Contrib. Astron. Obs. Skalnaté Pleso **53/3**, 148 – 155, (2023)
https://doi.org/10.31577/caosp.2023.53.3.148

Analyzing solar activity with Belgrade muon station: case study of 2021 November 4$^{\text{th}}$ Forbush decrease

N.B. Veselinović, M.B. Savić, D.M. Maletić, A.L. Dragić, R.M. Banjanac, D.R. Joković, D. Knežević, M. Travar and V.I. Udovičić

Institute of Physics Belgrade, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia, (E-mail: veselinovic@ipb.ac.rs)

Received: September 19, 2023; Accepted: October 16, 2023

Abstract. The first significant Forbush decrease of the solar cycle 25 was recorded on November 4$^{\text{th}}$, 2021. The Forbush decrease was observed with numerous ground based cosmic rays stations including Belgrade cosmic rays muons' station. Series of coronal mass ejections during October 28–November 4 2021. produce conditions for this Forbush decrease. We discuss here the variation of cosmic rays' flux detected with ground-based detectors and connection with conditions, measured in-situ, in interplanetary space around Earth, flux of solar wind protons measured with SOHO probe to assess implication for solar-terrestrial coupling processes.

Key words: Cosmic rays – Forbush decrease – Space weather – muon detector

1. Introduction

One of the methods of researching solar-terrestrial coupling processes is observing the response of the flux of cosmic rays (CR) to various types of disturbances (or drivers) in the heliosphere. Transient phenomena detected in CR flux due to modulation in the heliosphere is the Forbush decrease: a sudden drop in CR flux followed by a gradual return to the previous level. It occurs as CR interact with irregularities in the interplanetary magnetic field (IMF), usually connected with the emission of coronal plasma known as a coronal mass ejection (CME) and its interplanetary counterpart (ICME) (Yermolaev et al., 2021). In recent decades, space probes have measured IMF parameters in-situ as well as particle flux. The detected particles can be fast-moving particles, known as solar energetic particles (SEPs), related to violent eruptions from the Sun that can cause a sudden increase in measured CR flux at the surface - a ground level enhancement (GLE). The other particles detected with probes, aside from solar wind particles and SEPs, are energetic storm particles (ESP) accelerated locally by shocks driven by fast ICMEs (Desai & Giacalone, 2016) and low-energy CR

(Veselinović et al., 2021). It has been shown (Koldobskiy et al., 2019; Savić et al., 2023; Kolarski et al., 2023) that parameters measured in-situ correlate with the magnitude and time evolution of FD. The end of October and the beginning of November 2021 marked extreme activity with a strong X-class solar flare (CIT), accompanied by the first Ground Level Enhancement (GLE) event in this cycle on October 28$^{\text{th}}$, measured by several ground stations (Papaioannou, A. et al., 2022). There were several typical CMEs during this period. Most pronounced were two halo CMEs on October 28$^{\text{th}}$ and November 2$^{\text{nd}}$. The second halo CME, due to its speed, caught up with previous ICMEs and produced a CME-CME interaction (Li et al., 2022).These disturbances created additional modulation of CR, producing the first strong FD in the present solar cycle, detected by multiple ground stations around the globe (Chilingarian et al., 2022).

The present case-study combines in-situ measurements of solar wind parameters and proton flux in near-Earth space with measurements on the ground to analyze how these parameters affect parameters of the FD detected on November 4$^{\text{th}}$, 2021.

2. Ground level cosmic ray observations

The most widely method of detecting CR use detectors that are part of the worldwide network of Neutron Monitors (NM) (`https://www.nmdb.eu/nest/`). One of the other species of these secondary CR that can be detected and used for monitoring primary CR are muons.

2.1. Belgrade muon detector

The ground level Belgrade muon station (GLL) is a part of the Low-Background Laboratory for Nuclear Physics at the Institute of Physics, Belgrade, Serbia. The energy range of the observed primary CR extends and complements the energy ranges detected by the NM network, but is still sensitive to CR modulation of the heliosphere. Details of the experimental setup, as well as the calculated response function of the detectors, are presented in (Veselinović et al., 2017).

