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EXTENDED CATEGORISATION OF GROUND LEVEL ENHANCEMENTS (GLEs) OF COSMIC RAYS DUE TO RELATIVISTIC SOLAR ENERGETIC PARTICLES

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Abstract

The ground level enhancements (GLEs) due to solar cosmic rays (SCRs) are significant for a number of planetary processes on the Earth. The solar particles are the key for understanding of solar-terrestrial relations and space weather. On the basis of ground based observations of SCRs from 28 February 1942 (when they were discovered) to the end of 2015, have been determined some characteristic periods of GLEs and observed during the solar cycles 17÷24. It is made quantifying of GLEs and the frequency of occurrence of GLEs in the different solar cycles is determined.

This article presents also a categorization of the ground level enhancements (from the first GLE 01 on February 28, 1942 to the last GLE 72 on January 06, 2014) due to solar energetic particles reaching the Earth's surface. We have detected new groups of collective GLEs, recurrent GLEs, recurrent-collective GLEs, collective-recurrent GLEs, etc. Physical, methodical, and applied aspects, related to the SCR and GLE events have been discussed as well, because they have an extreme impact on Earth. The obtained results have prognostic value and significance for the ionization and radiation conditions in the Earth environment and for the mechanisms of solar-terrestrial influences.

Introduction

The solar energetic particles (SEPs) and solar cosmic rays (SCRs) are of outstanding cosmophysical and astrophysical interest [1–5]. The solar proton events (SPEs) occur as a result of massive acceleration of charged particles in the solar corona and/or interplanetary space. Usually such events provide quite a soft spectrum of energetic particles, but sometimes the spectrum is sufficiently hard, so that the initial solar protons can generate secondary nucleons that can be detected as an increase in the cosmic ray flux at the ground level [6–12]. Such exceptional events are called with the international name GLE (Ground Level Enhancement or Ground Level Event) of cosmic rays (CRs) and are numbered consecutively from the first event that was detected in 1942 [13]. On February 28, 1942, ground detectors for the first time registered that accelerated solar protons arrived to the Earth. A new similar event was registered on March 7, 1942 [14]. This was one of the greatest astrophysical discoveries of the 20th century: it turned out that charged particles can be accelerated to high energies in the interplanetary space [15].

However, researchers realized this fundamental fact and its close relation to solar flares with some delay. Only after the registration of the third similar event on July 25, 1946, the author of this discovery S. Forbush (1946) [13] wrote with caution that these observations "… make it possible to draw a rather unexpected conclusion that all three unusual CR intensifications can be explained by fluxes of charged particles emitted by the Sun." After the fourth ground level increase in SCRs on November 19, 1949 [16], the relationship between the observed relativistic particles and solar flares became an unquestionable fact, which motivated the appearance of a new concept for the nature of the intense flux of energetic particles, measures at the ground.

The SCRs can include other nuclei such as helium ions and HZE (high – H, atomic number – Z, and energy – E) ions [17]. These particles cause multiple effects. They can penetrate the Earth's magnetic field and cause ionization in the ionosphere [18–21]. The effect is similar to auroral events, however, instead of electrons, the protons are involved in the processes of ionization, dissociation, excitation etc. Energetic protons are also a significant radiation hazard to spacecrafts and spaceflights.

In the present paper we shall discuss and analyze some physical aspects of GLEs, namely, the distribution of GLEs during solar cycles 17÷24 (1942–2015), as well as the frequency of GLE event appearance. We will perform a new categorisation of different types of GLE events and we shall consider the cases of collective and recurrent GLEs. We will also illustrate some GLE effects on the Earth's atmosphere, i.e. the SCR geophysical effects. The prospects of studying SCRs/GLEs will be considered also in the end of this work.

Worldwide network of stations and data for GLEs

Ground-based observations of the secondary components (mainly muons and neutrons) are still the most reliable sources of data for primary SCRs, which are relativistic particles. Ionization chambers (ICs), muon telescopes (MTs), and neutron monitors (NMs, from the mid 1950s) were the first detectors that were used to register GLEs. The effective energies of particles, detected by these instruments at sea level, are ~25÷35, 15÷20, and 4÷6 GeV, respectively [15]. Neutron detector has been used for the first time to register GLE event of November 19, 1949 [16]. Geomagnetic cutoff rigidity (Rc) of particles during their motion in the Earth's magnetosphere is one of the main CR station characteristics.

