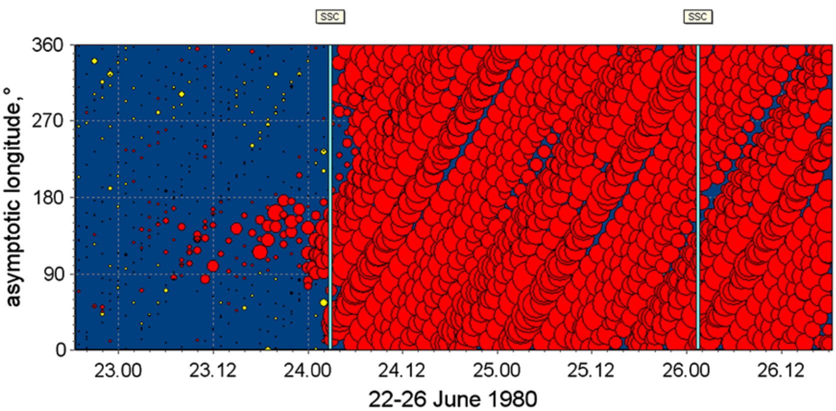


Figure 3 The event on 24 June 1980 presented as a longitude–time distribution (the horizontal axis refers to DD.HH).

sion does not always mark a strong CR intensity decrease (Kudela and Brenkus, 2004; Kane, 2010), as shown in Figure 2.

The asymptotic longitudinal CR distribution diagram for this event is presented in Figure 3. Here the CR intensity decreases, as measured by all neutron monitor stations used by the RS method, are depicted with red circles, while yellow circles refer to CR intensity 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 (for this case the first line describes the SSC associated to the particular event).

Figure 3 shows a long and narrow pre-decrease for all stations with asymptotic longitudes from 90° to 180°. In fact, the pre-decrease of these events seems to be about 20 – 30°

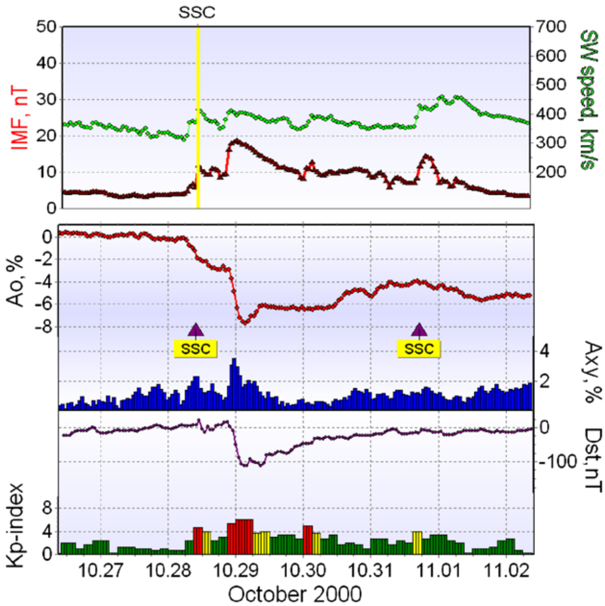


Figure 4 Variations of the interplanetary field and solar wind speed (upper panel), CR intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 28 October 2000 (the horizontal axis refers to MM.DD).

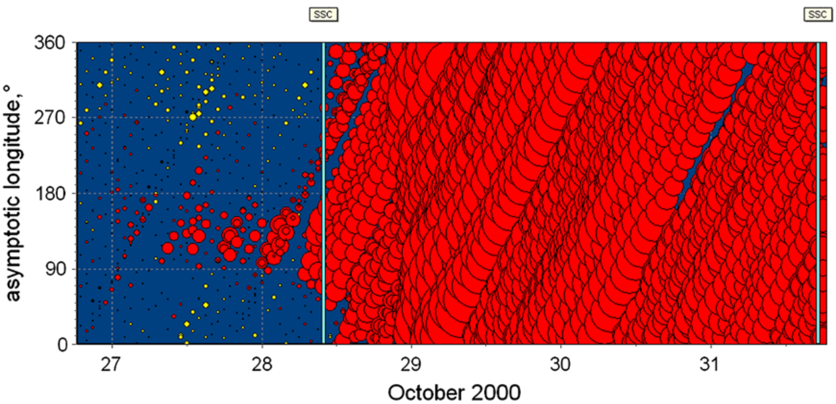


Figure 5 The event on 28 October 2000 presented as a longitude–time distribution (the horizontal axis refers to days).

narrower in space. The observed effect appears wider than it really is because neutron monitors record particles within a wide range of longitudes. The pre-decrease is registered some hours after 00:00 UT on 23 June until 02:00 UT on 24 June.

