Forbush decreases of cosmic radiation and connected space weather events

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Abstract—**Authors analyse in the paper the temporal evolution of 34 selected decreases (Forbush Decrease – FD) observed by the Neutron Monitor (NM) of the Institute of Experimental Physics SAS at Lomnický štít in the period of 1995 – 2007. Evolution of the individual FDs is supplemeted by data on the proton density and the magnetic field intensity in the interplanetary space according to measurements at the satellites WIND and ACE and by data on the magnetic field and the proton density with different energy in the Earth's magnetosphere according to measurements at the satellites GOES 8 – 11. Results of the analysis are summarized. It is shown that besides the known disturbance in the magnetic field of the Earth is the FD in the majority of events accompanied by an abrupt increase (up to 4 orders of magnitude) of the proton flux in the magnetosphere with energy of 0.4 – 4 MeV and by a contemporary decrease of the proton flux with energy of 165 – 500 MeV.**

1. INTRODUCTION

STATUS of the heliosphere – distribution of matter and its properties – can be characterized also using variations of the cosmic radiation (CR). The current monitoring of the heliosphere is based on an idea of modulation of the primary radiation level, which would be constant without this modulation. However, CR variations of different duration (from secular to periodic ones) connected with the length of the SA cycle or the length of the solar rotation (11-year and 27-day period) are observed. Moreover, 24-hour variation related to the rotation of the Earth is observed as well. These variations are connected with the manifestations of solar activity and are described in various monographies, e.g. [1]. These (more or less regular) variations are interrupted by the sporadic ones – a sudden decrease with slow recovery, FD - Forbush Decrease and an abrupt increase with immediate decrease, GLE – Ground Level Event. Both events are related to the occurrence of solar flares.

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The occurence of FDs in the period of 1995 – 2007, i.e. in the 23rd cycle of solar activity, was analyzed in this paper. The advantage of this selected period is that regular in situ observations at satellites WIND, ACE, and SOHO, which are outside of the Earth's magnetosphere, are available for this cycle. Further advantage is the fact that we can also use measurements at GOES satellites for a better description of complex evolution of the selected FDs. It is well known that FD is usually related to the occurrence of flares and subsequent transients.

In addition, a statistical study presented in this paper provides an opportunity to verify our hypothesis from [2]. According to this hypothesis, the recovery time after a FD depends on high-energy particle density in radiation belts of the Earth.

The second paragraph describes the input data and methods of processing. Results and consequent conclusions are presented in the third section.

2. DATA AND METHOD OF PROCESSING

The data from the Neutron Monitor (NM) at Lomnický štít with a resolution of 1 hour in the period of 1995 – 2007 were used as basic input for the analysis. The data from other neutron monitors, namely in Oulu, Haleakala, and at the South Pole were used as additional proof data for verification of temporal evolution of CR only in certain periods. We are aware of the fact that in some cases it is rather difficult to distinguish between FD and periodical changes and therefore we defined the following criteria for the selection process:

1) A total decrease in NM counts at Lomnický štít is at least 2% (in normalization of each year to 100%).
2) A decrease occurs at all stations.

Conditions in the heliosphere between the Earth and the Sun were determined using the data with a temporal resolution around 1 minute on proton density and magnetic field from the observatories WIND (till 1998) and ACE (since 1998).

The data on X-ray flux in the range of 0.1 – 0.8 nm were used for identifying a flare together with its importance as well as proton density at two energy levels, P1: 0.4 – 4.0 MeV and P7: 165 – 500 MeV. These data from the satellites GOES 8-11 have a temporal resolution of 5 minutes.

According to the defined criteria and using the described data we were able to select 34 events in the considered period. The temporal distribution of individual events is shown in

