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Statistical properties of the most powerful solar and heliospheric disturbances

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Abstract

We present and discuss here the first version of a data base of extreme solar and heliospheric events. The data base contains now 87 extreme events mostly since 1940. An event is classified as extreme if one of the three critical parameters passed a lower limit. The critical parameters were the X-ray flux (parameter R), solar proton flux (parameter S) and geomagnetic disturbance level (parameter G). We find that the five strongest extreme events based on four variables (X-rays SEP, Dst, Ap) are completely separate except for the October 2003 event which is one the five most extreme events according to SEP, Dst and Ap. This underlines the special character of the October 2003 event, making it unique within 35 years. We also find that the events based on R and G are rather separate, indicating that the location of even extreme flares on the solar disk is important for geomagnetic effects. We also find that $S = 3$ events are not extreme in the same sense as $R > 3$ and $G > 3$ events, while $S = 5$ events are missing so far. This suggests that it might be useful to rescale the classification of SEP fluxes.

Keywords: Sun; Heliosphere; Extreme solar events; X-ray flares; Solar proton events; Magnetic storms

1. Introduction

The study of space weather and solar-terrestrial relations remains topical and important both from scientific and practical point of view (Cole, 2003; Schwenn, 2006). While the basic concepts of solar-terrestrial physics are well established, many detailed questions and, e.g., the possibility of forecasting needs further investigation (Crooker, 2000; Gopalswamy et al., 2001; Daglis et al., 2003; Gonzalez et al., 2004). Moreover, the unexpected and extreme solar events during solar cycle 23 have raised questions about their causes and properties (Veselovsky et al., 2004; Panasyuk et al., 2003; Yermolaev et al., 2005a; Gopalswamy et al., 2005; Kane and Echer, 2007).

Geomagnetic storm development can be predicted fairly well based on the solar wind and interplanetary magnetic field measurements upstream from the Earth. Measurements in the L1 libration point allow to do this rather reliably about 10–40 min in advance, depending on the solar wind velocity. Also, less certain predictions for much longer lead times exist, based on solar observations (Schwenn et al., 2005).

Many properties of extreme solar and heliospheric events are still poorly known (Ishkov, 2005; Yermolaev et al., 2007). Their study is difficult because they are rare and sometimes out of the range of measurement capability. Also, reliable theoretical models are still lacking. Nevertheless, one can note on a few interesting properties. Extreme solar flares and active regions demonstrate a complicated multi-scale structure and time behavior characterized by

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dimensionless scaling parameters (Conlon et al., 2008; Sen, 2007). Strongest solar and heliospheric events, e.g., major flares and coronal mass ejections have a nonlinear and non-local character from smallest to largest scales. The coupling between the scales, which is still not well understood, often leads to a non-uniform time behavior with multiple energy releases which may be concentrated around one or several active regions, prominences or coronal holes, and have an asymmetric hemispheric or longitudinal distribution (Veselovsky et al., 2005; Mursula, 2007).

The aim of this paper is to present and investigate an empirical data base of the most powerful solar and heliospheric disturbances.

2. Compilation of extreme event data base

We are using the five-scale NOAA classification of space weather disturbances: minor (1), moderate (2), strong (3), severe (4), and extreme (5) (www.sec.noaa.gov/NOAAscales; Ishkov, 2005). Table 1 shows the five X-ray flare classes (R1–R5) ordered by the maximum intensity of soft X-rays in the energy range 1–12.5 keV (0.1–0.8 nm) observed at the Earth's orbit. It is worth to mention that X-ray flares can lead to sudden ionospheric disturbances and cause radio communication problems also called radio blackouts (which is why X-ray classification is indicated by *R*). We have considered extreme and, thereby, included in our data base all those events in the NOAA data base that have been classified as R4 or R5 (http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarflares.html).

Solar proton events (SEP classes S1–S5) are given in units of pfu (proton flux unit), which is the number of protons at the Earth's orbit per cm^2 per steradian per second with energy higher than 10 MeV. Solar proton events appear as a result of particle acceleration in solar flares and in heliospheric shocks. Events with SEP classes S3–S4 are included as extreme events in our data base. Note that no S5 class event has been observed yet (Shea and Smart, 1990; Miroshnichenko, 2003; http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt).

