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Statistical analysis of solar proton events

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Abstract. A new catalogue of 253 solar proton events (SPEs) with energy >10 MeV and peak intensity >10 protons/cm^2.s.sr (pfu) at the Earth's orbit for three complete 11-year solar cycles (1970–2002) is given. A statistical analysis of this data set of SPEs and their associated flares that occurred during this time period is presented. It is outlined that 231 of these proton events are flare related and only 22 of them are not associated with Ha flares. It is also noteworthy that 42 of these events are registered as Ground Level Enhancements (GLEs) in neutron monitors. The longitudinal distribution of the associated flares shows that a great number of these events are connected with west flares. This analysis enables one to understand the long-term dependence of the SPEs and the related flare characteristics on the solar cycle which are useful for space weather prediction.

Key words. Interplanetary physics (Energetic particles; Flare and stream dynamics; Interplanetary shocks)

1 Introduction

Solar energetic particles, high-energy neutral emissions, coronal mass ejections (CMEs) and shock waves associated with fast CMEs determine the space weather at the Earth's orbit. The most powerful sources of solar energetic particle fluxes observed at 1 AU are flares and interplanetary shock waves. The dynamic of energetic particles within the heliosphere involves the problems of acceleration, particles escaping and spreading near the Sun and propagation through the interplanetary medium. Actually, all of the above processes display a high degree of variability that results in the great diversity of the time behavior of the particle fluxes measured at 1 AU.

Significant progress has been made in the understanding of electromagnetic phenomena associated with the particle acceleration during the flares. The basic patterns of particle interplanetary transport and additional acceleration on the interplanetary shock have been elaborated during the period between 1960 and 1980 (Dorman and Miroschnichenko 1968; Miroshnichenko, 2001). Pitch angle scattering plays an important role in the particle propagation. Transport includes the diffusion parallel and perpendicular to the mean magnetic field direction, focusing, drift motion under large-scale field changes and sometimes "scatter-free" propagation. Acceleration can take place at a shock front with the help of additional scattering centers moving relative to the shock (McCracken et al., 1962; Roelof, 1969; Richter et al., 1981; Cliver et al., 1982; Valdes-Galicia et al., 1984; Mason et al., 1984; Forman et al., 1986; Reames D. V., 1999; Wibberenz et al., 1992).

For first time Van Hollebeke et al. (1975) using the data from the Goddard cosmic ray experiments on IMP-IV and -V, applied the procedure for identifying the associated flare of a solar proton enhancement and summarized the properties of 125 events in which the initiating flare location could be defined. The existence of a "preferable connection region" within 20° W to 80° W has been found. It was clarified that the maximum of the fluxes in each energy interval (energy spectrum) and high-energy threshold of the spectrum are the most important characteristics of solar energetic particle events. Cane et al. (1988) rested upon numerous original works and formulated that the intensity-time profiles of solar energetic particles display an organization with respect to heliolongitudes of parent flares, and the existing interplanetary shocks are the controlling agent. They explained the time behavior of solar energetic particles as a function of the longitude within the model framework for the large-scale structure of interplanetary shocks, which are probably driven by the piston of CME.

However, until now a persistent problem in the study of solar cosmic rays is the lack of exact information on the timing and on the conditions of accelerated protons spreading and escaping. One approach to understand the variability of the solar energetic particles fluxes measured at 1 AU is a statistical study of their association with solar flares, with the shock wave and CME propagation on a large number of events.

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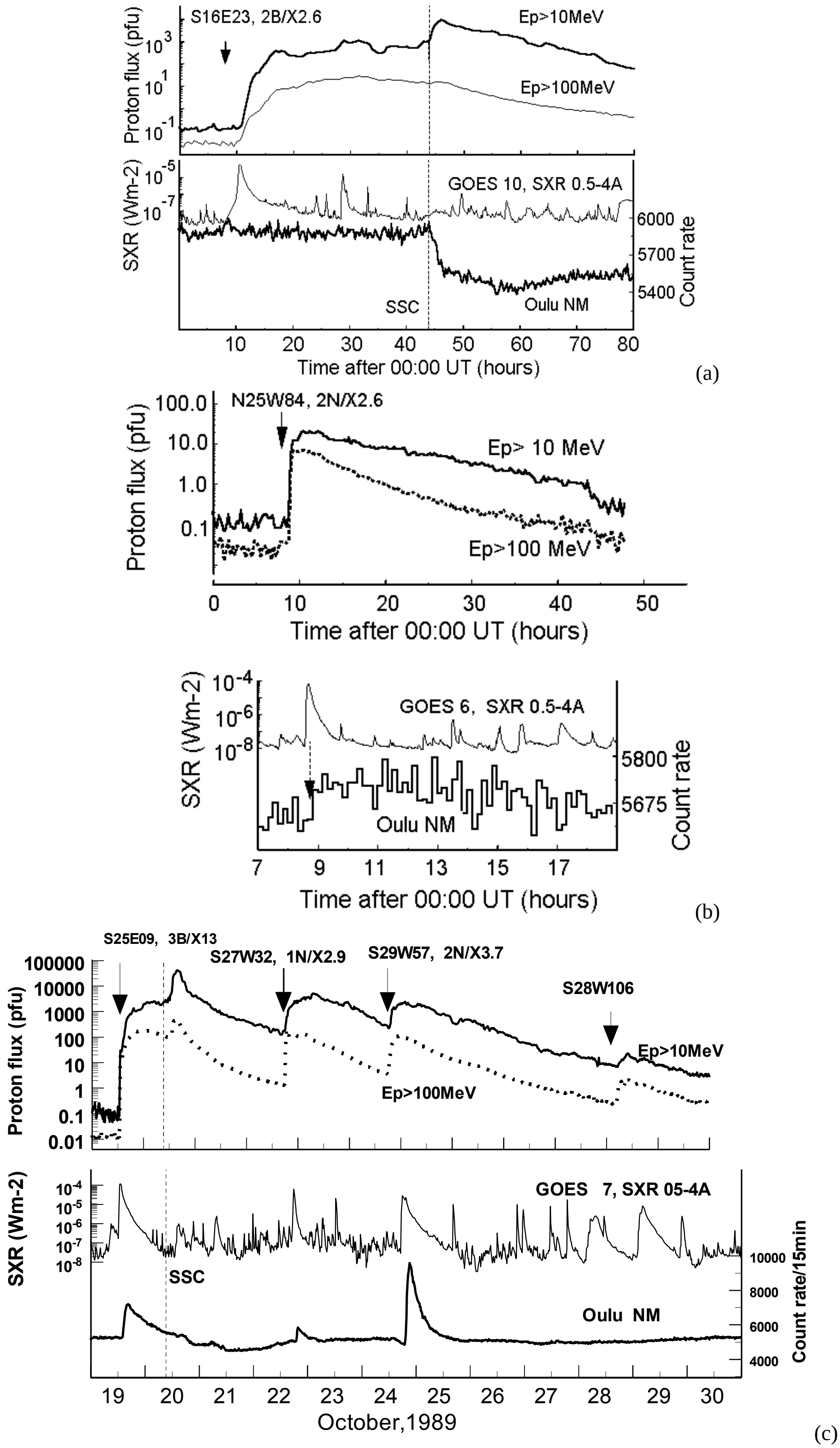

Fig. 1. Typical examples of large solar proton events which occurred on 24 September 2001, 25 July 1989 and during the time interval from 18 October to 31 October 1989, respectively.

