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Ground Level Enhancements of Solar Cosmic Rays during the Last Three Solar Cycles

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Abstract—The catalog of ground level enhancements of solar cosmic rays during cycles 21–23 of solar activity has been presented. The main properties, time distribution, and relation of these events to solar sources and proton enhancements observed on satellites have been studied.

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1. INTRODUCTION

Ground level enhancements of solar cosmic rays (GLEs) are the largest and most studied proton enhancements. These enhancements constitute a small (<5%) part of proton events but are much more attractive. Numerous scientific publications are devoted to almost each GLE, and many of these events are considered at special meetings and, sometimes, conferences. Studying particles accelerated on the Sun began with analyzing ground level enhancements and was based only on the data of ground cosmic ray detectors during the first two decades [Dorman and Miroshnichenko, 1965].

Among all phenomena of solar–terrestrial physics, only GLEs have serial numbers. These enhancements were counted from February 28, 1942, when ionized chambers registered GLE 1 [Smart and Shea, 1991], to the recent event (December 13, 2006, event 70; see, e.g., [Plainaki et al., 2008]). On average, one such event per year was registered. However, we should take into account that solar cosmic rays (CRs) were unreliably registered with ground detectors before the International Geophysical Year (IGY), when the global network of neutron monitors was created, and only the largest ground level enhancements could be in the first part of the list of these events. Only five GLEs were registered during the first 15 years; however, we can hardly doubt that many events, which would subsequently be registered as GLEs, were omitted in cycles 17 and 18. It is quite possible that the weakest enhancements in cycle 19 were also omitted.

Neutron monitors were created in order to study CR variations, and we should note that the largest variations in the neutron monitor data are observed during solar CR GLEs. These variations are sometimes two orders of magnitude as large as the greatest Forbush decreases and the 11-year modulation.

American scientists M. Shea and D. Smart have the largest number and the highest level of the works among numerous researchers of solar CR GLEs. Under the guidance of these researchers, data of many GLEs were standardized and collected [Gentile et al., 1990]. This database was given to the Australian Antarctic Data Center and has been supported and developed by Australian scientists [http://data.aad.gov.au/aadc/gle]. Unfortunately, one managed to collect and put into this database far from all ground-based observations of solar CRs. This is especially true with respect to early events.

Many works devoted to GLEs include an analysis of individual (usually large) events. Thus, several tens of the recent works have been devoted to GLE of January 20, 2005 (see, e.g., [Belov et al., 2006; Vashenyuk et al., 2006; Plainaki et al., 2007; Grechnev et al., 2008; McCraken et al., 2008; Perez-Peraza et al., 2008]). The works where many such events are generalized and compared have appeared much less frequently (see, e.g., [Shea and Smart, 1990; Miroshnichenko, 2001; Vashenyuk et al., 2006]). GLEs were included in the early catalogs of proton events [Bazilevskaya et al., 1986, 1990; Sladkova et al., 1998]; the most recent of them, in the (http://cdaw.gsfc.nasa.gov/meetings/lwscdaw2009/LWS_CDAW_GLE_data.html) catalog [Gopalswamy et al., 2008]. However, GLEs substantially differ from other proton enhancements at least methodically, and it is difficult to reflect the specificity of these enhancements in the general catalog of proton events. The recent work [Cliver, 2006] includes the catalog of GLEs for 1979–2005. This catalog continues the catalog of earlier GLEs observed in 1942–1978 [Cliver et al., 1982].

The aim of the present work is to generalize the ground-based observations of solar CRs in the last three solar cycles (1976–2007) in the form of a GLE catalog, which continues and specifies data published previously. In our catalog special attention is paid to the characteristics of solar events related to GLEs.

2. DATA

The results presented below were mostly achieved using the database of X-ray flares and proton events [Belov et al., 2005]. This database combines the X-ray flares (1–8 Å) that have been observed on the GOES satellites beginning from autumn of 1975, which is responsible for the period including the considered events.

The first GLE that fell in the catalog (the event of April 30, 1976) belongs to cycle 20 both formally (according to time) and essentially (in relation to solar activity). However, this event was observed only 2 months earlier than the minimum in the smoothed sunspot numbers. The last event in the catalog (December 13, 2006) was also the last GLE in cycle 23. Therefore, we actually consider the events in three complete solar cycles. We analyzed 44 GLEs, including almost two thirds of all such events registered.

Cosmic rays have mainly been detected with ground neutron monitors during the operation of GOES satellites. For the last decades, it has been considered that GLE of solar CRs is a proton event that is reliably identified in the data of at least one neutron monitor. Since July of 1957, when the global network of neutron monitors appeared, this network has made it possible to monitor solar proton events. The quality of this monitoring depends on the number of CR stations that operated during a specific period and on the character of these stations. This quality changes in time, but these changes have been insignificant for the last 50 years. This means that the numbered GLEs would be registered at any time during these 50 years. The capability to observe solar CRs most strongly depends on the presence of high-latitude stations in the global network (such Antarctic stations as Vostok and South Pole). Vostok (3488 m above sea level; geographic coordinates 78.5° S, 106.8° E) episodically operated in the soviet epoch. In 1990 this station ceased to operate and had no time to demonstrate its unique potential. South Pole (2820 m; 90° S) continuously operated from February 1977 to November 2005, when it was closed for technical reasons. Precisely South Pole usually registered the largest increases caused by solar CRs. We should acknowledge that the closing of this station (temporary, as we would like to hope) resulted in the less effective operation of the global network of neutron monitors as an instrument used to detect and study solar proton events. For example, such an event as GLE of January 17, 2005, would not be registered on the ground in the near future.

Some of the cataloged events were registered not only with neutron monitors but also with detectors sensitive to higher CR energies (muon detectors, ionization chambers). This is observed very rarely during very large events, the greatest of which can be GLE 42 of September 29, 1989. During most events, an enhancement is not registered not only with muon detectors but also with many (as a rule, low-latitude) neutron monitors. In the present work, we used only the data of neutron monitors among the ground-based CR observations. Our catalog includes the last GLEs numbered from 27 to 70. GLEs with the same numbers are presented in the database of solar CR GLEs (http://data.aad.gov.au/aadc/gle) and in other catalogs (see, e.g., [Cliver, 2006]). The catalog can be considered complete because the periods of possible GLEs were thoroughly verified and discussed by many experienced researchers who could not omit any considerable enhancement.

