NMDB Meeting 2025: Cosmic Ray studies with Neutron Detectors

Athens, 19 – 21 March 2025

Precursors of large Forbush decreases:

The threshold value 0.8% of the equatorial anisotropy

M. Papailiou[1], M. Abunina[2], H. Mavromichalaki[1], N. Shlyk[2], S. Belov[2],

A. Abunin[2], M. Gerontidou[1], A. Belov[2], V. Yanke[2]

[1]Nuclear and Particle Physics Section, Physics Department, National and Kapodistrian University of Athens, 15784 Athens, Greece

[2]Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation RAS (IZMIRAN), Troitsk, Moscow, Russia

1. Introduction

- Precursory signs preceding the main phase of the cosmic ray intensity (CRI) decrease: pre-decreases and/or pre-increases of the CRI before the evolution of a Forbush decrease (FD) (Fenton et al., 1959; Blokh et al., 1960).

- The investigation of precursory signs has developed into an essential chapter of Space Weather research (Leerungnavarat et al., 2003; Dorman, 2005), and an important contributor to the forewarning of Space Weather phenomena (Badruddin, et al., 2019).

Responsible for the occurrence of precursors

the kinetic interactions between cosmic ray particles and the approaching interplanetary shock (Ruffolo et al., 1999)

pre-decrease

cosmic ray particles exit the FD zone along the magnetic field lines. This happens because the Earth and the cosmic ray depleted region behind the shock front are magnetically connected, i.e. “loss cone” effect (Leerungnavarat et al., 2003; Munakata et al., 2005)

pre-increase

cosmic ray particles reflect from the approaching interplanetary disturbance and are accelerated at the front of approaching shock (Dorman et al., 1995; Kudela & Storini, 2006)

The two precursory signs, i.e. pre-decreases and/or pre-increases of the CRI, differ regarding the mechanism that creates them, but coexist in the area in front of the shock wave (Abunina et al., 2020). Both types of precursors can last from some hours up to one day before the main phase of the decrease.

2. Materials & Methods

- ❖ Forbush Effects and Interplanetary Disturbances (FEID) database (https://tools.izmiran.ru/feid) of IZMIRAN (Abunin et al., 2013).
- ❖ Cosmic ray variation parameters (i.e. density and anisotropy) in this database are computed using the Global Survey Method (GSM) (Belov et al., 2018) for the 10 GV rigidity particles with the neutron monitor network data.
- ❖ Data on solar flares (ftp://ftp.swpc.noaa.gov/pub/indices/events/), interplanetary conditions (solar wind speed and interplanetary magnetic field) and geomagnetic activity (geomagnetic indices Dst, Ap and Kp) provided by the OMNI database (http://omniweb.gsfc.nasa.gov), SSCs (http://isgi.unistra.fr/data_download.php) etc. were also assessed.

Ring of Stations method (RSM) (https://tools.izmiran.ru/ros)

Hourly CRI data derived from neutron monitor stations located in different parts of the world that:

1. have a geomagnetic cut-off rigidity R_i less than 4 GV,
2. a coupling coefficient for the North – South component of the cosmic-ray anisotropy $\left|C_{10}^{i}\right|$ less than 0.55 and finally
3. are located in altitude h_i less than 1200m

In total, the method derives data from 36 neutron monitor stations (Abunina et al., 2020).

- ✓ The hourly values of the CRI variations at each station are calculated in regard to a quiet period. They are, then, plotted for various asymptotic longitudes in relation to time.
- ✓ Each neutron monitor station records particles from certain asymptotic directions.
- ✓ The sufficient number of neutron monitors stations that are used by this method ensures as much as possible the most complete scanning of the celestial sphere.

3. Results

Large FDs (with magnitude > 5%), accompanied by geomagnetic storms (geomagnetic index Dst < -100nT and 5 ≤ Kp-index ≤ 9)

from 1957 to 2023

A_{xyb} less than 0.8%

(Papailiou et al., 2024a)

Control group
68 events

A_{xyb} greater than 0.8%

(Papailiou et al., 2024b)

Test group
59 events
(9 events with GLEs were excluded)

Mean values of different parameters concerning the 59 FDs of the test group and the 68 FDs of the control group