The worldwide network of NMs was created more than 50 years ago based on IGY-type NMs. Data acquisition and analysis systems were constantly modernized, and a new modification of such a system, a SNM-64 neutron supermonitor [15], was designed in the early 1960s. Here we use the international

GLE database organized by the University of Oulu [6]. A new generation of the International GLE database is accessible at the web-site URL: https://gle.oulu.fi collecting and archiving data from the worldwide neutron monitor network concerning GLE events. The GLE database covers events starting from № 5 (GLE05 on February 23, 1956) and provides a useful tool for an analysis of the most energetic solar particle events.

Distribution of all GLEs during solar cycles 17-24 (1942-2015)

Seventy two GLEs were registered from February 1942 to the end of 2015. From February 28, 1942 (GLE 01), all events were numbered for the convenience of researchers. The last event in cycle 23 of solar activity (SA) was observed on December 13, 2006 (GLE 70). In cycle 24 (started in January 2009), SCR activity was registered with a delay: the first GLE in the new cycle occurred only on May 17, 2012 (GLE 71). To all appearance, this pause not only reflects the specific properties of cycle 23 (in particular, a very long period of SA minimum) but also characterizes the unusual character of cycle 24, which is most probably a critical cycle in the SA behavior for the last 150÷200 years [15, 22].

Analyzing a list of all GLEs, we can determine several characteristic periods, which are important parameters for manifestations of SA in a concrete solar cycle. The quantifying of GLEs in solar cycles 17÷24 is presented in Table 1. Here are given the introduced periods A, Π, and Δ.

Table 1. Quantifying the GLEs in solar cycles 17÷24 and the corresponding characteristic periods

Solar cycle №	Started (YYYY.MM)	Finished (YYYY.MM)	Duration (years)	№ of GLE	A	Π	Δ
17	1933.09	1944.01	10.4	2	– –	1W	4Y 5M
18	1944.01	1954.02	10.1	2	2Y 6M	3Y 4M	6Y 3M
19	1954.02	1964.10	10.7	10	2Y	5Y 5M	5Y
20	1964.10	1976.05	11.7	12	1Y 9M	6Y 9M	3Y
21	1976.05	1986.08	10.3	13	1Y	7Y 10M	5Y 5M
22	1986.08	1996.08	10.0	15	2Y 11M	3Y 3M	5Y
23	1996.09	2008.12	12.2	16	1Y 2M	9Y 1M	5Y 5M
24	2009.01	2018	Still ongoing	(2)	3Y 5M		

In Table 1, A is the period from the beginning of the considered solar cycle to the appearance of the first GLE. This is a passive period of accumulation of energy, after that begins the next active period Π;

Π is an active period from the first GLE to the last GLE in the considered solar cycle;

Δ is a passive period from the last GLE in the current solar cycle to the appearance of the first GLE of the next solar cycle.

All periods in the Table 1 are expressed in years (Y), months (M) and weeks (W).

From Table 1 we can determine the ratio

(Number of GLE) / Π or N(GLE) / Π

These results are shown in Table 2. From here it is seen that the highest occurrence rate of the GLEs is in the solar cycles 19, 20, and 22.

Table 2. Determination of GLE frequency of occurrence in solar cycles 18÷23

Solar cycle №	17	18	19	20	21	22	23	24
N(GLE) / Π	–	0.6	1.85	1.78	1.66	4.62	1.76	–

Based on Tables 1 and 2, we can assume that some weak GLEs were not registered in the early years of observations due to technical and methodological difficulties. If the average occurrence rate of the GLEs is η ~1.0 yr^{-1}, the number of omitted events in 1942–1956 could be considerable [15]. A prolonged minimum of cycle 23 ended in December 2008; however, cycle 24 (started in January 2009) is proceeding very slowly [23] and sunspot formation as well solar flare and proton activities are generally at a rather low level. Thus, the first GLE 71 on 17 May 2012 was registered during more than three years off the cycle and more than five years after the last event in cycle 23 (GLE 70 on December 13, 2006). More precisely from Table 1 follows: A = 3Y 5M and Δ = 5Y 5M.