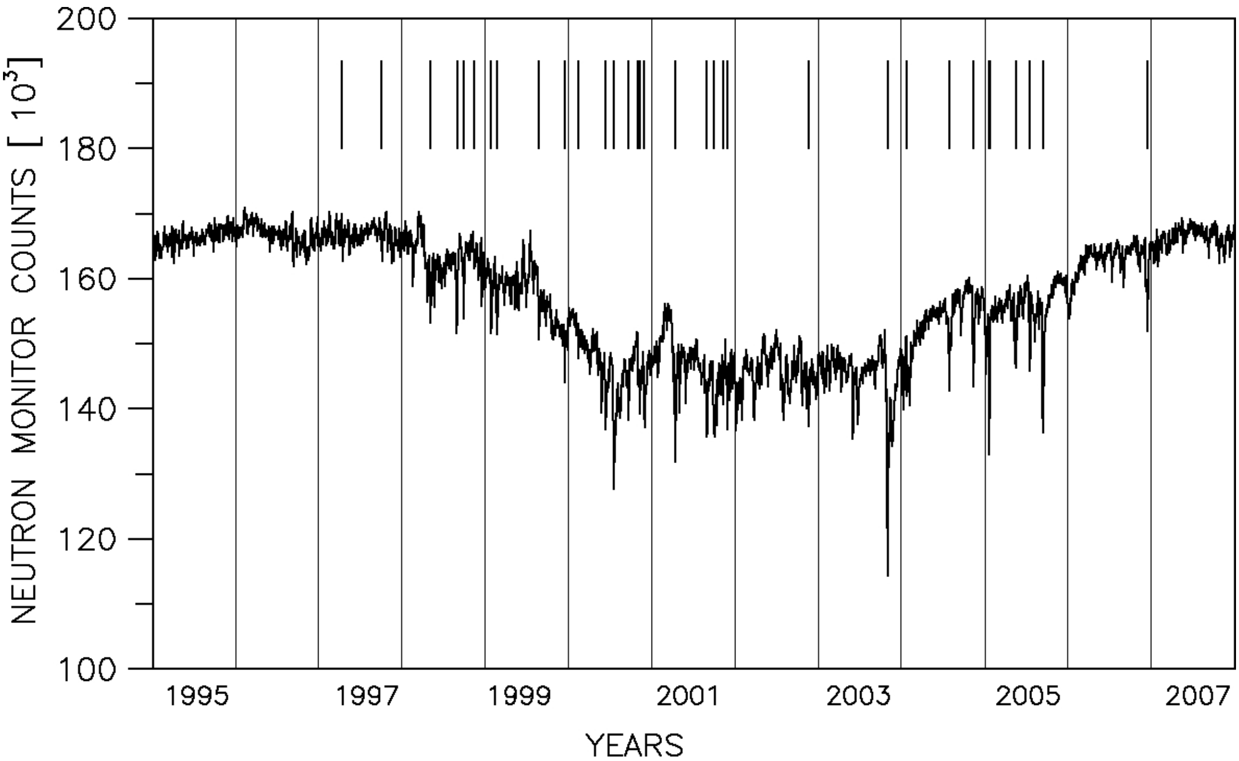

Fig. 1. Temporal evolution of cosmic radiation level from NM at Lomnický štít in the period between 1995 and 2007 together with an indication of FDs studied.

Fig. 1. It is important to note that there were no events fulfilling our criteria in the years 1995 – 1996, and 2007 (minima of the solar activity). We collected temporal evolution of all input data in a graphical form with a resolution as high as possible for each selected event and we attempted to decide:

a) whether it is possible to find a flare on the Sun associated to the given FD and what is its importance;

b) whether it is possible to identify the passage of CME around the satellites WIND and ACE;

c) what is the temporal evolution of proton counts in energetic channels P1 and P7.

Moreover, we determined time shifts between the changes in individual series. Figs. 2 and 3 show the examples of our analysis.

Data on P1 and P7 are determined in a certain period before a FD, when the temporal evolution is undistrurbed, as well as during that FD.

3. RESULTS AND CONCLUSIONS

Results of our statistical investigation are presented in the Table I.

We can summarize conclusions to the following items:

1) Only in one case out of 34 the origin of FD cannot be connected with a flare in X-ray flux. The average time between the flare and the start of FD is 41.5 hours with the limit values of 18 and 57 hours, respectively. That corresponds to the speed of shock propagation from 304 to 960 km s^{-1}.

2) The depth of decrease is maximally 7%, each year being normalized separately. The increase before the decrease of FD occurs only in 7 of 34 cases.

3) Most FDs are of type A – 14 events; type B – 10 events, type C – 8 events, D and E types – 1 event each.