According to the National Oceanic and Atmospheric Administration of the Solar Environment Center (NOAA/SEC) definition, a "solar proton event" (SPE) is the solar energetic particles' enhancement in which proton flux with energy Ep>10 MeV is greater or equal to 10 part/cm^2.s.sr (10 pfu) up to the background level near 1AU. The onset time of a proton event is defined by the first three consecutive 5 min average data points with fluxes greater than or equal to 10 pfu. The end of the event is the last time when the flux was greater than or equal to 10 pfu. This definition allows for multiple proton enhancements to be considered as one proton event.

Several catalogues of SPEs have been created and their data are analyzed within the framework of particle acceleration in different sources at or near the Sun (Van Hollebeke et al., 1974; Svestka and Simon, 1975; Basilevskaya et al., 1983; 1986; Sladkova et al., 1990; 1998; Cliver et al., 1991; Stolpovsky et al., 1988; Goswami et al., 1988; Shea and Smart, 1990; Feynmann et al., 1993; Gabriel and Feynmann, 1996; King 1984; Crosby et al., 1993; Mendoza et al., 1997; Gerontidou et al., 2002)

This work presents a new updated catalogue of solar energetic particles events for the time interval 1970–2002. Statistical properties of SPEs and their association with neutron monitor enhancements as well as some properties of the solar flares, identified as "associated", are discussed. This catalogue is mainly based on the catalogue of solar proton events edited by Logachev at the Institute of Nuclear Physics of Moscow University (Basilevskaya et al., 1983; 1986; Sladkova et al., 1990; 1998) that covers the time span 1970–1996. In these issues the particle flux time profiles are taken from the Meteor satellite observations (Fedorov, Institute of Applied Geophysics), GOES, IMP and balloon (Lebedev Physical Institute of Russian Academy of Sciences) measurements and Neutron Monitor Network (NMN), as well. The intensity-time profiles of proton fluxes in several energy bands, the integral proton energy spectrum, as well as information on the possible SPE sources for each event, can be found in these issues. Listing of these events was extended up to now using the issues from NOAA SEC (2002). The NMN database of IZMIRAN (http://www.izmiran.rssi.ru) was also used for identification of the ground level enhancements (GLEs).

2 Catalogue description

Protons can be accelerated to energies more than 10 MeV during the flare development or near the shock front associated with the CME propagation. Thus, when one speaks about the source of the solar proton event, these two different sources are mentioned. Time profiles of SPEs appear to be different for these two sources and depend on the relative position of the observation point.

In order to demonstrate this difference among SPE characteristics, time profiles for three different cases of SPEs are presented in Fig. 1a, 1b and 1c. A typical solar proton event which occurred on 24 September 2001 is given in Fig. 1a. The "associated flare" of this event occurred with importance 2B/X2 and was located at S16 E23, while the soft X-rays duration was about 97 minutes. A coronal mass ejection and a shock wave were associated with this flare. When the interplanetary disturbance reached the Earth, a strong geomagnetic storm and a big Forbush decrease started on 25 September at 20:25 UT. The peak values of 10 MeV proton flux was achieved at about 08:00–09:00 UT on 26 September, simultaneously with the minimum value of cosmic ray intensity recorded at NM stations. Time profile of the SPE exhibits two strongly pronounced increases; nevertheless, according to the NOAA SEC definition, proton enhancement is considered as "one" event, and maximum flux values (Tmax and Imax) have been attributed to fluxes registered simultaneously with the shock.

An exceptional event of our catalogue is the event of 25 July 1989, presented in Fig. 1b. In spite of the fact that the peak flux for Ep>10 MeV protons was only three times greater than the threshold intensity (10 pfu), it was recorded as ground level enhancement at the Earth. The time profile of 10 MeV protons was very sharp with a time rise of about 180 minutes. An associated flare with importance X2.6/2N was located at N25W84 and had a total duration of 29 minutes.

The widely known time interval from 18 October to 31 October 1989 is the period with the highest proton fluxes over the history of space explorations. The spectacular time profiles of the protons are presented in Fig. 1c. A powerful flare at 19 October with importance 3B/X13 was the first one in the series of long duration SXR flares accompanied by SPE. The maximum flux was registered simultaneously with sudden storm commencement (SSC) and Forbush decrease at 09:20 UT on 20 October. Three GLEs were recorded at neutron monitors on 19, 22 and 24 October. The GLEs on 19 and 24 October, having at the South Pole neutron monitor magnitudes greater than of 90% and 200%, respectively, are among the biggest GLEs of the solar cycles 20–23.

In this study the associated sources of each solar proton event with peak flux >10 pfu were found. Contrary to the NOAA/SEC definition, we tried to find and to distinguish a diffusion maximum of each event. Of course, there are events without any association with flares and when an SPE is created by far eastern flares, the associated flare identification is poor. The time profile of these events exhibits only one maximum that coincided in time with the sudden commencement occurence. In this case this is adopted as the maximum value of the event. A list of 253 solar proton events with energy >10 MeV and peak intensity >10 pfu over the time period 1970–2002 is presented in Table 1. After the numbering of the events the first two columns of this Table are the date and the onset time of each event. The time interval with intensity ≥90% of the peak flux (peak duration) and peak flux are given in the next two columns.

Table 1. List of solar proton events with energy > 10 MeV and intensity > 10 pfu for the period 1970–2002.