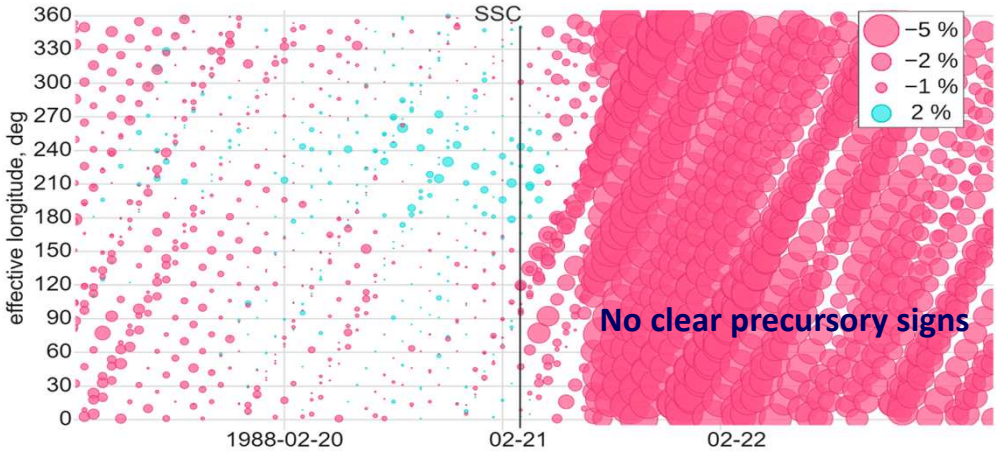
Parameter	59 FDs, Test group	68 FDs, Control group
A_F, %	8.5 ± 0.4	8.1 ± 0.4
A_{xyb}, %	1.3 ± 0.05	0.5 ± 0.02
A_{xymax}, %	3 ± 0.1	2.9 ± 0.2
Kp_{max}	7.9 ± 0.1	7.8 ± 0.1
Dst_{min}, nT	–193 ± 10	–195 ± 11
Ap_{max}, 2 nT	217 ± 10	211 ± 10
B_{max}, nT *	31 ± 1.8	28 ± 1.4
V_{max}, km s^{-1} *	737 ± 24	720 ± 25
Long, ° *	2.8 ± 4.5	–4 ± 5.6