GLEs in the current solar cycle 24

In cycle 24 (started in January 2009) the first GLEs was registered at the beginning of 2012 (Table 3). This time delay reflects the specific properties of cycle 23 (in particular, the long lasting solar minimum) and correspondingly the unusual character of cycle 24 [15]. Solar Cycle 24 has been the weakest in the space era according to the measured sunspot number (SSN). The average SSN over the first 73 months of cycle 24 was ~46, compared to 76 over the same epoch in cycle 23. This corresponds to a decrease of ~40% [23]. The solar activity has already entered into the declining phase, but the number of high-energy solar energetic particle (SEP) events has remained very low. During the first 73 months of cycle 24, there were only two ground level enhancement (GLE) events: 2012 May 17 and 2014 January 6 (Table 3). Over the same epoch, there were 9 GLE events in cycle 23. Thus the reduction in the number of GLE events is by 78 %, much higher than that in SSN. The number of SEP events, emitting particles with energies >500 MeV, was also higher in cycle 23 (18 vs. 6 in cycle 24) [24, 25].

Besides GLEs, four more solar energetic proton events are included in Table 3. Three of them occurred in January and March 2012 and have a significant increase of the integral proton fluxes with energies > 500 MeV, registrated by the data from subpolar neutron monitors. As it was found these events were followed by a cosmic ray enhancement of about 2 % at several subpolar and high latitude neutron monitors. Nevertheless, these events may contain some contribution of solar cosmic rays in the ground level observations [26].

Table 3. List of GLEs and contenders for GLEs during solar cycle 24

Event №	Event Date	Baseline Date (YYMMDD)	Recommended Baseline Time Start - End (UT)
(*)	27 January 2012	120127	160000 - 170000
(*)	07 March 2012	120306	230000 - 240000
(*)	13/14 March 2012	120313	160000 - 170000
071	17 May 2012	120517	000000 - 010000
072	06 January 2014	140106	070000 - 080000
(*)	29 October 2015	151029	000000 - 010000

(*) Events 27 January 2012, 7 March 2012, 13 March 2012, and 29 October 2015 are GLE contenders

All four events marked with (*), the three events at the beginning of 2012, as well as the SEP event from 29 October 2015, may be considered as candidate GLEs of SCRs. We will name them quasi-GLEs or abbreviated as qGLEs.

Collective GLEs in solar cycle 24 and before that

Analysis of Table 3 reveals an existence of a collective GLE. Thus the second and the third qGLEs (on 07 March 2012 and on 13/14 March 2012, respectively) represent one common collective event. The flare positions of the corresponding collective GLEs (cGLEs) on the Sun are [26]:

17N 27E for 07 March 2012 and
19N 59W for 13/14 March 2012,

i.e. both qGLEs are generated by one and the same active area AR11429 on the Sun, which has 27-day solar rotation period.

Here we show a number of other cases of cGLEs before solar cycle 24. We demonstrate the new evidence about these phenomena. In Table 4 is presented information about the flare position of every concrete GLE, the universal time (UT) of the onset of event, the Hα/X flare importance, the active area (AR) [15] and the sequence number of the corresponding collective GLE.

List of all collective GLEs during cycles 17÷24

From the above mentioned list of all GLEs (1942-2015), we can show 14 cases of collective GLEs (cGLEs). Yet the first two cases of GLEs (GLE01 on February 28, 1942 and GLE02 on March 7, 1942) represent one collective event. The flare positions of the corresponding GLEs on the Sun were [15]:

07N 04E for GLE01 and
07N 90W for GLE02,

i.e. both cGLEs are generated by one and the same active center on the Sun, which has 27-day solar rotation period. In Table 4 is presented the list of the cGLEs during solar cycles 17÷24.

