GLEs in the last three solar cycles

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***Abstract*. The catalogue of ground level enhancements (GLE) of solar cosmic rays (CR) over the 21-23 solar activity cycles is presented in this report. The main properties and time distribution of these events are studied and their connection to solar sources and proton enhancements observed by satellites is analyzed.**
***Keywords*: solar cosmic rays, groundlevel, flares**

I. Introduction

Making a small part (<5 %) from total of solar energetic proton events, ground level enhancements (GLEs) involve, nevertheless, a considerable share of attention. The study of accelerated solar particles during two first decades was based only on the data from ground level cosmic ray detectors. Since solar cycle 19 the main part of data on the GLE observation is provided by neutron monitors (NM). The greatest CR variations in these data occur directly during the GLEs, sometimes they exceed by orders the largest Forbush decreases or 11-year modulation effect. Majority of the works devoted GLE is an analysis of separate (usually big) events. The works with a generalization or comparative analysis of many events are more rare. The aim of this work is to generalize ground level observations of the solar CR over three last solar cycles in the catalogue of GLEs, which will supplement the previous information [1-7]. The special attention in this catalogue is given to the solar event characteristics and their relation to GLEs.

II. Data

We used database of X-Ray flares and proton events [8], combining mostly the GOES observations. The first ground level enhancement in this database observed on April 30, 1976 relates to the 20-th cycle by the time and connection with active region. But it was ahead of minimum in the smoothed number of sunspots only on two months. The last event in the catalogue (December 13, 2006) was the last GLE in the 23-rd cycle. So, we considered the events over the full three solar cycles that includes 44 GLEs - almost 2/3 of all recorded events of such a kind (Fig.1).
Because of closing South Pole station the world wide network became less effective to revealing of the solar proton events. If, for example, such an event as GLE of January 17 occurs at the nearest time, it will not be recorded at Earth. This example shows that even the catalogue of such great and rare events as GLEs can contain the occasional elements, although it concerns only the weakest of included events. The characteristics of GLEs, proton events, associated solar flares and active regions (USAF number, maximum area) are presented in Table 1.

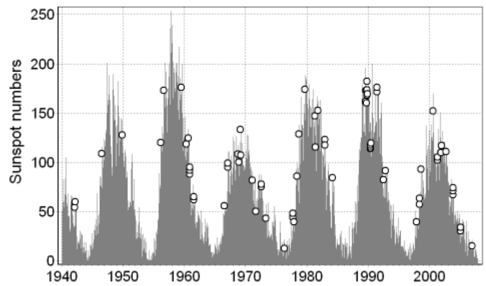

Fig. 1: Sunspot numbers and GLEs during 1942-2008

III. Time distribution of GLEs

Time distribution of the GLEs (Fig.1) is complicated, in many respects occasional and it changes from cycle to cycle. Ground level enhancements occur in all the phases of solar activity cycle [3], including minimum, but in the minimum they are rarer than in the other periods. The longest breaks in the GLE observation fall on directly on the minimum of solar activity: 5 years and 4 days in 1992-1007, and 5.5 years from February 16 1984 to August 16 1989. For a comparison, the shortest period between individual GLEs (about 35 hours) was in the recent October 2003. It is well seen in Fig.1 that the GLEs occur in the periods of short time local maxima of the sunspot numbers, since the GLEs are a kind of manifestation of the large bursts of solar activity which is directly connected with sunspot number. Amount of GLEs varies very slightly from cycle to cycle. Within 19-23 cycles there were recorded consequently 10, 13, 12, 15 and 16 GLEs. One can think that a number of GLEs increases with the time, since the smallest number occurred in the earliest cycle and the biggest one - in the latest. However, the possibilities to observe the weak GLEs in 23-rd cycle were significantly better than in the cycle 19. So, for several studied cycles we can surely say about weak variation of GLE numbers from cycle to cycle. There is a similarity in the annual variations of a number of powerful ($\leq$ X1) X-Ray flares N_X and ground level enhancements N_G. Indeed, the year 1989 with a record number of flares $\leq$X1 (59) turned out to

TABLE I: Ground level enhancements of solar CR during 1976-2006.