Geomagnetic storms (classes G1–G5) result from the impact of the disturbed solar wind and interplanetary magnetic field upon the magnetosphere of the Earth. The key controlling factor of the intensity and duration of the storm is the southward component of the interplanetary magnetic field. Index *G* is based on the planetary geomagnetic 3-h Kp index, which is produced from measurements at 12 ground-based magnetic observatories at mid-latitudes. Geomagnetic storms of index G4 and G5 are included as extreme events in the data base (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/, http://swdcwww.kugi.kyoto-u.ac.jp/kp/index.html).

Table 2 presents our data base of extreme events based on the three parameters (R, S, G) so that if either the *R* value or the *G* value of the event was 4 or 5, the event was considered extreme and included in the data base. Also, if the *S* value was 3 or 4, the event was included in the data base. The columns in Table 2 indicate (1) the event number; (2) the year; (3) date and (4) UT time of the event in the Sun; (5) the coordinates and (6) NOAA classification number of the solar active region; (7) the X-ray and/or optical flare classes; (8) the speed (in km/s) of the possibly related coronal mass ejection according to the SOHO LASCO CME catalogue (http://cdaw.gsfc.nasa.gov/CME_list/); (9) the solar energetic proton flux (in pfu); (10) the duration (in hours) of the geomagnetic storm, (11) the maximum Ap index; (12) the minimum Dst index; the related five-scale NOAA classes for (13) *R* , (14) *S*, and (15) *G*. Blank entries in the table indicate gaps in data or irrelevance.

From early 1970s onward, the data base is more or less complete and homogeneous with all three selection parameters (R, S, G) having measured values. In earlier times, since 1932, the event selection was only based on the *G* value or, from 1942 onwards, partially on both *G* and *S* (Miroshnichenko, 2003). As additional information on flare activity, we have also included the flare classes based on white-light (optical) observations. From about 1940 to 1966, the flares observed in white light were classified in three classes (1–3), with 3+ indicating the largest flares. Thereafter they were classified in four main classes (1–4), with subdivisions indicated by letters (see, e.g., Dodson and Hedeman, 1975).

Note that the data base can be extended even further back in time using the long-term geomagnetic indices like the Aa* index (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/). In the future we will extend the data base by using the relation between the Ap/Kp indices known since 1932 with the aa index (Mayaud, 1980), the recent Ah index (Mursula and Martini, 2007) and with the extended and corrected Dst/Dcx index (Mursula and Karinen, 2005).

Table 1
NOAA classification of space weather perturbations (www.sec.noaa.gov/NOAAscales; Ishkov, 2005).

NOAA scale	*R* radio blackouts (X-ray flux)	*S* SEP (flux of $E > 10$ MeV particles)	*G* geomagnetic storm (Kp value)
5 – Extreme	>*X*20 (2×10^{-3} W m^{-2})	>100,000 pfu	9
4 – Severe	>*X*10 (10^{-3} W m^{-2})	>10,000 pfu	8 and 9
3 – Strong	>*X*1 (10^{-4} W m^{-2})	>1000 pfu	7
2 – Moderate	>M5 (5×10^{-5} W m^{-2})	>100 pfu	6
1 – Minor	>M1 (10^{-5} W m^{-2})	>10 pfu	5

Table 2
The compiled data base of the most powerful perturbations on the Sun and in the heliosphere.

