ORIGINAL ARTICLE



Galactic cosmic ray spectral index: the case of Forbush decreases of March 2012

M. Livada¹ · H. Mavromichalaki¹ · C. Plainaki²

Received: 9 September 2017 / Accepted: 4 December 2017 / Published online: 11 December 2017 © Springer Science+Business Media B.V., part of Springer Nature 2017

Abstract During the burst of solar activity in March 2012, close to the maximum of solar cycle 24, a number of X-class and M-class flares and halo CMEs with velocity up to 2684 km/s were recorded. During a relatively short period (7-21 March 2012) two Forbush decreases were registered in the ground-level neutron monitor data. In this work, after a short description of the solar and geomagnetic background of these Forbush decreases, we deduce the cosmic ray density and anisotropy variations based on the daily cosmic ray data of the neutron monitor network (http://www.nmdb.eu; http://cosray.phys.uoa.gr). Applying to our data two different coupling functions methods, the spectral index of these Forbush decreases was calculated following the technique of Wawrzynczak and Alania (Adv. Space Res. 45:622-631, 2010). We pointed out that the estimated values of the spectral index γ of these events are almost similar for both cases following the fluctuation of the Forbush decrease. The study and the calculation of the cosmic ray spectrum during such cosmic ray events are very important for Space Weather applications.

Keywords Cosmic rays \cdot Spectral index \cdot Forbush decreases \cdot Neutron monitor

H. Mavromichalaki emavromi@phys.uoa.gr

1 Introduction

Fast decreases of the galactic cosmic ray (GCR) intensity in one-two days followed by a gradual recovery in about 8-10 days are called as Forbush decreases (Fds) (Forbush 1954). They are observed after large solar flares and coronal mass ejections (CME) (Burlaga 1995; Cane 2000). One of the basic characteristics of Fds is the dependence of their amplitude on the rigidity of GCR. The rigidity dependence of the Fd's amplitude is shown by Cane (2000) and can be approximated by a power law $R^{-\gamma}$, where γ varies from ~ 0.4 to 1.2. The rigidity dependence of the transient modulations using mean rigidity of response of a detector was described by Ahluwalia and Fikani (2007) and their results were in agreement with their new methodology with negative exponents (Ahluwalia et al. 2009). A dependence on the energy of the recovery time was noted by Usoskin et al. (2008) only for events with amplitude exceeding 10%, while for Fds with lesser amplitude no correlation was confirmed (Wawrzynczak and Alania 2010).

In this work we focus on the determination of the cosmic ray spectral index during the Forbush decreases of March 2012 following the technique of Wawrzynczak and Alania (2010). Specifically the galactic cosmic ray spectral index was calculated using the coupling coefficient method that couples the secondary cosmic rays recorded at Earth to the primary cosmic ray flux at the edge of the magnetosphere. Specifically by using the ground count rate of GCR recorded at several neutron monitor stations located over the world and applying the method of coupling coefficients, the amplitude of the Forbush decrease in the heliosphere (independent of the magnetic field of the Earth) for various values of spectral index in a particular range, was calculated. An acceptable spectral index must correspond to the values of amplitude in the hemisphere that is almost the same for all neutron monitors.

¹ Nuclear and Particle Physics Department, Faculty of Physics, National and Kapodistrian University of Athens, Zografos, 15784 Athens, Greece

² ASI - Agenzia Spaziale Italiana, Via del Politecnico snc, 00133 Rome, Italy

 Table 1
 Characteristics of the neutron monitor stations used in this work

NM stations	Abbr.	Detector's type	Geographic coordinates	Altitude (m)	Cut-off rigidity (GV)	1st Fd ampl. (%) 9/3/2012	2nd Fd ampl. (%) 13/3/2012
South Pole (Antarctica)	SOPO	3NM64	90.0°S	2820	0.10	-14.4	-11.7
Fort Smith (Canada)	FSMT	18-NM-64	60.02°N 111.93°W	180	0.30	-12.7	-9.48
McMurdo (Antarctica)	MCMU	18NM64	77.9°S 166.6°E	48	0.30	-12.8	-10.7
Apatity (Russia)	APTY	18NM64	67.57°N 33.40°E	181	0.65	-10.9	-7.94
Oulu (Finland)	OULU	9-NM-64	65.05°N 25.47°E	15	0.81	-11.5	-8.74
Kiel (Germany)	KIEL	18-NM64	54.34°N 10.12°E	54	2.36	-11.5	-9.48
Jungfraujoch (Switzerland)	JUNG	18-IGY	46.55°N 7.98°E	3570	4.50	-10.2	-8.47
Baksan (Russia)	BKSN	6NM64	43.28°N 42.69°E	1700	5.60	-7.96	-6.84
Rome (Italy)	ROME	20NM64	41.86°N 12.47°E	Sea level	6.27	-6.62	-5.43
Athens (Greece)	ATHN	6NM64	37.97°N 23.78°E	260	8.53	-5.87	-4.65