Table 4. List of collective GLEs (cGLEs) and corresponding flares and active areas (AR) during solar cycles 17÷24

Event №	Event Date		Flare Position	Onset UT	Importance Hα/X	cGLE №
01	28 February	1942 (1)	07N 04E	1228	3+	1
02	07 March	1942 (2)	07N 90W	N.O.	–/–	Double 1
01	28 February	1942 (1)	07N 04E	1228	3+	1
02	07 March	1942 (2)	07N 90W	N.O.	–/–	Double 1
10	12 November	1960 (1)	27N 04W	1315	3+	2
11	15 November	1960 (2)	25N 35W	0207	3+	
12	20 November	1960 (3)	28N 112W	2017	2	Triple 1
13	18 July	1961 (1)	07S 59W	0920	3+	3
14	20 July	1961 (2)	6S 90W	1553	3	Double 2
16	28 January	1967 (1)	22N 150W	<0200	–/–	4
17	28 January	1967 (2)	22N 150W	<0800	–/–	Double 3
24	04 August	1972 (1)	14N 08E	0617	3B/X4	5
25	07 August	1972 (2)	14N 37W	1449	3B/X43D	Double 4
28	19 September	1977 (1)	08N 57W	<0955	3B/X2	6
29	24 September	1977 (2)	10N 120W	<0552	–/–	Double 5
43	19 October	1989 (1)	25S 09E	1229	3B/X13	7
44	22 October	1989 (2)	27S 32W	1708	1N/X2.9	
45	24 October	1989 (3)	29S 57W	1738	2N/X5.7	Triple 2
47	21 May	1990 (1)	34N 37W	2212	2B/X5.5	8

Table 4. List of collective GLEs (cGLEs) and corresponding flares and active areas (AR) during solar cycles 17÷24 (cont.).

Event №	Event Date		Flare Position	Onset UT	Importance Hα/X	cGLE №
48	24 May	1990 (2)	36N 76W	2046	1B/X9.3	
49	26 May	1990 (3)	35N 103W	2045	–/–	
50	28 May	1990 (4)	35N 120W	<0516	–/–	Quadruple 1
51	11 June	1991 (1)	32N 15W	0105	2B/X12	9
52	15 June	1991 (2)	36N 70W	0633	3B/X12	Double 6
56	02 May	1998 (1)	15S 15W	1334	3B/X1.1	10
57	06 May	1998 (2)	11S 65W	0758	1N/X2.7	Double 7
60	15 April	2001 (1)	20S 85W	1319	2B/X14.4	11
61	18 April	2001 (2)	23S 117W	0211	–/–	Double 8
65	28 October	2003 (1)	16S 08E	1100	4B/X17.2	12
66	29 October	2003 (2)	19S 09W	2037	–/X10	
67	02 November	2003 (3)	18S 59W	1718	2B/X8.3	Triple 3
68	17 January	2005 (1)	15N 25W	0659	3B/X3.8	13
69	20 January	2005 (2)	14N 61W	0639	2B/X7.1	Double 9
(*)	07 March	2012 (1)	17N 27E	1100	AR11429/X5.4	14
(*)	13/14 March	2012 (2)	19N 59W	0700	AR11429/M7.9	Double 10

(*) Events 7 March 2012, 13/14 March 2012 are now only contenders for GLEs

List of the recurrent GLE

Some of the investigated events are complex and require more special examinations and analyses. A careful study of the complete list of GLEs available at URL: ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS/ground-level-enhancements/ground-level-enhancements.txt, determinate the existence of different types recurrent ground level enhancements (rGLEs). Some of them are shown in Table 5. A number of these groups are subject to a detailed study with subsequent comprehensive analysis and modeling.

Table 5. List of the recurrent GLEs (rGLEs) and the corresponding flares and active areas (AR) during solar cycles 17÷24