N	Date	Solar x-ray flare			Active region		Max. NM enhancement			Max. proton flux, pfu	
		Importance	Onset and max. time	Location	Num.	Max. area	%	time	station	>10 MeV	>100 MeV
27	1976.04.30	X2.0/2B	20:48-21:08	S09W47	700	250	4	22:00-22:05	OULU	170	52
28	1977.09.19	X2.0/3B	10:28-10:38	N08W58	889	1100	3	11:50-11:55	OULU	200	1.7
29	1977.09.24	/	?-5:55[1]	N10W116	889	1100	11	08:00-09:00	SOPO	81	22
30	1977.11.22	X1.0/2N	10:26-?:?	N24W38	939	440	55	10:42-10:48	SOPO	300	73
31	1978.05.07	X2.0/2B	03:33-?:?	N22W68	1095	1150	214	03:40-03:45	KERG	213	42
32	1978.09.23	X1.0/3B	9:47-10:29	N35W50	1294	1120	13	11:00-12:00	SOPO	2250	48
33	1979.08.21	C6.0/1B	06:11-06:13	N15W38	1926	90	9	06:30-06:35	GSBY	274	19
34	1981.04.10	X2.5/3B	16:32-17:03	N07W35	3025	310	2	18:05-18:10	ALRT	55	7.5
35	1981.05.10	M1.3/2B	07:12-07:31	N03W75	3079	470	3	08:30-08:35	CALG	180	13.5
36	1981.10.12	X3.1/3B	06:22-06:36	S18E30	3390	1630	18	09:10-09:12	SOPO	590[2]	26
37	1982.11.26	X4.5/2B	02:30-02:37	S11W87	3994	1680	6	04:00-05:00	SOPO	161	7.8[2]
38	1982.12.07	X2.8/1B	00:00-00:05	S19W82	4007	780	56	04:00-05:00	KERG	900	56
39	1984.02.16	C2.3/	07:36-07:43	S16W94	4408	300	212	09:12-09:14	SOPO	165[2]	75
40	1989.07.25	X2.6/2N	08:39-08:43	N25W84	5603	180	8	09:38-09:40	SOPO	30	7
41	1989.08.16	X20/2N	01:08-01:17	S18W84	5629	1250	24	02:52-02:54	SOPO	1500	84
42	1989.09.29	X9.8/	10:47-11:33	S26W100	5698	1180	404	12:55-13:00	CALG	4500	560
43	1989.10.19	X13/4B	12:29-12:45	S27E10	5747	1100	92	16:22-16:24	SOPO	2360	400
44	1989.10.22	X2.9/2B	17:08-17:57	S27W31	5747	1100	193	18:06-18:08	MCMD	4450	380
45	1989.10.24	X5.7/3B	17:36-18:31	S30W57	5747	1100	162	19:58-20:00	SOPO	5000	270
46	1989.11.15	X3.2/3B	06:38-07:05	N11W26	5786	510	12	07:10-07:15	TERA	72	11
47	1990.05.21	X5.5/2B	22:12-22:17	N35W36	6063	790	24	22:46-22:48	THUL	276	31
48	1990.05.24	X9.3/1B	20:46-20:49	N33W78	6063	790	52	21:14-21:15	MTWL	96	19
49	1990.05.26	X1.4/	20:45-20:58	N33W104	6063	790	13	00:38-00:40	SOPO	68	20
50	1990.05.28	C9.7/	05:15-05:21	N33W120	6063	790	6	10:30-10:32	SOPO	29[2]	5.3
51	1991.06.11	X12/3B	02:09-02:29	N31W17	6659	2200	12	04:12-04:14	SOPO	2300[2]	95[2]
52	1991.06.15	X12/3B	08:08-08:31	N33W69	6659	2200	42	10:00-10:02	SOPO	950	116
53	1992.06.25	X3.9/2B	19:47-20:11	N09W67	7205	1080	7	20:50-20:55	TXBY	255	15[2]
54	1992.11.02	X9.0/	02:31-03:08	S25W100	7321	1580	6.5	05:30-05:32	SOPO	630[2]	150
55	1997.11.06	X9.4/2B	11:49-11:55	S18W63	8100	890	19	13:34-13:36	SOPO	380	78
56	1998.05.02	X1.1/3B	13:31-13:42	S15W15	8210	450	7	14:05-14:10	OULU	150	9.2
57	1998.05.06	X2.7/1N	07:58-08:09	S11W65	8210	450	4[2]	09:30-09:35	OULU	210	5.4
58	1998.08.24	X1.0/3B	21:50-22:12	N35E09	8307	500	4[2]	23:30-23:35	CAPS	200	5.1
59	2000.07.14	X5.7/3B	10:03-10:24	N22W07	9077	1000	59	11:52-11:53	SOPO	8400	623
60	2001.04.15	X14/2B	13:19-13:50	S20W85	9415	830	237	14:34-14:35	SOPO	950	250
61	2001.04.18	C2.2/	02:11-02:14	S20W115	9415	830	26	03:34-03:35	SOPO	320	23
62	2001.11.04	X1.0/3B	16:03-16:20	N06W18	9684	510	8	18:06-18:07	SOPO	31700	220
63	2001.12.26	M7.1/1B	04:32-05:40	N08W54	9742	1060	13	06:20-06:21	SOPO	800	50
64	2002.08.24	X3.1/1F	00:49-01:12	S02W81	10069	1960	14	01:51-01:52	SOPO	220	27
65	2003.10.28	X17/4B	09:51-11:10	S16E08	10486	2370	47	11:52-11:53	MCMD	29500	186
66	2003.10.29	X10/2B	20:37-20:49	S15W02	10486	2370	35	21:30-21:31	SOPO	2300	107
67	2003.11.02	X8.3/2B	17:03-17:25	S14W56	10486	2370	39	17:51-17:52	SOPO	1560	49
68	2005.01.17	X3.8/3B	06:59-09:52	N15W25	10720	1610	3.5	11:29-11:30	SOPO	4900	28
69	2005.01.20	X7.1/2B	06:36-07:01	N14W61	10720	1610	5400	06:53-06:54	SOPO	1800	650
70	2006.12.13	X3.4/4B	02:14-02:40	S06W23	10730	680	92	03:05-03:10	OULU	700	89