For the calculation of the spectral index during the events of March 2012, an appropriate coupling function was needed to be used. Dorman (1963) introduced these functions and different parameters of them are optimized. The rigidity dependent of coupling functions $W(R, Z, t_0)$ were calculated using an altitude dependence function after parameterization of the results of Dorman and Yanke (1981) and Clem and Dorman (2000). In this work two types of coupling functions were used, firstly the total response function of Clem and Dorman (2000) used for polar and middle latitude stations and secondly the function of Belov and Struminsky (1997) was applied using a separate term $E^{3.17}$ for stations with energy between 1 GV < E < 2.78 GV. Both of these functions are useful to study galactic and solar cosmic ray variations (Belov et al. 1994, 2005b; Belov and Eroshenko 1996; Plainaki et al. 2007, 2014) for the NM64 and IGY type of neutron monitor stations with no important difference (Clem and Dorman 2000).

In this paper the Fds of March 2012 occurred on the ascending phase of solar cycle 24, were studied. This period was characterized by a series of two Fds starting from March 7 till March 21, 2012. A number of strong X-class and M-class solar flares and fast coronal mass ejections occurred. It was interesting that in less than one hour two X-class flares were recorded from solar activity in the active region AR1429, where a associated CME reached the velocity of 2684 km/s. For these Fds the spectral index was calculated using the coupling function of Clem and Dorman

(2000) and Belov and Struminsky (1997). A discussion of the obtained results is performed.

2 Data selection

In this work daily corrected for pressure and efficiency values of the cosmic ray intensity recorded at polar, high and middle latitude neutron monitor stations over the world, were used. These data has been obtained from the Highresolution real time Neutron Monitor Database—NMDB (http://www.nmdb.eu) and the geographic coordinates, the altitude and the cut-off rigidity each station are given in Table 1. The cosmic ray data were normalized according to the equation

$$J_i^k = \frac{(N_k - N_0)}{N_0}$$
(1)

where J_i^k is ground-based amplitude of the Fds, N_k is the running daily average count rate (k = 1, 2, 3, ... days) and N_0 is the 3 days average count rate before the beginning of the Fd (Wawrzynczak and Alania 2010). Time profiles of these data for all stations used in this work are presented in Fig. 1, while the Fd amplitude for each station and each Fd are given in Table 1. It is observed that the Fd amplitude for the used here stations is ranged in the first case from 14.4% in South Pole to 5.87% to Athens and in the second case from 11.7% in South Pole to 4.65% in Athens. A discrepancy in the profiles of the polar stations (South Pole,



Fig. 1 Daily values of the normalized CR intensity for polar and middle latitude neutron monitor stations obtained from the High resolution Neutron Monitor Database—NMDB for the time period 7 to 21 March, 2012

Fort Smith, McMurdo, Apatity, Oulu), the high latitude (Kiel, Jungfraujoch) and the middle latitude (Baksan, Rome, Athens) stations is observed. These results confirm the dependence of the Fd's amplitude from the cut-off rigidity of each station, as it is presented in Fig. 2 (Usoskin et al. 2008; Lingri et al. 2016). In this figure it is observed that in both Fds firstly on March 9, 2012 and secondly on March 13, 2012, the dependence of the Fd's amplitude on the cut-off rigidity of each station is important.

Characteristics of these strong solar events, such as Mand X-solar flares and halo CMEs related to these Fds, were obtained from NOAA (ftp.ngdc.noaa.gov; http://cdaw.gsfc. nasa.gov; http://umtof.umd.edu/pm/) are listed in Table 2.

For this study, the Fds database of the IZMIRAN of the Russian academy of Sciences (http://spaceweather.izmiran. ru/eng/dbs.html) has been used. Firstly data of the solar wind velocity and the IMF are presented in the upper panel of Fig. 3. Moreover the CR density and anisotropy for cosmic ray particles of rigidity 10 GV which is close to the effective rigidity of the particles being registered by the neutron monitor worldwide network by using the GSM method are given in the middle panel of Fig. 3. The indices of geomagnetic activity Dst and Kp for the examined events are presented in the lower panel of Fig. 3 (Belov et al. 2005a).

