Peculiarities in Evolutions of Cosmic Radiation Level after Sudden Decreases

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Abstract. In the analysis of sudden decreases (Forbush Decrease - FD) in the 23rd solar activity cycle we have found that a recovery back to the original level after an FD does not always have, in general, the same time evolution. In this paper we analyze cases where, within an order of magnitude ten hours, an FD is followed by a recovery back to the original level, and then the same decrease as the original one follows, but – according to the satellite data - with no apparent external cause.

Keywords: The Sun, solar cycle, cosmic radiation, Forbush decreases

Time evolution of Forbush decreases (FD)

In recent papers ([1], [2]) we analyzed the evolution of the FDs that were recorded by the Lomnický štít Neutron Monitor (NM) in Slovakia in years 1998 - 2006, and the accompanying phenomena observed by the ACE and GOES satellites. We briefly review some results of these analyses that represent a starting point for the present analysis.

Input data

The basic data set is a time series of measurements with temporal resolution of one hour recorded by the Neutron Monitor at Lomnický štít, Slovakia (49°12' N, 20°13' E) from 1998 to 2006. Any gaps in the measurements did not take longer than one day and were filled in by the data from the Oulu and Moscow stations with proper correlation correction. A total of 78,888 input data has been analyzed.

Definition of FD

Because a general definition of what FD is and what it is not is not known, for the purposes of this contribution we have made our own definition. For the whole time series we determined differences in individual consecutive measurements with the one-hour resolution, and for the onset of an FD we consider the interval where the difference is $\Delta I \leq -3000$ at average level of 152947, which represents a decrease of 1.96%. In the analyzed period, there were 60 such events. Excluding obvious errors and decreases after GLEs (Ground Level Enhancements) we are left with 37 events suitable for further analysis.

The ΔI distribution resembles a normal distribution with half-width σ = 0.3792%, and with relatively large deviations in the tails of the distribution. Following the selected criterion it is evident that for an FD we can take a decrease with a count less than the count of the normal distribution at x = 5.17 σ (see Fig. 1).

List of FDs from the Lomnický štít NM in the period 1998 –2006 and their characteristics

A subset of the results of the time evolution analysis of these 37 FDs is listed in Table 1. In the first column

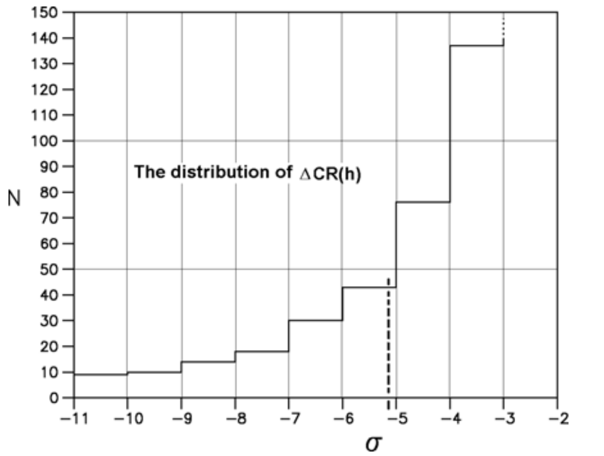

Fig.1. A subset of the distribution of the hourly differences in the NM counts during the period 1998 – 2006. The data total is 78,888. The approximation yields N = 7650 exp(-(x/0,379)2), where x is a deviation from the mean value in per cents. The actual distribution in this region is much higher than the normal distribution, for instance at σ = -3 we get N = 0.94 but actually it is 137.

there is the serial number of a FD, followed in the rest of the columns by the year, day of the year, hour (UT), magnitude of the decrease in per cents, and type of the time evolution. We have determined the type of a FD (column 6) according to the time evolution of the neutron level. We found that an FD is not always standard, as claimed by [3], i.e. a sudden decrease is not always followed by a slow recovery back to the original level. We identified this evolution as **type A.** From the 37 analyzed events 21 events have such an evolution. (Sometimes, the recovery back to the original level is rather quick, within 24 hours).13 cases were determined to be **type B.** For this type, a sudden decrease is followed by a rather rapid recovery back to the original or nearly original level, which is then followed by another sudden decrease with a slow recovery as for type A events. The time interval between the first and second decreases is between 4 to 19 h, on average it is 10.3 h. In **type C** events, there are several decreases, each followed by a recovery. In **type D**, after a sudden decrease the neutron level remains