4) Almost in all cases FD is related to an increase of Np and B at the WIND and ACE satellites. However, there are cases when this increase follows only after the FD. There are 7 of 34 such cases. A component of the magnetic field was used for indicatiing the disturbance from the GOES satellites; it is denoted in the original data as Hn (in the plane of orbit), because other components are relatively stable. It is sometimes difficult to indicate the disturbances because the measured magnetic field has a relatively strong daily variation.

5) The most interesting is evolution of P1 and P7 during FD. P1 during FD strongly increases, in maximum to 3 – 4 orders of magnitude higher than the quiet value, and P7 decreases. The decrease in P7 is often superimposed by a burst in this energetic range, which usually occurs immediately after the flare or is caused by a flare different from that which caused the FD studied (Fig. 2). Almost each FD is connected with an increase in P1. However, not each increase of P1 causes a FD, as can be seen in Fig. 3. There is aparently a hidden requirement which has to be revealed yet. FD is usually accompanied by an abrupt count increase in the channel P1 and by a simultaneous decrease in the channel P7, often as far as the threshold values of the instrument. This finding can be considered as the main result of the analysis of FD evolution. Then an impression arises that during FD the protons of the primary CR are absorbed on the low-energy protons indicated

in the channel P1 and simultaneously also the protons from channel P7.

6) The analysis of the temporal evolution of FD did not confirm the hypothesis from [2] on different recovery time after a FD as a function of the energy distribution of the particles penetrating into radiation belts of the Earth. There are two reasons: 1) in most cases, the recovery time cannot be determined owing to other variations occurring during the recovery period and 2) the channel P7 is either overloaded due to a previous burst or is at a threshold value.

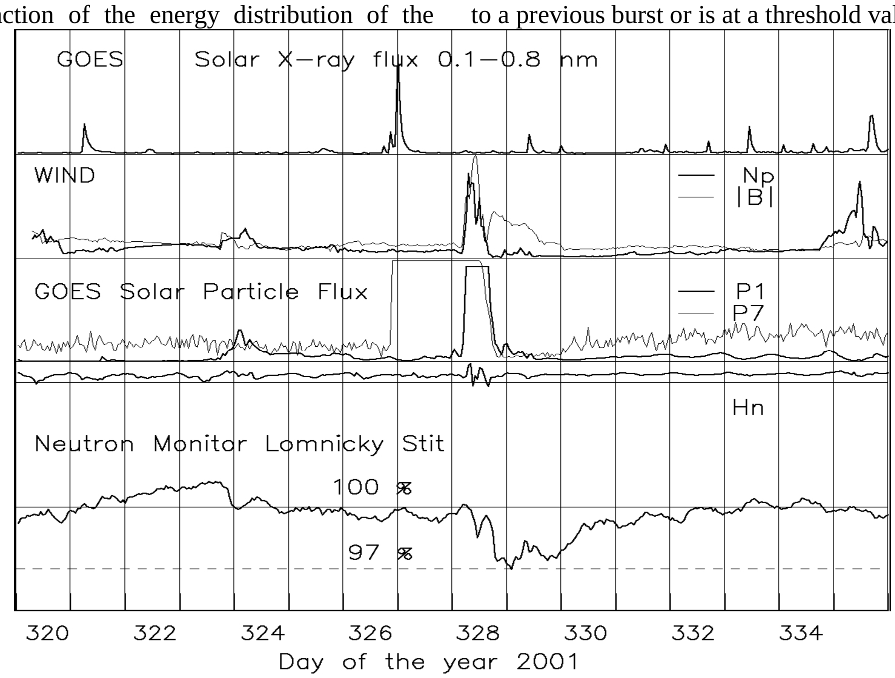

Figure 2. FD on the 328th day (24 November) in 2001: temporal evolution of NM measurements with a resolution of 1 hour (the bottom part of the y-axis), from top: GOES, solar X-ray flux (GOES), proton density Np and interplanetary magnetic field intensity │B│(ACE), proton fluxes P1, P7 and magnetic field component Hn (GOES).