3 The events of March 2012

During the time period of March 2012, that is near the maximum of solar cycle 24, significant powerful solar X-ray flares were recorded. The solar activity related to the Forbush decreases of March 7–21, 2012 was originated from the solar active region AR 11429 (National Oceanic and Atmospheric Administration—NOAA). Within a relatively short period of March 4–21, 2012, a number of 17 M-class and 3 X-class flares and a number of partial and halo CMEs took



Fig. 2 The amplitude of the first Fd (*above panel*) and of the second Fd (*down panel*) of recorded at the neutron monitor stations in relation to their cut-off rigidity

place on the Sun, as they were observed from GOES and SOHO/LASCO satellites (ftp.ngdc.noaa.gov; cdaw.gsfc. nasa.gov; http://umtof.umd.edu/pm/) and are listed in Table 2. According to this Table the most important activity in this AR was recorded on March 7, 2012 with a barrage of two X-class eruptive flares in rapid succession, associated with two ultra-fast CMEs with velocity up to 2684 km/s. The first flare was an X5.4 one originated at heliographic coordinates N18, E31 and the second flare was an X1.3 one originated from the same region at heliographic coordinates N15, E26. The solar activity on March 7, 2012 is also related to the geomagnetic indices, specific the Dst index reached a minimum of -143 nT and Kp index reached the maximum value of 8+ on March 9, 2012 (Fig. 3). The coincidence of the maximum value of the Kp index with the minimum value of the Dst index and the greater amplitude of the Fds on March 9, 2012, means that an intense geomagnetic storm took place (Belov et al. 2005a; Livada et al. 2015; Patsourakos et al. 2016).

As a consequence of these solar and geomagnetic activities a series of Fds from 7 to 21 March 2012 was detected by the neutron monitors of the worldwide network (http:// www.nmdb.eu). The first one being the greater of the so-

Solar flares start time DD/MM/YYYY hh:mm:ss	GOES class	Derived position	CMEs DD/MM/YYYY hh:mm:ss	<i>V</i> (km/s)
04/03/2012	M2.0	AR 1429	04/03/2012	1306
10:29:00		N16E65	11:00:07	
05/03/2012	X1.1	AR 1429	05/03/2012	1531
02:30:00		N19E58	04:00:05	
05/03/2012	M2.1	AR 1429	05/03/2012	402
19:10:00		N16E45	19:24:07	
05/03/2012	M1.8	AR 1429	-	-
19:27:00		N16E45		
05/03/2012	M1.3	AR 1429	_	_
22:26:00		N16E43		
06/03/2012	M1.3	AR 1429	_	_
00:22:00		N16E42		
06/03/2012	M1.2	AR 1429	_	_
01:36:00		N16E41		
06/03/2012	M1.0	AR 1429	06/03/2012	536
04:01:00		N16E39	04:48:06	
06/03/2012	M1.0	AR 1429	06/03/2012	599
07:52:00		N17E40	08:12:08	
06/03/2012	M2.1	AR 1429	_	_
12:23:00		N21E40		
06/03/2012	M1.3	AR 1429	_	_
21:04:00		N16E30		
06/03/2012	M1.0	AR 1429	_	_
22:49:00		N19E32		
07/03/2012	X5.4	AR 1429	07/03/2012	2684
00:02:00		N18E31	00:24:06	
07/03/2012	X1.3	AR 1429	07/03/2012	1825
01:05:00		N15E26	01:30:24	
09/03/2012	M6.3	AR 1429	09/03/2012	950
03:22:00		N15W03	04:26:09	
10/03/2012	M8.4	AR 1429	10/03/2012	1296
17:15:00		N17W24	18:00:05	
13/03/2012	M7.9	AR 1429	13/03/2012	1884
17:12:00		N17W66	17:36:05	
14/03/2012	M2.8	AR1432	14/03/2012	411
15:08:00		N13E05	16:36:05	
15/03/2012	M1.8	AR1432	15/03/2012	485
07:23:00		N14W03	09:24:05	
_	_	_	16/03/2012	862
			20:36:03	
17/03/2012	M1.3	AR1434	_	_
20:32:00		S20W24		
_	_	_	18/03/2012	1210
			00:24:05	-
_	_	_	21/03/2012	1178
			07:36:05	

 Table 2
 Solar flares and associated CMEs during the period 4–21 March 2012



Fig. 3 The intensity of the interplanetary magnetic field and the solar wind velocity (*upper panel*), the density (A0) and anisotropy (Axy) of the CR (*mid panel*), and the Dst and Kp indices of geomagnetic activity (*lower panel*) during March 2012 are given (Sudden Shock Commencement—SSC corresponds to the times of shock arrival at the Earth)

lar cycle 24 happened on March 8, 2012 and had amplitude 14.4% for South Pole and the second one took place on March 12, 2012 with amplitude 11.7% for the same station considering as baseline the one of March 7, 2012.