SOLAR PROTON EVENTS					"ASSOCIATED" Hα FLARES					GLEs
Number of Event	Date yy/mm/dd	Onset time dd/hh	Peak duration dd/hh-dd/hh	Peak flux pfu	Tstart dd/hh:min	Tmax dd/hh:min	Position	Imp.	Region	NM incr
1	70/01/31	31/~18	31/20-01/01	20	31/15:12	31/15:35	S23 W62	2B/M4	10542	No
2	70/03/08	08/~12	08/00-08/03	100	08/01:38	08/01:52	S12 E10	2B/M5	10614	No
3	70/03/23	23/~20	23/21-23/24	10	23/15:45	23/15:48	N18 W62	1N	10638	No
4	70/03/29	29/~01	29/19	60	29/00:32	29/00:46	N13 W37	2B/X2	10641	No
5	70/05/30	30/~02	30/20-30/21	20	30/02:18	30/03:38	S08 W30	2B/>M4	10760	No
6	70/06/25	25/~23	26/07-26/08	10	25/18:33	25/18:38	N10 E11	2B/M3	10801	No
7	70/07/23	23/~23	25/00-25/01	10	23/18:31	23/18:43	N09 E09	1B/X2	10845	No
8	70/11/05	05/~05	07/06:00	40	05/03:08	05/03:30	S12 E36	3B/X2	11019	No
9	71/01/25	25/~00	25/07-25/18	1000	24/22:15	24/23:31	N18 W49	3B/X5	11128	10-100%
10	71/04/06	06/~12	06/13-06/22	40	06/09:36	06/09:44	S19 W80	1B/>M1	11221	No
11	71/05/16	16/~15	16/15-17/04	12			Over limb			No
12	71/09/02	01/~22	01/22-02/14	350			Over W limb			10-100%
13	72/01/20	20/~02	20/21-20/22	20	19//16:39	19/16:44	S16 E10	1B	11693	No
14	72/04/18	17/~23	18/03-18/07	15						No
15	72/04/19	19/~02	19/02	100						No
16	72/05/28	28/~14	29/01-29/04	10	28/13:10	28/13:32	N09 E09	2B/X5	11895	No
17	72/06/08	08/~18	08/16-09/02	10						No
18	72/06/16	16/~01	17/07-17/18	10	15/09:51	15/09:58	S10E11	1N/M1	11926	No
19	72/07/22	22/~06	22/13-22/15	12	22/05:52	22/05:55	S14 W00	1F/M6	11957	No
20	72/08/03	03/~22	04/04-04/06	>60000	03/19:58		N14E28	2B	11976	3-10%
21	72/08/07	07/~20	09/00-09/01	>1000	07/14:49	07/15:34	N14 W37	3B/>X5	11976	3-10%
22	72/08/11	11/~13	11/18-11/21	15	11/12:17	11/12:47	N14W90	1B/M8	11976	No
23	73/04/29	29/~21	29/22-30/04	40	29/20:56	29/21:04	N14W73	2B/X2	12322	<3%
24	73/09/07	07/~12	07/13-	55	07/11:41	07/12:12	S18W46	2B/X1	12507	No
25	74/07/03	03/~22	04/03-	35	03/02:59	03/03:18	S15E09	1B	13043	No
26	74/07/05	05/~10	05/15-05/24	400	04/13:38	04/13:57	S16W08	2B	13043	No
27	74/07/06	06/~00	06/03-	20	05/21:23	05/21:43	S15W26	1B/X10	13043	No
28	74/07/07	07/~10	07/11-07/13	100	07/09:20	07/10:14	S16W47	1B/X1	13043	No

Table 1. Continued.

29	74/09/10	10/~23	11/24	80	10/21:21	10/21:46	N10E61	2B/X5	13225	No
30	74/09/19		20/14-20/15	100	19/22:20	19/22:40	N09W62	2N/X2	13225	No
31	74/09/24	23/~22	24/19-24/23	50	23/12:00		N07W90	1N/M3	13225	No
32	74/11/05	05/~22	05/22-05/23	80	05/15:29	05/15:38	S12W78	1N/X1	13310	No
33	75/08/21	21/~18	21/18-21/20	15	21/15:09	21/15:17	N26W74	1B/X1	13811	No
34	75/08/22	22/~02	22/03-22/06	10	<22/01:08	22/01:18	N27W81	1B/M9	13811	No
35	76/04/30	30/~21	30/22-01/01	130	30/20:59	30/22:18	S09W47	2B/X2	14179	3-10%
36	76/08/22	22/~12	22/17	20	22/12:17	-	S02W90	SN/M3	14366	No
37	77/09/17	17/~00	17/01-17/02	10	16/21:23	16/21:41	N07W20	2N/M5	14943	3%
38	77/09/24	24/~01	24/07-24/18	100			Over the limb			3-10%
39	77/11/22	22/~10	22/10-22/12	300	22/09:45	22/10:05	N24W40	2B/X1	15031	10-100%
40	78/02/13	13/~12	13/17-134/10	1000			N15W20	2N	15139	No
41	78/04/11	11/~20	11/20-11/24	30	11/13:34	11/14:10	N22W56	2B/X2	15221	No
42	78/04/20	20/~01	20/07	12	19/14:53	19/14:58	N17W46	SN/C1	15235	No
43	78/04/21	21/~10	25/00	12	19/14:53	19/14:58	N17W46	SN/C1	15266	No
44	78/04/29		29/05-29/19	120	29/20:10	-	N20E14	2B/X3	15266	No
45	78/05/07	07/~04	07/03-07/08	110	07/03:27	07/03:53	N23W72	1N/X2	15266	>100%
46	78/06/02	07/07:30	02/09:35	11		31/10:09	N23W50	M5/2B	1129	No
47	78/06/24	23/~20	24/15	10	22/16:43	>22/22:40	N18E16	2BM3	15368	No
48	78/09/23	23/~10	24/02-24/18	1000	23/09:44	23/12:15	N35W50	3B/X1	15543	3-10%
49	78/10/09	09/~22	09/23-10/02	200	09/19:51	09/20:22	S18W61	1B/M4	15570	No
50	79/02/17	17/~20	17/21	35	16/01:44	16/03:15	N18E09	3B/X2	15830	No
51	79/06/06	06/~20	06/20-06/21	330	05/04:55	05/08:38	N18E09	2B/X2	16051	No
52	79/07/07	05/~12	07/11-	10	04/19:03	04/21:10	N11E36	1B/M2	16122	No
53	79/08/20	19/~09	20/06-20/09	400	18/14:00	18/14:02	S25E17	SN/X1	16239	No
54	79/08/21	21/~06	21/06-21/08	600	21/05:50	21/06:13	N17W40	2B/C6	16239	6%
55	79/09/17	14/~12	17/07-17/21	200	14/07:55	14/09:01	N07W08	1B/M3	16279	No
56	79/11/16	15/~22	16/11	60	15/20:21	15/21:42	N10W14	1B/M4	16421	No
57	80/02/06	06/~19:00	07/02-07/06	10	05/17:27	05/17:27	S17 W09	1B/M3	6631	No
58	80/04/04	04/~16:00	04/19-04/24	10	04/14:54	04/15:09	N27 W35	1N/M5	6740	No
59	80/06/21	21/~02:00	21/07-21/08	20	21/01:21	21/01:21	N19 W90	1B/X2.6	6898	No
60	80/07/17	17/~23:00	18/16-18/20	120	17/05:36	17/06:10	S12 E07	3B/M3.4	6978	No
61	80/10/15	15/~12:00	15/20-15/21	20	15/05:24	15/07:28	N21 E55	3N/M2	7204	No

Table 1. Continued.

