

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

M. Livada¹ · H. Mavromichalaki¹ · C. Plainaki²

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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 · Spectral index · Forbush decreases · Neutron monitor

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.

✉ H. Mavromichalaki
emavromi@phys.uoa.gr

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 $1 \text{ GV} < E < 2.78 \text{ GV}$. 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 High-resolution 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

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

where J_i^k is ground-based amplitude of the Fds, N_k is the running daily average count rate ($k = 1, 2, 3, \dots$ 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,

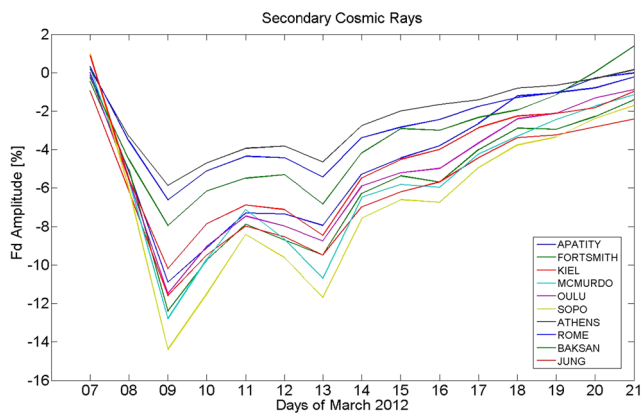


Fig. 1 Daily values of the normalized CR intensity for polar and middle latitude neutron monitor stations obtained from the High resolution Neutron Monitor Database—NMDB for the time period 7 to 21 March, 2012

Fort Smith, McMurdo, Apatity, Oulu), the high latitude (Kiel, Jungfrauoch) 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 M- and 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

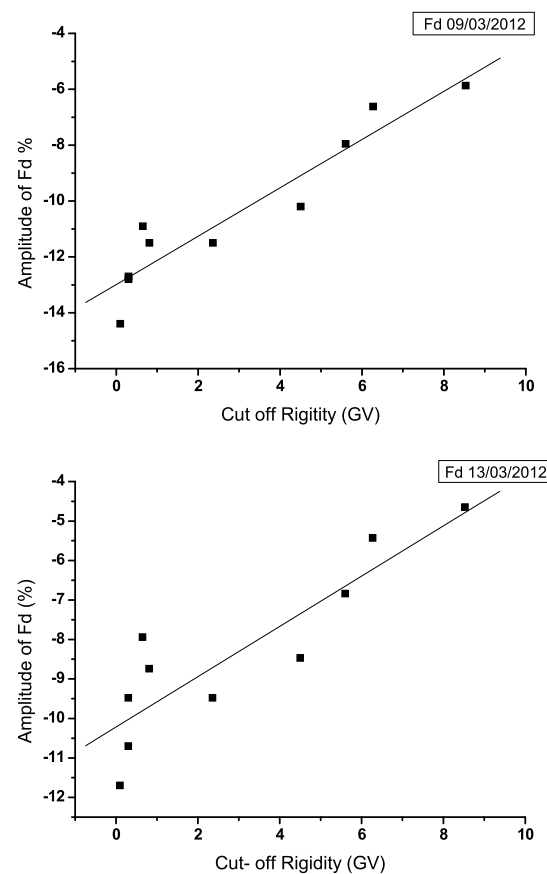


Fig. 2 The amplitude of the first Fd (*above panel*) and of the second Fd (*down panel*) of recorded at the neutron monitor stations in relation to their cut-off rigidity

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-

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

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 10:29:00	M2.0	AR 1429 N16E65	04/03/2012 11:00:07	1306
05/03/2012 02:30:00	X1.1	AR 1429 N19E58	05/03/2012 04:00:05	1531
05/03/2012 19:10:00	M2.1	AR 1429 N16E45	05/03/2012 19:24:07	402
05/03/2012 19:27:00	M1.8	AR 1429 N16E45	–	–
05/03/2012 22:26:00	M1.3	AR 1429 N16E43	–	–
06/03/2012 00:22:00	M1.3	AR 1429 N16E42	–	–
06/03/2012 01:36:00	M1.2	AR 1429 N16E41	–	–
06/03/2012 04:01:00	M1.0	AR 1429 N16E39	06/03/2012 04:48:06	536
06/03/2012 07:52:00	M1.0	AR 1429 N17E40	06/03/2012 08:12:08	599
06/03/2012 12:23:00	M2.1	AR 1429 N21E40	–	–
06/03/2012 21:04:00	M1.3	AR 1429 N16E30	–	–
06/03/2012 22:49:00	M1.0	AR 1429 N19E32	–	–
07/03/2012 00:02:00	X5.4	AR 1429 N18E31	07/03/2012 00:24:06	2684
07/03/2012 01:05:00	X1.3	AR 1429 N15E26	07/03/2012 01:30:24	1825
09/03/2012 03:22:00	M6.3	AR 1429 N15W03	09/03/2012 04:26:09	950
10/03/2012 17:15:00	M8.4	AR 1429 N17W24	10/03/2012 18:00:05	1296
13/03/2012 17:12:00	M7.9	AR 1429 N17W66	13/03/2012 17:36:05	1884
14/03/2012 15:08:00	M2.8	AR1432 N13E05	14/03/2012 16:36:05	411
15/03/2012 07:23:00	M1.8	AR1432 N14W03	15/03/2012 09:24:05	485
–	–	–	16/03/2012 20:36:03	862
17/03/2012 20:32:00	M1.3	AR1434 S20W24	–	–
–	–	–	18/03/2012 00:24:05	1210
–	–	–	21/03/2012 07:36:05	1178