Event №	Event Date		Flare Position	Onset UT	Importance Hα/X	rGLE №
18	29 September	1968 (1)	17N 51W	1617	2B	
19	18 November	1968 (2)	21N 87W	1026	1B	1
20	25 February	1969 (1)	13N 37W	0900	2B/X2	
21	30 March	1969 (2)	19N 103W	0332	1N	2
28	19 September	1977 (1)	08N 57W	0955	3B/X2	
30	22 November	1977 (3)	24N 40W	0945	2B/X1	3
29	24 September	1977 (2)	10N 120W	0552	–/–	
30	22 November	1977 (3)	24N 40W	0945	2B/X1	4
34	10 April	1981 (1)	07N 36W	1632	2B/X2.3	
35	10 May	1981 (2)	03N 75W	0715	1N/M1	5
42	29 September	1989 (1)	24S 105W	1141	1B/X9	
43	19 October	1989 (2)	25S 09E	1229	3B/X13	6
42	29 September	1989 (1)	24S 105W	1141	1B/X9	
44	22 October	1989 (3)	27S 32W	1708	1N/X2.9	7
42	29 September	1989 (1)	24S 105W	1141	1B/X9	
45	24 October	1989 (4)	29S 57W	1738	2N/X5.7	8
42	29 September	1989 (1)	24S 105W	1141	1B/X9	
46	15 November	1989 (5)	11N 28W	0638	2B/X3.2	9
43	19 October	1989 (2)	25S 09E	1229	3B/X13	
46	15 November	1989 (5)	11N 28W	0638	2B/X3.2	
44	22 October	1989 (3)	27S 32W	1708	1N/X2.9	
46	15 November	1989 (5)	11N 28W	0638	2B/X3.2	
45	24 October	1989 (4)	29S 57W	1738	2N/X5.7	
46	15 November	1989 (5)	11N 28W	0638	2B/X3.2	
(*)	07 March	2012 (1-2)	17N 27E	1100	AR11429/X5.4	
(*)	13/14 March	2012 (1-2)	19N 59W	0700	AR11429/M7.9	
71	17 May	2012 (3)	11N 76W	0151	AR11476/M5/1	10

(*) Events 7 March 2012, 13/14 March 2012 are now only contenders for GLEs

Recurrent-collective and collective-recurrent GLEs

The consideration of previous Tables shows the presence of some combined cases of recurrent-collective GLEs (rcGLEs) and collective-recurrent GLEs (crGLEs), which are represented in Table 6. Some of these groups are subject to a detailed study with subsequent detailed analysis and the further numerical or theoretical modeling. These are the most complicated cases, because there is a superposition of different GLE groups. They are presented in Table 6.

Table 6. List of recurrent-collective GLEs (rcGLEs), collective-recurrent GLEs (crGLEs) and corresponding flares, and active areas (AR)

Event №	Event Date	Flare Position	Onset UT	Importance Hα/X	rcGLEs & crGLEs №
42	29 September 1989 (1)	24S 105W	1141	1B/X9	1
43	19 October 1989 (2)	25S 09E	1229	3B/X13	
44	22 October 1989 (2)	27S 32W	1708	1N/X2.9	
45	24 October 1989 (2)	29S 57W	1738	2N/X5.7	
46	15 November 1989 (3)	11N 28W	0638	2B/X3.2	
28	19 September 1977 (1)	08N 57W	< 0955	3B/X2	2
29	24 September 1977 (2)	10N 120W	< 0552	–/–	
30	22 November 1977 (3)	24N 40W	0945	2B/X1	
(*)	07 March 2012 (1)	17N 27E	1100	AR11429/X5.4	3
(*)	13/14 March 2012 (2)	19N 59W	0700	AR11429/M7.9	
71	17 May 2012 (3)	11N 76W	0151	AR11476/M5/1	

(*) Events 7 March 2012, 13/14 March 2012 are now only contenders for GLEs

Presentation of all ground level enhancements GLE 01 – GLE 72 during the period 1942-2015

In Table 7 are presented all ground level enhancements (from GLE 01 to GLE 72) during the whole period of investigation of these events (1942-2015). There in detail are identified the single GLEs, collective GLEs (cGLEs), recurrent GLEs (rGLEs), recurrent-collective GLEs (rcGLEs) and collective-recurrent GLEs (crGLEs). Also are included four contenders for GLEs in the current solar cycle 24. Really these nominees are quasi GLEs (qGLEs) and they are marked by the indication (*). The marked (*) events from 27 January 2012, 7 March 2012, 13 March 2012, and 29 October 2015 are GLE contenders.

Table 7. List of all 72 Ground Level Enhancements (GLEs) during 1942-2015 in the solar cycles 17÷24. Included are: single – sGLEs, collective – cGLEs, recurrent – rGLEs, recurrent-collective – rcGLEs, collective-recurrent – crGLEs, quasi – qGLEs contenders