At the same time, we should remember that ground-based observations of solar CRs are affected by many factors (interplanetary conditions, geomagnetic disturbances, inhomogeneous distribution of ground detectors over the globe, etc.). If these factors were combined in another way, our catalog could be different. Some events could escape notice; on the contrary, other events would be added to the catalog. Thus, even a catalog of such large and rare events as solar CR GLEs can include random elements. However, this is true only for the smallest events included in this catalog.

3. DESCRIPTION OF THE CATALOG

The GLE number and date of beginning (year, month, and day) are given in the first two columns of Table 1. The characteristics of a flare associated with GLE are presented in the next three columns: the X-ray and optical importance, the time of the X-ray flare beginning and maximum, and the flare coordinates (heliolatitude and heliolongitude). The flare characteristics are present not always. During one of the earliest events (September 24, 1977), X-ray observations were absent (moreover, the flare was far behind the limb); therefore, the time of the flare beginning was absent, and the time of the maximum is presented conditionally according to the time of beginning of a type II radio burst. In this case (as well as in the cases of other flares that occurred behind the limb) the flare coordinates were estimated rather than were taken from observations. Usually, this estimation is rather simple because an active region generates many powerful flares before it disappears behind the western limb, and several proton enhancements are often related to these flares. This makes it possible to include an assumed flare into this sunspot group and to estimate the flare position before GLE. The event of February 16, 1984, is most complex in this respect. Kane et al. [1992] justified the assumption that this event is

Table 1. Solar CR GLEs in 1976–2006

GLE	Date	Flare			Active region (AR)		Maximal neutron monitor enhancement			Maximal neutron flux, pfu (IMP, GOES)	
		importance	time of beginning and maximum	coordinates	number	max area	enhancement, %	time	CR station	>10 MeV	>100 MeV
27	Apr. 30, 1976	X2.0/2B	2048–2108	S09W47	700	250	4	2200–2205	OULU	170	52
28	Sept. 19, 1977	X2.0/3B	1028–1038	N08W58	889	1100	3	1150–1155	OULU	200	1.7
29	Sept. 24, 1977	/	????–555[a]	N10W116	889	1100	11	0800–0900	SOPO	81	22
30	Nov. 22, 1977	X1.0/2N	1026–????	N24W38	939	440	55	1042–1048	SOPO	300	73
31	May 7, 1978	X2.0/2B	0333–????	N22W68	1095	1150	214	0340–0345	KERG	213	42
32	Sept. 23, 197	X1.0/3B	0947–1029	N35W50	1294	1120	13	1100–1200	SOPO	2250	48
33	Aug. 21, 1979	C6.0/1B	0611–0613	N15W38	1926	90	9	0630–0635	GSBY	274	19
34	Apr. 10, 1981	X2.5/3B	1632–1703	N07W35	3025	310	2	1805–1810	ALRT	55	7.5
35	May 10, 1981	M1.3/2B	0712–0731	N03W75	3079	470	3	0830–0835	CALG	180	13.5
36	Oct. 12, 1981	X3.1/3B	0622–0636	S18E30	3390	1630	18	0910–0912	SOPO	590[b]	26
37	Nov. 26, 1982	X4.5/2B	0230–0237	S11W87	3994	1680	6	0400–0500	SOPO	161	7.8[b]
38	Dec. 7, 1982	X2.8/1B	0000–0005	S19W82	4007	780	56	0400–0500	KERG	900	56
39	Feb. 16, 1984	C2.3/	0736–0743	S16W94	4408	300	212	0912–0914	SOPO	165[b]	75
40	July 25, 1989	X2.6/2N	0839–0843	N25W84	5603	180	8	0938–0940	SOPO	30	7
41	Aug. 16, 1989	X20/2N	0108–0117	S18W84	5629	1250	24	0252–0254	SOPO	1500	84
42	Sept. 29, 1989	X9.8/	1047–1133	S26W100	5698	1180	404	1255–1300	CALG	4500	560
43	Oct. 19, 1989	X13/4B	1229–1245	S27E10	5747	1100	92	1622–1624	SOPO	2360	400
44	Oct. 22, 1989	X2.9/2B	1708–1757	S27W31	5747	1100	193	1806–1808	MCMD	4450	380
45	Oct. 24, 1989	X5.7/3B	1736–1831	S30W57	5747	1100	162	1958–2000	SOPO	5000	270
46	Nov. 15, 1989	X3.2/3B	0638–0705	N11W26	5786	510	12	0710–0715	TERA	72	11
47	May 21, 1990	X5.5/2B	2212–2217	N35W36	6063	790	24	2246–2248	THUL	276	31
48	May 24, 1990	X9.3/1B	2046–2049	N33W78	6063	790	52	2114–2115	MTWL	96	19
49	May 26, 1990	X1.4/	2045–2058	N33W104	6063	790	13	0038–0040	SOPO	68	20

Table 1. (Contd.)