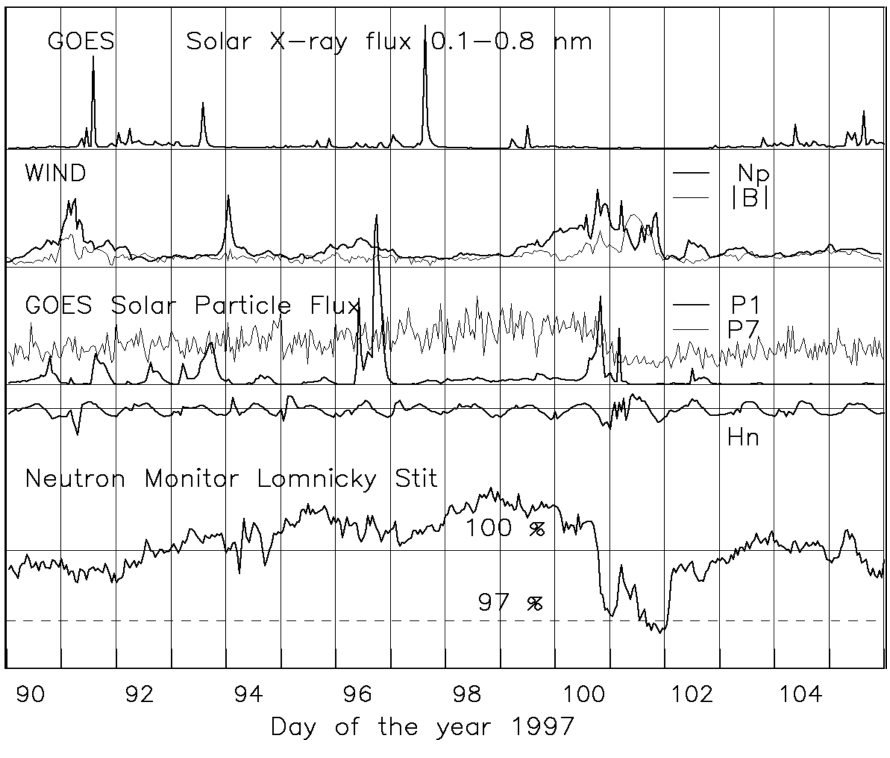

Fig. 3. FD on the 100th day (10 April) in 1997: temporal evolution of NM measurements with a resolution of 1 hour (the bottom part of the y-axis), from top: GOES, solar X-ray flux (GOES), proton density Np and interplanetary magnetic field intensity │B│(ACE), proton fluxes P1, P7 and magnetic field component Hn (GOES).

TABLE I
RESULTS OF THE ANALYSIS OF THE SELECTED EVENTS (details are in the text).