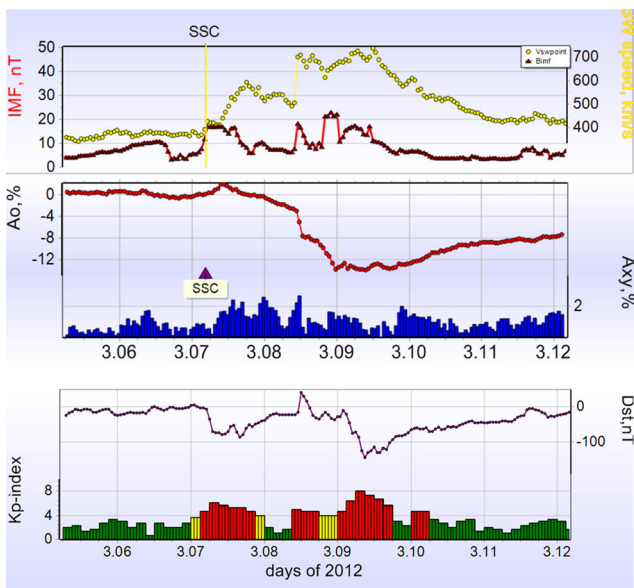


Fig. 3 The intensity of the interplanetary magnetic field and the solar wind velocity (*upper panel*), the density (A0) and anisotropy (Axy) of the CR (*mid panel*), and the Dst and Kp indices of geomagnetic activity (*lower panel*) during March 2012 are given (Sudden Shock Commencement—SSC corresponds 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 (Apacity, 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 ground-based 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 $R_{\max} = 200$ GV

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

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:

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

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:

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

Yasue et al. (1982) for neutron monitors and Fujimoto et al. (1984) for muon telescopes calculated the aforementioned coupling integral for discrete magnitudes of $R_{\max} = 30, 50, 100, 200, 500$ 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 $\Delta A_i^k = |A_i^k - \overline{A_i^k}|$ as the difference between the mean amplitude and the amplitude of the specific detector and calculated its standard deviation $\sigma_\gamma^k = \sqrt{\sum_{i=1}^n (|A_i^k - \overline{A_i^k}|)^2 / (n-1)}$ for a series of 151 values of γ . Then we demanded the standard deviation to be minimum for an acceptable γ_0^k , because the aim is the difference of the amplitudes to be minimum, i.e. $\Delta A_i^k = |A_i^k - \overline{A_i^k}|$ in order the A_i^k in the heliosphere being

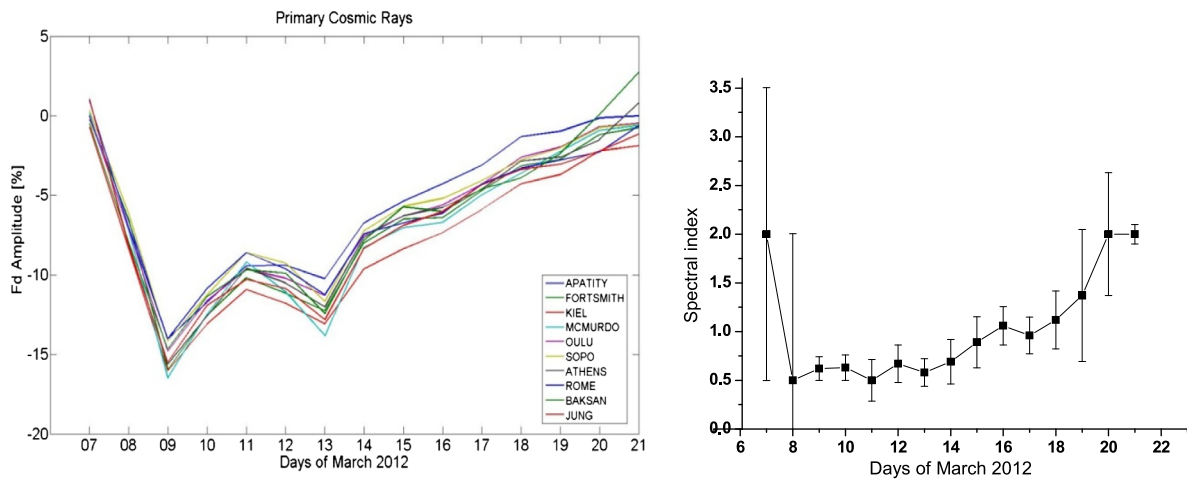


Fig. 4 The calculated variations of the GCR intensity in the heliosphere recorded at the neutron monitor stations (*left panel*) and the temporal changes of the rigidity spectrum exponent γ applied the coupling function of Clem and Dorman (2000) (*right panel*) from 7 to 21 March 2012