Event №	Event Date		Baseline Date	Class GLE	Type GLE
			Solar cycle № 17		
01	28 February	1942	420228	cGLE 1	Double (1)
02	07 March	1942	420307	cGLE 1	Double (2)
			Solar cycle № 18		
03	25 July	1946	460725	sGLE 1	Single
04	19 November	1949	491119	sGLE 2	Single
			Solar cycle № 19		
05	23 February	1956	560223	sGLE 3	Single
06	31 August	1956	560831	sGLE 4	Single
07	17 July	1959	590716	sGLE 5	Single
08	04 May	1960	600504	sGLE 6	Single
09	03 September	1960	600902	sGLE 7	Single
10	12 November	1960	601112	cGLE 1	Triple (1)
11	15 November	1960	601115	cGLE 1	Triple (2)
12	20 November	1960	601120	cGLE 1	Triple (3)
13	18 July	1961	610718	cGLE 2	Double (1)
14	20 July	1961	610720	cGLE 2	Double (2)
			Solar cycle № 20		
15	07 July	1966	660706	sGLE 8	Single
16	28 January	1967	670128	cGLE 3	Double (1)
17	28 January	1967	670128	cGLE 3	Double (2)
18	29 September	1968	680929	rGLE 1	Recurrent (1)
19	18 November	1968	681118	rGLE 1	Recurrent (2)
20	25 February	1969	690225	rGLE 2	Recurrent (1)
21	30 March	1969	690330	rGLE 2	Recurrent (2)
22	24 January	1971	710124	sGLE 9	Single
23	01 September	1971	710901	sGLE 10	Single
24	04 August	1972	720804	cGLE 4	Double (1)
25	07 August	1972	720807	cGLE 4	Double (2)
26	29 April	1973	730429	sGLE 11	Single
			Solar cycle № 21		
27	30 April	1976	760430	sGLE 12	Single
28	19 September	1977	770919	cGLE 5	Double (1)
29	24 September	1977	770924	cGLE 5	Double (2)
30	22 November	1977	771122	rGLE 3-4	Recurrent (1-2)
31	07 May	1978	780507	sGLE 13	(Single) Rec. (?)
32	23 September	1978	780923	sGLE 14	(Single) Rec. (?)
33	21 August	1979	790821	sGLE 15	Single
34	10 April	1981	810410	rGLE 5	Recurrent (1)
35	10 May	1981	810510	rGLE 5	Recurrent (2)

Event №	Event Date	Baseline Date	Class GLE	Type GLE
36	12 October 1981	811012	sGLE 16	Single
37	26 November 1982	821126	sGLE 17	Single
38	07 December 1982	821207	sGLE 18	Single
39	16 February 1984	840216	sGLE 19	Single
		Solar cycle № 22		
40	25 July 1989	890725	sGLE 20	Single
41	16 August 1989	890815	sGLE 21	Single
42	29 September 1989	890929	rGLE 6-9	Recurrent (1-4)
43	19 October 1989	891019	cGLE 2	Triple (1)
44	22 October 1989	891022	cGLE 2	Triple (2)
45	24 October 1989	891024	cGLE 2	Triple (3)
46	15 November 1989	891115	rGLE 6-9	Recurrent (1-4)
47	21 May 1990	900521	cGLE 1	Quadruple (1)
48	24 May 1990	900524	cGLE 1	Quadruple (2)
49	26 May 1990	900526	cGLE 1	Quadruple (3)
50	28 May 1990	900528	cGLE 1	Quadruple (4)
51	11 June 1991	910611	cGLE 6	Double (1)
52	15 June 1991	910615	cGLE 6	Double (2)
53	25 June 1992	920625	sGLE 22	Single
54	02 November 1992	921102	sGLE 23	Single
		Solar cycle № 23		
55	06 November 1997	971106	sGLE 24	Single
56	02 May 1998	980502	cGLE 7	Double (1)
57	06 May 1998	980506	cGLE 7	Double (2)
58	24 August 1998	980824	sGLE 25	Single
59	14 July 2000	000714	sGLE 26	Single
60	15 April 2001	010415	cGLE 8	Double (1)
61	18 April 2001	010418	cGLE 8	Double (2)
62	04 November 2001	011104	sGLE 27	Single
63	26 December 2001	011226	sGLE 28	Single
64	24 August 2002	020824	sGLE 29	Single
65	28 October 2003	031028	cGLE 3	Triple (1)
66	29 October 2003	031029	cGLE 3	Triple (2)
67	02 November 2003	031102	cGLE 3	Triple (3)
68	17 January 2005	050117	cGLE 9	Double (1)
69	20 January 2005	050120	cGLE 9	Double (2)
70	13 December 2006	061213	sGLE 30	Single
		Solar cycle № 24		
(*)	27 January 2012	120127	qGLE 1	
(*)	07 March 2012	120307	c(qGLE 2) 10	Double (1)
(*)	13 March 2012	120313	c(qGLE 3) 10	Double (2)
71	17 May 2012	120517	rGLE 10	Recurrent(1-2)
72	06 January 2014	140106	sGLE 31	Single
(*)	29 October 2015	151029	qGLE 4	