be a record by a number of GLEs - 7. From the other side, during 9 years when the number of flares ≤X1 was observed less than 3, no one GLE was recorded. The linear regression may describe a relation between discussed numbers: N_G=0.34+0.073N_X (correlation coefficient is 0.69). It may be used for an estimation of the flare number in the former years. For example, in 20-th solar cycle there was no regular X-Ray observations, but a number of flares ≤X1 in 1966-1976 may be estimated as 140±30.

IV. RELATION GLEs TO SATELLITE SEPs

If consider those events when solar CR were recorded both by ground and satellite detectors (IMP8 and GOES) the correlation between proton flux J_{100} (>100 MeV) and maximum of ground level enhancement Δ_{max} is sufficiently good (Fig.2) and corresponds to power law $J_{100} = b\Delta_{max}^{\alpha}$, where α=0.64±0.09, b =2.22±0.14 (correlation coefficient cc=0.74). Analogous calculations for integral proton flux with the energy >10 MeV give rather worse correlation with Δ_{max} (cc=0.42).

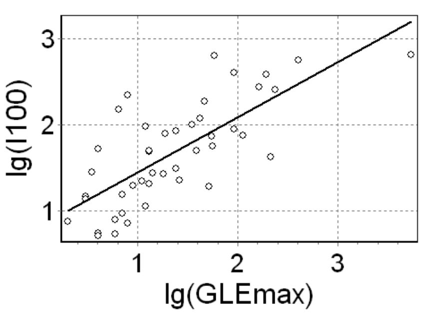

Fig. 2: Interrelation between maximal GLE (%) and >100 MeV proton flux

[1]no optical and x-ray observations, time of type II radioburst
[2]not complete data

The lowest proton flux (5.3 pfu) with energy >100 MeV, which was accompanied by GLE, was recorded on May 28, 1990. From the other side, 9 times the flux J_{100} exceeded 10 pfu without GLE, for example, it reached 450 pfu in November 8, 2000. Only three times during the last decades much bigger proton flux has been recorded, and in all these cases (September 29, 1989, July 14, 2000 and January 20, 2005) not simply GLEs but very large GLEs were observed. A big portion of anomalous events ($J_{100} > 10$ pfu, no GLE) was presented by the events from far solar sources (eastern or western). But there are also such events which force to suppose a sharp change of the solar acceleration efficiency in the energy range 100-1000 MeV/n.