TABLE 1. List of selected FDs from the Lomnický štít NM in the period 1998 –2006. In nine columns is consecutively: the serial number of a FD, year, day of the year, hour (UT), magnitude of the decrease in percents, type of the time evolution, heliographic longitude (+ means E) and heliographic latitude (both in degrees) of the flare which caused the observed FD, and in the last column the size of the time interval (in hours) between these phenomena.

1	1998	238	15	5.92	B+05	35	-09	40.7	20	2001	310	3	6.54	A	06	18	34.5
2	1998	268	5	6.15	B+05	18	-09	45.9	21	2001	328	19	3.28	B+07	−16	36	43.7
3	1998	312	1	2.97	A	22	18	65.4	22	2003	301	2	2.40	A	02	38	33
4	1999	23	103	2.50	B+11	−24	25	62.0	23	2003	302	3	2.46	A	−16	−08	18.0
5	1999	49	14	1.99	B+09	−23	14	58.7	24	2003	324	12	2.43	C	0	−18	52.3
6	1999	346	21	2.19	B+16	9	12	41.5	25	2004	22	3	1.98	A	−16	12	43.4
7	2000	43	1	2.14	D	−17	40	53.4	26	2004	209	4	4.46	B+10	10	31	46.2
8	2000	160	15	1.97	A	21	−13	49.4	27	2004	257	21	2.12	A	04	−42	44.2
9	2000	178	2	1.97	A	26	72	59.5	28	2004	312	23	2.06	B+13	10	−08	46.4
10	2000	197	23	2.93	A	20	73	59.0	29	2004	314	22	2.73	B+04	10	10	54.0
11	2000	198	4	2.36	B+04	22	07	41.7	30	2004	324	12	2.01	A	−14	42	22.0
12	2000	262	2	2.56	A	14	07	45.6	31	2005	17	16	2.19	C	14	08	41.1
13	2001	101	21	3.55	A	−23	09	39.6	32	2005	18	24	3.38	B+14	13	23	38.2
14	2001	197	22	2.07	A	−19	04	45.7	33	2005	21	20	3.88	A	12	58	37.2
15	2001	229	18	2.40	A	−07	56	78.0	34	2005	135	4	6.73	A	12	−51	35.6
16	2001	239	22	2.03	B+17	−17	−34	53.3	35	2005	198	18	3.99	B+19	11	90	79.3
17	2001	268	22	2.64	A	−17	−29	35.5	36	2005	254	2	7.19	A	−12	−67	29.9
18	2001	284	22	2.20	A	−28	−08	58.8	37	2006	348	20	2.05	A	−06	23	41.4
19	2001	294	20	2.23	C	16	18	67.0									