N	Year	Date	UT	Coordinates	AR	Flare class	CME	SEP	Duration (Δ*t*)	Ap	Dst	*R*	*S*	*G*
1	1859	01.09.1859										5		5
2	1940	23.03.1940	11:30	N27E37		3			23–27.03 (78)	277				5
3		27.03.1940	17:10	N12W17		3			28.03–2.4(87)	226				4
4	1941	03.07.1941	15:09	N12E03		3+			04.–08.7(69)	222				5
5		17.09.1941	7:35	N08W08		3+			17–20.09 (60)	312				4
6	1946	27.03.1946	4:10	N19E05		3			27–29.03(39)	215				4
7		25.07.1946	16:10	N21E16		3+			25–28.07(36)	212				5
8		19.09.1946	3:15	N21E08		3			21–24.09(63)	214				5
9	1949	19.11.1949		S02W70		3+		41 (>435)		80			3	2
10	1956	23.02.1956		N23W80		3		250 (>435)		236			4	4
11	1957	31.08.1957	13:21	N25W02		3			01–6.09(105)	221	−324			5
12	1958	07.07.1958	0:20	N28W07		3+			07–10.07(48)	216	−330			5
13	1959	14.07.1959	3:42	N17E07		3+		240 (>88)	15–17.07 (42)	252	−429		4	5
14	1960	29.03.1960	6:50	N12E31		2+			30.03–4.4(93)	251	−327			4
15		10.11.1960	10:09	N29E20		3+			12–16.11 (54)	293	−339			4
16		12.11.1960		N26W05		3+		21,000					4	5
17		15.11.1960		N26W33		3+		21,000					4	4
18	1961	12.07.1961		S07E22		3+		25,000					4	4
19	1967	23.05.1967	18:35	N28E25		3B			24–27.05 (45)	241	−387			5
20	1969	10.04.1969	3:59	N11E90		3		1375	–	32	−26		3	1
21		02.11.1969	11:22	N14W90		3+		1317	8–10.11(9)	45	−46		3	2
22	1971	24.01.1971	23:31	N18W49		3B		1171	27–28.01(6)	41	−97		3	2
23	1972	04.08.1972	6:17	N14E08	331	*X* > 5/3B		86,000	03–07.08(81)	223	−125	5	4	5
24		07.08.1972			331	*X* > 5.4(>30)		3500	8–10.08(27)	111	−154	5	3	5
25	1974	04.07.1974		S14L156	433			329	4–07.07(57)	142	−204	4	2	4
26	1978	28.04.1978	13:06	N22E41	1092	*X*5/4B		1000	29.04–5.05(111)	130	−145	4	3	4
27		11.07.1978		N18E45L170	1203	*X* > 12.5? (*X*15)		20	13–15.07(15)	51	−54	4	1	2
28		23.09.1978	10:23	N35W50	1294	*X*1/3B		2200	25–27.09(6)	43	−62	3	3	2
29	1981	07.10.1981	23:08	S19E88	3390	*X*3/1B		2000	10–11.10(15)	51	−113	3	3	2
30	1982	06.06.1982	16:37	S11E26L086	3763	*X*12.0/3B		30	9–11.06(21)	51	−66	4	1	2
31		09.07.1982	7:20	N18E76	3804	*X*9/3B		2900	11–15.07(78)	229	−325	4	3	5
32		13.07.1982		N11E36	3804	*X*7.1/3B		2900	11–15.07(78)	229	−325	3	3	5
33		07.12.1982	23:54	S14W81	3390	*X*2/0B		1000	9–11.12(15)	50	−78	3	3	2
34		15.12.1982	2:02	S09E24L077	4026	*X* > 12.5? (*X*12.9/2B)		130	19–12.12(21)	62	−106	4	3	3