V. GLEs AND SOLAR FLARES

For clear majority of GLEs the relation to powerful flares is a rule: 38 of 44 GLEs are associated with major (>M5) X-ray flares. Only one of them had a power <X1. In two of six rest events flares were not observed, and in the other were of power from C2 to M1. In 4 of 6 cases including both events without flare, the source of accelerated particles was on invisible side of the Sun. It is clear that under C9.7 flare with estimated longitude W120 a giant flare should be hidden, of ≫X1 importance. And for all other behind the limb sources the real power of the associated flare must be essentially higher than observable. Thus, four discussed behind the limb sources of particle should be related with sufficiently power flares, and these are the exclusions which confirm the rule. Only two events are not associated with major flares: in August 21, 1979 (C6.0/1B N15W38) and in May 10, 1981 (M1.3/2B N01W75), and they became an objective of the special detailed study [5]. It is worthy to note that after these relatively weak but suitable located flares very small GLEs were recorded, with maximum increase at NMs of 6 and 3 %.

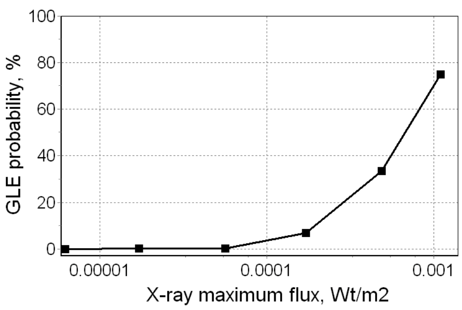

Fig. 3: Dependence of GLE probability on X-ray flare importance

A portion of GLE-flares arises with increasing of X-ray power. To obtain the Fig.3 all X-ray flares over 1976-2007 occurred in the favorable longitudinal region W0-W80 were divided into the groups accordingly to the x-ray importance (C3-C9.9, M1-M2.9, M3-M9.9, X1-X2.9, X3-X9.9 and ≥X10) and then, in each group a part of GLE associated flares has been found. This part is practically equal to zero for three less powerful groups. It increases significantly only for the flares of X importance, and in the group X1-X2.9 there is already 10 GLEs of 146 flares, and among 33 flares from X3 to X9.9 power every third one become GLE-flare. At last, 3 of 4 mostly powerful (≥X10) flares turned out to be connected with ground level proton enhancements. The considered 44 GLEs are connected only with 32 sunspot groups because of a series (from 2 to 4) GLE flares occured sometimes in one active region (AR). Among these 32 ARs the large groups dominated: 14 of them have a square from 1000 up to 2400 millionth parts of the solar surface, and only 2 has a square <300. The smallest sunspot group was found AR 1926 in August 1981, i.e. the group where the weakest GLE flare occurred. We may conclude that, although GLEs are associated with power X-ray flares and large sunspot groups, in separate cases the relation to moderate flares and middle size AR is possible.

Unlike smaller energy SEP, we have the information practically on all the flares associated with ground level proton enhancement with reliable definition of a connection "flare-enhancement". In 37 events of 44 flares were observable both in X-Ray and optical diapasons. And we can state that in 7 other cases the GLEs occurred behind the western limb, and almost always these flares continued the series of proton flares or even GLE flares generated in the same AR earlier. Among all 9 flares of $> X10$ importance and located to the west of the longitude E20, 6 flares (i.e. $2/3$) are associated with GLE. The rest 3 flares are also proton flares. One of them is the weakest from selected flares (X10.1), but two others are most powerful (X20 and X28). These two last are occurred (April 2, 2001 and November 4, 2003) near the western limb (W82 and W83) and were followed by great >100 MeV proton enhancements (7.9 and 1.3 pfu, correspondingly). This longitudinal region should not be consider as unfavorable since there are a lot of GLE flares of less power and close or more western longitudes. A deficit of high energy particles near Earth in these events may be explained by two classes of reasons. First, probably, these flares have any special characteristics related to low efficiency of solar accelerator. Indeed, their duration is certainly shorter than average for the proton flares, not saying on GLE-flares. Secondly, during and after these flares there could be special conditions of particle propagation in the interplanetary space, interfering arrival to the Earth of high energy particles. Anyhow, it is necessary to consider, that not each from the most powerful flares located in an optimal longitudinal zone, is accompanied by GLE.