62	81/03/30	30/~09:00	30/11	10	30/00:17	30/00:47	N13 W72	1B/M3.5	7535	No
63	81/04/04	04/~05:00	04/05-04/22	10	04/05:00	04/05:00	S44 W87	2N/X1.9	7539	No
64	81/04/10	10/17:45	10/18-10/24	40	10/16:32	10/16:51	N07W36	2B/X2.5	7568	<3%
65	81/04/24	24/15:15	24/18-24/23	160	24/13:46	24/14:08	N18 W50	2B/X5.9	7590	No
66	81/04/28	28/~24:00	29/00-29/03	100	28/<21:05		N16 W90	SB/X1.2	7590	No
67	81/04/30	30/~12:00	30/18-30/19	200				Over limb		No
68	81/05/04	04/~24:00	06/10-07/24	15	04/08:35	04/08:39	N15 E18	1B/M9.5	7620	No
69	81/05/09	09/12:00	09/22-09/24	150	08/22:01	08/22:14	N09 E37	2B/M7	7638	No
70	81/05/10	10/~09:00	10/09-10/15	120	10/07:15	10/07:17	N03 W35	1N/M1.3	7624	<3%
71	81/05/16	16/17:00	16/18-16/24	500	16/07:53	16/08:31	N11 E14	3B/X1.1	7644	No
72	81/07/20	20/14:30	20/17-20/21	13	20/13:10	20/13:22	S25 W75	1B/M5.4	7736	No
73	81/10/08	08/12:35	09/12-11/09	70	07/23:15	07/23:15	S19 E88	1B/X3.6	7906	No
74	81/10/12	12/~08:00	12/00-14/06	2800	12/06:15	12/06:20	S18 E31	2B/X3.1	7906	3-10%
75	81/12/09	09/~22:00	10/09-10/12	120	09/18:17	09/19:12	N10 W21	3B/M5.2	8058	No
76	82/01/31	31/00:55	31/11-31/20	1000	30/23:25	30/23:44	S14 E14	2B/X1.1	8202	No
77	82/02/01	?	01/20-02/12	350	01/13:50	01/14:07	S16 W09	3B/X2.6	8176	No
78	82/02/08	08/~13:00	08/14:46	15	08/12:04	08/12:23	S15 W88	1B/X1.4	8176	No
79	82/03/07	07/~04:00	07/04-07/09	10	07/02:49	07/02:50	N19 W53	2B/X2.7	8240	No
80	82/06/06	05/~00:00	05/03-09/18	30	06/16:30	06/16:36	S09E25	3B/X12	8206	No
81	82/07/09	09/~10:00	10/09-10/19	30	09/07:20	09/07:37	N18 E76	3B/X9.8	8474	No
82	82/07/17	17/~23:00	17/24	15	17/10:28	17/10:32	N14 W33	2B/X3.2	8474	No
83	82/07/22	22/20:30	22/23-22/24	200	22/16:48	22/17:07	N16 W89	1N/M4.9	8474	No
84	82/08/14	14/~06:00	14/06-14/08	20	14/05:06	14/05:07	N11 W63	1B/M4.1	8511	No
85	82/11/22	22/19:40	22/21-22/24	45	22/15:14	22/18:17	S11 W36	1N/M4.7	3994	No
86	82/11/23	23/~22:00	24/02-24/10	35	23/11:09	23/11:20	S06 W54	1N/M1.2	3994	No
87	82/11/26	26/06:05	26/06-26/15	150	26/02:30	26/02:36	S12W87	2B/X4.5	3994	3-10%
88	82/12/08	08/00:10	08/08-	800	07/23:41	07/23:51	S19 W86	1B/X2.8	4007	10-100%
89	82/12/17	17/18:45	17/23-18/03	100	17/18:20	17/18:57	S07 W20	3B/X10.1	40025	No
90	82/12/19	19/19:20	20/00-20/03	100	19/15:08	19/16:32	N10 W75	1B/M9	4022	No
91	82/12/26	26/~20:00	27/11-27/15	50	26/01:44	26/01:51	S11W110	1N/C9.8	4033	No
92	83/01/05	05/~10:00	05/12-05/14	2000	05/04:59	05/05:20	S11W123	1N	4052	No
93	83/01/06	06/~15:00	06/17-06/19	20	06/08:06	06/08:12	S10E75	1N	4053	No
94	83/02/03	03/~09:00	04/06-04/08	340	03/05:41	03/06:08	S17 W07	2B/X4.1	4077	No

Table 1. Continued.