35		17.12.1982		S08W20L089	4025	*X*10.1		85	19–21.12(21)	46	−58	4	1	3
36	1984	24.04.1984		S11E45L334	4474	*X* > 12.5? (*X*13/4B)		2500	25–27.04(42)	102	−93	4	3	4
37		20.05.1984		S07E53L357	4492	*X*10.1		31	20–22.05(21)	80	−69	4	1	2
38	1986	06.02.1986	6:06	S08W02	4711	*X*1/3B		130	6–10.02(63)	228	−307	3	2	5
39	1989	06.03.1989	14:05	N33E71L	5395	(*X*15/3B)		3500	–	56	−44	4	3	1
40		08.03.1989		N33E71	5395	*X* > 12/3B		3500	12–16.03 (69)	285	−589	4	3	1
41		10.03.1989	18:37	N32E22	5395	*X*4		3500	12–16.03 (69)	285	−589	3	3	5
42		17.03.1989	17:44	N33W60	5395	*X*6/2B		2000	20–22.03(36)	70	−75	3	3	3
43		12.08.1989	14:27	S16W38	5629	*X*2.6/2B		9200	13–16.08 (54)	77	−145	3	4	3
44		16.08.1989	0:54	S15W85L076	5629	*X* > 12.5? (*X*20)		1000	17.08(3)	44	−65	5	3	2
45		29.09.1989	11:39	S32W90	5698	*X*9.8/2N		4500	–	27	−37	4	3	1
46		19.10.1989	12:58	S25E10L211	5747	*X* > 12.5/3B(*X*13/4B)		39,000	19–23.10(69)	236	−268	4	4	4
47		30.11.1989	12:27	N25W52	5800	*X*2.6/2N(*X*2/3B)		4340	7300 (20)	80	−85	3	3	2
48	1991	25.01.1991		S12E90L	6471	*X*10.7			–	39	−23	4	1	1
49		22.03.1991	22:47	S26E28	6555	*X*9.4/3B		50,000	24–27.03(84)	181	−298	4	4	4
50		01.06.1991	14:56	N25E90L248	6659	*X* > 12.5/1F(26 m)			3–7.06(54)	196	−218	5	1	4
51		04.06.1991	3:37	N30E70L248	6659	*X* > 12.5/3B(19 m)		3000	3–7.06(54)	196	−218	5	3	4
52		06.06.1991	0:58	N33E44L248	6659	*X* > 12.5/4B(26 m)		3000	8–14.06(132)	111	−140	5	3	3
53		09.06.1991		N32E13L248	6659	*X*10.0		3000	8–14.06(132)	271	−140	4	3	4
54		11.06.1991	1:56	N32W15L248	6659	*X* > 12.5/2B(17 m)		3000	16–18.06(24)	179	−114	5	3	4
55		15.06.1991	8:10	N33W66L248	6659	*X* > 12.5/3B(22 m)		1400	16–18.06(24)	154	−70	5	3	3
56		07.07.1991	2:23	N26E03	6703	*X*1/2B		2000	7–10/07(48)	128	−194	3	3	4
57	1992	08.05.1992	15:46	S25E07	7154	M7.4/2N		4550	9–12.05(54)	193	−288	2	3	4
58		30.10.1992	18:16	S22W61	7321	*X*1/2B2700		2700	–		−36	3	3	1
59		02.11.1992	2:31	S23W107	7321	*X*9		2000	4–5.11(18)	44	−67	4	3	2
60	1994	20.02.1994	1:41	No9W02	7671	M4/3B(21–22)		10,000	20–23.02(39)	139	−144	2	4	4
61	1997	06.11.1997	11:55	S18W632B	8100	*X* 9.4/2B	1300	490	06–08.11(21)	49	−110	4	3	3
62	1998	20.04.1998	10:21	S43W90	8194	M1/Epl	1007	1700	23–24.04(6)	40	−69	1	3	2
63		30.09.1998	13:50	N23W82	8340	M2/2N	NA	1200	–		−56	1	3	2