Forbush Effect on 28 October 2000 The shock registered on 28 October 2000 at 9:54 UT was the result of a slight increase of the IMF intensity (red line) and the solar wind speed (green line), which however remained rather low ($< 450\ \mathrm{km\,s^{-1}}$), as shown in Figure 4 (upper panel). After several hours a second increase of the IMF intensity (up to 20 nT) occurred above the background of the same low solar wind velocity. These changes were followed by a strong two-step FD ($\approx 8\%$) registered on 29 October 2000 (Figure 4, middle panel). As shown in Figure 4 (bottom panel), a geomagnetic storm ($\mathrm{Kp_{max}} = 6$ and $\mathrm{Dst_{min}} =$

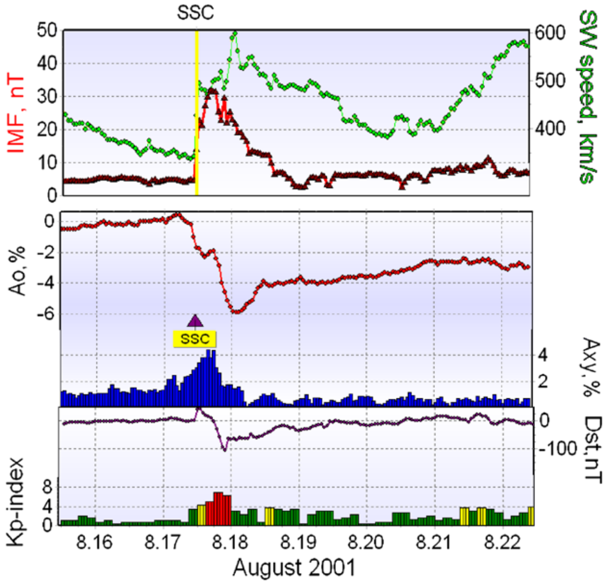


Figure 6 Variations of the interplanetary field and solar wind speed (upper panel), CR intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 17 August 2001 (the horizontal axis refers to MM.DD).

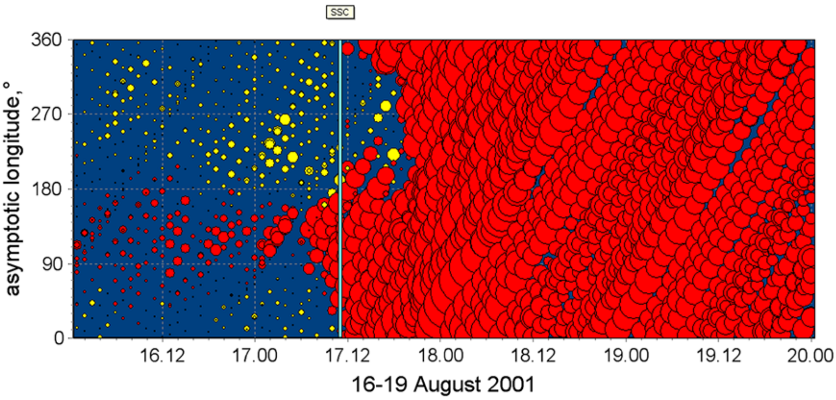


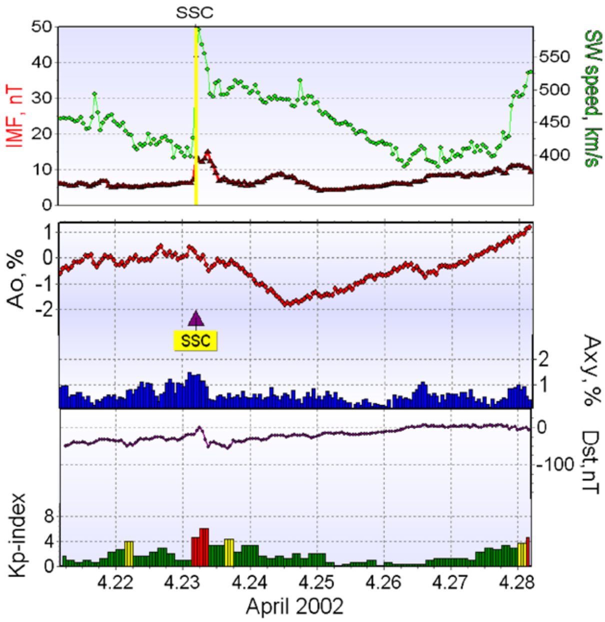
Figure 7 The event on 17 August 2001 presented as a longitude–time distribution (the horizontal axis refers to DD.HH).