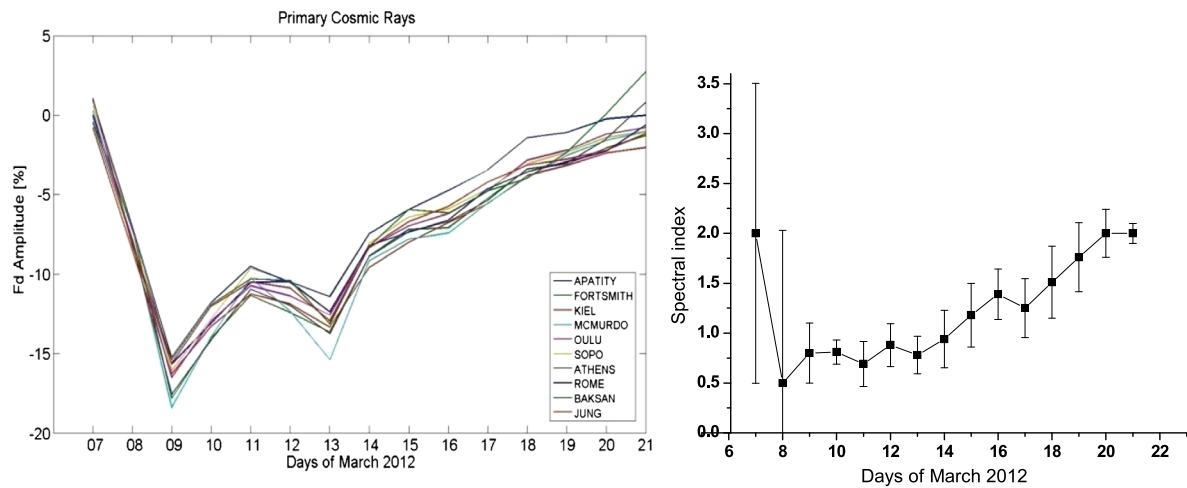


Fig. 5 The calculated variations of the GCR intensity in the heliosphere recorded at the neutron monitor stations (*left panel*) and the temporal changes of the rigidity spectrum exponent γ applied the coupling function of Belov and Struminsky (1997) (*right panel*) from 7 to 21 March 2012

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 $\sigma_{\gamma_0^\kappa}$ 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 $w_i(R_i h_i)$ 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:

$$N(R) = N(0)(1 - \exp(-\alpha R_C^{-\kappa+1})) \tag{5}$$

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

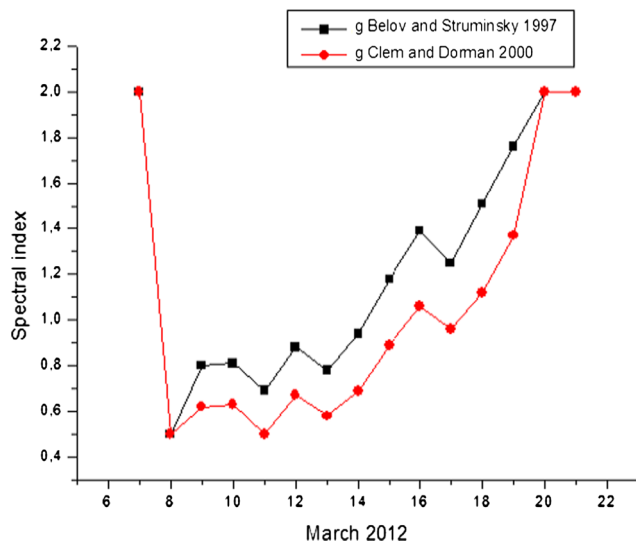


Fig. 6 A comparison of the temporal changes of the rigidity spectrum exponent γ from 7 to 21 March 2012 applied the coupling functions of Clem and Dorman (2000) (red line) and the corresponding one of Belov and Struminsky (1997) (dark line)

the total response function

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

For solar minimum activity the derived parameters are given as:

$$\ln a = 1.84 + 0.094h - 0.09 \exp(-11h), \quad (7)$$

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

and for solar maximum activity are:

$$\ln a = 1.93 + 0.15h - 0.18 \exp(-10h), \quad (8)$$

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

where h is the atmospheric depth in bars. These functions give a good representation of calculations in the rigidity range of $2 \text{ GV} < R < 50 \text{ GV}$ (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 $0.5 \text{ GeV} < E < 2 \text{ GeV}$ or $1 \text{ GV} < R < 2.78 \text{ GV}$ 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:

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

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 $R_C < 1 \text{ GV}$ 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 neutron 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 $R_C = 0.1 \text{ GV}$,

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

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

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 dur-

ing 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; Maugeard et al. 2016), independent of the spectrum of incoming particles (e.g. GCR, SEP, etc.), is intended.

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