4 Method of analysis

Using the method of Wawrzynczak and Alania (2010) and Alania and Wawrzynczak (2012), the Fds of the GCR intensity observed on 7-21 March 2012, were analyzed. The temporal changes of the rigidity spectrum of these Fds were studied from the daily average corrected for pressure and efficiency cosmic ray data of ten neutron monitors (Apatity, Fort Smith, Kiel, McMurdo, Oulu, South Pole, Athens, Rome, Baksan, Jungfraujoch). For the Fds of 7-21 March 2012, the biggest Fd amplitudes were observed on March 9, 2012 and on March 13, 2012 (Fig. 1, Table 1). As it was mentioned above, it is observed that polar stations as South Pole and McMurdo are appeared with the great groundbased amplitude of the Fds (14.4% for South Pole, 12.8% for McMurdo) in comparison to middle latitude stations, as Athens and Rome (5.87% for Athens, 6.62% for Rome). This is due to the fact that polar stations cover a more extended range of the primary GCR spectrum having smaller magnetic rigidity cut-off. Therefore, different cosmic ray events are expected to be registered with higher amplitude there, depending also on the station altitude.

According to the method of Wawrzynczak and Alania (2010), secondary cosmic ray measurements can be connected to the primary incident cosmic ray particles via specific mathematical functions taking into account the acceptance vectors for each detector (neutron monitor), based on its local characteristics. Temporal intensity variations of GCRs during Forbush decreases can be represented as a power law in rigidity by Eq. (2), where $R_0 = 1$ GV and R_{max} is the rigidity above which the Forbush decrease of the GCRs vanishes (Dorman 2004). A usual choice for the upper limit is $R_{\text{max}} = 200$ GV

$$\frac{\delta D(R)}{D(R)} = \begin{cases} A \left(\frac{R}{R_0}\right)^{-\gamma}, & R \le R_{\max} \\ 0, & R > R_{\max} \end{cases}$$
(2)

The daily average amplitude of the Fd for the '*i*' neutron monitor was calculated according to Eq. (1). The amplitude of the '*i*' detector with the geomagnetic cutoff rigidity R_i and the average atmospheric depth h_i are defined as:

$$J_i^k = \int_{R_i}^{R_{\text{max}}} \left(\frac{\delta D(R)}{D(R)}\right)_k W_i(R_i h_i) dR \tag{3}$$

where $(\delta D(R)/D(R))_k$ is the rigidity spectrum of the Fd for the *k* day, $W_i(R_i, h_i)$ is the coupling coefficient for the neutron or muon component of GCR (Dorman 1963).

Inserting Eq. (2) into Eq. (3) and solving this towards the amplitude of the Forbush decrease in free space A_i^k , we can take Eq. (4), where A_i^k should be independent of the local characteristics of the detector:

$$A_i^k = J_i^k / \int_{R_i}^{R_{\text{max}}} \left(\frac{R}{R_0}\right)^{-\gamma^{\kappa}} w_i(R_i h_i) dR \tag{4}$$

Yasue et al. (1982) for neutron monitors and Fujimoto et al. (1984) for muon telescopes calculated the aforementioned coupling integral for discrete magnitudes of $R_{\text{max}} =$ 30, 50, 100, 200, 500 GV and for discrete values of $\gamma =$ -1.5, -1, -0.5, 0. In our analysis we calculated the integral ourselves providing values of γ ranging from 0.5 to 2 with a step of 0.01 (Alania and Wawrzynczak 2008; Wawrzynczak and Alania 2010). In order to calculate the spectral index γ , we followed the scheme that the differences of the amplitude A resulting from the above calculation, will be a series of estimated numbers, according to Wawrzynczak and Alania (2010). We also considered $\Delta A_{i}^{\kappa} = |A_{i}^{\kappa} - \overline{A_{i}^{\kappa}}|$ as the difference between the mean amplitude and the amplitude of the specific detector and calculated its standard deviation $\sigma_{\gamma}^{\kappa} = \sqrt{\sum_{l=1}^{n} (|A_{l}^{\kappa} - \overline{A_{l}^{\kappa}}|)^{2}/(n-1)}$ for a series of 151 values of γ . Then we demanded the standard deviation to be minimum for an acceptable γ_0^{κ} , because the aim is the difference of the amplitudes to be minimum, i.e. $\Delta A_{l}^{\kappa} = |A_{l}^{\kappa} - \overline{A_{l}^{\kappa}}|$ in order the A_{l}^{κ} in the heliosphere being