Table 2 (*continued*)

N	Year	Date	UT	Coordinates	AR	Flare class	CME	SEP	Duration (Δ*t*)	Ap	Dst	*R*	*S*	*G*
64	2000	14.07.2000	10:54	N22W07	9077	*X*5/3B	1674	24,000	13–17.07(54)	192	−301	3	4	5
65		08.11.2000	23:06	N10W77	9213	M.7.4/3F	1738	14,800	9–11.11(12)	84	−96	2	4	2
66	2001	29.03.2001	10:26	N20W19	9393	*X*1/1N	942	35	30.03–1.04(42)	192	−387	3	1	4
67		02.04.2001	22:06	N19W90L152	9393	$X > 17.5$(<5 m) *X*20	2505	1100	–	48	−36	5	3	1
68		10.04.2001	5:30	S23W09	9415	*X*2/3B	2411	335	10–13.04(30)	236	−271	3	2	4
69		15.04.2001	14:06	S20W85L001	9415	*X*14.4/2B	1199	951	17–19.04(21)	111	−114	4	3	3
70		24.09.2001	10:30	S16E23	9632	*X*2/2B	2402	12,900	25–26.09(21)	154	−102	3	4	3
71		01.10.2001	5:15	S22W91	9628	M9	530	2360	1–4.10(42)	82	−166	2	3	3
72		04.11.2001	16:35	N06W18	9684	*X*1/3B	1810	31,700	05–7.11(39)	142	−292	3	4	4
73		22.11.2001	23:30	S15W34	9704	M9/2N	1437	18,900	23–25.11.(30)	104	−221	2	4	4
74	2002	21.04.2002	1:27	S14W84	9906	*X*1/F1	2409	2520	–	80	−53	3	3	2
75	2003	28.10.2003	11:30	S16E08L286	10,486	*X*17.2/4B	2459	29,500	29.10.–1(78)	252	−383	5	4	5
76		29.10.2003	20:54	S15W02L286	10,486	*X*10/2B	2029	29,500	29.10.–1(78)	200	−307	4	4	5
77		02.11.2003	17:30	S14W56	10,486	*X*8.3/2B	2598	1570	04.11.2003	132	−69	3	3	3
78		04.11.2003	19:54	S19W83L286	10,486	$X > 17.5$/3B(12 m)*X*28	2657	353	–		−20	5	2	2
79		18.11.2003	8:50	N00E18		2N/M3.2/M39	1660	13	19–22.11(36)	170	−422	2	1	4
80	2004	25.07.2004	15:14	N08W33	10,652	M1/1F	1530	2086	26–27.07	300	−197	1	3	4
81		06.11.2004	0:11	N10E08	10,696	2N/M9.3/M5.9/M3.6	1960	495	7–11.11(90)	206	−370	1	2	4
82		07.11.2004	15:42	N03W17	10,696	*X*2.0/2B	1800	460	7–11.11(90)	161	−289	3	2	4
83	2005	15.01.2005	22:25	N14W08L179	10,720	*X*2.6	2596	5040	16–18.01(66)	91	−121	3	3	4
84		13.05.2005	16:13	N11E11	10,759	M8/2B	1689	3140	14–17.05(45)	236	−263	2	3	4
85		07.09.2005	17:17	S06E89L229	10,808	*X*17.1/3B	NA	1880	10–14.09(72)	101	−147	5	3	3
86	2006	06.12.2006	10:45	S06E59	10,930	*X*9.0		1980	–	20	−17	4	3	1
87		13.12.2006	2:14	S07W22	10,930	*X*3.4		698	14–16.12(33)	120	−139	3	2	4

3. Analysis of extreme events

Fig. 1 shows the distribution of the extreme events of Table 2 during the solar cycles 17–23. It is seen that extreme events can occur even during solar minima, but quite rarely (e.g., in February 1986 and December 2006).

Table 3 shows the number of extreme X-ray flares ($X > 10$) and the maximum values of the three critical parameters, SEP flux, Ap index, and Dst index for each solar cycle. The strongest proton event (highest SEP flux)

Table 3
Largest values for each solar cycle.

SC	Period	Number of flares with $X > 10$	SEPmax	Ap max	Dst min
18	02.1944–04.1954	4		215	
19	04.1954–10.1964	8	25,000	293	−429
20	10.1964–06.1976	3	86,000	241	−387
21	06.1976–09.1986	6	2900	229	−325
22	09.1986–05.1996	10	50,000	285	−589
23	05.1996–11.2006	6	24,000	252	−472