Year	DOY	UT	Type	+ΔI	–ΔI	Δtn	ΔNp/Δt	ΔB/Δt	I	Δt	Bn	P1	P7[x10^5]	Rem.
1997	100	17	C	N	4	3	+35/0	+20/0	C6.2	–75	Y+0	3 – 38	25.2 –10.4	
	273	20	C	5	5	0	?	?	N	N	Y+4	0 – 220	14.4 –11.7	
1998	121	21	B	N	3	7	+35/0	+15/0	C2.5	–50	Y+4	8 – 847	17.4 – 6.9	
	238	8	C	N	3	6	+10/0	+15/0	X1.1	–34	Y+0	29 – 5720	19.4 – 5.4	
	268	0	C	N	5	4	+10/0	+15/0	M6.9	–41	Y+0	103 – 5150	14.6 – 6.0	
	312	4	D	3	5	2	–10/0	+50/0	M8.2	–56	Y+0	7 – 646	27.8 – 9.4	
1999	22	20	C	N	5	17	+15/+18	+30/0	M5.2	–48	Y+8	22 – 195	24.7 – 8.4	
	49	11	B	2	3	3	+25/0	–15/0	M3.4	–57	Y+0	52 – 2070	12.2 – 6.4	
	231	16	A	N	2	12	+20/+80	+20/+40	Cser.	?	N	73 – 137	13.4 – 8.0	
	346	17	B	N	3	7	+20/+8	+5/–4	N	N	Y+15	66 – 27	15.2 – 7.6	
2000	43	0	E	N	2	2	+30/0	+30/0	C2.1	–30	Y+4	46 – 679	13.3 – 6.8	
	160	12	A	N	3	9	+10/0	+20/0	X1.2	–46	Y+0	14 – 5100	11.4 – 6.8	
	195	11	A	0.5	3	?	+50/0	+5/0	X1.1	–47	Y+0	6 – 1190	10.2 – 3.1	
	197	20	A	N	3	4	+30/0	+50/0	X5.6	–36	Y+0	?	?	
	261	18	C	N	2	7	+40/0	+40/0	Mser.	?	Y+0	568 – 1120	11.6 – 5.3	
	303	0	A	N	2	15	+50/–12	+25/–12	Cser.	?	Y–12	82 – 24	12.7 – 7.1	
	311	12	A	N	2	2	+40/+5	+8/–5	C5.5	–36	Y+0	3 – 1950	12.9 – 7.2	
	331	13	A	N	2	12	+50/0	+30/0	Mser.	–36	Y+0	57 – 1150	burst	
2001	101	18	A	1	4	6	+28/0	+29/5	X2.3	–36	Y–1	255 – 4565	42.8 – 2.8	+GLE
	239	19	B	N	3	7	+9/1	+13/1	X5.3	–26	N	18 – 738	18.8 – 6.9	
	268	20	A	N	3	14	+40/2	+21/1	X2.6	–34	Y+3	138 –19725	burst	
	310	1	A	1.5	3	5	+27/1	+65/1	X1.0	–31	Y+3	63 –15878	burst	
	328	5	A	1	3	4	+27/7	+50/4	M9.9	–29	Y+0	224 –29442	13.8 – 3.3	
2002	321	11	C	N	3	5	N	N	M1.2	–36	N	4 – 44	12.9 – 3.3	
2003	302	5	A	N	7	11	+21/–4	+37/10	X1.7	–18	Y+0	10 – 43742	burst	
2004	22	1	B	N	3	20	+15/2	+22/7	M6.1	–41	Y+10	21 – 2456	13.4 – 6.0	
	208	23	B	N	4.5	4	N	+21/5	M1.1	–32	Y+8	190 –10019	21.4 – 4.3	
	312	16	B	N	4.5	8	+64/-4	+43/7	M9.3	–39	Y+0	2 – 1016	13.2 – 4.7	
2005	17	12	B	0.5	6.5	8	+49/3	+31/0	X2.9	–37	Y+7	34 – 12293	burst	+GLE
	21	16	A	N	3	1	+32/2	+25/2	X7.1	–33	Y+8	194 – 10835	burst	
	135	0	B	N	3	7	+20/4	+48/6	M8.0	–31	Y+10	145 – 23842	14.0 – 4.4	
	197	18	C	N	3	3	+13/-2	+10/9	X1.2	–55	Y–1	46 – 124	22.9 – 5.2	
	254	0	B	N	5	11	+13/7	+13/1	X3.6	–38	N	16 – 9680	18.6 – 4.6	
2006	348	16	A	N	3.5	3	+10/5	+14/8	X3.6	–37	Y+5	568 – 52008	18.3 – 6.2	

Legend:
DOY – the day of the year;
UT – the start time of a decrease;
Type of FD – selected according to the shape of the evolution:
A – is a classical evolution, i.e. an abrupt decrease and a slow uniform recovery;
B – non uniform recovery, interrupted by an increase and a decrease;
C – denotes the decrease and increase on the same day followed by a second slower decrease and a gradual recovery to the initial level;
D – has a similar evolution as B, but the interval between the first decrease and increase is longer;
E – is a decrease to a certain level, then a longer persistent period followed by an abrupt incerase to the initial level.
+ΔI – an increase in % that precedes the decrease (if occurs);
–ΔI – the magnitude of the decrease in %;
The data from WIND/ACE:
ΔNp/Δt – a change of the proton density Np [cm^{-3}] together with time in hours between the start of FD and the corresponding change;
ΔB/Δt – a change of the magnetic field B [nT] together with time in hours between the start of FD and the corresponding change;
The data from GOES:
I – the importance of a flare estimated from 5-minute measurements;
Δt – time in hours between the occurence of a flare and the corresponding start of FD;
Bn – for the magnetic field we determine only whether a change occurs: yes (Y) or no (N) and with which time shift in hours;
P1 and P7 – these data are estimated at certain time before FD when the temporal evolution is undistrubed and during FD;
Rem. – remarks.

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