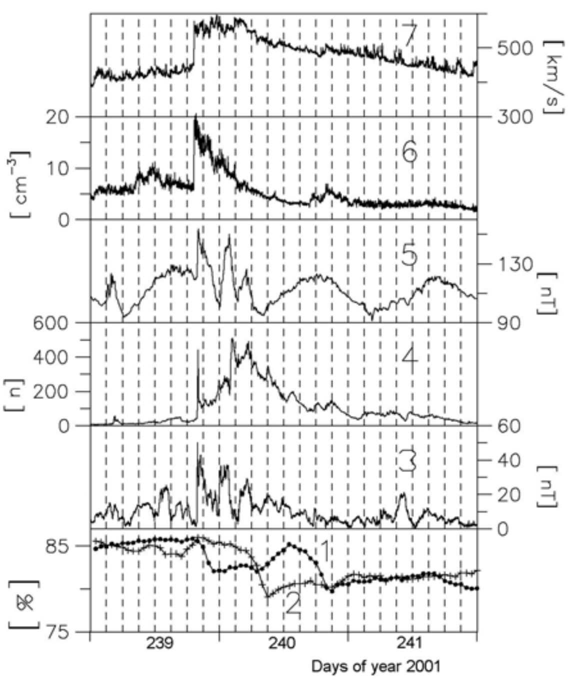

Fig.2. Time evolutions of various measurements in the vicinity of the FD from 27 August 2001 (239). 1 ~ • NM Lomnický štít, time resolution 1 hour; 2 ~ + NM Calgary; 3 ~ Geomagnetic Observatory Hurbanovo, variation contribution to the net vector of geomagnetic induction, time resolution 1 minute; 4 ~ GOES 8, protons with energy in the interval 0,8 – 4,0 MeV, time resolution five minutes; 5 ~ GOES 8, magnitude of the vector of magnetic induction; 6 ~ ACE, proton concentration, time resolution 64 seconds; 7 ~ speed of the SW, resolution 64 seconds. The time evolutions are depicted in relative scales. Comments to specific evolutions can be found in the text.

constant for some time, and then an equally sudden rapid recovery follows.

The next three columns indicate the position of the flare which caused the observed FD, and the size of the time interval between these phenomena (in particular, the heliographic distance from the central meridian (+ means E), heliographic latitude in degrees and interval in hours).

In this paper we try to analyse the evolution of the events that are denoted as type B in Table 1 and have a time period listed, in hours, during which the NM level recovers back to the original level. While the first decrease is usually related to changes in parameters of the solar wind (SW), for the following second decrease we did not find any correlation with the SW.

In his review paper [4] describes time evolution of an FD from 26 January 1968, based on the records from various stations. There it can be seen that at some stations time evolution of this FD looks like type A, and at other stations it looks like type B. We recorded a total of 13 such events. A typical example of the time evolution of an FD of type B, according to our classification, is the FD from 27 August 2001, whose time evolution, recorded at Lomnický štít, is shown in Fig. 2.

Time evolutions 7 and 6 were recorded by instruments on-board the ACE satellite. The first one, graph (7), shows the time evolution of the solar wind speed, and the second one, graph (6), shows the concentration of the protons. In both graphs the time resolution is 64s. At 19:19 UT we observe the arrival of a shock wave. We can observe sharp increases in speed from 440 to 550 $km.s^{-1}$, and in concentration from 5 to 20 cm^{-3}. Time evolutions (5) and (4) are from the GOES 8 satellite with a resolution of 1minute: (5) is a time evolution of the vector of magnetic induction, and (4) is the flux of the protons with energy from 0.8 to 4.0 MeV. Here we can see a sharp increase at 19:51 UT. No change was recorded for the protons with higher energy. The ACE satellite is in a distance $1.52x10^6$ km away from the Earth, while GOES 8 is located at the geostationary orbit 42,540 km away from the center of the Earth. From these data the speed of the impulse transmission comes out to be in the range between 750 and 790 kms^{-1}, which is inconsistent with the measured speed of the solar wind (around 550 kms^{-1}). Three minutes later, at 19:54 UT, we observe a rapid increase of 50 nT in the net vector of magnetic induction observed at the Geomagnetic Observatory in Hurbanovo (47° 52 'N, 18° 11' E), as shown in time evolution (3). The start of the FD observed at Lomnický štít, time evolution (1), with the resolution of 1 hour, was only recorded at 21:00 UT. (We got the same time using the data with the resolution of 1 minute - we have verified it also from the measurements at the APATITY station). Time evolution (2) shows the NM time evolution at the CALGARY station (51° 06 'N, 114° 06' W). There the FD became apparent only about 11h later without noticeable changes in the interplanetary medium.

Time evolution of FD from 27 August 2001 as recorded at 34 NMs

From this description of the time evolution it is clear that time evolution of an NM level can depend on daytime period, local time, and hence on the geographic longitude of the station.