95	83/04/15	15/~03:00	15/13-15/18	10	15/01:58	15/02:01	S12 W90	1B/C3.9	4104	No
96	83/05/15	15/~10:00	15/11	20	15/08:39	15/08:45	S12 W82	1B/X2.3	4173	No
97	83/06/15	15~10:00	15/13-15/19	10				Over the limb		No
98	84/02/16	16/09:15	16/14	100				Over the limb		10-100%
99	84/02/18	18/~10:00	18/14-19/20	15	17/22:26	17/23:29	N17 E81	1N/X2.3	4421	No
100	84/03/14	14/04:05	14/06-14/10	30	14/03:15	14/03:24	S11 W43	2B/M2	4433	No
101	84/04/25	25/~06:00	26/09-26/14	700	24/23:56	24/00:01	S11 E45	3B/X13	4474	No
102	84/05/31	31/13:15	31/14:15	15	31/	31/11:42	S09W90	M1	4492	No
103	85/01/22	22/04:15	22/04-22/20	14	21/23:08	21/23:20	S10 W40	1N/X4.7	4617	No
104	85/04/24	24/14:30	24/16-25/10	40	24/08:50	24/09:02	N05 E24	2B/X1.9	4647	No
105	85/04/26	26/~00:00	26/03-26/06	110	25/19:06	25/19:08	N06E03	1B/X1	4647	No
106	85/07/09	09/02:35	09/03-09/04	100	09/01:33	09/01:40	S13 W25	1N/M2.9	4671	No
107	86/02/05	05/~02:00	05/19-	10	05/12:34	05/12:47	S07E06	2N/M3	4711	No
108	86/02/06	06/~10:00	06/12-06/14	140	06/06:18	06/06:22	S07 W02	2B/X1.7	4711	No
109	86/02/07	07/~12:00	07/18-	300	07/10:11	07/10:24	S11W21	2B/M5.2	4711	No
110	86/02/14	14/11:55	14/18-14/24	200	14/09:09	14/09:22	N00 W78	1N/M6.4	4713	No
111	86/03/06	06/18:35	06/19:30	25	06/17:03		N02E01	C4/1F	4717	No
112	86/05/04	04/12:55	04/14-04/15	25	04/09:39		N09W90	M1.2	4727	No
112	87/11/08	07/~22:00	08/10-08/12	60	07/20:28	07/20:30	N31 W90	1N/M1	4875 □	No
113	88/01/02	02/~23:00	03/09-03/11	60	02/21:11	02/21:35	S34W18	3B/X1.4	4912	No
114	88/03/25	25/~22:00	25/23-26/01	38				No flare		No
115	88/06/30	30/~11:00	30/11-30/15	10	30/09:04	30/09:06	S16 E22	2B/M9.2	5060	No
116	88/11/08	08/~12:00	08/16-09/02	15	07/11:34	07/11:53	S20 W48	1N/M3	5212	No
117	88/12/15	14/~12:00	15/03-15/08	10	13/10:28	13/10:29	N20 W40	1B/C7	5278 □	No
118	88/12/16	16/~11:00	16/18-17/13	18	16/08:26	16/08:33	N27 E33	1B/X4	5278	No
119	89/03/07	09/~01:00	09/10-10/02	150	06/13:54	06/14:15	N35E69	3B/X5	5395	No
120	89/03/10	10/~22:00	13/07-13/09	115	10/18:48	10/18:50	N31 E22	3B/X4.5	5395	No
121	89/03/17	17/~20:00	18/08-18/11	1000	17/17:29	17/17:37	N33 W60	2B/X6.5	5395	No
122	89/03/23	23/~22:00	23/21-23/24	30	23/19:25	23/19:37	N18 W28	3B/X1.5	5409	No
123	89/04/11	11/~12:00	12/00-12/04	500	10/00:44	09/00:59	N35 E29	4B/X3.5		No
124	89/04/22	22/~08:00	23/07-23/18	10	22/05:45	22/05:46	N12 W39	1N/C6	5451	No
125	89/05/06	06/~01:00	06/11-06/14	40	05/07:23	05/07:39	N30 E01	3B/X2	5470	No
126	89/06/18	18/~15:00	18/17-18/20	10	18/14:40	18/14:44	N12 W30	SF	5536 □	No

Table 1. Continued.

127	89/07/25	25/~10:00	25/09-25/14	30	25/08:40	25/08:43	N25 W84	2N/X2.6	5603	Yes
128	89/08/12	12/~14:00	13/04-13/09	9000	12/13:57	12/14:23	S16 W38	2B/X2.6	5629	No
129	89/08/15	15/~10:00	15/17-15/23	316	15/01:42	15/02:17	S16 W73	1N/X1	5629	No
130	89/08/16	16/~01:00	16/03-16/09	1000	16/00:58	16/01:07	S15 W85	2N/X>12	5629	10-100%
131	89/08/17	17/~08:00	17/10-17/17	631	17/01:32	17/01:35	S17 W88	SN/X2,9	5629	No
132	89/08/19	19/~20:00	20/03-20/04	250	19/19:11	19/19:46	S18W125		5645 □	No
133	89/08/22	22/~10:00	22/18-23/03	60	22/02:04	22/02:12	S20E24	1B	5657	No
134	89/09/04	04/~10:00	04/05-04/10	10	03/14:28		S18E16	1B/X1.2	5669	No
135	89/09/13	13/~05:00	13/08-13/11	30	13/03:29	13/03:36	N17 E10	2N	5687 □	No
136	89/09/29	29/12:05	29/13-29/24	1995	29/10:00	29/10:05	S32 W90	2N/X9.8	5698	>100%
137	89/10/19	19/~13:00	20/15-20/18	25119	19/12:29	29/12:39	S25 E09	3B/X13	5747	10-100%
138	89/10/22	22/~18:00	22/18-23/07	2512	22/17:08	22/17:19	S27W32	1N/X2.9	5747	>100%
139	89/10/24	24/~1800	24/20-25/03	5000	24/17:38	24/17:48	S29W57	2N/X3.7	5747	>100%
140	89/10/29	29/~05:00	29/08-29/12	55				*Over the limb*	No	No
141	89/11/15	15/~07:00	15/07-15/11	70	15/06:38	15/06:56	N11 W28	3B/X3.2	5786	10-100%
142	89/11/26	27/~02:00	28/12-28/13	130	26/17:49	26/18:15	N25 W03	2B/M4	5800 □	No
143	89/11/30	30/~13:00	01/01-01/15	1995	30/11:45	30/12:25	N24 W52	3B/X2.6	5800	No
144	90/02/03		03/03-03/08	18	03/01:08	03/01:09	S10 W79	1N/M6.9	5917	No
145	90/03/19	19/07:05	19/17-20/01	900		19/05:08	N31W43	2B/X1	5969	No
146	90/04/07	07/22:40	08/00-08/15	18	04/13:15	04/13:18	N23E72	SN/M7.1	6007	No
147	90/04/15	15/~12:00	17/11-17/13	10	15/02:30	15/02:57	N32 E54	2B/X1	6022	No
148	90/04/28	28/~03:00	28/18-28/20	100	28/00:23	28/00:24	--------	*Over the limb*		No
149	90/05/21		21/23-22/08	410	21/22:12	21/22:17	N34 W37	2B/X5	6063	10-100%
150	90/05/24	24/~22:00	24/21-25/03	199	24/20:46	24/20:49	N36 W76	1B/X9	6063	10-100%
151	90/05/26	26/~21	26/22-27/04	158	--------	26/20:45	N33W104	X1.4		10-100%
152	90/05/28	28/~10:00	28/08-29/02	45	28/06:01	28/06:01	N33W121			3-10%
153	90/06/12	12/~10:00	12/14-12/20	70	12/04:29	12/04:34	N10 W33	2B/M6	6089	No
154	90/07/25	25/~24:00	26/04-26/10	10	25/22:21	25/22:32	S14 E56	2N/M2,3	6174	No
155	90/07/30		01/17-01/22	200				2N/	6180	No
156	91/01/31	31/~10:00	31/15-31/20	200	31/01:57	31/02:00	N17 W35	2B/X1	6462	No
157	91/02/25	25/~11:00	25/11-25/14	10	25/08:09	25/08:22	S16 W80	2N/X1.2	6497	No
158	91/03/22	22/~23:00	24/04-24/06	43000	22/22:45	22/22:47	S26 E28	3B/X9	6555	No
159	91/04/03	03/~00:00	04/05-04/12	30	02/22:51	02/23:20	N14 W00	3B/M6.1	6562	No

Table 1. Continued.

