Ground level enhancements of the solar cosmic rays and Forbush decreases in 23rd solar cycle

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***Abstract*. The outstanding effects of 23rd cycle of solar activity, such as ground level enhancements of solar cosmic rays and the largest Forbush decreases, are investigated. The analysis shows that both GLEs and great Forbush effects are connected with anomalously fast ejections of solar matter with similar properties. The main difference between those is in the heliolongitude: the sources of the greatest Forbush effects (FE) are usually located in the central part of visible solar disk whereas flares associated with GLEs are mostly in the western part of disk. It is shown that accelerative and modulative efficiencies of the solar events are tightly correlated. Coronal mass ejection followed by GLE creates with a high probability a very large FE in the Earth orbit.**

***Keywords*: solar cosmic rays, Forbush decrease, coronal mass ejections (CMEs)**

I. INTRODUCTION

There was no big sunspot numbers in the 23-rd solar activity cycle, but there were a lot of other manifestations of solar activity, in particular, in the ground level cosmic ray (CR) observations. 16 ground level solar cosmic ray enhancements (GLEs) were recorded in 23-rd cycle, and it is more than in any other preceding solar cycle (eg. [1]). They extended by the time with more than 9 years in this unusually long cycle, from November 1997 to December 2006. For comparing, all 15 GLEs in the 22-nd cycle occured during the four years - from July 1989 to June 1992. The last solar cycle turned out to be rich also on Forbush effects (FEs) of galactic cosmic rays. The number of large FEs in the cycle 23 exceeded that occurred in the earlier cycles [2]. Among these events was FE of unusual magnitude observed in the end of October 2003. Just ended cycle brought an extensive material for studying both GLEs and Forbush effects and for comparing of different kind events as well. The GLEs and FEs both are members of powerful sporadic solar events, are observable after the power solar flares and tightly connected to a big coronal mass ejections (CMEs). These phenomena should be related to each other. The aim of the presented work is to study the greatest CR variations: both of solar (GLEs) and galactic (FEs) cosmic rays and their connection in the solar cycle 23.

II. DATA AND METHODS

To investigate GLEs and FEs the two created in IZMIRAN databases were combined in use: 1) database on x-ray flares and proton events [3], comprising x-ray measurements onboard of GOES satellites, observations of solar CR at Earth and on the IMP-8 and GOES satellites; 2) database of interplanetary disturbances and Forbush effects [2]. In the last database the cosmic rays are presented as results of the global survey method for the CR of rigidity 10 GV, and data on the solar wind are taken mostly from the OMNI database [4]. Except of the own databases the information collected in the CDAW database [5] has been used. It is worthy to note that in the study and observations of FE associated with GLE there are specific objective difficulties. The GLEs are observed as a part of the solar activity bursts and, as a rule, in disturbed conditions. In this period and often simultaneously with GLE, the large variations in galactic CR are recorded, so it is hard to separate the effects in solar and galactic CR. If it is added also strong geomagnetic storm, as it was, for example, in October 29, 2003, the separation of the effects turns to be very complicated.

III. DISCUSSION OF RESULTS

In Table 1 the information about all 16 GLEs of the last solar cycle is presented (maximum increase of the neutron monitor counting rate is in the last column). For each event the onset time for associated flare (yy.mm.dd,hh:mm), its x-ray/optical importance and coordinates are entered. Herewith the information about associated CMEs is given: type (h - halo, ph - partial halo) and initial velocity V_i [6,7]. To these data we added a magnitude of the FE (for the CR of 10 GV rigidity) which was, supposedly, caused by the same CME.