GLE	Date	Flare			Active region (AR)		Maximal neutron monitor enhancement			Maximal neutron flux, pfu (IMP, GOES)	
		importance	time of beginning and maximum	coordinates	number	max area	enhancement, %	time	CR station	>10 MeV	>100 MeV
50	May 28, 1990	C9.7/	0515–0521	N33W120	6063	790	6	1030–1032	SOPO	29^b	5.3
51	June 11, 1991	X12/3B	0209–0229	N31W17	6659	2200	12	0412–0414	SOPO	2300^b	95^b
52	June 15, 1991	X12/3B	0808–0831	N33W69	6659	2200	42	1000–1002	SOPO	950	116
53	June 25, 1991	X3.9/2B	1947–2011	N09W67	7205	1080	7	2050–2055	TXBY	255	15^b
54	Nov. 2, 1992	X9.0/	0231–0308	S25W100	7321	1580	6.5	0530–0532	SOPO	630^b	150
55	Nov. 6, 1997	X9.4/2B	1149–1155	S18W63	8100	890	19	1334–1336	SOPO	380	78
56	May 2, 1998	X1.1/3B	1331–1342	S15W15	8210	450	7	1405–1410	OULU	150	9.2
57	May 6, 1998	X2.7/1N	0758–0809	S11W65	8210	450	4^b	0930–0935	OULU	210	5.4
58	Aug. 24, 1998	X1.0/3B	2150–2212	N35E09	8307	500	4^c	2330–2335	CAPS	200	5.1
59	July 14, 2000	X5.7/3B	1003–1024	N22W07	9077	1000	59	1152–1153	SOPO	8400	623
60	Apr. 15, 2001	X14/2B	1319–1350	S20W85	9415	830	237	1434–1435	SOPO	950	250
61	Apr. 18, 2001	C2.2/	0211–0214	S20W115	9415	830	26	0334–0335	SOPO	320	23
62	Nov. 4, 2001	X1.0/3B	1603–1620	N06W18	9684	510	8	1806–1817	SOPO	31700	220
63	Dec. 26, 2001	M7.1/1B	0432–0540	N08W54	9742	1060	13	0620–0621	SOPO	800	50
64	Aug. 24, 2002	X3.1/1F	0049–0112	S02W81	10069	1960	14	0151–0152	SOPO	220	27
65	Oct. 28, 2003	X17/4B	0951–1110	S16E08	10486	2370	47	1152–1153	MCMD	29500	186
66	Oct. 29, 2003	X10/2B	2037–2049	S15W02	10486	2370	35	2130–2131	SOPO	2300	107
67	Nov. 2, 2003	X8.3/2B	1703–1725	S14W56	10486	2370	39	1751–1752	SOPO	1560	49
68	Jan. 17, 2005	X3.8/3B	0659–0952	N15W25	10720	1610	3.5	1129–1130	SOPO	4900	28
69	Jan. 20, 2005	X7.1/2B	0636–0701	N14W61	10720	1610	5400	0653–0654	SOPO	1800	650
70	Dec. 13, 2006	X3.4/4B	0214–0240	S06W23	10730	680	92	0305–0310	OULU	700	89

Note: (a) X-ray observations absent, optical flare absent, radio burst of type II; (b) incomplete data on proton fluxes; (c) incomplete data on CR ground based observations.

related to sunspot group 4408 that left the disk on February 13. When this active region crossed the disk, it generated two M flares and several C flares but was not related to any proton event. However, before this region left the disk, it complicated its magnetic structure to the delta configuration, became more active, and generated the most significant flares (on February 10 and 11). If this region continued developing behind the disk, this could create conditions for a large proton event. We accepted this assumption, according to which the associated flare occurred at a longitude of W125–130 and is the most distant western flare in our catalog. However, we should take into account that it is problematic to localize a solar source for this event, and several researchers (see, e.g., [Debrunner et al., 1985]) assumed that this source was localized closer to the disk. The X-ray measurements were incomplete for two early events (November 22, 1977, and May 7, 1978); therefore, it was impossible to establish the time of the X-ray flux maximum.

The next two columns present the data on the active regions with the flares associated with GLE, obtained from the USAF-MWL catalog (ftp://ftp.ngdc.noaa.gov.STP.SOLAR_DATA/SUNSPOT_REGIONS/USAF_MWL). Since many flares related to GLE occurred near or behind the limb, it is difficult or impossible to determine the active region area at a flare instant. Therefore, Table 1 includes the maximal sunspot area for this group rather than rather than the active region (AR) area at a flare instant.

Table 1 also presents the maximal count rate growth ($\Delta_{\max}$) with the period and station where this growth was the largest. To comparatively analyze different GLEs, it is important to have any characteristic reflecting an enhancement value. The value of the maximal count rate growth could seemingly be such a characteristic; however, this is true only with substantial reservations. First of all, we have no complete data on many GLEs. Specifically, that is why Oulu (Finland) many times appears in Table 1 as a station with the maximal enhancement. This is a high-latitude station, and the sensitivity of this station to solar CRs is not higher than that of other similar stations. However, the registrations of all GLEs at this station were collected and are adequately presented in our table and in the Internet (http://cosmicrays.oulu.fi/GLE.html). Other stations could be referred to more frequently if the members of these stations followed the positive experience of the Finnish colleagues. In this case the maximal GLEs for some stations would be slightly larger than the presented values. The problem of data incompleteness is not among the grand problems that make it difficult to use the $\Delta_{\max}$ value as one of the main GLE characteristics and can be solved. Two other problems (time variations in the network of ground detectors and differences in the conditions of observing different GLEs) are more serious, and it is impossible to solve them completely. Both these problems are related to considerable differences in the capabilities of individual neutron monitors to register solar CRs. Variations in galactic CRs are usually observed at all neutron monitors and differ by a factor of not more than several unities from one another; at the same time, such differences often reach several orders of magnitude for highly anisotropic solar CRs with a much softer energy spectrum. One altogether fails to detect any effect in many GLEs using low-latitude neutron monitors, and the largest enhancements should simultaneously be registered with high-latitude and high-altitude neutron monitors. Thus, the network observational capabilities are in many respects explained by the presence of high-latitude detectors. For example, if South Pole station operated in December 2006, the $\Delta_{\max}$ value would most probably be larger for this event. On the contrary, without South Pole values, the maximal GLE 69 value in January 2005 would be smaller and GLE 68 would altogether be unnoticed. The $\Delta_{\max}$ value depends on the season and times of a day when a certain enhancement is registered because the CR detectors are inhomogeneously distributed over the globe. The point is that the maximal enhancement is as a rule registered at the beginning of an event, when a narrow intense beam of high-energy particles approaches the Earth (see, e.g., [Shea and Smart, 1990; Smart and Shea, 2003; Belov et al., 2005a; Vashenyuk et al., 2006]). Such a beam is observed only for a short time (sometimes, for several minutes), and the location of the most sensitive neutron monitors relative to this beam at that time is of prime importance. If a beam fall in the zone located far from asymptotic directions of these monitors, the $\Delta_{\max}$ value will be substantially smaller. On the contrary, this value will increase if a beam falls on such a station as South Pole. Thus, the values of the maximal enhancements ($\Delta_{\max}$) observed on the ground cannot exactly reflect not only the number of charged particles accelerated to high energies on the Sun but also the number of such particles that reached the Earth during different events. A decrease in the correlation between ground-based and satellite measurements of solar proton events has the same causes.