To check this dependence we used measurements available from an NM network. We found a total of 130 NMs in the list. Many of them are no longer in operation and some started taking data only recently, so for each year we have data from a different number of stations. For example, for the year 2001 it is 34 stations. Stations from which we took the data for further analysis are shown in Fig. 3 where they are marked with a black square.

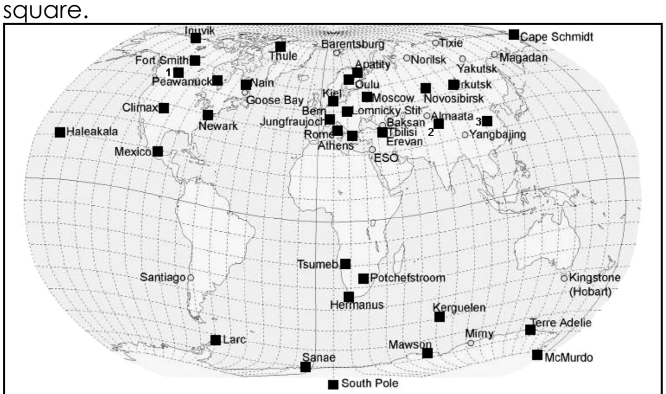

Fig.3. Neutron monitors (NM) from which we took the data for the analysis in this paper are marked with a black square. The map was down-loaded from the internet. Neutron monitors NM 1: Calgary, 2: Tibet, and 3: Beijing have been added to the map.

We depicted the time evolution of the investigated FD for each station, and from the analysis of these time evolutions we found out that the period of the level maximum in the recovery phase at an NM agrees with the period of the maximum of the daily variation.

Daily variations of the NM level at 34 stations in 2001

Daily variations are periodic changes in the NM level with amplitudes rarely reaching 0.5%. The amplitude, if it can be detected at all, varies a lot and its changes are likely related to the level of solar activity ([5]). For each station they have been defined as the difference between the 25-hour moving averages and measured (corrected) values, and then normalized to 100%. We then averaged them for the whole year excluding the disturbed days, which we defined by the difference of the extremes exceeding 0.5%.

For the average daily variation (DV) obtained in the way described above we determined at each station the amplitude and local time of the maximum positive (θM) and negative (θm) deviation. (Their magnitudes are not equal, and they are not separated by 180°.)Vypočuť

According to our preliminary results we have found out the following about the DV (Table 2):

- at polar stations the DV shows small amplitude and therefore it is problematic to estimate its phase parameters;
- at low-latitude stations the DV amplitude is larger than at mid-latitude stations, and θ_M is there close to zero;
- at low-latitude stations the DV amplitude deviates only a little from the average value;
- θ_M in general increases with increasing φ (Fig. 4); the exact form of the dependence has not been estimated.

Surveying the evolutions of FDs and DVs at the listed NMs it turned out that the recovery time in case of FD 2001/239 is equal to the time of the maximum of FD at the respective station. This is illustrated in Figure 5. At this time the DV is amplified approximately ten times. The amplification, however, does not last longer than for 24 hours. There are two effects overlapping which may cause the different profiles of NM records at different sites during the strong disturbance as illustrated in Figures 2 and 5, namely (i) the evolution of anisotropy of primary cosmic ray flux in interplanetary space and (ii) the changes of transmissivity of magnetosphere due to reconfiguration of geomagnetic field (different for using different field models as shown in paper by [6]. Both effects are important for the change of "quiet-time diurnal variation" which is thus differently seen at statiopns with different cut-offs and at different local time positions. The further analysis using geomagnetic transmissivity computations may help in understanding the process and, to some extent, to give insight on valididty of geomagnetic field models with external current systems.