We see a wide range of sizes of FEs, associated with the GLEs in Table 1,- from lowest (<1%) magnitude up to the biggest of known FEs (28% on October 29, 2003). Let's consider the disturbed periods in October-November, 2003 (Fig.1) and in April, 2001 (Fig.2), included 5 GLEs and FEs of different magnitudes. These events show the big variety of Forbush effects at certain similarity of associated GLEs and CMEs. In these examples CMEs, connected with GLE and originated in the central zone, create very big Forbush effects. For similar CME in the western zone FE magnitudes

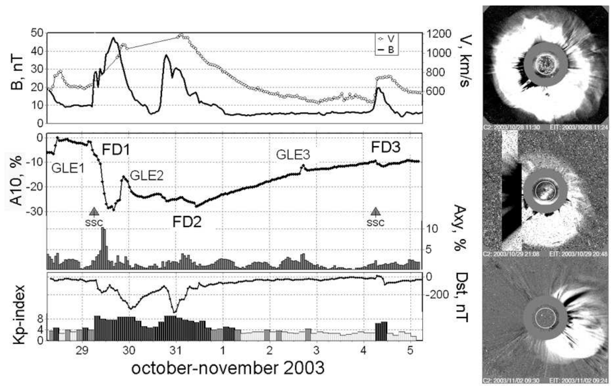

Fig. 1: Behaviour of a solar wind speed V and interplanetary magnetic field intensity B; variations A10 of CR (10 GV) density and equatorial component of the 1st harmonic Axy of CR anisotropy; Kp and Dst-indexes of geomagnetic activity from October 28 till November 5, 2003. CMEs, connected with GLEs, are shown in the right part of figure (SOHO/LASCO data)

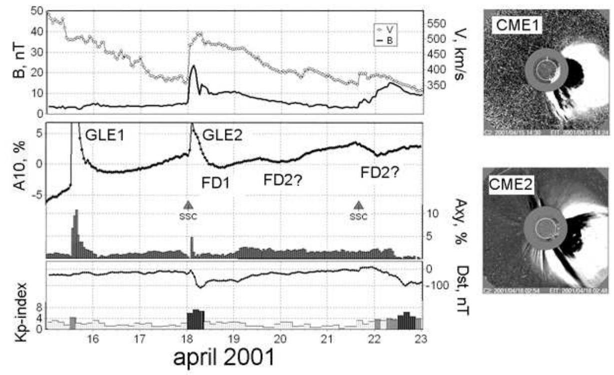

Fig. 2: The same that in Fig. 1 for the April 15-22, 2001

are much smaller, but greater, nevertheless, than it was possible to expect from such far sources. The events followed by GLEs and combined into Table 1 may be considered as the most powerful from the solar particle events. For comparing we selected the same number (16) of the greatest FEs in the cycle 23 (Table 2). In Table 2 the following parameters are presented: day and onset time of the FEs (yyyy.mm.dd.h:mm), x-ray/optical importance and coordinates of associated flare, type and initial speed [S] of the associated CME, mean velocity of the interplanetary disturbance between Sun and Earth, maximum speed in the interplanetary disturbance near the Earth, maximum intensity of the IMF, maximum Kp-index in the associated geomagnetic storm, magnitude of the Forbush decrease (in %), magnitude of the proton flux enhancement for the energies >100 MeV, related to the same solar events.

Both groups, each of 16 events, mainly combine very powerful flares. Scatter of X-ray fluxes for the flares associated with large FEs is much wider than for the

TABLE I: Ground Level Enhancements of 23-rd solar cycle

X-ray flare onset	Flare import., location	CME type,V_i	FD, %	GLE, %
97.11.06 11:49	X9.4/2B,S18W63	h,1726	<1.9	19
98.05.02 13:31	X1.1/3B,S15W15	h,1332	3.5	7
98.05.06 07:58	X2.7/1N,S11W65	ph,1208	0.7	>4
98.08.24 21:50	X1.0/3B,N35E09	-	7.2	>4
00.07.14 10:03	X5.7/3B,N22W07	h,1741	11.4	59
01.04.15 13:19	X14/2B,S20W85	ph,1203	2.2	237
01.04.18 02:11	C2.2/,S20W115	h,2712	<2.2	26
01.11.04 16:03	X1.0/3B,N06W18	h,1846	12.4	8
01.12.26 04:32	M7.1/1B,N08W54	ph,1779	2.2	13
02.08.24 00:49	X3.1/1F,S02W81	h,1937	1.6	14
03.10.28 09:51	X17/4B,S16E08	h,2754	28	47
03.10.29 20:37	X10/2B,S15W02	h,2049	4.7	35
03.11.02 17:03	X8.3/2B,S14W56	h,2981	2.6	39
05.01.17 06:59	X3.8/3B,N15W25	h,2802	11.8	3.5
05.01.20 06:36	X7.1/2B,N14W61	h,3675	9.0	5400
06.12.13 02:14	X3.4/4B,S06W23	h,2164	8.6	92