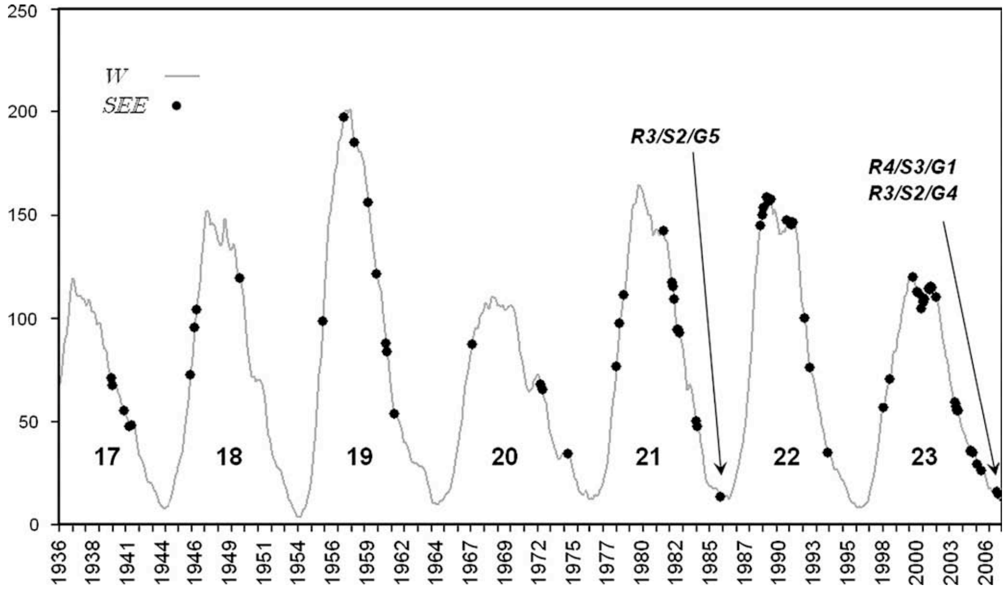

Fig. 1. The temporal distribution of extreme events (dots) during solar cycles 17–23. Extreme events can occur even at solar minima (arrows).

Table 4
The five strongest events according to X-ray flux, SEP flux, Dst and Ap indices.

$X > 10$	01.06.1991	$X > 12.5$/1F (26 m)	Dst	14.03.1989	−589
	06.06.1991	$X > 12.5$/4 (26 m)		18.11.2003	−472
	04.11.2003	$X > 17.5$/3 (11 m) X28		29.10.2003	−401
	15.06.1991	$X > 12.5$/1F (22 m)		14.07.1959	−429
	07.09.2005	$X > 17.1$		29.03.2001	−387
SEP	04.08.1972	86,000	Ap	17.09.1941	312
	19.10.1989	39,000		10.11.1960	293
	22.03.1991	50,000		10.03.1989	285
	14.07.2000	24,000		23.03.1940	277
	28.10.2003	33,600		28.10.2003	252

was observed during solar cycle 20, the largest Ap index was found during solar cycle 19, and the strongest storm (minimum Dst value) was detected during solar cycle 22.

Table 4 presents the five strongest events of Table 2 according to the solar X-ray flux, the SEP flux, the Dst index and the Ap index. It is interesting to note that the five strongest extreme events selected based on each of the four variables are completely separate except for one event in October 2003 which is in three of the four lists based on SEP, Dst and Ap. This underlines the special character of the October 2003 event, making it unique within 35 years. We also note that the fact that the strongest events are separate even in the Ap and Dst index lists underlines their mutual difference.

Fig. 2 shows the histogram distributions of the three critical parameters (R, S, G) for all events in Table 2. One can see that the maxima take place for $R = 3$, $S = 3$ and $G = 4$. So, the maxima for S and G occur for values classified as extreme, while for R it is slightly below it. In all cases, there are several events which have a non-extreme value.

In order to have a homogeneous statistics, we have next selected only those of Table 2 for which all the three critical parameters (R, S, G) are known, and projected them in the three projections of the R, S, G index space in Fig. 3. Out of these 65 events, 32 events (roughly 50%) are classified as extreme according to R, 50 (roughly 77%) according to S and 30 (roughly 46%) according to G. This indicates that the selection criterium was less strict for S than the other two variables, in accordance with including even $S = 3$ events as extreme. When studying the statistics of R-based extreme events in more detail, one finds that 78% are extreme also according to S, but only 38% according to G. Similarly, out of the 30 G-based extreme events 40% were extreme also in R and 77% in S. However, out of the 50 extreme S-events, 50% were also extreme according to R and 46% according to G.

This statistics shows that the extreme events based on R do not typically lead to an extreme event in G and vice versa. Only in about 40% of events, both parameters attain the extreme classification. This is physically quite understandable since large flares do not have to lead to CMEs

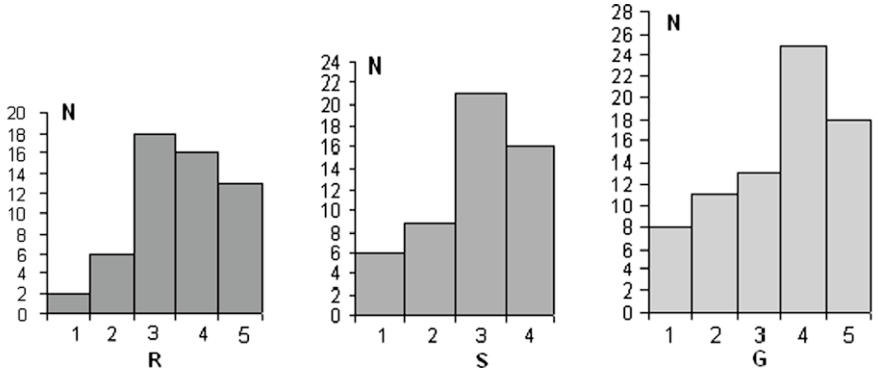

Fig. 2. Distributions of the number of extreme events from Table 2 according to parameters R, S, G.