2.2. Ground level data analysis

Both NM and muon detectors measure integral flux over different energy ranges, so the median energy of the detected primary CR is used in the analysis of the measured data. Another property of the detector system is Cut-off rigidity, the minimal magnetic rigidity that the CR must have in order to penetrate the IMF and geomagnetic field. To determine the amplitude of the FD for each station, which differs in median energy and asymptotic direction, a baseline was established using the average hourly count rate during mid-October 2021 when solar activity was low. For this study, we utilized 1-hour time series of CR flux detected at 17 NM stations and GLL data (Table 1).

Table 1. Cut-off rigidity (R_c) and median energy (E_m) of primary CR for several stations.

Stations	R_c (GV)	E_m (GeV)	Stations	R_c (GV)	E_m (GeV)
Belgrade	5.3	63	Kerguelen	1.14	10.4
Athens	8.53	17.8	Oulu	0.8	10.3
Guadalajara	6.95	15.4	Apatity	0.65	10.3
Baksan	5.6	13.7	Norilsk	0.63	10.3
Jungfraujoch	4.5	12.6	Tixie Bay	0.5	10.2
Lomnicky stít	3.84	12	Fort Smith	0.3	10.2
Dourbes	3.18	11.5	Inuvik	0.3	10.2
Kiel	2.36	11	S. Pole bare	0.1	10.1
Yakutsk	1.65	10.6	S. Pole	0.1	10.1

Median energy for NM was found using formula given in Li et al. (2023) and median energy for GLL was found using Monte Carlo method of CR transport. Dependence of FD amplitude on CR median energy is given by power law (Cane, 2000)

$$\frac{\Delta N}{N} = E^{-a} \tag{1}$$

Here N is CR flux, E is median energy and a is power exponent that depends on heliospheric conditions.

A scatter plot of the selected event is given (Figure 1) plotted in log-log scale and it show clear median rigidity dependence of the amplitude of FD.

Steeper spectrum during this event shows greater modulation of primary CR. If GLL data is included in the plot, the power exponent is not so large so that can be interpreted as stronger modulation of the lower energy CR due to CME-CME interaction. Linear regression is performed to found power indices correspond to November 2021 event. Power index for NM only is 1.23 ± 0.22 and for NM and GLL power index is 0.62 ± 0.10. This is, in general, in good agreement with some previous studies (Lingri et al. (2016) and references within).

3. Relation to in-situ measured data

In this study we used measured in-situ parameters relevant for heliospheric studies which are available at GSFC/Space Physics Data Facility, in the form of 1-hour resolution OMNI data (https://spdf.gsfc.nasa.gov/pub/data/omni/lowresomni/). Also we used proton flux date gathered by SOHO probe with two detectors, ERNE and EPHIN, onboard SOHO probe (Torsti et al., 2000; Kühl & Heber, 2019) at Lagrange point 1 in vicinity of Earth. Comparison between 1-hour time series of selected parameters of IMF from OMNI data and

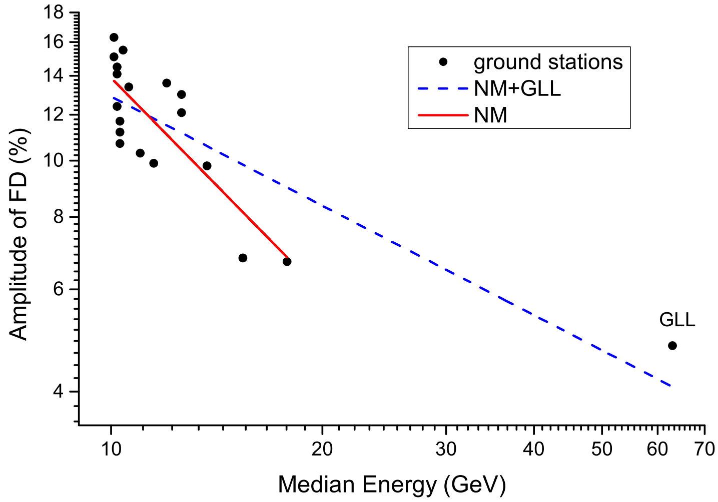

Figure 1. Rigidity spectrum of FD from November 4th 2021. Points represent the amplitude of the Forbush decrease as seen by 18 NMs and Belgrade GLL muon station.

relative detected CR flux of NM with low cut-off rigidity at South Pole and Belgrade muon detector and similar comparison for the same time interval between CR flux detected with two ground level detectors and selected channels of SOHO/ERNE and SOHO/EPHIN proton flux data is shown in Figure 2.