GLE flares, but within this set the majority of flares have also an importance >X1. The main distinguish of these two sets (GLE-flares and FE-flares) is in heliolongitude distribution of associated flares (Fig.3). FE-flares are distributed almost symmetrically relatively the central meridian within E67 - W61 region and have an average longitude (4±8)°. Heliolongitudinal distribution of GLE-flares has approximately the same width but shifted strongly to the west. It includes flares with the longitudes from E09 to W115 - and their mean longitude is (41±9)°. Obtained for cycle 23 distributions are well agreed with well known distributions of solar sources of GLEs [8,9] and large FEs [10].

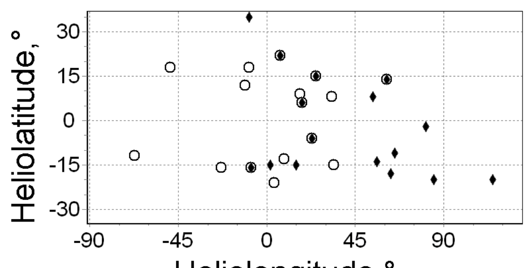

Fig. 3: Coordinates of the 23-rd solar cycle flares associated with GLEs (black rombus) and with the greatest FEs (open circles)

One can see from Fig.3 that half of a number of GLE flares are located to the west of W40, and only one flare associated with the greatest FE is located there. The opposite situation is with the eastern flares: there are mostly FE-flares to the east from the central meridian and only two of GLE-flares, the most central from eastern ones. Data on the last solar cycle allow to state (and this is confirmed by a wider statistics), that the sources from eastern zone are almost not effective in the creation of GLEs, whereas the sources from western region are not effective in the FE creation. For a comparative analysis of the modulating and accelerating

TABLE II: The largest Forbush effects of 23-rd solar cycle

FE onset	flare	CME type & speed, km/s	V_t,km/s	V_{max},km/s	B_{max},nT	Kp	FD,%	P_{100},pfu
1998.09.24 23:45	M7.1/3B N18E09	-	1014	839	28.7	8+	9.2	0.1
2000.07.13 9:42	M5.7/2B N18E49	phalo 1352	687	667	24.6	7	9.0	0
2000.07.15 14:37	X5.7/3B N22W07	halo 1674	1459	1107	51.9	9	11.7	620
2001.04.11 13:43	M7.9/2B S21W04	halo 1192	898	833	34.5	8+	12.8	0.5
2001.09.25 20:25	X2.6/2B S16E23	halo 2402	1194	677	24.6	7+	8.3	20
2001.11.06 1:52	X1.0/3B N06W18	halo 1810	1232	729	65.6	9-	12.4	220
2001.11.24 5:56	M9.9/3B S15W24	halo 1443	1437	1040	56.9	8+	9.2	4
2003.10.29 6:11	X17/4B S16E08	halo 1810	2049	1986	47.5	9	28.0	190
2004.01.22 1:37	C5.5/ S13W09	halo 965	808	666	25.4	7	8.6	13
2004.07.26 22:49	M1.1/1F N08W33	halo 1913	1282	1002	26.1	9-	13.5	0.1
2004.11.09 19:00	X2.0/ N09W17	halo 2459	812	809	40.7	9-	8.3	0.5
2005.01.18 6:00	X3.8/3B N15W25	halo 2094	1810	997	21.8	8-	11.8	28
2005.01.21 18:11	X7.1/2B N14W61	halo 3675	1171	950	29.5	8	9.0	650
2005.05.15 2:38	M8.0/2B N12E11	halo 1689	1211	959	54.2	8+	9.5	0.15
2005.09.11 1:14	X6.2/ N12E67	halo 2257	1388	1059	18.2	8-	12.1	0
2006.12.14 14:14	X3.4/4B S06W23	halo 1774	1157	896	17.9	8+	8.6	89