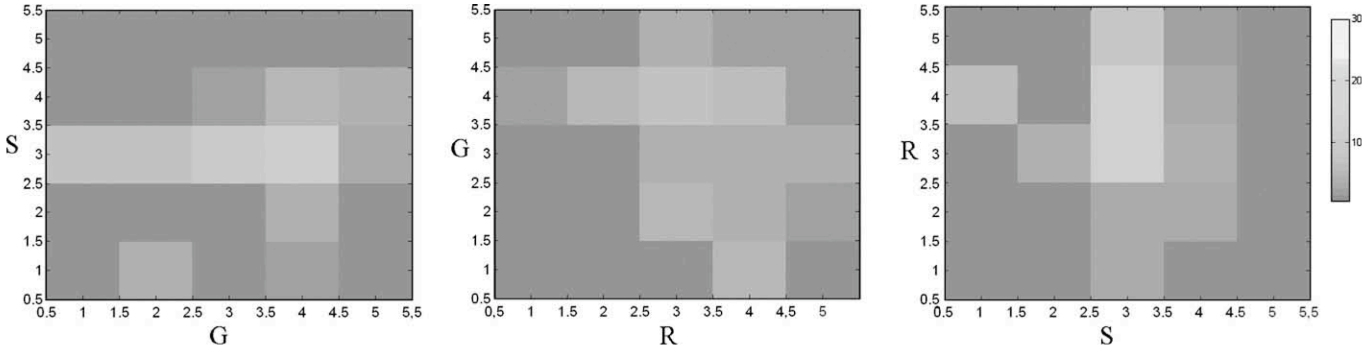

Fig. 3. The occurrence frequency distribution of extreme events in the generalized (R, G, S) space of parameters.

that are sufficiently directed towards the Earth to cause an intense storm. Rather, this depends very much on the location of the flare event on the solar disk. The statistics found is very well in accordance with this view. The same argument also applies to correlation of events based on *R* and *S* because the direction of protons produced during a flare depends on the flare location and the momentary direction of the interplanetary magnetic field.

On the other hand, both for *R* and *G*-based extreme events, a clearly larger percentage (almost 80%) were also extreme according to *S*. So, fluences of class $S = 3$ could be found in a very large fraction of *R*-based or *G*-based extreme events. In reverse, out of $S = 3$ or $S = 4$ events, roughly 50% were extreme in both other parameters. This further indicates that the classification of $S = 3$ is indeed too low to be considered as "extreme" in the same sense as $R = 4$, 5 or $G = 4$, 5. Remember that our selection of $S = 3$ as extreme was based on the fact that no $S = 5$ events have been observed by now. It might be useful if the classification of proton events was based a denser than a decadal classification.

4. Conclusions

We have created and presented here the first version of a data base of extreme solar and heliospheric events. The data base contains now the Carrington storm in 1859 and 86 extreme events since 1932. An event was classified as extreme if one of the three critical parameters passed a lower limit. The critical parameters were those used by NOAA: X-ray flux (parameter *R*), solar proton flux (parameter *S*) and geomagnetic disturbance level (parameter *G*). Extreme events can occur at any phase of the solar cycle, although maximum times are more probable than minima.

Some 40% of *R*-based extreme events are seen as extreme in *G* and vice versa. This suggests that the "big flare syndrome" is partially valid, but the location of even extreme flares on the solar disk is important for their geomagnetic effects. We also found that $S = 3$ events are not extreme in the same sense as $R > 3$ and $G > 3$ events, while $S = 5$ events are missing so far. This suggests that it might be useful to rescale the classification of SEP fluxes.

We found that the five strongest extreme events based on four variables (X-rays SEP, Dst, Ap) are completely separate except for the October 2003 event which is one the five most extreme events according to SEP, Dst and Ap. This underlines the special character of the October 2003 event, making it unique within 35 years.

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