* Data is not available for all events

3. Results

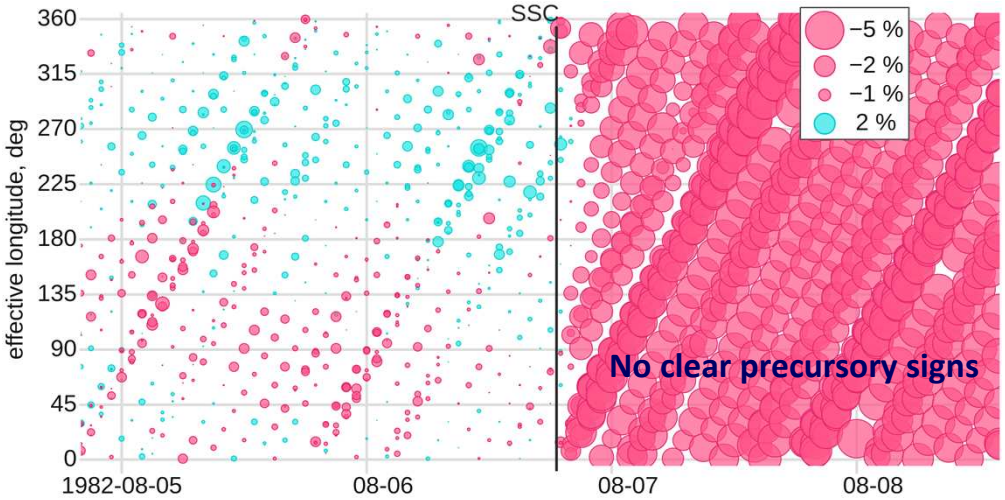
21 February 1988

A_f = 8.7%, Dst_{min} = -130nT,
Kp_{max} = 7+, A_{xyb} = 0.41%



6 August 1982

A_f = 6%, Dst_{min} = −155nT,
Kp_{max} = 8–, A_{xyb} = 0.42%



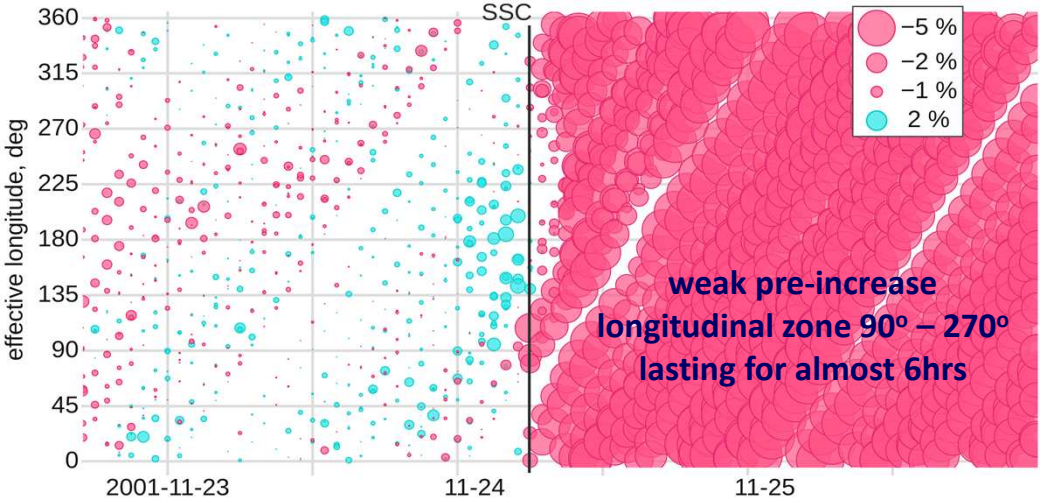
Control group A_{xyb} < 0.8%

Magenta colored circles: CRI decreases
Blue colored circles: CRI increases
(both estimated with respect to an undisturbed base period)

- ✓ Each neutron monitor station's recording for 24h is demonstrated diagonally (i.e., line of circles)
- ✓ The circle's size depends on the size of the variation
- ✓ The vertical line denotes the FDs' onset

24 November 2001

A_f = 9.8%, Dst_{min} = −221nT,
Kp_{max} = 8.33, A_{xyb} = 0.67%



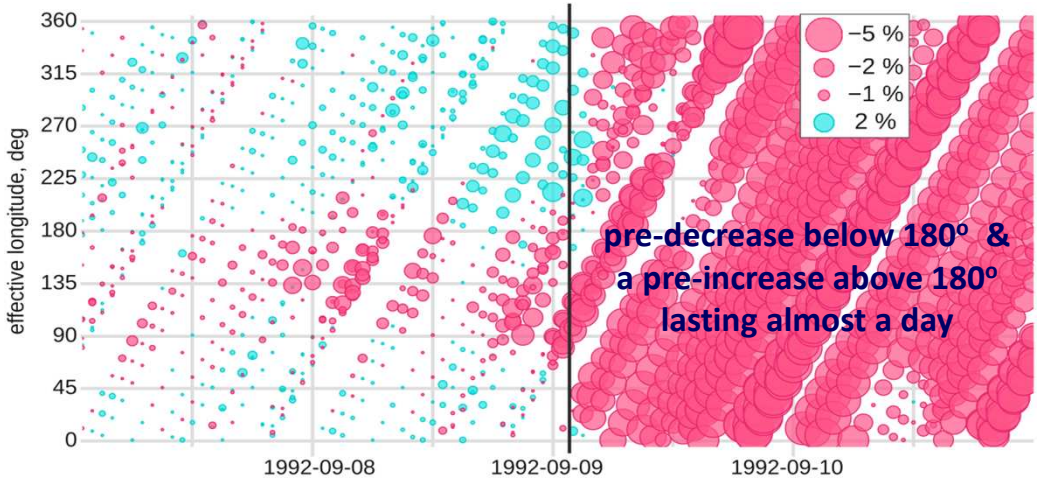
(Papailiou et al., 2024a)