efficiencies the events in central zone are suitable most of all. Considering this we compare the FEs and relevant phenomena which were related to GLEs (GLE-set) with events, not related to GLEs (noGLE-set), but associated with flares of approximately the same power and within the same longitudinal zone from E10 to W30 (Table 3). The averaged X-ray importance was $(5.0\pm1.8)10^{-4}$ Wt/m2 for GLE-set (flares from X1.0 to X17.2), and (4.4 ± 0.9) 10^{-4} Wt/m2 for the control (noGLE) set (flares from X2.5 to X10.1). In the control set we did not limit the time by 23-rd cycle only, because the last cycle had only two fitted flares.

Mean values of the FEs in two sets differ more than three times. Since in the GLE-set the greatest over a history FE is presented and range of the A_F (from 2.1 to 28%) exceeds an order, one can have a doubt in the rightness of using of the mean value in this case. But at comparison of median values of A_F (10.2 and 2.4% correspondingly) shows even more difference. In GLE-set all the FEs have magnitude exceeded the median A_F of the control (noGLE) set. In the opposite side, in the noGLE-set all the 11 events are significantly less than median AF from GLE-set. It is worthy to notice that 3 largest FEs (>5%) from noGLE-set are related to the great enhancements of high energy (>100 MeV) solar protons. For example, after the X2.5/3B (S08W25) flare on October 30, 1991, the flux of such protons reached 7.3 pfu. The transit speed V_t in these three events was the highest - >1000 km/s. The events from noGLE-set characterized by the small magnitude of the FE and relatively low V_t, in majority, did not include the enhancements of high energy particle fluxes at all. Thus, if to say about FE magnitude, two considered sets are almost not overlapped. This means close connection between the highest energy solar particle events and the greatest FEs. One can suppose that this connection is not only statistical, but the physical also. If any complex of solar sporadic phenomena possess special accelerating properties it should be shown strongly in the CR modulation. Large distinguishes are seen also in the geomagnetic activity in these two sets. For GLE-group Ap-index of geomagnetic activity increased in average up to 303 ± 32, and in noGLE-set - only to 93 ± 18. In a noGLE-set maximum Kp-index varied from 4_+ to 8_0 and the most part of FEs is associated with minor or moderate magnetic storms. Only two storms turned out to be severe, and two - strong. In one case even the level of a minor storm was not reached. However, all 8 magnetic storms connected with GLE events were extreme or severe with maximum Kp-index of 8_- - 9_0. These statistical data allow us to consider the GLE observations in combination with a flare in the central portion of solar disk as an important prognostic factor for prediction of the most powerful geomagnetic storm. If the GLE events in the cycle 23 are typical then ground level observation of solar CR related to flare to the east of W30, must predict as minimum severe geomagnetic storm (with Kp-index 8_- or more), which will be start in the first 36 hours after flare. The mean time of delay is 27.4 ± 2.4 hours, mean decrease of Dst-index is down to -253 ± 36 nT.