The discrepancies between time series of CR flux detected with ground stations and parameters of the IMF shows that CR was influenced by complex interactions in the heliosphere where low energy proton flux detected in-situ with detectors on board SOHO does not contribute substantially either to condition in heliosphere or CR flux.Increase of SEP flux, apparent in all detected proton flux from SOHO/ERNE and SOHO/EPHIN, produce GLE event detected with NM with low cut-off rigidity. Shape of detected FD on different stations varied, as expected due to difference cut-off rigidity, median energy, detector design, and sensitivity.

Correlation between respective time series was found using Pearson correlation coefficient using 2-tail test for significance is given at Table 2.

As expected correlation of CR flux is greater for NM detector at South Pole due to lower energy of detected CR which are more sensitive to disturbances of IMF. Inverse correlation of average magnetic field and solar wind plasma speed with CR flux is expected due to scattering of CR on turbulent magnetic field that produce a decrease in detected CR flux. The lack of correlation between proton fluxes and higher energy CR flux detected with GLL shown that monitor only some of the proton energy channel is not sufficient to model FD over range of CR energies during complex event with CME-CME interaction. Modeling of

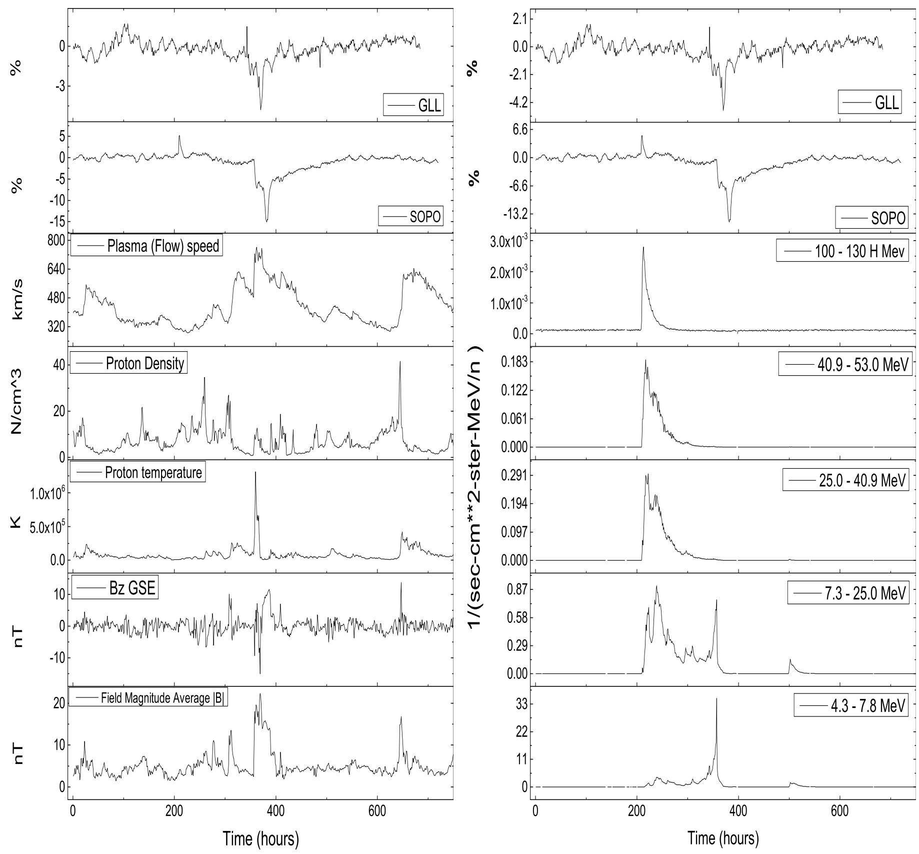

Figure 2. Left: Time series for plasma parameters (taken from OMNI database) and cosmic ray flux (measured at South Pole NM and GLL) from October 20th until November 20th, 2021. Right: Hourly time series for different proton energy channels from SOHO/ERNE and SOHO/EPHIN and two CR detectors time series for the same period.