3. Results

Test group $A_{xyb} \geq 0.8\%$

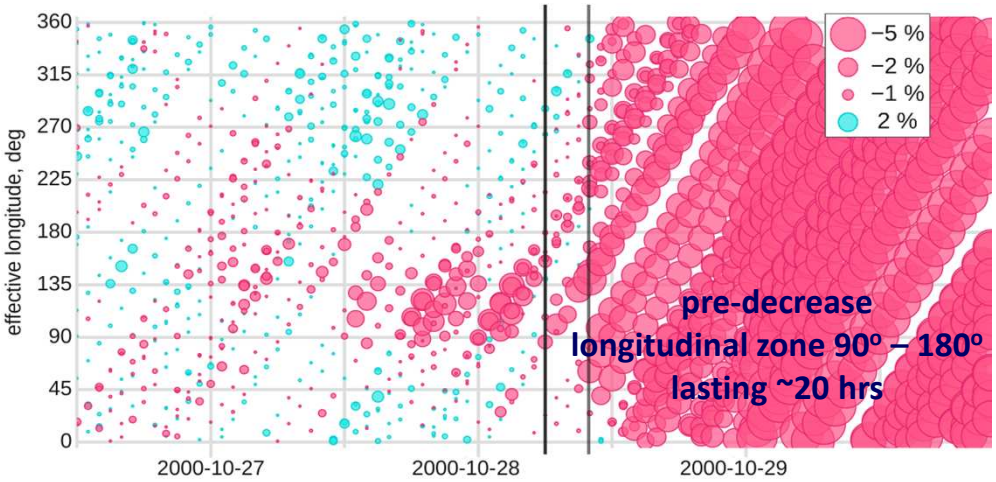
A_f = 6.6%, Dst_{min} = -131nT,
Kp_{max} = 7+, A_{xyb} = 2.56%

9 September 1992



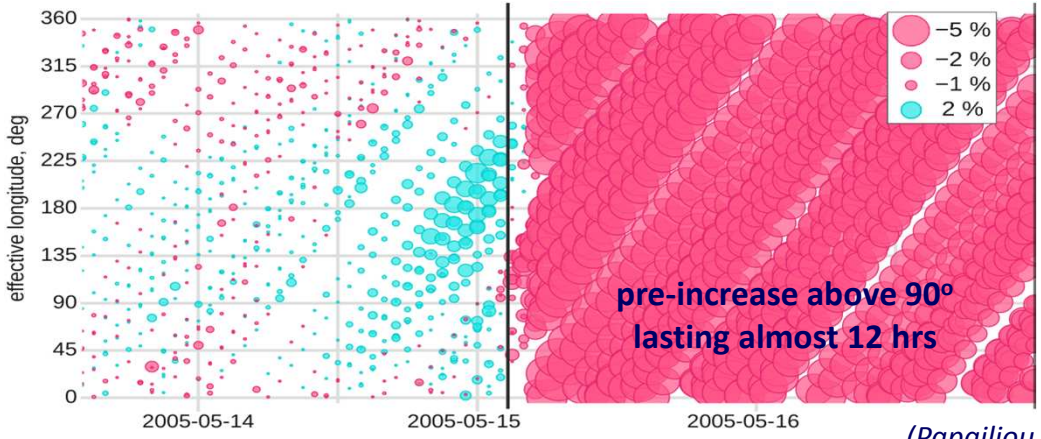
28 October 2000

A_f = 8%, Dst_{min} = -126nT,
Kp_{max} = 6, A_{xyb} = 1.64%



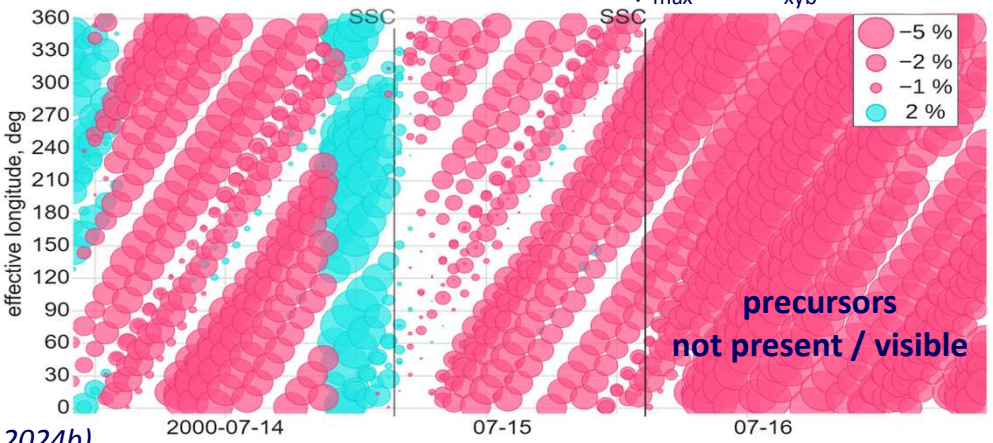
A_f = 11.5%, Dst_{min} = -247nT,
Kp_{max} = 8+, A_{xyb} = 0.8%

15 May 2005



15 July 2000 (GLE 59)

A_f = 12.7%, Dst_{min} = -300nT,
Kp_{max} = 9, A_{xyb} = 0.9%



(Papailiou et al., 2024b)