160	91/05/13	13/~02:00	13/04-13/11	300	13/1:35	1:44	S07W90	SN	6615	No
161	91/05/31	31/~04:00	31/09-31/17	20	31/02:32	31/02:44	N07E21	1B	6654 □	No
162	91/06/02	02/~14:00	02/19-02/23	18	02/13:50	02/14:08	S08 W20	2B/M2.8	6652 □	No
163	91/06/04	04/~05:00	07/06-08/17	280	04/17:00		N34E75	3B/X12	6659 □	No
164	91/06/11	11/~02:00	11/13-11/16	1995	11/01:05	11/02:27	N32 W15	2B/X12.5	6659	3-10%
165	91/06/15	15/~08:00	15/09-15/17	1400	15/06:33	15/08:20	N36 W70	3B/X12	6659	10-100%
166	91/06/29	29/~15:00	30/13-01/01	25	29/05:42	29/04:54	S08 E08	SN	6693 □	No
167	91/07/01	01/~16:00	01/19-02/01	100	01/01:26	01/02:34	N28 E78	1N/M5.8	6703	No
168	91/07/07	07/~03:00	08/05-08/07	1000	07/01:20	07/01:23	N28 E00	3B/X1	6703	No
169	91/07/10	10/~14:00	11/05-11/07	20	10/11:59	10/12:07	S22 E32	2N/M3.6	6718	No
170	91/08/25	25/~17:00	27/17-27/21	200	25/00:26	25/00:49	N23 E76	2B/X2.1	6805	No
171	91/10/28		28/14-28/17	25				2B	6891	No
172	91/10/30	30/~07:00	30/09-30/13	60	30/06:11	30/06:21	S08 W25	3B/X2.5	6891	No
173	92/02/07	07/~11:00	07/11-07/12	60	07/11:40	07/12:02	S21 W53	2B/M3.7	7035	No
174	92/03/16	16/~08:00	16/09-16/13	-10	15/01:21	15/01:46	S14 E29	3B/M7	7100	No
175	92/05/08	08/~22:00	09/12-09/23	1585	08/15:37	08/15:40	S26 E08	4B/M7.4	7154	No
176	92/06/25	25/~22:00	25/23-26/09	300	25/17:49	25/17:55	N09 W69	1B/X3	7205	Yes
177	92/06/28	28/~12:00	28/15-29/05	20	28/05:14	28/05:20	N11W90		7205	No
178	92/10/30	30/~20:00	31/02-31/08	2700	30/15:41	30/17:30	S22W61	2B/X1.7	7321	Yes
179	92/11/02	02/~04:00	02/06-02/15	2000	02/03:10	02/03:14	S23W90	2B/X9	7321	Yes
180	93/03/04	04/~13:00	04/14-04/18	15	04/12:14	04/12:22	S13W55	1N/C8.1	7434	No
181	93/03/12	12/~20:00	12/21-13/04	30	12/17:03	12/18:01	S03W48	3B/M7	7440	No
182	94/02/20	20/~03:00	21/07-21/11	9000	20/01:38	20/01:41	N09 W02	3B/M4	7671	No
183	94/10/19	19/~23:00	20/00-20/16	30	19/22:35	19/23:13	N12 W24	?/M3,2	7790 □	No
184	95/10/20	20/~08:00	20/08-120/15	40	20/05:53	20/05:58	S11 W53	1N/M1.5	7912	No
185	97/11/04	04/08:30	04/10-04/14	72	04/05:54	04/05:58	S14W33	X2/2B	8100	No
186	97/11/06	06/13:05	06/23-07/05	490	06/11:22	06/11:55	S18W63	2B/X9	8100	Yes
187	98/04/20	20/14:00	21/09-21/15	1700		20/10:21	S43W90	M1	8194	No
188	98/05/02	02/14:20	02/15:30-02/17:30	150	02/13:34	02/13:42	S15W15	M3/X1	8210	Yes
189	98/05/06	06/08:45	06/09-06/13	210	06/07:14	06/08:09	S11W65	1N/X2	8210	Yes
190	98/08/24	24/23:55	26/03-26/18	670	24/21:48	24/22:04	N35E09	3B/X1	8307	Yes
191	98/09/25	25/00:10	25/01-25/02	44	23/06:44	23/07:06	N18E09	3B/M7	8340	No
192	98/09/30	30/15:20	30/22-01/04	1200	30/14:02	30/14:34	N23W81	2N/M2	8340	No

Table 1. Continued.

193	98/11/08	08/02:45	07/23-08/04	11	--	----	-----	------	-----	No
194	98/11/14	14/08:10	14/11-14/13	310				No flare	8377	No
195	99/01/23	23/11:05	23/09-23/18	14	22/13:27	22/13:30	N24W50	1N	8439	No
196	99/04/24	24/18:04	24/21-25/06	32	---	24/14:00	W90	/B3	-----	No
197	99/05/05	05/18:20	05/15-06/06	14	03/05:48	03/05:36	N15E32	2N/M4	8525	No
198	99/06/02	02/02:45	02/09-02/24	48		01/~19:30	CME			No
199	99/06/04	04/18:20	04/11-04/24	64	04/06:55	04/07:00	N17W69	2B/M3	8552	No
200	00/02/18	18/00:00	18/11-18/15	13	17/20:19	17/20:31	S29E07	2N/M1	8872	No
201	00/04/04	04/20:55	05/08-0511	55	04/15:11	04/15:34	N16W66	2F/C9	8933	No
202	00/06/07	07/13:35	08/06-08/15	84	06/12:06	06/15:21	N20E18	2X/3B	9026	No
203	00/06/10	10/18:05	10/18-10/24	46	10/16:37	10/16:55	N22/W38	3B/M5	9026	No
204	00/07/14	14/10:45	15/06-15/15	24000	14/10:12	14/10:21	N22/W07	3B/X5	9077	Yes
205	00/07/22	22/13:20	22/14-22/20	17	22/11:19	22/11:25	N14/W56	2N/M3	9085	No
206	00/07/28	28/03:00	28/05-28/14	18	28/10:08	28/10:12	N12W80	1N	9090	No
207	00/08/11	11/12:00	11/16-11-17:30	17	---	----	----	----	---	No
208	00/09/12	12/15:55	12/21-13/09	320	12/11:22	12/12:00	S17W09	2N/M1	9163	No
209	00/10/16	16/11:25	16/12-16/24	15		16/07:28	N04W90	M2	9182	No
210	00/10/26	25/14:00	26/00-26/06	15		25/11:25	N00W90	M2		No
211	00/11/08	08/23:50	09/06-09/18	14800	08/22:59	08/23:10	N10W75	1N/M7	9212	No
212	00/11/24	24/15:20	26/15-27/03	942	24/04:57	24/05:01	N20W05	3B/X2	9236	No
213	01/01/28	28/20:25	29/03-29/06	49	28/15:40	28/16:00	S04W59	1N/M1	9313	No
214	01/03/29	29/16:35	30/00-30/12	35	29/09:55	29/10:15	N24W12	1N/X1	9393	No
215	01/04/02	02/23:40	03/06-03/12	9000	02/21:32	02/21:51	N14W82	X20	9393	No
216	01/04/10	10/08:50	11/18-11/24	355	10/05:06	10/05:26	S23W09	3B/X2	9415	No
217	01/04/15	15/14:10	15/18-15/24	951	15/13:19	15/13:50	S20W85	2B/X14	9415	Yes
218	01/04/18	18/03:15	18/08-18/16	321	18/02:11	18/02:14	S20W115	2B/C2	9415	Yes
219	01/04/28	28/04:30	28/04:30-28/05:30	57	26/11:26	26/13:12	N17W31	2B/M7	9433	No
220	01/05/07	07/19:15	08/03-08/12	30	07/11:32	07/12:07	N26W38	2N	9445	No
221	01/06/15	15/17:50	15/19-16/04	26	15/10:13	15/10:01		1N	9502	No
222	01/08/10	10/10:20	10/10-10/14	17	09/11:26	09/11:22	----	---	---	No
223	01/08/16	16/01:35	16/04-16/06	493	---	----	-----	Over the West limb	-----	No
224	01/09/15	15/12:30	15/14:30-15/16:00	11	15/11:04	15/11:28	S21W49	1N/M1	9608	No
225	01/09/24	24/12:15	25/21-26/01	12900	24/09:32	24/10:38	S16E23	2B/X2	9632	No