The last columns of Table 1 presents the maximal increases in the integral fluxes of protons with energies of >10 and >100 MeV, measured on the IMP-8 and GOES satellites [Belov et al., 2005b].

4. TIME DISTRIBUTIONS OF GLES

Figure 1 shows how all registered GLEs of solar CRs are distributed in time.

We can see that the time distribution of the GLE instants is complex, mainly random, and varies from cycle to cycle. GLEs are observed in all solar cycle phases [Shea and Smart, 1990], including the minimum phase, but are less frequent at minimums than during other periods. The longest gaps in GLE obser-

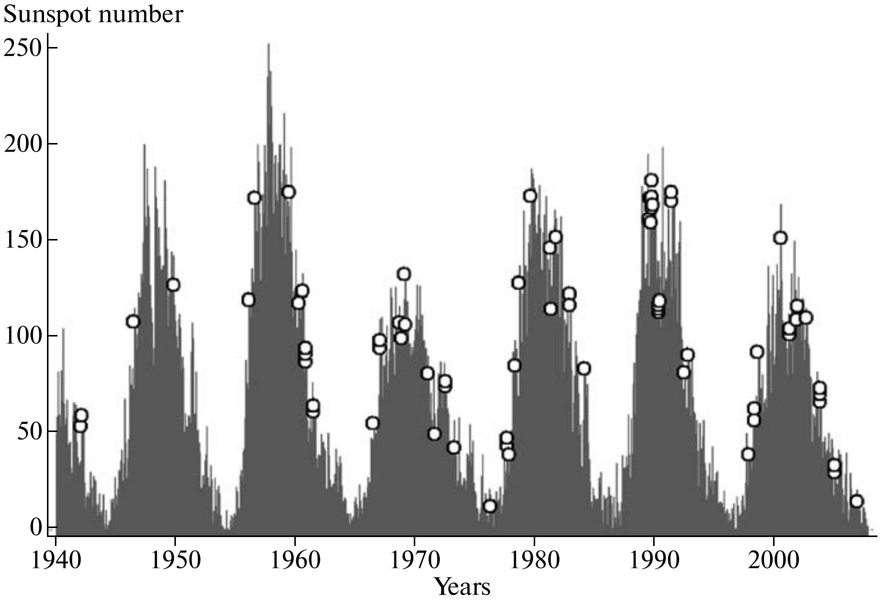

Fig. 1. Average monthly sunspot numbers in the last seven solar cycles and the instants of all known GLEs of solar CRs.

vations fall on solar activity minimums: 5 years and 4 days in 1992–1997 and exactly 5.5 years during the period from February 16, 1984, to August 16, 1989. For comparison, we indicate that the shortest period between individual GLEs (about 35 h) corresponds to the events of October 28 and 29, 2003. Figure 1 demonstrates that the GLE instants fall on the periods of local short-term maximums of the sunspot number. The point is that GLEs of solar CRs are among the manifestations of large solar activity bursts, when the number of sunspots inevitably increases. Table 2 presents the data on the GLE distribution between the last three solar cycles.

In Table 2 the logarithms were used to average the X-ray power for flares in the E85–W85 range of visible longitudes.

The number of GLEs varies slightly from cycle to cycle [Shea and Smart, 1985]. This becomes even more evident if we recall that ten and 13 GLEs were registered in cycles 19 and 20, respectively. The impression can originate that the number of GLEs increases in the course of time since these events were minimal and maximal in the earliest (19) and latest (23) cycles, respectively. However, it is important to remember that the possibilities of observing weak GLEs were much higher in cycle 23 than in cycle 19. Taking this circumstance into account, we can rather confidently speak that the number of GLEs varies slightly from cycle to cycle. On the other hand, it is clear that this conclusion can only be applied to several studied cycles, and variations in the number of GLEs can substantially increase in the future.

Table 2. Certain characteristics of solar CR GLEs in cycles 21–23

Cycle	Years	GLE number	GLE average number, %	Flare average power, 10^{-4} W m^{-2}
21	1976–1985	12	15 ± 6	1.0 ± 0.4
22	1986–1995	15	28 ± 10	6.6 ± 1.4
23	1996–2007	16	28 ± 13	3.9 ± 1.0

Table 2 indicates that the average number of GLEs (the $\Delta_{\max}$ value averaged over all events in a cycle) also insignificantly varies from cycle to cycle. The average importance of an X-ray flare associated with GLE demonstrates more significant variations.

5. RELATION OF GLES TO ENHANCEMENTS OF LOWER-ENERGY PROTONS

We compare the events when solar CRs were registered on the ground and with satellite detectors (IMP-8 and GOES).

In spite of the cataloged causes, disturbing the relation between satellite and ground level enhancements, and differences in the energy dependence of solar CR fluxes in different events, the correlation between the flux of protons with an energy higher than 100 MeV (J_{100}) and the maximal GLE value ($\Delta_{\max}$) is rather high (Fig. 2) and corresponds to the power dependence $J_{100} = c\Delta_{\max}^{\alpha}$, where $\alpha = 0.64 \pm 0.09$, and $c = 2.22 \pm 0.14$ (the correlation coefficient is 0.74). Note that similar calculations for the integral flux of protons with an energy of >10 MeV give a much lower correlation with $\Delta_{\max}$ (the correlation coefficient is 0.42).