this complicated shock-associated ICME disturbance where multiple shocks and transient flows merged is challenging and other studies (Zhao & Zhang, 2016; Werner et al., 2019) showed similar complex dependence of CR flux on different parameters of the IMF condition.

4. Summary

In this work we studied the FD occurred in November 4th, 2021, using data from Belgrade muon station and other multiple sources. Increased solar activity at the begging of the November 2021 had a measurable effect on CR, observed as a

Table 2. Pearson correlation coefficients for the correlation between CR flux detected at Belgrade CR station (GLL), at South pole (SOPO), flux of protons of different energies from SOHO/ERNE and SOHO/EPHIN and plasma parameters (from OMNI database) for the period from October 20th until November 20th, 2021.

	SOPO		GLL	
	Pearson Corr.	p-value	Pearson Corr.	p-value
SOPO	1		0.52	$<10^{-5}$
GLL	0.52	$<10^{-5}$	1	
|B| Average	-0.55	$<10^{-5}$	-0.48	$<10^{-5}$
Bz	−0.4	$<10^{-5}$	−0.15	$<10^{-4}$
Proton temperature	-0.18	$<10^{-5}$	-0.23	$<10^{-5}$
Proton Density	0.23	$<10^{-5}$	0.14	$<10^{-4}$
Plasma (Flow) speed	-0.61	$<10^{-5}$	-0.53	$<10^{-5}$
7.3-25.0 MeV p	0.17	$<10^{-5}$	-0.12	0.002
4.3-7.8 MeV p	0.01	0.67	-0.29	$<10^{-5}$
25.0-40.9 MeV p	0.21	$<10^{-5}$	0.02	0.5
40.9-53.0 MeV p	0.21	$<10^{-5}$	0.03	0.45
80-100 H Mev p	0.22	$<10^{-5}$	0.03	0.37

decrease in measured flux by all relevant CR stations. Energy range of affected primary CR was wide enough so effect was detected by neutron monitors but also muon detectors. Rapid decrease was detected with CR detectors around the world and it was one of the consequence, along with the strong G3-class geomagnetic storm, auroras and GLE event, of series of overlapping CMEs. We showed that based on measured amplitude of FD of the range of ground station that higher energy CR was less affected with heliospheric disturbance. Cross correlations between time series of CR flux and IMF and solar wind characteristics during these strongly disturbed heliospheric conditions were presented. Lack of strong correlation is also apparent for higher energy CR flux time series and time series of the heliospheric parameters and proton flux of certain energy ranges. This proves that, in order to better understand solar-terrestrial coupling processes, particularly its effect for higher energy particles requires more data from various sources and various probes and this analysis can be done in the future.

Acknowledgements. The authors acknowledge funding provided by the Institute of Physics Belgrade, through the grant by the Ministry of Science,Technological Development and Innovations of the Republic of Serbia. We also acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb (or CDAWeb or ftp) service, and OMNI data as well as team behind SOHO, which is a project of international collaboration between ESA and NASA. We acknowledge the NMDB database, founded under the European Union's FP7 program (contract no.213007) for providing data.