−113 nT) occurred after the second jump of the IMF. The flare on 25 October 2000 at 8:45 UT associated to this event was located far to the west (N10W66) and was of class C4.0.

Figure 5 is the asymptotic longitudinal CR distribution diagram for this FD. The pre-decrease, which appears some hours after 00:00 UT on 27 October, lasts for almost 24 hours until the main FD and is also limited to the range of longitudes 90 – 180°.

Forbush Effect on 17 August 2001 A strong increase in the IMF intensity and the solar wind speed (≈ 600 km s^{-1}) resulted in the strong SSC that was recorded on 17 August 2001 at 11:03 UT (Figure 6, upper panel). The two-step FD recorded on 17 – 18 August 2001 (Figure 6, middle panel) was of almost 6% and was followed by a significant increase of so-

Figure 8 Variations of the interplanetary field and solar wind speed (upper panel), CR intensity A_0 and A_{xy} anisotropy (middle panel), and Dst- and Kp-indices (bottom panel) for the event on 23 April 2002 (the horizontal axis refers to MM.DD).



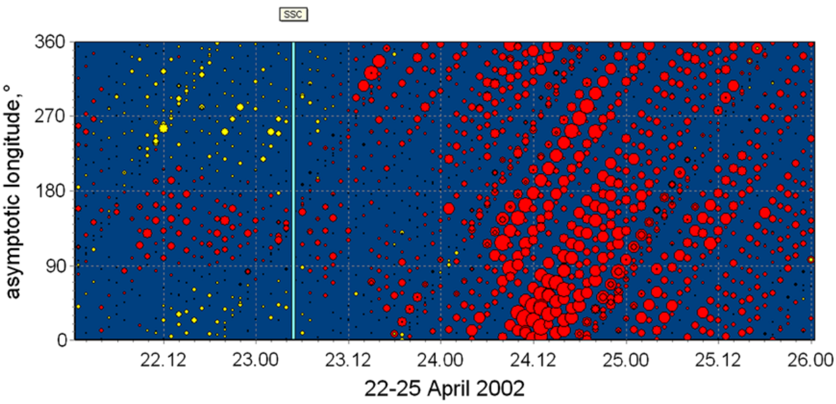


Figure 9 The event on 23 April 2002 presented as a longitude–time distribution (the horizontal axis refers to DD.HH).

lar diurnal CR anisotropy. The associated C2.3 flare (N26W10) was recorded on 14 August 2001 at 11:30 UT and belongs to the central heliolongitudinal sector. The geomagnetic indices Kp and Dst during this event were 7 and −107 nT, respectively (geomagnetic storm), as shown in Figure 6 (bottom panel).

The asymptotic longitudinal CR distribution diagram for this event is seen in Figure 7. The pre-decrease lasts almost 24 hours and is accompanied by a pre-increase at longitudes above 180°.

Forbush Effect on 23 April 2002 The slight increase of the IMF intensity (15.1 nT) resulted in a weak SSC, which was registered on 23 April 2002 at 4:48 UT. However a jump in the solar wind speed was recorded, which reached 593 $\mathrm{km\,s^{-1}}$ (Figure 8, upper panel). The effect on CR intensity (Figure 8, middle panel) was weak (a 2% decrease in the CR intensity), and the geomagnetic activity was moderate (geomagnetic indices Kp and Dst had values 6.0 and −56 nT, respectively), as shown in Figure 8 (bottom panel). The associated western (S14W84) flare of class X1.5 was recorded on 21 April 2002 at 00:43 UT.

In this event, besides the pre-decrease, which is noticed almost 16 hours before the FD, a pre-increase is also registered at longitudes above 180° (Figure 9).