The lowest (5.3 pfu) flux of protons with an energy of >100 MeV, when GLE was observed, was registered on May 28, 1990. However, the events with much higher J_{100} fluxes but without GLEs were also registered: nine times GLEs were not registered on the ground in the cases when the J_{100} flux was higher than 10 pfu. The largest of these proton events occurred in the last solar cycle on November 8, 2000, when the flux of protons with an energy of >100 MeV reached 451 pfu. The J_{100} flux was even higher only three times during the last decades, and GLE was large in all these cases (on September 29, 1989; July 14, 2000; and January 20, 2005).

The absence of GLE at high J_{100} fluxes can apparently be explained by the combination of specific features of a solar accelerator in these cases with specific conditions of solar CR propagation. Note that the anomalous events (J_{100} > 10 pfu, no GLE) included many events with distant solar sources (eastern, behind-the-limb, or near-limb). The events, during which the effectiveness of solar acceleration in the 100–1000 MeV nucleon^{-1} range of energies is supposedly abruptly decreases, are also registered.

Table 3 makes it possible to compare the average characteristics of two classes of powerful proton events (GLEs and proton enhancements in the cases when the integral of protons with energies of >100 MeV was higher than 2 pfu according to the satellite data but GLE was not registered) as well as the average characteristics of X-ray flares related to these two classes of proton events. We can see that differences in the duration, latitude, and even power between the associated flares are not very large. Differences in the average longitudes of these flares are larger. This does not inevitably follow a real difference in the average longitude of the acceleration region. To a greater extent, this is related to the fact that the longitudinal distribution of the flares associated with J_{100} > 2 pfu but not with GLE is much wider than the distribution of GLE-flares and extends almost to the eastern limb. Probably, this distribution also widens westward (to large distances from the western limb). Since we have to map out behind-the-limb regions (and this is true almost for western behind-the-limb flares), the average longitudes shift eastward, and this shift is evidently smaller for GLE-flares.

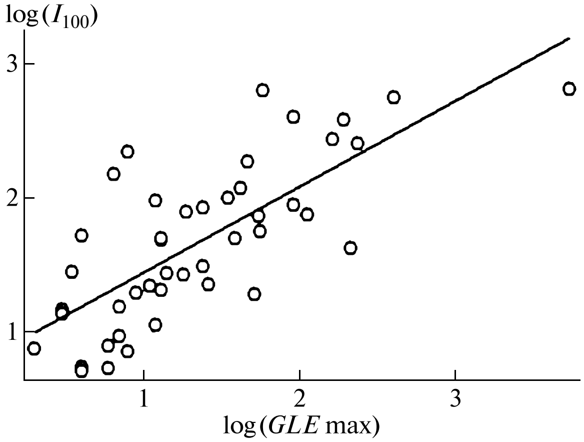

Fig. 2. Interrelation between the maximal integral fluxes of protons with an energy of >100 MeV and the maximal increases in the neutron monitor count rates during the same events in 1976–2006. A straight line corresponds to the power law regression dependence.

A difference in the energy spectra between the considered groups of powerful events is apparently the largest [Bazilevskaya and Sladkova, 2003; Osokin et al., 2007]. The average index γ presented in Table 2 was obtained on the assumption that the integral spectrum of protons in the 10–100 MeV range is power-law. It is clear that events with harder (on average) energy spectral of accelerated particles, observed near the Earth, become ground level proton enhancements. The causes of such a spectrum hardening are less evident. It is unclear whether the spectrum of particles is especially hard already in the acceleration zone during such events or enrichment in high energies results from particle propagation from the Sun to the Earth.

6. STATISTICAL RELATIONS BETWEEN GLES AND SOLAR X-RAY FLARES

Figure 3 makes it possible to observe a similarity in the time variations in the annual numbers of powerful (≥X1) X-ray flares (N_X) and ground-level proton

Table 3. Average characteristics of GLE-related flares and flares related to large proton enhancements outside the ground

Characteristic of proton events and associated flares	Number	Flare power, W m^{-2}	Duration, min		Flare heliolongitude, deg	Latitudinal difference between the Earth and a flare, Δλ°	J_{10}, pfu	J_{100}, pfu	γ
			flare	flare growth phase					
GLE-related flares	36	(3.2 ± 0.6) × 10^{-4}	96 ± 19	28 ± 5	43 ± 5	18.5 ± 1.8	640 ± 190	50 ± 11	1.11 ± 0.07
Flares related to J_{100} > 2 pfu rather than to *GLE*	32	(2.0 ± 0.5) × 10^{-4}	123 ± 21	25 ± 4	18 ± 10	18.6 ± 1.4	240 ± 100	6.1 ± 1.3	1.60 ± 0.09

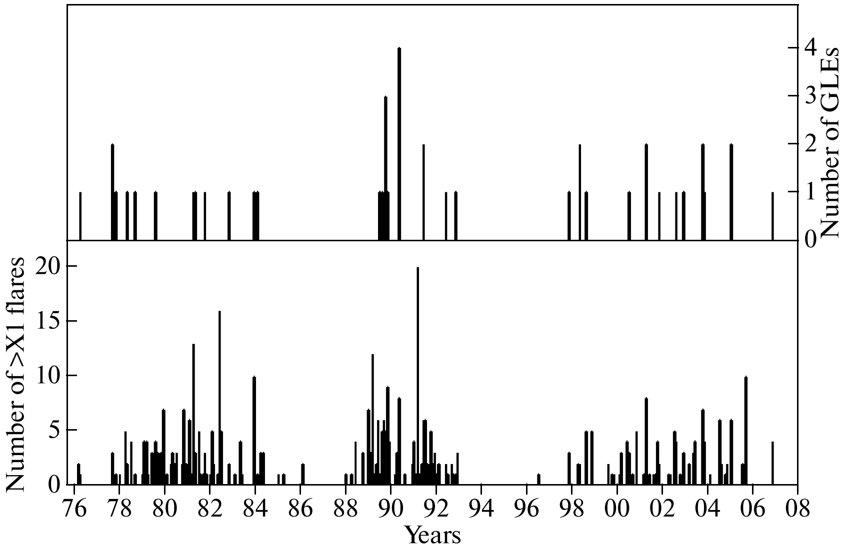

Fig. 3. Variations in the annual numbers of powerful (>X1) X-ray flares and solar CR GLEs in 1976–2007.

enhancements (N_G). Indeed, the year with the record number (59) of ≥X1 flares (1989) also included the record number of GLEs (7). On the other hand, none GLE was registered during nine years with less than three ≥X1 flares.