References

Cane, H. V., Coronal Mass Ejections and Forbush Decreases. 2000, *Space Science Reviews*, **93**, 55, DOI: 10.1023/A:1026532125747

Chilingarian, A., Hovsepyan, G., Martoyan, H., et al. 2022, Forbush decrease observed by SEVAN particle detector network on November 4, 2021

Desai, M. & Giacalone, J., Large gradual solar energetic particle events. 2016, *Living Reviews in Solar Physics*, **13**, 3, DOI: 10.1007/s41116-016-0002-5

Kühl, P. & Heber, B., Revising More Than 20 Years of EPHIN Ion Flux Data-A New Data Product for Space Weather Applications. 2019, *Space Weather*, **17**, 84, DOI: https://doi.org/10.1029/2018SW002114

Kolarski, A., Veselinović, N., Srećković, V. A., et al., Impacts of Extreme Space Weather Events on September 6th, 2017 on Ionosphere and Primary Cosmic Rays. 2023, *Remote Sensing*, **15**, DOI: 10.3390/rs15051403

Koldobskiy, S. A., Bindi, V., Corti, C., Kovaltsov, G. A., & Usoskin, I. G., Validation of the Neutron Monitor Yield Function Using Data From AMS-02 Experiment, 2011-2017. 2019, *Journal of Geophysical Research: Space Physics*, **124**, 2367, DOI: https://doi.org/10.1029/2018JA026340

Li, W.-h. et al., A study of Forbush Decreases effects with DAMPE experiment. 2023, *PoS*, **ICRC2023**, 1311, DOI: 10.22323/1.444.1311

Li, X., Wang, Y., Guo, J., & Lyu, S., Solar Energetic Particles Produced during Two Fast Coronal Mass Ejections. 2022, *The Astrophysical Journal Letters*, **928**, L6, DOI: 10.3847/2041-8213/ac5b72

Lingri, D., Mavromichalaki, H., Belov, A., et al., Solar Activity Parameters and Associated Forbush Decreases During the Minimum Between Cycles 23 and 24 and the Ascending Phase of Cycle 24. 2016, *Solar Physics*, **291**, 1025, DOI: 10.1007/s11207-016-0863-8

Papaioannou, A., Kouloumvakos, A., Mishev, A., et al., The first ground-level enhancement of solar cycle 25 on 28 October 2021. 2022, *A&A*, **660**, L5, DOI: 10.1051/0004-6361/202142855

Savić, M., Veselinović, N., Dragić, A., et al., New insights from cross-correlation studies between solar activity indices and cosmic-ray flux during Forbush decrease events. 2023, *Advances in Space Research*, **71**, 2006, DOI: https://doi.org/10.1016/j.asr.2022.09.057, recent progress in the physics of the Sun and heliosphere

Torsti, J., Mäkelä, P., Teittinen, M., & Laivola, J., SOHO/Energetic and Relativistic Nucleon and Electron Experiment Measurements of Energetic H, He, O, and Fe Fluxes during the 1997 November 6 Solar Event. 2000, *The Astrophysical Journal*, **544**, 1169, DOI: 10.1086/317219

Veselinović, N., Dragić, A., Savić, M., et al., An underground laboratory as a facility for studies of cosmic-ray solar modulation. 2017, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, **875**, 10, DOI: https://doi.org/10.1016/j.nima.2017.09.008

Veselinović, N., Savić, M., Dragić , A., et al., Correlation analysis of solar energetic particles and secondary cosmic ray flux. 2021, *The European Physical Journal D*, **75**, 173, DOI: 10.1140/epjd/s10053-021-00172-x

Werner, A. L. E., Yordanova, E., Dimmock, A. P., & Temmer, M., Modeling the Multiple CME Interaction Event on 6–9 September 2017 with WSA-ENLIL+Cone. 2019, *Space Weather*, **17**, 357, DOI: https://doi.org/10.1029/2018SW001993

Yermolaev, Y. I., Lodkina, I. G., Dremukhina, L. A., Yermolaev, M. Y., & Khokhlachev, A. A., What Solar-Terrestrial Link Researchers Should Know about Interplanetary Drivers. 2021, *Universe*, **7**, DOI: 10.3390/universe7050138

Zhao, L.-L. & Zhang, H., Transient galactic cosmic-ray modulation during solar cycle 24: A comparative study of two prominent Forbush decrease events. 2016, *The Astrophysical Journal*, **827**, 13, DOI: 10.3847/0004-637X/827/1/13