Table 1. Continued.

226	01/10/01	01/11:45	02/06-02/10	2360	01/04:41	01/05:15	S22W91	M9	9608	No
227	01/10/19	19/22:25	19/18-19/24	11	19/16:13	19/16:30	N15W29	2B/X1	9661	No
228	01/10/22	22/19:10	22/20-23/01	24	22/17:44	22/17:59	S18E16	2B/X1	9672	No
229	01/11/04	04/17:05	05/21-06/06	31700	04/16:03	04/16:20	N06W18	3B/X1	9684	Yes
230	01/11/19	19/12:30	19/21-20/12	34	17/04:49	17/05:25	S13E42	1N/M2	9704	No
231	01/11/22	22/23:20	22/05-22/06	18900	22/22:32	22/23:30	S15W34	2N/M9	9704	No
232	01/12/26	26/06:05	20/10-20/14	779		26/05:40	N08W54	1B/M7	9742	Yes
233	01/12/29	29/05:10	29/07-29/09	76		28/20:45		X3	9767	No
234	01/12/30	30/02:45	31/15-31/22	108						No
235	02/01/10	10/20:45	11/03-11/09	91		09/17:42	N13W02	2B/M9.5	9773	No
236	02/01/15	15/14:35	15/12-15/24	15	14/05:25	14/06:27	Wlimb	M4		No
237	02/02/20	20/07:30	20/7:25-20/8:15	13	20/06:12	20/06:30	N12W72	M5/1N	9825	No
238	02/03/17	17/08:20	17/07-17/13	13	15/23:06	15/23:10	S08W03	M2/1F	9866	No
239	02/03/18	18/13:00	18/13:00	53			-			No
240	02/03/20	20/15:10	20/15-20/19	19	18/02:54	18/02:16		M1	9871	No
241	02/03/22	22/20:20	23/12-23/22	16	22/11:06	22/11:14	Wlimb	M1	9866	No
242	02/04/17	17/15:30	17/16-17/21	24	17/08:24	17/08:26	S14W34	M2/2N	9906	No
243	02/04/21	21/02:25	21/21-22/03	2520	21/01:27	21/01:51	S14W08	X1/F1	9906	No
244	02/05/22	22/17:55	23/09-23/12	820	22/03:26	22/03:54	S19W56	C5/		No
245	02/07/07	07/18:30	07/18-08/03	22	07/11:06	07/11:43	Wlimb	M1	10017	No
246	02/07/16	16/17:50	17/14-17/17	234	15/20:30	15/20:08	N19W01	X3/3B	10030	No
247	02/07/19	19/10:50	19/09-19/16	13						No
248	02/07/22	22/06:55	22/21-23/24	28	20/20:42	20/21:30	Selimb	X3	10039	No
249	02/08/14	14/09:00	14/12-14/20	26	14/02:06	14/02:12	N09W54	M2/1N	10061	No
250	02/08/22	22/04:40	22/05-22/12	36	4/02:00	22/01:57	S07W62	M5/2B	10069	No
251	02/08/24	24/01:40	24/06-24/18	317	24/01:27	24/01:12	S08W90	X3/F1	10069	Yes
252	02/09/07	07/04:40	07/16:30-07/17:30	208	05/16:54	05/17:06	N09E28	C3/	10102	No
253	02/11/09	09/19:20	10/03-10/08	404	09/13:31	09/13:23	S12W29	M4/2B	10180	No

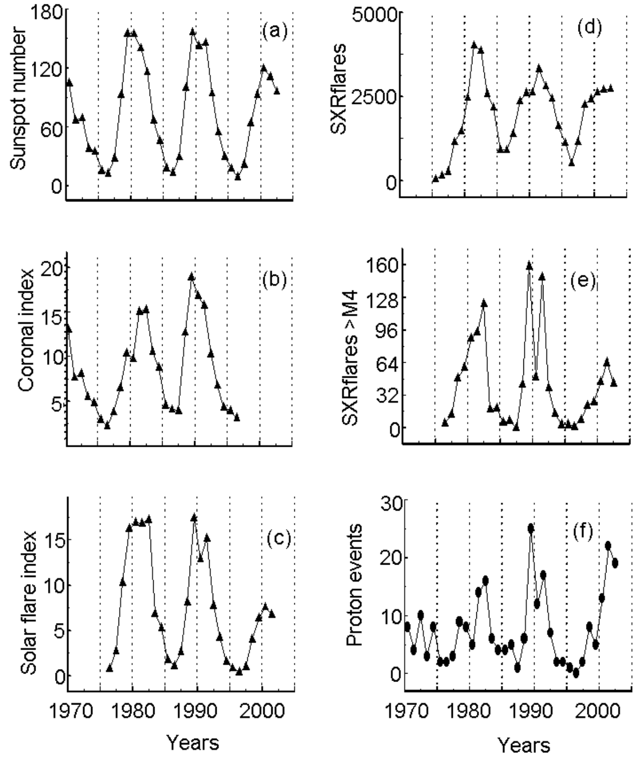

Fig. 2. Time distributions of the yearly values of (**a**) sunspot number, (**b**) coronal index, (**c**) solar flare index, (**d**) SXR flares number, (**e**) SXR flares number with importance > M4 and (**f**) proton event number with E>10 MeV and peak intensity >10 pfu, during the time interval 1970–2002.