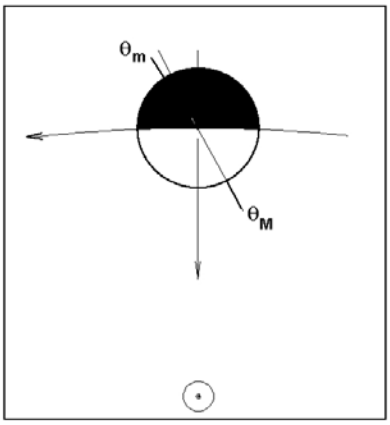

Fig.4. The NM position at the maximal and minimal values of the daily variation: in Rome it is 13,1°, at Lomnický štít 22,2°, in Moscow 25,7°, in Oulu 34,2° and at the Apatity Station 37,2°. In units of time it means that the DV maximum occurs at Apatites 1.6 h later than in Rome.

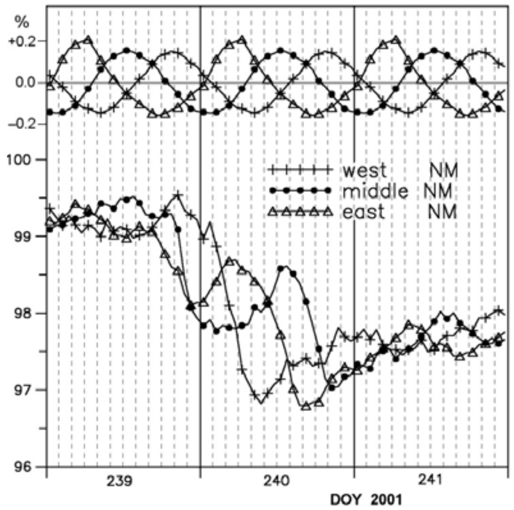

Fig.5. Time evolution of FD 2001/239 and average yearly DV at various measuring stations. For the „middle NM" evolution the average value from stations OULU and LOMNICKÝ ŠTÍT was used, for the one marked as „west NM" the average from NEWARK and PEAWANUCK was used, and finally „east NM" represents the average from IRKUTSK and BEIJING. One can see that the recovery time after a FD is equal to the maximum DV, and the DV is at the moment of its maximum amplified by about a factor of ten. The amplification, however, does not last longer than for 24 hours. (At „middle NM" and „east NM" we observe weak DV maximum, after next 24 hours).

Acknowledgements

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References

[1] Dorotovič, I., Kudela, K., Rybanský, M.: 2009, Characteristics of energetic protons during selected Forbush decrease events in the period of 1995 – 2007, poster in JENAM -European Week of Astronomy and Space Science 2009, 20-23 April, 2009, University of Hertfordshire, UK.

[2] Dorotovič, I., Pintér, T., Kudela, K., Rybanský, M.: 2009, Heavy ions in the solar wind and the cosmic radiation, poster in 2009 UN BSS & IHY Workshop, 21-25 September, 2009, Daejeon, Korea.

[3] Usoskin, I.G., Kovaltsov, G.A., Braun, I., Gladysheva, O.G., Hoerandel, J.R., Jamsen, T., Starodubtsev, S.A.: 2008, Phenomenological study of the energy dependence of Forbush decrease recovery time, CD Proceedings of the 21st ECRS, 9–12 Sep., 2008, Košice, Slovakia, Paper No. 3.07.

[4] Lockwood , J.A. : 1971, Forbush Decreases in the Cosmic Radiation, Space Science Reviews, 12, 658-715.

[5] Kudela, K., Firoz, K.A. , Langer, R., Kollár,V.: 2008, On diurnal variation of cosmic rays: statistical study of neutron monitor data including Lomnický Štít, CD Proceedings of the 21st ECRS, 9 – 12 September, 2008, Košice, Slovakia, Paper No. 4.15.

[6] Kudela, K., Bučík, R., Bobík P.: 2008, On transmissivity of low energy cosmic rays in disturbed magnetosphere, Adv. Space Res., 42, 1300-1306.

TABLE 2. Characteristics of daily variations of the NM level at 34 stations in 2001. Geographic position of the NM: geographic latitude φ and geographic longitude; M – time of the local noon of at the position of the NM [UT], θM - the NM position at the maximal values of the daily variation (DV) , θm - the NM position at the minimal values of the DV, A+ - amplitude of the DV in positive direction, A– - amplitude of the DV in negative direction.