The bold and underlined numbers EVENT # indicate the collective GLEs, which are sorted in ascending order. The collective GLEs are also classified in Double, Triple and Quadruple;

The bold and italic numbers EVENT # indicate the recurrent GLEs, which are classified and sorted also in ascending order;

The remaining GLEs are simple, i.e. they are individual increases in CR intensity. Some of them may be substantially strong, as was the case of 23 February 1956 (GLE 05). This is the maximum proton flare in GLE history.

Single GLEs

There are a total of 31 single GLEs, which are designated as sGLE. These are the following events: 03, 04, 05, 06, 07, 08, 09, 15, 22, 23, 26, 27, (31, 32), 33, 36, 37, 38, 39, 40, 41, 53, 54, 55, 58, 59, 62, 63, 64, 70, and 72.

Collective GLEs

We noticed 10 groups of *Double GLEs*: (01, 02); (13, 14); (16, 17); (24, 25); (28, 29); (51, 52); (56, 57); (60, 61); (68, 69); and (71b, 71c).

To GLE 71b and GLE 71c relate the events on 7 March 2012 and 13 March 2012 that already have not autonomous numbering. In such a manner we have a total of 20 double GLEs.

In Table 7 there are also three groups of *Triple GLEs* (10, 11, 12); (43, 44, 45); (65, 66, and 67) and one group of *Quadruple GLEs* (47, 48, 49, and 50).

The recapitulation is as follows:

31 sGLE + 20 double GLEs + 9 triple GLEs + 4 quadruple GLEs = 64 GLEs

Recurrent GLEs

The remaining events are the recurrent GLEs, covering the following 10 groups: (18, 19); (20, 21); (28, 30); (29, 30); (34, 35); (42, 43); (42, 44); (42, 45); (42, 46); and (71c, 71).

It is noteworthy that the events GLE 31 and GLE 32 might appear as recurrent as the delay between them is about five solar rotational periods of 27 days. So to the abovementioned 10 groups of GLEs, probably should be added and this 11th recurrent GLE group (31, 32).

Multi-stage GLEs - recurrent-collective, collective-recurrent, and other complex GLE groups

In Table 7 are observed and the more complex combined groups. For example the GLE group (42, 43, 44, 45, and 46) represents a group of *Recurrent-collective GLEs* (rcGLEs) and the GLE groups (28, 29, and 30) and (71b, 71c, and 71) present *Collective-recurrent GLEs* (crGLEs) (Table 6).

It can be argued that the multi-stage GLE group (42, 43, 44, 45, and 46) represents a group of *Recurrent-collective-recurrent GLEs* (rcrGLEs). This is a new multi-stage GLE series.

Statistics of types and groups of GLEs

The analysis of Table 7 shows that the 31 single GLEs represent only 41.9 % from all 74 GLE events. And if we consider the concerned recurrent GLE group (31, 32), the number of the single GLEs reduces to 29, i.e. 39.2 % from all GLEs.

The number of the collective GLEs is 33 (20 double, 9 triple and 4 quadruple GLEs), which makes the relative number 44.6 % from all 74 GLEs. These types of GLEs dominate over single GLEs.

The number of the recurrent GLEs is 20 (or 22 with the group 31, 32), making 27 % (or 29.7 %) from all 74 GLE events.

Geophysical and applied aspects of GLE effects

The high energetic protons of SCRs that are guided into the middle latitude and Polar Regions collide with atmospheric constituents and release their energy through the process of ionization [3–5]. The majority of the energy is extinguished in the lower region of the ionosphere (around 50÷80 km in altitude), stratosphere (10÷50 km) and troposphere (0÷10 km) .