The linear regression relationship ($N_G = 0.34 + 0.073N_X$) exists between the discussed numbers (the correlation coefficient is 0.685). This relationship means that one GLE corresponds to ~14 ≥X1 flares.

According to the annual data, the number of GLEs evidently closely correlates with the number of powerful (≥X1) X-ray flares than with that of sunspots (the correlation coefficient is 0.51). At the same time, we can note that the relation between N_G and N_X is not always evident. This relation was most evidently disturbed in 1980, when GLEs were absent but 21 ≥X1 flares were observed. However, this year was the only exception among 13 most flare-active years, when the number of ≥X1 flares was larger than 13. GLEs were observed in the remaining 12 such years.

The above empirical regression equation can be used to roughly estimate the number of anticipated GLEs during rather long periods, for which we can predict the numbers of flares. This equation can also be used to estimate the number of flares in the previous years. For example, regular X-ray observations were not performed in cycle 20, but we know that 13 GLEs were registered in 1966–1976. Proceeding from the same equation, we can estimate that 140 ± 30 ≥X1 flares should have been observed in cycle 20.

7. GLES AND SOLAR FLARE POWER

It is difficult to doubt about the statistical relation between flares and ground level proton enhancements, but it is unclear whether this relation is simultaneously physical. Are all GLEs related to flares? If this is the case, it is unclear whether these flares should be large. We try to answer all these questions. Thirty eight of 44 considered GLE events are related to major (>M5) X-ray flares. Only one of these flares had a power lower than X1 (the M7.1 flare of December 26, 2001); i.e., the relation to major flares exists and is a rule for the evident majority of GLEs. We discuss the remaining six events. Flares were altogether not observed in two of them (September 24, 1977, and February 16, 1984). The remaining flares had powers from C2 to M1. In four cases of six (excluding both events without flares), we have every reason to believe that the source of accelerated particles was on the hidden side of the Sun. This phenomenon is rather frequent for proton enhancements, especially for GLEs. Seven of 44 discussed GLEs are related to sources behind the western limb. In these cases we do not observe a flare or observe only the highest part of this flare (i.e., the observed flare power is substantially lower). In four problematic events, the longitude of associated behind-the-limb flares was estimated based on the indirect data and varies from ~W95 to ~W120. It is clear that the C9.7 flare with an estimated longitude of W120 should be the manifestation of a giant ⩾X1 flare. For al other behind-the-limb sources, a true power of associated flares should also be substantially higher than the visible power. Thus, four discussed behind-the-limb sources of particles should be related to rather powerful flares, and these are those exceptions that confirm the rule.

Thus, we have only two events independent of major flares: GLEs of August 21, 1979 (C6.0/1B N15W38 flare) and May 10, 1981 (M1.3/2B N01W75 flare). To all appearance, these two events should be considered as real exceptions to the rule, relating GLEs to major flares, and this caused a special detailed study [Cliver, 2006]. We should note that small GLEs with maximal neutron monitor increases of 6 and 3% were registered after these two relatively weak but properly located flares.

The overwhelming majority of the GLE-flares on the visible part of the solar disk have a power of X1 and higher. Only three of 36 such flares had importance M, and only one flare discussed above was even weaker (C6). The contribution of GLE-flares generally increases with increasing X-ray power. We consider (Fig. 4) the probability of observing ground level proton enhancement after flares with different powers in the soft (1–8 Å) X-ray range, which were registered in the favorable longitudinal zone W0–W80 [Belov et al., 2008]. To construct Fig. 4, we divided all X-ray flares observed in 1976–2007 into groups in accordance with the X-ray importance (C3–C9.9, M1–M2.9, M3–M9.9, X1–X2.9, X3–X9.9, and ≥X10) and subsequently found the contribution of GLE-associated flares for each group. The contribution of GLE-flares is almost zero for three weakest groups of flares in Fig. 4. Although each such group included one GLE, the total number of flares with such a power is sufficiently large (4943, 1482, and 467), and we consider that the GLE probability is negligible. This probability increases only in going to X flares: ten GLEs correspond to 146 flares already in the X1–X2.9 group, and one in three X3–X9.9 flares in the group of 38 events becomes a GLE-associated flare. Finally, three of four most powerful (≥X10) flares were related to GLEs. We can conclude that GLEs can sometimes be related to flares of medium importance, although ground level proton enhancements are usually related to powerful X-ray flares.

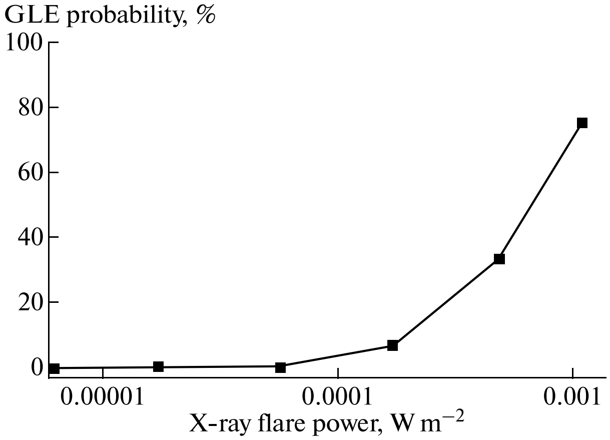

Fig. 4. Observation probability of a ground level proton enhancement after different-power flares in the soft (1–8 Å) X-ray range, observed in the favorable longitudinal zone (W0–W80).

Approximately the same can be spoken about the relation of GLEs to ARs (sunspot groups). Forty four of the considered GLEs are only related to 32 sunspot groups because the series of GLE-flares, including from two to four events (May 1990), is sometimes observed in one AR. Large groups predominate among these 32 ARs: the areas of 14 groups are 1000–2400 millionths of a solar hemisphere (msh), and only two groups has areas <300 msh. The smallest sunspot group was AR 1926 in August 1981: the weakest GLE-flare occurred precisely in this group.