Fig. 4 The calculated variations of the GCR intensity in the heliosphere recorded at the neutron monitor stations (*left panel*) and the temporal changes of the rigidity spectrum exponent γ applied the coupling function of Clem and Dorman (2000) (*right panel*) from 7 to 21 March 2012



Fig. 5 The calculated variations of the GCR intensity in the heliosphere recorded at the neutron monitor stations (*left panel*) and the temporal changes of the rigidity spectrum exponent γ applied the coupling function of Belov and Struminsky (1997) (*right panel*) from 7 to 21 March 2012

the same for all selected neutron monitors. To find out the values of γ^{κ} e.g. with a confidence level of 95%, we had to determine γ^{κ} corresponding to two standard deviations of $\sigma_{\gamma \rho}^{\kappa}$ and comparing it with the value of γ_0^{κ} .

Using this method we calculated the rigidity spectrum exponent γ^{κ} and the variations of the GCR intensity in the heliosphere for polar and middle latitude neutron monitor stations from 7 to 21 March 2012 close to the solar maximum with two separately coupling functions. The results of our analysis are given in Figs. 4 and 5 respectively.

5 Coupling functions and results

Using the coupling coefficient $w_i(R_ih_i)$ in the above mentioned Eq. (3) results from two different kinds of coupling functions were obtained and compared. A first atmospheric cascade calculation to determine yield functions suitable for neutron monitor stations located at mountain altitudes, was introduced by Dorman and Yanke (1981). They created transport equations of differential particle multiplicity and identified a solution with the method of successive generations, not taking into account scattering effects and pion and muon production. The solution was used to determine the yield function and the response function for sea level stations. The obtained results using a depth dependent function was parameterized by Belov and Struminsky (1997) and Belov et al. (1999) as below:

$$N(R) = N(0) \left(1 - \exp(-aR_C^{-K+1}) \right)$$
(5)

where R_C is the cut-off rigidity and α and κ are depthdependent parameters. The first derivative of Eq. (5) gives



Fig. 6 A comparison of the temporal changes of the rigidity spectrum exponent γ from 7 to 21 March 2012 applied the coupling functions of Clem and Dorman (2000) (*red line*) and the corresponding one of Belov and Struminsky (1997) (*dark line*)

the total response function

$$W(R_C) = \frac{-dN}{N(0)dR_C}$$
$$= \alpha(\kappa - 1)\exp(-\alpha R_C^{-K+1})R_C^{-K}$$
(6)

For solar minimum activity the derived parameters are given as:

$$\ln a = 1.84 + 0.094h - 0.09 \exp(-11h),$$

$$k = 2.40 - 0.56h + 0.24 \exp(-8.8h)$$
(7)

and for solar maximum activity are:

$$\ln a = 1.93 + 0.15h - 0.18 \exp(-10h),$$

$$k = 2.32 - 0.49h + 0.18 \exp(-9.5h)$$
(8)

where *h* is the atmospheric depth in bars. These functions give a good representation of calculations in the rigidity range of 2 GV < R < 50 GV (Dorman and Yanke 1981). The least square fit of this parameterization was applied to calculate data only within this rigidity range and results obtained outside of these limits are unphysical (Clem and Dorman 2000).

The form of the coupling functions in the low kinetic energy range 0.5 GeV < E < 2 GeV or 1 GV < R < 2.78 GV was considered as a power law with respect to kinetic energy of the primary particles, close to $E^{3.17}$ (Belov and Struminsky 1997; Plainaki et al. 2007, 2014).

For this reason the coupling functions become:

$$w(R, h, t_0)dR$$

$$= \begin{cases} w_T(R, h, t_0) dR, \\ R \ge 2.78 \text{ GV} \\ W \left(R = 2.78 \text{ GV}, h, t_0 \left(\frac{E}{2 \text{ GeV}} \right)^{3.17} \right) dR, \\ R < 2.78 \text{ GV} \end{cases}$$
(9)

The coupling functions (9) are referred to cut-off rigidity R_C from 1 GV and above. But for the polar neutron monitor stations with $R_C < 1$ GV the coupling functions (6) and (7) were used due to that 90% of the count rates of the polar NM64 stations are initiated by CRs above 5 GV (Maurin et al. 2015).