The ionospheric area is particularly important for propagation of radio waves and communications in wide frequency range because this is the area where the most of the absorption of radio signal energy occurs. The enhanced ionization produced by incoming energetic protons increases the absorption levels in the lower ionosphere and can have the effect of completely blocking all ionospheric radio communications through the polar regions. Such events, the so called Polar Cap Absorption (PCA) events commence and last as long as the energy of incoming protons at approximately greater than 10 MeV exceeds roughly 10 pfu (1 pfu = 1 particle.$cm^{-2}s^{-1}sr^{-1}$) at geosynchronous satellite altitudes.

The relativistic solar particles of GLEs are substantial in many others geophysical processes owing to their ionizing effect, for instance the effects of ozone layer depletion [27, 28], the generation of nitrogen (NOx) and hydrogen (HOx) oxides, generation of cosmogenic isotopes, sudden disturbances in the global atmospheric electrical circuit (GAEC) and many others.

Conclusions

The present article is an attempt to contribute to the detailed investigations of poorly studied SCR/GLE events. These events initiate a nucleonic-electromagnetic cascades in the Earth’s atmosphere [1, 7–12], affecting its physicochemical properties and ion balance [1, 27, 28]. Our consideration indicates that GLEs during registration period (1942-2015) have a complicated distribution (Table 1) and occurrence rate (Table 2). In 14 cases are seen collective GLEs (Table 4), in 10 cases there are recurrent GLEs (Table 5) and also more complex combined groups – recurrent-collective GLEs (rcGLEs), collective-recurrent GLEs (crGLEs), and recurrent-collective-recurrent GLEs (rcrGLEs) (Table 6). In Table 7 are presented all ground level enhancements (from GLE 01 to GLE 72) during the whole period (1942-2015) of investigation of these events. There are identified also the single GLEs. Here are included as well four contenders for GLEs in the current solar cycle 24. Really these are quasi GLEs (qGLEs). The credibility of so indicated groups, however, should be carefully analyzed further. But in all cases one can say confidently that the contribution of the collective GLEs, recurrent GLEs, and other more complex GLE groups, dominates over the contribution of the simple GLE events – sGLEs. This demonstrates that the GLE events in most cases are not single, separate and individual, but joint and group phenomenon.

The SCR/GLE events are not the main source of geophysical disturbances (as compared, e.g., to coronal mass ejections and geomagnetic storms) [15]. However, the arrival of SCRs, the enhancement of the flux of accelerated charged particles (solar protons, helium ions and heavier HZE nuclei) in the Earth's environment and the corresponding appearance of GLEs, can be a sporadic but considerable trigger component of the global mechanism of solar-terrestrial relations.

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РАЗШИРЕНА КАТЕГОРИЗАЦИЯ НА ПОВИШЕНИЯТА НА КОСМИЧЕСКИТЕ ЛЪЧИ НА ЗЕМНАТА ПОВЪРХНОСТ (GLEs) ПОРОДЕНИ ОТ ВИСОКОЕНЕРГИЙНИ СЛЪНЧЕВИ ЧАСТИЦИ

П. Велинов

Резюме

Явлението "увеличение на потока космически лъчи на нивото на земята", т.н. ground level enhancement (GLE), вследствие проникването на слънчеви енергийни частици, има важно значение за редица процеси на Земята. Слънчевите частици са ключът за разбирането на слънчево-земните връзки и космическото време. Въз основа на наземните наблюдения на GLE от 28 февруари 1942 (когато са открити) до края на 2015 г., сме определили някои характерни техни периоди през време на слънчевите цикли 17÷24. Направено е количествено изследване на GLE и е определена честотата на възникването им в различните слънчеви цикли. В работата е представена и една категоризация на изследваните явления (от първото GLE 01 на 28 февруари 1942 до последното GLE 72 на 6 януари 2014 г.) вследствие на слънчевите енергийни частици, достигащи земната повърхност. Установени са нови групи на колективни, рекурентни, рекурентно-колективни, колективно-рекурентни и др. GLEs през време на изследвания период. Обсъдени са също така редица физически, методически и приложни аспекти, свързани със събитията GLE, защото те имат екстремално въздействие върху Земята. Получените резултати имат прогностична стойност и значение за йонизационните и радиационни условия на околната среда и за механизмите на слънчево-земните въздействия.