8. LONGITUDINAL AND LATITUDINAL DISTRIBUTION OF ASSOCIATED SOLAR FLARES

Speaking about the distribution of GLE-flares over the solar surface, we should first of all emphasize that GLEs are much closer related to solar sources in contrast to proton enhancements as a whole. We have information about almost all flares associated with ground level proton enhancements, and the flare–enhancement relation is reliably determined almost always. Flares in the X-ray and optical ranges were observed in 37 of 44 events. This relation is almost indisputable even when direct observations of such flares were absent and only indirect data on these flares are available. Moreover, in these cases we have data (although less accurate) on the flare time and position. We can almost unconditionally state that all seven GLE-flares, not related to the optical range, occurred behind the western limb. These flares almost always continued the series of proton and even GLE-associated flares, previously observed in the same AR. Such a situation was in September 1977, when GLE 29 (occurred on September 24) was the fourth proton enhancement and the second GLE in AR 889. The famous event (GLE 42) in September 1989 was the fourth proton event in AR 5698, although the first three events were weak. On November 2, 1992, GLE 54 occurred two days after another large proton enhancement related to the same active region (AR 7321). In April 2001 GLEs 60 and 61 were related to AR 9415; this AR approached and was far behind the western limb during the first and second enhancements, respectively. Four more earlier proton enhancements with smaller magnitudes were also related to the same AR. The series of four GLEs in May 1990 was most impressive. The first two events (May 21 and 24) were related to visible flares; the last two events (May 26 and 28), to invisible behind-the-limb flares; however, all these flares were in the same active region (AR 6063). Two more small proton enhancements were apparently related to the eastern and central flares that occurred on May 15 and 18 in the same AR. Thus, six of seven optically nonidentified GLEs entered into the series of rather powerful proton flares. GLE 39 (observed on February 16, 1984) was the only exception and, simultaneously, the most problematic event.

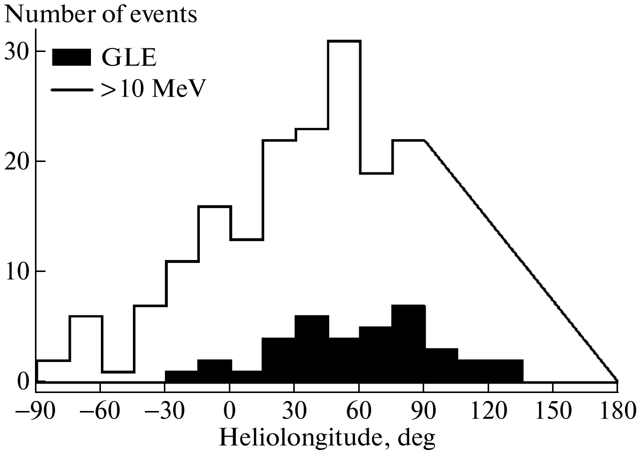

Fig. 5. Heliolongitudinal distribution of the sunspot numbers in 1975–2007, related to GLEs and proton enhancements with the maximal proton flux (>10 pfu) for particles with an energy of >10 MeV.

Six (i.e., two thirds) of nine >X10 flares, located west of longitude E20, are related to GLE. The remaining three flares are also proton. One of them is the weakest flare (X10.1) among the selected events; however, two other flares are most powerful (X20 and X28). The last two flares occurred relatively recently (on April 2, 2001, and November 4, 2003) near the western limb (longitudes W82 and W83) and were accompanied by rather large GLEs for an energy of >100 MeV (7.9 and 1.3 pfu, respectively). This longitudinal zone can in no way be considered unfavorable since many weaker GLE-flares with close or more western longitudes occurred there. The absence (or at least deficit) of high-energy particles near the Earth during these events can be explained by two classes of causes. First, these flares show possibly some properties related to a decreased effectiveness of the solar accelerator. Indeed, the duration of these flares is evidently shorter than the average duration of proton flares apart from GLE flares. Second, special conditions of the interplanetary particle propagation, hindering the appearance of higher-energy particles near the Earth, could be during and after these flares. The combination of two classes of causes is also possible. Somehow or other, we should take into account that not all most powerful flares, located in the most favorable longitudinal zone, are accompanied by GLEs.

We can distinguish the narrower region ($I_X \gg$ X11, longitude E10–W80), which includes only four flares; however, all these flares are related to GLEs. It is interesting to trace this relation for further flares with the same characteristics. Most probably, exceptions will also appear in this zone in the course of time.

Figure 5 shows the distribution of GLE-flares and flares associated with proton enhancements in the case when the flux of protons with energies higher than 10 MeV reached 10 pfu. When we constructed Fig. 5, we considered that nonlocalized or unreliably localized events are western behind-limb ones and assumed that the frequency of these events linearly decreases with increasing distance behind the limb. One can see that GLE-flares occupy a rather wide longitudinal zone (from E30 to W130); however, this zone is nevertheless narrower than the zone without GLE sources. In addition, only four GLE-flares were observed east of the central meridian, and only one flare occurred east of E20 (S18E30; October 12, 1981). Sources of GLEs are absent east of E30 and west of W130, and the density of these sources is maximal in the longitudinal zone between W50 and W90. The longitudinal distribution of GLE-flares is pronouncedly narrower than the distribution of weaker proton enhancements [Shea and Smart, 1996; Bazilevskaya and Sladkova, 1986; Belov et al., 2005; Belov, 2008]. More than 70% of all GLE-flares and less than a half of the flares related to usual (>10 MeV, 10 pfu) proton enhancements are located in the W15–W90 zone.

We also note that all GLE-flares with a relatively low X-ray power (<X1) occurred in the western zone part (from W38 to W75) where the IMF lines extending toward the Earth originate.