The above mentioned two coupling functions according to Clem and Dorman (2000) and Belov and Struminsky (1997) respectively, were applied to several middle and polar neutron monitor stations for the calculation of the spectral index during the Forbush decreases of March 2012. A comparison of the calculated spectral index values with the two different functions is presented in Fig. 6. The two curves seem to have the same behavior with a parallel shift each of other. Possibly it is coming from the term of the solar cosmic rays including in the function of Belov and Struminsky (1997) and for this reason it is more appropriate for the study of GLEs due to the extreme flux of the solar cosmic rays.

6 Discussion and conclusions

From the above analysis it is concluded the following:

- It is known that the amplitude of the Fds observed at the cosmic ray data of the different neuron monitor stations is related to the solar activity. In specific, the great amplitude which occurred in the Fd of March 9, 2012, was occurred after the two X-class flares of March 7, 2012 and from the corresponding CME with the velocity up to 2684 km/s. Respectively the second Fd of March 13, 2012 originated from M-class flare on March 13, 2012 and from the corresponding CME recorded with velocity 1884 km/s, was recorded with a smaller ground-based amplitude (Fig. 1, Table 2). Moreover during the Fds of March 2012 the ground-based amplitude had the greater value on March 9, 2012, when a geomagnetic storm took place and the Kp index reached the maximum value 8+, while the Dst index reached the minimum value -143 nT, as it is presented in Figs. 1 and 3 (Aslam and Badruddin 2017).
- Also it is observed from Fig. 1 and Table 1 that as the cut-off rigidity R_C of the selected stations increases, the amplitude of the Fd decreases. Specifically the polar stations such as South Pole station with $R_C = 0.1$ GV,

Days	Spectral index (Clem and Dorman 2000)	Spectral index (Belov and Struminsky 1997)	Difference
07/3/2012	2.00 ± 1.50	2.00 ± 1.50	0.00
08/3/2012	0.50 ± 1.50	0.50 ± 1.50	0.00
09/3/2012	0.62 ± 0.12	0.80 ± 0.30	0.18
10/3/2012	0.63 ± 0.13	0.81 ± 0.12	0.18
11/3/2012	0.50 ± 0.21	0.69 ± 0.22	0.19
12/3/2012	0.67 ± 0.19	0.88 ± 0.21	0.21
13/3/2012	0.58 ± 0.14	0.78 ± 0.19	0.20
14/3/2012	0.69 ± 0.23	0.94 ± 0.29	0.25
15/3/2012	0.89 ± 0.26	1.18 ± 0.32	0.29
16/3/2012	1.06 ± 0.20	1.39 ± 0.25	0.33
17/3/2012	0.96 ± 0.19	1.25 ± 0.29	0.29
18/3/2012	1.12 ± 0.30	1.51 ± 0.36	0.39
19/3/2012	1.37 ± 0.68	1.76 ± 0.35	0.39
20/3/2012	2.00 ± 0.63	2.00 ± 0.24	0.00
21/3/2012	2.00 ± 0.10	2.00 ± 0.10	0.00

 Table 3 Daily values of the spectral index for the time period 7–21 March 2012

had the biggest amplitude of all stations (A = -14.4%and A = -11.7% for the two Fds respectively), while the middle latitude stations as Athens station, had the smaller amplitude (A = -5.87% and A = -4.65% respectively for the two Fds). The dependence of the Fd amplitude on the cut-off rigidity of each station is also confirmed for both Fds from Fig. 2 (Usoskin et al. 2008; Lingri et al. 2016).

- With the technique of Wawrzynczak and Alania (2010) and Alania and Wawrzynczak (2012) the spectral index of the Fds of March 2012 was calculated firstly with the total response function of Clem and Dorman (2000) used polar and middle latitude stations (Table 3) and secondly with the functions of Belov and Struminsky (1997) that use a separate term for stations with energy lower than 2.78 GV (Table 3). The values of the spectral index are in agreement with the fluctuations of Fds in both cases of coupling functions, that means that the calculated spectral index is observed to have the same behavior with the amplitude of the Fd (Figs. 4 and 5).
- The ground based amplitude of the Fds calculated for the selected stations and presented in Fig. 1, seems to be different for each station depending on their cut-off rigidity. It is interesting to note that the Fd amplitude in the heliosphere obtained from the application of both coupling functions seems to be almost the same for all stations (Figs. 4 and 5). This result confirms the technique of Wawrzynczak and Alania (2010) and Alania and Wawrzynczak (2012) that suggests in order to obtain reliable calculations of the spectral index values, it is important to have the same values of A_i^k .
- In the case of the neutron monitor stations used in this study the difference of the spectral index values obtained

by the two coupling functions is significant, as it is shown in Table 3 and Fig. 6. The difference is a parallel shift of the values taken from the Belov and Struminsky (1997) function including the term of solar cosmic ray flux for the stations with energy < 2.78 GV. This term is sensitive in the case of GLEs and not in the case of FDs.