No. and name of NM		φ	λ	M [UT]	θ_M[°]	A+	θ_m[°]	A–	$(\theta_m)-(\theta_M)$
Near-equator stations									
16 HLE1	HALEAKALA	20.7	203.7	22.42	-3.9	0.171	192.8	-0.132	196.6
10 CLMX	CLIMAX	39.4	253.8	19.08	24.8	0.147	206.9	-0.111	182.1
35 MXCO	MEXICO CITY	19.3	260.8	18.61	3.3	0.135	174.1	-0.119	170.8
52 TSMB	TSUMEB	-19.2	17.6	10.83	16.8	0.219	199.9	-0.175	183.1
7 ATHN	ATHENS	38.0	23.7	10.42	-29.3	0.126	167.1	-0.108	196.4
50 TIBT	TIBET	30.1	90.5	5.97	-60.5	0.106	133.2	-0.109	193.6
6 BJNG	BEIJIN	39.1	116.3	4.25	-6.2	0.187	170.1	-0.153	176.3
	Average				-7.8	0.156	177.7	-0.130	185.6
Mid-latitude stations									
8 CALG	CALGARY	51.1	245.9	19.61	42.3	0.112	223.5	-0.110	181.2
43 PWNK	PEAWANUCK	55.0	274.6	17.69	42.6	0.121	221.9	-0.127	179.3
39 NWRK	NEWARK	39.7	284.2	17.05	19.5	0.147	200.6	-0.135	181.1
36 NAIN	NAIN	56.5	298.3	16.11	31.0	0.113	218.6	-0.119	187.5
27 LARC	LARC King Grg	-62.2	301.0	15.93	13.9	0.145	206.7	-0.138	192.8
24 JUNG	JUNGFRAUJOCH	46.5	8.0	11.47	20.4	0.119	205.6	-0.116	185.3
26 KIEL	KIEL	54.3	10.1	11.33	21.0	0.161	208.9	-0.148	187.9
44 ROME	ROME	41.9	12.5	11.17	13.1	0.169	192.6	-0.159	179.6
18 HRMS	HERMANUS	-34.4	19.2	10.72	18.5	0.162	209.3	-0.139	190.8
28 LMKS	LOMNICKY STIT	49.2	20.2	10.65	22.2	0.123	206.9	-0.128	184.7
40 OULU	OULU	65.0	25.5	10.30	34.2	0.150	219.4	-0.142	185.3
41 PTFM	POTCHEFSTROM	-26.7	27.1	10.19	23.9	0.160	202.8	-0.137	178.9
3 APTY	APATITY	67.6	33.3	9.78	37.2	0.144	221.7	-0.133	184.5
33 MOSC	MOSCOW	55.5	37.3	9.51	25.7	0.167	212.4	-0.152	186.8
48 TBLS	TBILISI	41.7	44.8	9.01	59.1	0.118	259.5	-0.125	200.4
32 MWSN	MOWSON	-67.6	62.9	7.81	72.6	0.123	263.4	-0.113	190.8
25 KERG	KERGUELEN	49.3	70.3	7.31	56.7	0.162	246.6	-0.148	189.9
38 NVBK	NOVOSIBIRSK	54.8	83.0	6.47	27.5	0.164	225.3	-0.135	197.9
22 IRKT	IRKUTSK	52.5	104.0	5.07	20.3	0.173	212.1	-0.140	191.9
	Average				31.7	0.144	218.8	-0.134	187.2
Polar stations									
49 TERA	TERRE ADELIE	-66.7	140.0	2.67					
30 MCMD	MCMURDO	-77.8	166.7	0.89					
53 THUL	THULE	76.5	291.3	16.58					
46 SOPO	SOUTH POLE	-90.0	0.0	12.00					
45 SNAE	SANAE	-70.7	357.2	12.19					
19 INVK	INUVIK	68.3	226.3	20.91					
9 CAPS	CAPE SHMIDT	68.9	180.5	23.97					
14 FSMT	Fort SMITH	60.0	248.1	19.46					