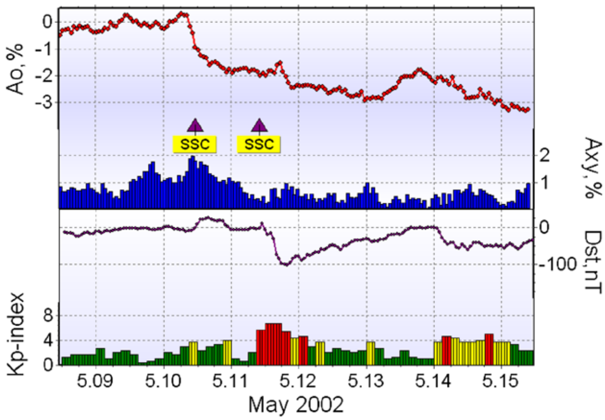


Figure 10 Variations of CR intensity A_0 and A_{xy} anisotropy (upper panel), and Dst- and Kp-indices (bottom panel) for the event on 10 May 2002 (the horizontal axis refers to MM.DD).

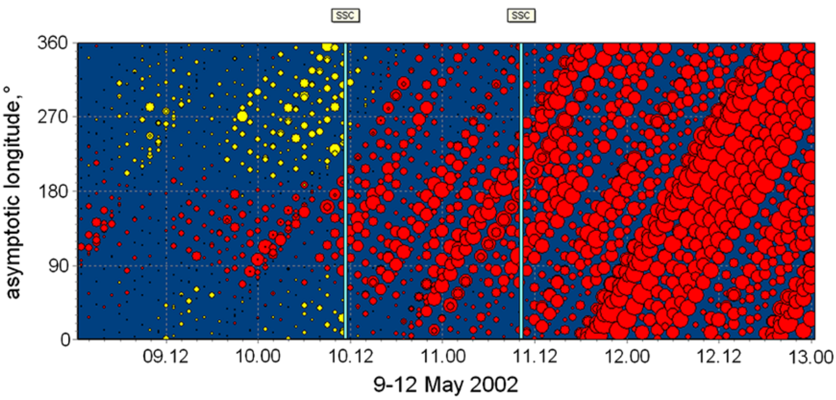


Figure 11 The event on 10 May 2002 presented as a longitude–time distribution (the horizontal axis refers to DD.HH).

Forbush Effect on 10 May 2002 A CR intensity decrease started after the shock registered on 10 May 2002 at 11:23 UT. As shown in Figure 10 (upper panel), the CR intensity decreased $\approx 2\%$, while the geomagnetic activity (Figure 10, bottom panel) was rather low (geomagnetic indices Dst and Kp reached values of -11 nT and 4, respectively). A geomagnetic storm (Dst ~ -100 nT, Kp up to 7) and an additional CR decrease (-1%) occurred after the second SSC on 11 May. This disturbance was associated to a solar filament disappearance (SFD) in the north-north-east quadrant of the solar disk, which produced a halo CME with velocity $\approx 611\ \mathrm{km\,s^{-1}}$ near the Sun. At the same time an M1.4 flare with coordinates S08E28 (on the southern part of the SFD) was registered on 7 May 2002 at 3:37 UT. The SFD and flare seemed not to be associated based on their locations; thus the real source of the event seems to be the SFD, the coordinates of which are not well defined.

The pre-decrease for this event is localized again in the longitudinal zone 90 – 180° and lasts almost 24 hours starting from 12:00 UT on 9 May, as shown in Figure 11. In this event there is also a clear pre-increase above 180°.

4. Summary and Conclusions

An analysis of 93 FDs with anisotropy $A_{xy} > 1.2\%$ before the shock for the time period 1967 – 2006 was conducted to determine the presence of precursors. Clear precursors were registered for a group of 27 events ($\sim 29\%$), which in turn were separated into three categories according to the precursor effect presented in their longitude–time distribution. In this study the first group of events has been presented. The precursor is a pre-decrease in the longitudinal zone 90 – 180° lasting for almost 24 hours until the shock arrival. An increase in IMF and solar wind speed has been measured for the majority of these events; moreover, the specific decreases were connected to strong geomagnetic activity.

The analysis of these FDs has shown that a strong decrease in CR intensity is usually accompanied by precursors, pre-decreases or pre-increases, appearing some hours, in some cases up to 24 hours, before the FD onset. The RS and GSM methods make it possible to study these anomalies in CR intensity by using data from the worldwide network of neutron monitor stations.

The study of precursors is a useful tool for the analysis and forecast of space weather effects; therefore, it is of great importance to investigate a large amount of these phenomena. An extensive analysis is also needed because these phenomena demonstrate themselves differently each time, according to varying interplanetary conditions.

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