GLE-flares are almost equally distributed between the Sun's Southern and Northern hemispheres (Fig. 6). Twenty three of 44 such flares occurred north of the equator; the remaining flares, south of the equator. The range of heliolatitudes of GLE-flares is rather wide: from S30 to N35. The highest-latitude GLE-flares (the flares of September 23, 1978; May 21, 1990; and August 24, 1998) and the lowest-latitude flare, registered on May 10, 1981, at a latitude of N03, belong to the Northern Hemisphere. It is interesting that 12 comparatively high-latitude GLE-flares (with a latitude >20°) occurred in the Northern Hemisphere, and only five flares were registered in the Southern Hemisphere (all flares occurred in cycle 22). For each event, we calculated a difference in the flare and the Earth heliolatitudes $\Delta\theta = \mathrm{abs}(\theta_F - \theta_E)$, which varied from 1° in the event of September 19, 1979 to 37° in the event of May 21, 1991. The average importance of seven X-ray GLE-flares in the visible part of the Sun, which were most distant ($\Delta\theta > 30°$) from the Earth along latitude, was X7.7, and this indicator was much lower (X2.1) for 18 flares located at the smallest latitudinal distances from the Earth ($\Delta\theta < 10°$). It is indicative that the weakest GLE-flares discussed above (C6 and M2) were located at distances of 8° and 7° from the Earth, respectively. This makes it possible to assume that flares, located at smaller heliolatitudinal distances from the Earth, can more probably become GLE-flares than flares of the same power located at larger distances from the Earth. The same assumption holds true for a longitudinal difference (see [Belov et al., 2008]). It is worse noting that all GLE-flares close in latitude ($\Delta\theta < 14°$) had not the highest powers during the considered period; the X4.5 flare had the highest X-ray importance in this group. At a higher

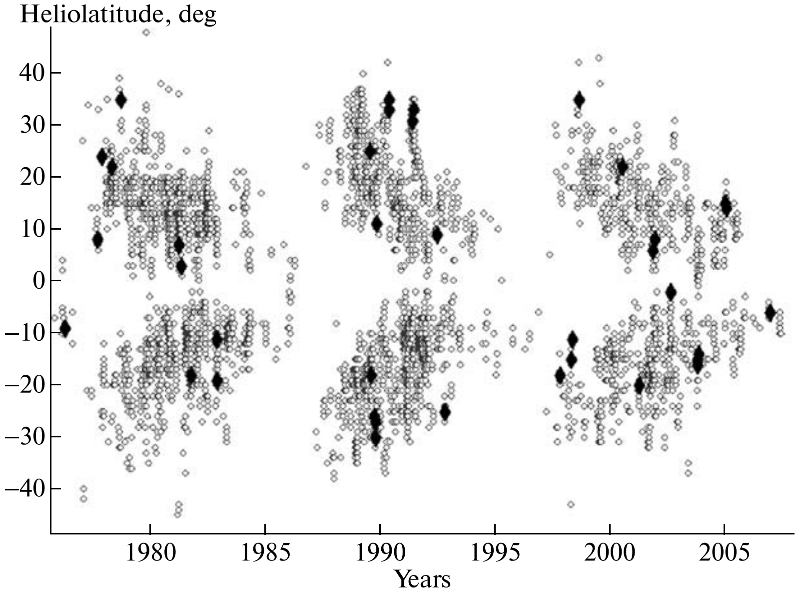

Fig. 6. Heliolatitudes and observation instants of all ≥M1 X-ray flares (open circles) and flares related to solar CR GLEs (diamonds).

power of solar flares, we could possibly observe larger GLEs of solar CRs.

9. CONCLUSIONS

Solar CR GLEs are rare but not single phenomena. They appear during almost all most powerful bursts of solar activity and are one of the most striking manifestations of sporadic solar activity. GLEs always appear together with other sporadic phenomena (abrupt increases in the solar radiation at all observed frequencies from the radio range to gamma rays, shock waves, phenomena of reconnection and dissipation in the solar magnetic field, etc.). In the present work we concentrated on a comparison of GLEs with X-ray flares not because we are sure that GLEs are physically closely related to X-ray flares or soft X rays better reflect the operation of the solar accelerator than other sporadic solar phenomena. Most probably, this is not the case; however, the advantage of X-ray flares consists in that precisely these flares (among all phenomena accompanying solar acceleration) give the most complete and statistically reliable data for a long period. Unfortunately, many gaps are present in the data on radio bursts and, especially, solar matter ejections. We can assume that, having complete data, we would realize that CMEs (as well as flares) are related to each GLE and, possibly, each proton enhancement observed near the Earth. Moreover, relations (at least statistical) should exist between characteristics of proton enhancements and CMEs. CMEs were registered for 14 of 15 GLEs, during which the SOHO/LASCO observations were performed, and the fastest CMEs with an average velocity about 1800 km/s near the Sun proved to be related to GLEs not accidentally [Gopalswamy et al., 2005].

Solar CR GLEs are part of proton (and not only proton) enhancements observed near the Earth at lower energies. Characteristics of GLEs correlate well with those of proton events registered with the satellite equipment, especially with the highest-energy channels of this equipment. The relation of high-energy satellite enhancements and GLEs to solar sources manifests itself in a similar way. We have no reason for assuming that ground level events can be explained by some special acceleration mechanisms or unusual conditions, which make acceleration processes qualitatively different from a usual operation of the solar accelerator during these events.

Substantial differences are certainly present, but they are quantitative and are mainly caused by the fact that GLEs are the highest-energy events among solar CR enhancements. That is why proton enhancements begin earlier and proceed faster than other types of enhancements. That is why these ground level events are to a lesser degree affected by the interplanetary medium and are more closely related to an acceleration zone. We assume that a rather narrow heliolongitudinal distribution of GLE-related flares and their better correspondence to a longitudinal zone, from which IMF lines extend toward the Earth, indicate that the zone of effective solar acceleration is substantially restricted. Grechnev et al. [2008] analyzed many various observations performed on January 20, 2005, and indicated that the main and most effective part of the acceleration processes during this event was very limited in time and was localized in a small area of the Sun in the zone of a flare. It is quite possible that such a localization and substantial limitation in time and space is the common property of all solar events with acceleration to energies of several GeV nucleon^{-1}.

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