The results of the calculation of the spectral index are in agreement with previous work of Wawrzynczak and Alania (2010) examining the event of September 2005. At the beginning of the Fd at September 9, 2005 and in the recovery phase of it at September 18-19, 2005, the calculated spectral index values reached the biggest ones ranged from 2-0.5, while during the main phase of the Fd characterized by the biggest amplitude, the spectral index values had minimum values. It means that the fluctuation of the Fd's amplitude had the same behavior with the fluctuation of the spectral index. These results of the relation of the spectral index with respect to the amplitude of the Fd in the events of March 2012 are in agreement with the results concerning the Fd of August 2010 (Livada et al. 2013), as well as the events of December 2014–January 2015 (Livada and Mavromichalaki 2017).

Concluding, we can say that the spectrum of the GCR becomes harder during the Forbush decrease main phase. This is because lower energy galactic particles get reflected from the magnetic structures prior to the Fd event, e.g. ICMEs, magnetic clouds, etc. and therefore what gets registered to the ground are more energetic cosmic rays. A further study of the calculated spectral index values during other selected Fds of the cosmic ray intensity and using 12-hourly averaged CR count rate values beyond of the daily ones, will provide a more complete approach of the spectral index values during these cosmic ray events considering the most appropriate function. The results will be useful to the Space Weather applications.

In this paper we used the method of coupling functions developed by Lev Dorman (1963) to analyze Neutron Monitor data during FDs. At first approximation, our analysis depends on the GCR spectrum and thus on the level of solar activity. Our approach did not allow us to disentangle two crucial effects: 1) the effect of the NM detection efficiency to the incoming particles; 2) the effect of the primary spectrum to the secondary flux reaching the ground. Nevertheless, our results confirm in general the dependence of the FD amplitude on solar activity conditions, as evidenced also in previous works. In the future, the application of NM data analysis methods accounting for strict yield function formalism (e.g. Mishev et al. 2013; Mangeard et al. 2016), independent of the spectrum of incoming particles (e.g. GCR, SEP, etc.), is intended.

Acknowledgements Special thanks to the colleagues of the NM stations (www.nmdb.eu) for kindly providing the cosmic ray data used in this study in the frame of the High resolution Neutron Monitor database NMDB, funded under the European Union's FP7 Program (contract no. 213007). Thanks are due to the IZMIRAN group of the Russian Academy of Sciences for kindly providing the Forbush decrease data.

References

- Ahluwalia, H.S., Fikani, M.M.: Cosmic ray detector response to transient solar modulation: Forbush decreases. J. Geophys. Res. 112, A08105 (2007)
- Ahluwalia, H.S., Ygbuhay, R.C., Duldig, M.: Two intense Forbush decreases of solar activity cycle 22. Adv. Space Res. 44, 58–63 (2009)
- Alania, M.V., Wawrzynczak, A.: Forbush decrease of the galactic cosmic ray intensity: experimental study and theoretical modeling. Astrophys. Space Sci. Trans. 4, 59–63 (2008)
- Alania, M., Wawrzynczak, A.: Energy dependence of the rigidity spectrum of Forbush decrease of galactic cosmic ray intensity. Adv. Space Res. 50, 725–730 (2012)
- Aslam, O.P.M., Badruddin: A study of the geoeffectiveness and Galactic cosmic ray response of the VarSITY-ISEST campaign events in solar cycle 24. Sol. Phys. 292, 135 (2017)
- Belov, A.V., Eroshenko, E.A.: The energy spectra and other properties of the great proton events during 22nd solar cycle. Adv. Space Res. 17, 167 (1996)
- Belov, A.V., Struminsky, A.B.: Neutron monitor sensitivity to primary protons below 3 GeV derived from data of ground level events. In: Proc. 25th Int. Cosmic Ray Conf., vol. 1, Durban, p. 201 (1997)
- Belov, A.V., Eroshenko, E.A., Livshits, M.A.: The energy spectra of the accelerated particles near the Earth and in the source in 15 June 1991 enhancement. In: Proc. 8th Intern. Symp. on Solar Terrestrial Physics, Sendai (1994)
- Belov, A., Struminsky, A., Yanke, V.: Neutron monitor response functions for galactic and solar cosmic rays. In: ISSI Workshop on Cosmic Rays and Earth (1999)
- Belov, A.V., Baisultanova, L., Eroshenko, E., et al.: Magnetospheric effects in cosmic rays during the unique magnetic storm on November 2003. J. Geophys. Res. Space Phys. 110(9), A09520 (2005a)