TABLE III: The events with and without GLE

	GLE	No GLE
Number	8	11
V_t, km/s	1574 ± 135	767 ± 88
V_{max}, km/s	943 ± 62	623 ± 66
B_{max}, nT	37.6 ± 6.1	19.9 ± 3.7
Kp_{max}	8.5 ± 0.2	6.00 ± 0.40
Dst_{min}, nT	-253 ± 36	-86 ± 14
A_F, %	11.0 ± 2.7	3.28 ± 0.71
A_{xy}, %	4.52 ± 0.90	1.78 ± 0.24

High efficiency of the related to GLE events in the creation of FEs and geomagnetic storms supposes essentially powerful interplanetary disturbances arriving to Earth. Maximum speed of the solar wind in these disturbances varies from 729 to 1986 km/s and in average equal to 1162 ± 176 km/s. Maximum IMF intensity varied from 17.9 nT to 65.6 nT (mean value is 37.6 ± 6.1 nT). In the control group mean solar wind velocity was $Vmax=623\pm66$ km/s, and mean IMF intensity - $B_{max}=19.9\pm3.7$ nT. At least partially, strong

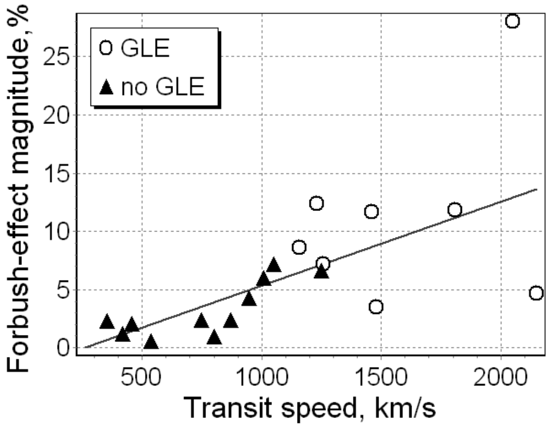

Fig. 4: Dependence of FE magnitudes A_F on transit speed of interplanetary disturbances for events, related and not related to GLEs and associated with powerful X-ray flares in E10-W30 heliolongitude range

disturbance of the solar wind in the events associated with GLEs is explained by high speed of corresponding CMEs. Gopalswami *et al.* [7,8] noted very high speed of CMEs for GLE events in 23-rd solar cycle (≈2000 km/s). Mean velocity of propagation between Sun and Earth (transit speed V_t) of the interplanetary disturbances caused by CMEs from the central zone and connected with GLE is exclusively high 1574±135 km/s. Even the minimum transit speed in this group is also very high (1157 km/s). In the control group the mean transit velocity is V_t=767±88 km/s, i.e. twice lower.

IV. Conclusion

CME associated with GLE creates, as a rule, very large Forbush effect. Central CMEs associated with the GLEs are so geoeffective, that their appearance is used for a prediction very large (usually >7 % for 10 GV rigidity) Forbush decrease and strong or severe magnetic storm (with Kp-index of 8 or 9). CME outcoming from the western part of the Sun and associated with GLEs as a rule are not connected with large variations of the galactic CR density near the Earth, but they, nevertheless, create large FEs. Simply, in these cases at Earth we observe only a periphery part of the FE, in which the CR decrease is not big, and the main part of a decrease (sometimes of very large) goes to the west of Earth. Thus, the accelerating and modulating ability of sporadic solar events are tightly interrelated. If any CME is connected with solar acceleration of charged particles up to energies GeV/n this CME creates a large FE in the Earth orbit. The high geoefficiency of such CMEs seems to be caused in the first turn by their abnormally high velocity. In these events the initial speed of the CME near the Sun as well as velocity of a disturbance propagation from Sun to Earth and solar wind speed inside the interplanetary disturbances are also very high [6,7]. High efficiency of anomalously fast CMEs may be easy explained if attribute an acceleration up to relativistic and ultra relativistic energies to interplanetary shock directly (eg. [11,12]). In such accelerating process the CME velocity directly influences a number of accelerated particles and their maximal energy. On the other hand, the higher CME velocity the faster expands the interplanetary disturbance and larger decreases of background cosmic ray density (eg. [13]). Thus, we observe a physical connection between accelerating and modulating abilities in one solar event. However, another explanation is possible, where obtained relation has rather statistical than physical nature and caused by those that in sporadic solar event the energy release is proportionally distributed between a CME creation and acceleration of the charged particles (eg. [14]).

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