Fig.4 demonstrates longitudinal distribution of GLE-flares and flares associated with proton enhancements where the flux of >10 MeV protons reached 10 pfu. The not localized or unreliably localized >10 MeV events in Fig.4 were considered behind of western limb and it was supposed that their frequency linearly falls down

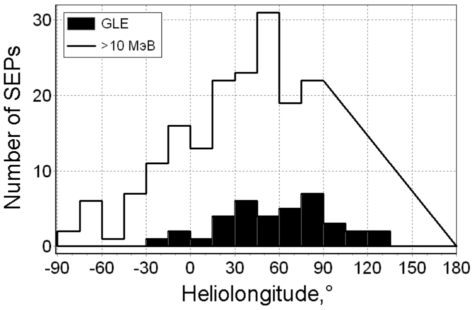

Fig. 4: Dependence of SEP ($>$10 MeV) and GLE number on associated X-ray flare heliolongitude

at removal behind of limb. It is possible to see that GLE flares occupy wide enough longitudinal zone from 30 to W130, but all the same it is still narrower than the area without GLE sources. Besides, to the east of the central meridian there were only 4 GLE-flares, and in the area to the east of E20 - only one (S18E30, December 12,1981). The GLE sources are absent on East of 30 and on West of W130, and their biggest density falls within W30-W90 range. Longitudinal distribution of GLE-flares is significantly narrower than those for less powerful proton enhancements [8-10]. In zone W15-W90 there is more than 70% of all GLE-flares and less than half of the flares connected with usual ($>$10 MeV, $\geq$10 pfu) proton enhancements. We should notice also that all GLE-flares $<$X1 have occurred in that part of the western zone (from W38 to W75), where the force field lines of an interplanetary magnetic field going to the Earth originate.

VI. Conclusion

Ground level enhancements of solar cosmic rays - the phenomena rare, but not individual. They are one of the brightest manifestation of sporadic solar activity and appear during the most powerful bursts in solar activity in a complex with other sporadic effects (sharp increases of solar radiation in all frequencies from radio waves to gamma rays, shocks, reconnection and dissipation in the solar magnetic field and so on). In the given work we compare GLEs to X-ray flarts because among all phenomena accompanying acceleration they give the fullest and statistically provided material. Unfortunately, there is a lot of breaks in the data on radio bursts or about coronal mass ejection (CME). Having the complete data we could see that the CMEs (so as the flares) are related to each GLE, and possible, to each proton enhancement. There should be connection (at least, statistical) between characteristics of proton enhancements and CMEs. It is not occasional relation between GLEs and the fastest CME with average speed near the Sun about 1800 km/s [11]. Ground level enhancements of solar cosmic rays make a part of particle enhancements observable near the Earth on smaller energies (SEPs). GLE characteristics well correlate with characteristics of SEPs, registered by the satellite equipment, especially by high energy channels. Connection of high energy SEPs and GLEs with solar sources looks similarly. It is not visible the bases to propose for GLE any special mechanisms of acceleration or any unusual conditions qualitatively distinguishing from usual work of the solar accelerator. Essential differences are present, but they have quantitative character and are caused, mainly, by the higher energy of solar cosmic ray in the GLEs. By this reason GLEs begin earlier and go faster of other kinds of enhancements. For the same reason they are influenced less by the interplanetary environment, and they are more closely connected with an acceleration place. Narrow enough heliolongitudinal distribution of the flares connected with GLE, and their better conformity to a longitudinal zone which leaves power lines of an interplanetary magnetic field going to the Earth, in our opinion, testify in favor of essential limitation and rather small sizes of a zone of effective solar acceleration. Grechnev et al. [12], having analyzed a considerable quantity of the diverse observations spent on January 20, 2005, have shown that the main part of accelerating processes in this event has been rather limited in time and localized in a small region of the Sun near to a flare zone. Quite probably that such localization and essential limitation in time and space is the general property of all solar events in which there is acceleration to energies of the GeV/n.

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