- Belov, A., Eroshenko, E., Mavromichalaki, H., Plainaki, C., Yanke, V.: Solar cosmic rays during the extremely high ground level enhancement of February 23, 1956. Ann. Geophys. 23, 1 (2005b)
- Burlaga, L.F.: Interplanetary Magnetohydrodynamics. Oxford University Press, New York (1995)
- Cane, H.V.: Coronal mass ejections and Forbush decreases. Space Sci. Rev. 93, 55–77 (2000)
- Clem, J., Dorman, L.: Neutron monitor response functions. Space Sci. Rev. 93, 335–359 (2000)
- Dorman, L.I.: Cosmic Rays Variations and Space Exploration. Nauka, Moscow (1963)
- Dorman, L.I.: Cosmic Rays in the Earth's Atmosphere and Underground. Kluwer Academic, Dordrecht (2004)
- Dorman, L.I., Yanke, V.: The coupling functions of NM-64 neutron supermonitor. In: Proc. 17th Int. Cosmic Ray Conf., vol. 4, p. 326 (1981)
- Forbush, S.: World-wide cosmic ray variations, 1937–1952. J. Geophys. Res. 59, 525 (1954)
- Fujimoto, K., Inoue, A., Murakami, K., et al.: In: Coupling Coefficients of Cosmic Ray Daily Variations for Meson Telescopes, Nagoya, Japan (1984)
- Lingri, D., Mavromichalaki, H., Belov, A., Eroshenko, E., Yanke, V., Abunin, A., Abunina, M.: Solar activity parameters and associated Forbush decreases during the minimum between cycles 23 and 24 and the ascending phase of cycle 24. Sol. Phys. 291, 1025 (2016). doi:10.1007/s11207-016-0863-8
- Livada, M., Mavromichalaki, H.: Galactic cosmic ray spectrum during the Forbush decreases of December 2014–January 2015. In: 10 Years NMDB Workshop, p. 13 (2017)
- Livada, M., Papaioannnou, A., Mavromichalaki, H.: Galactic cosmic ray spectrum and effective radiation doses on flights during Forbush decreases. In: Proc. 11th Hel.A.S Conference, S1-22 (2013)
- Livada, M., Lingri, D., Mavromichalaki, H.: Galactic cosmic ray spectrum of the Forbush decreases of March 7, 2012. In: Proc. 12th Hel.A.S Conference, S1.12 (2015)
- Mangeard, P.S., Ruffolo, D., Saiz, A., Madlee, S., Nutaro, T.: Monte Carlo simulation of the neutron monitor yield function. J. Geophys. Res. 121, 7435–7448 (2016). doi:10.1002/2016JA022638
- Maurin, D., Cheminet, A., Derome, L., Ghelfi, A., Hubert, G.: Neutron monitors and muon detectors for solar modulation studies: interstellar flux, yield function, and assessment of critical parameters in count rate calculations. Adv. Space Res. 55, 363–389 (2015)
- Mishev, A.L., Usoskin, I.G., Kovaltsov, G.A.: Neutron monitor yield function: new improved computations. J. Geophys. Res. 118, 2783–2788 (2013). doi:10.1002/jgra.50325
- Patsourakos, S., Georgoulis, M.K., Vourlidas, A., et al.: The major geoeffective solar eruptions of 2012 March 7: comprehensive Sun-to-Earth analysis. Astrophys. J. 817, 14–35 (2016)
- Plainaki, C., Belov, A., Eroshenko, E., Mavromichalaki, H., Yanke, V.: Modeling ground level enhancements: event of 20 January 2005. J. Geophys. Res. **112**, A04102 (2007)
- Plainaki, C., Mavromichalaki, H., Laurenza, M., Gerontidou, M., Kanellakopoulos, A., Storini, M.: The ground level enhancement of 2012 May 17: derivation of solar proton event properties through the application of the NMBANGLE PPOLA model. Astrophys. J. 785, 160–172 (2014). doi:10.1088/0004-637X/785/2/160
- Usoskin, I.G., Braun, I., Gladysheva, O.G., et al.: Forbush decreases of cosmic rays: energy dependence of the recovery phase. J. Geophys. Res. 113, A07102 (2008)
- Wawrzynczak, A., Alania, M.: Modeling and data analysis of a Forbush decrease. Adv. Space Res. 45, 622–631 (2010)
- Yasue, S., Mori, S., Sakakibara, S., et al.: Coupling coefficients of cosmic rays daily variations for neutron monitors, 7, Nagoya (1982)