4. Conclusions

The Cosmic Ray Groups of the NKUA and the IZMIRAN investigated the existence of precursors preceding large FDs accompanied by geomagnetic storms

The results of this work are summarized as follows:

1) **The chosen criterion confirms the existence of precursors preceding large FDs accompanied by geomagnetic storms. In total, 50 out of 59 FDs (85%) revealed clear signs of precursors. Specifically, 5 FDs had pre-decreases as a precursor, 30 FDs showed clear signs of pre-increases, and finally 15 events appeared with both precursory signs.**

2) **The chosen criterion does not fully determine the intensity of the precursory signs. This is partially defined by the position of the neutron monitor station in relation to the disturbance (i.e., the asymptotic directions it registers).**

3) **The chosen limit value of the equatorial component of the first harmonic of cosmic ray anisotropy 1 hour before the shock arrival is successfully set at 0.8%, since precursors are rarely reported for lower values of the cosmic ray anisotropy.**

4) **For 9 FDs connected to GLEs the criterion has neither succeeded nor failed. For these events, due to the background conditions, the precursor signs are not visible but a definite answer about whether they exist or not cannot be provided.**

5. References

1. Abunin, A., Abunina, M., Belov, A. et al., Forbush-decreases in 19th solar cycle. J. Phys. Conf. Ser. 2013, 409, 012165. https://doi.org/10.1088/1742-6596/409/1/012165.
2. Abunina, M., Belov, A., Eroshenko, E. et al., Ring of Stations Method in Cosmic Rays Variations Research. Solar Physics. 2020, 295. 10.1007/s11207-020-01639-7
3. Badruddin, B., Aslam, O.P.M., Derouich, M. et al., Forbush decreases and geomagnetic storms during a highly disturbed solar and interplanetary period, 4–10 September 2017. Space Weather. 2019, 17, 487–496. https://doi.org/10.1029/2018SW001941
4. Belov, A., Eroshenko, E., Yanke, V. et al., The Global Survey Method Applied to Ground-level Cosmic Ray Measurements. Solar Physics. 2018, 293, 68. https://doi.org/10.1007/s11207-018-1277-6
5. Blokh, Ya.L, Dorman, L.I., Kaminer, N.S., Proc. 6th ICRC, 4, 77, 1959
6. Dorman, L.I., Iucci, N., Villoresi, G., The nature of cosmic ray Forbush decrease and precursory effects. In: Iucci, N., Lamanna, E. (eds.), Proc. 24th ICRC, International Union of Pure and Applied Physics, Rome, Italy, 4, 892 – 895, 1995
7. Dorman, L. I. Space weather and dangerous phenomena on the Earth: principles of great geomagnetic storms forecasting by online cosmic ray data, Ann. Geophys., 2005, 23, 2997–3002. https://doi.org/10.5194/angeo-23-2997-2005
8. Fenton, A.G., McCracken, R.G., Rose, D.C., Wilson, B.G., Can. J. Phys. 1959, 37, 970
9. Kudela, K., & Storini, M., Possible tools for space weather issues from cosmic ray continuous records. Advances in Space Research. 37, 2006, 1443 – 1449
10. Leerungnavarat, K., Ruffolo, D., Bieber, J.W., Loss cone precursors to Forbush decreases and advance warning of space weather effects. The Astrophysical Journal. 2003, 593, 587 – 596
11. Munakata, K., Kuwabara, T., Yasue, S., et al., A "Loss-Cone" Precursor of an Approaching Shock Observed by a Cosmic-Ray Muon Hodoscope on October 28, 2003. Geophys. Res. Lett. 2005, 32, L03S04, doi:10.1029/2004GL021469
12. Papailiou, M.-C., Abunina, M., Mavromichalaki, H., et al., Precursory Signs of Large Forbush Decreases in Relation to Cosmic Rays Equatorial Anisotropy Variation. Atmosphere. 2024a, 15, 742. https://doi.org/10.3390/atmos15070742
13. Papailiou, M., Abunina, M., Mavromichalaki, H., et al., Precursory signs of Large Forbush decreases: The criterion of anisotropy. Solar Physics. 2024b, 299, 154 https://doi.org/10.1007/s11207-024-02391-y
14. Ruffolo, D., Bieber, J.W., Evenson, P., Pyle, R., Precursors to Forbush decreases and space weather prediction. In: Kieda, D., Salamon, M., Dingus, B. (eds.), Proc. 26th ICRC, International Union of Pure and Applied Physics, Salt Lake City, USA, 6, 440 – 443, 1999