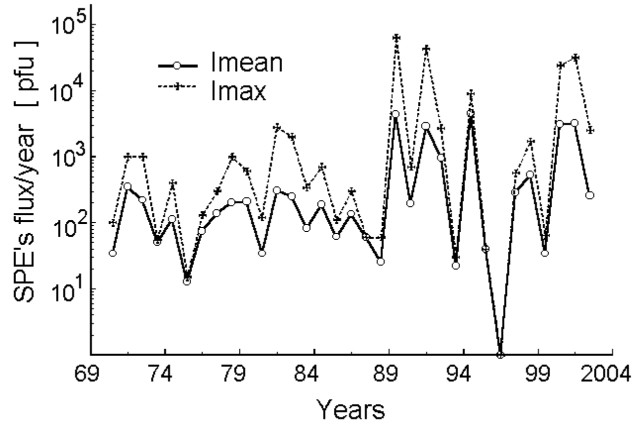

Fig. 3. Time distribution of yearly averaged and maximum intensity of the SPEs flux from 1970 to 2002.

The next five columns concern Ha flares identified as the source of SPEs. These columns consist of onset time, peak time, importance, as well as SXR importance (by GOES classification), flare location and active region number. The last column of the Table indicates cosmic ray variations recorded at the neutron monitors as ground level enhancements. With this catalogue we obtain a possibly homogeneous data set comprising 253 SPEs that provides a significant statistical basis. Furthermore, as the catalogue covers the descending phase of the cycle 20, two solar cycles, 21 and 22, and the ascending phase of the cycle 23, it enables us to analyze the long time dependency of the SPEs and flare-related characteristics (Temmer et al., 2001).

In our Table only large events with energy >10 MeV and peak intensity >10 pfu are included, while smaller events with intensity <10 pfu are not selected (Shea and Smart, 1990). Possible differences between our Table and other relative tables are due to the fact that this Table is mainly based on the catalogue of solar proton events edited by Logachev (Moscow University) which is not commonly used. This catalogue is a very useful issue, as it collects measurements from Neutron Monitors, balloons and different satellites containing time profiles and combined spectra of each event with maximum intensity >1 pfu.

3 Statistical treatment

3.1 Correlation analysis

The relationship of SPEs number with different manifestations of solar activity, such as sunspot number Rz, coronal index (total irradiance of the green corona in line 5303 nm; Rusin and Rybansky, 2002), solar flare index (total energy emitted by H_α flares; Ozguc and Atac, 1994), SXR flares registered by GOES satellites, is analyzed. All relevant data are extracted from NOAA SEC data base.

Time distributions of these solar activity indices, as well as of the number of SXR flares of importance >M4 over the time interval 1970–2002, covering more than three solar activity cycles, are presented in Fig. 2. We can say that sunspot numbers, coronal index, solar flare index and SXR flare number differ by their maximum values in cycles 21 and 22 by not more than 20%. On the contrary, the number of solar proton events in the maximum of cycle 22 is double in comparison with cycle 21. The events distribution for solar cycle 22 differs completely from those in the previous cycle. About 70% of these events originated during the three years at the maximum of this cycle, that is in agreement with the result of Shea and Smart (1995). The results can also be confirmed by the calculation of maximum and yearly averaged intensity of the SPEs flux. These intensities appear to be ten times smaller in the period 1970 to 1988 than those in interval 1989 up to 2002, as can be seen in Fig. 3. The increased occurrence rate of the SPEs during solar cycle 22 is in accordance with the number of solar flares of ≥M4 importance.

Comparing yearly values of proton events with sunspot number, coronal index, solar flare index, total SXR flares and SXR flares of ≥M4 importance, we have found that the largest values of the correlation coefficient among these parameters are those for coronal index (0.86±0.05) and for SXR flares with importance ≥M4 (0.81±0.07). Scatter plots and linear approximations of the SPE yearly number dependences on the above mentioned parameters, are given in Fig. 4. We do not discuss how the coronal index is connected

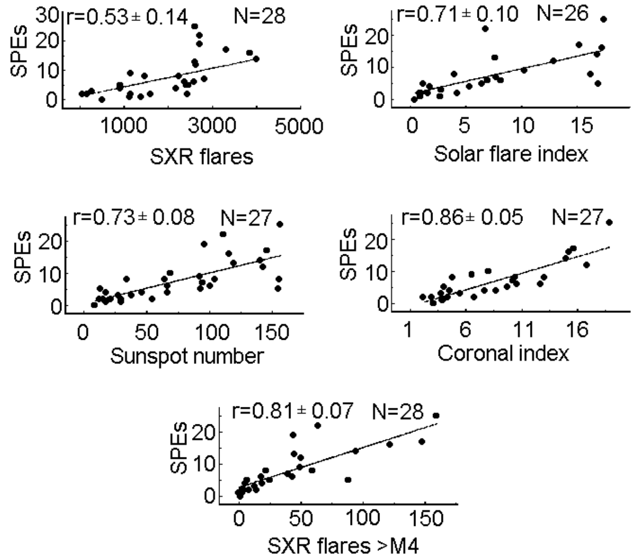

Fig. 4. Scatter plots and linear approximations of SPEs yearly number dependences on the total SXR flares, sunspot number, solar flare index, coronal index and SXR flares with importance >M4.

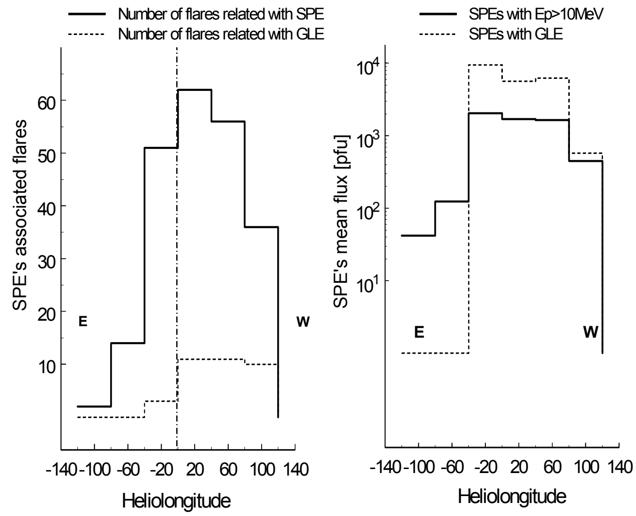

Fig. 6. Longitudinal distribution of the associated with SPEs flares and of the flares related to GLEs concerning the number of them (left panel) and the mean flux per 20° longitudinal interval (right panel).

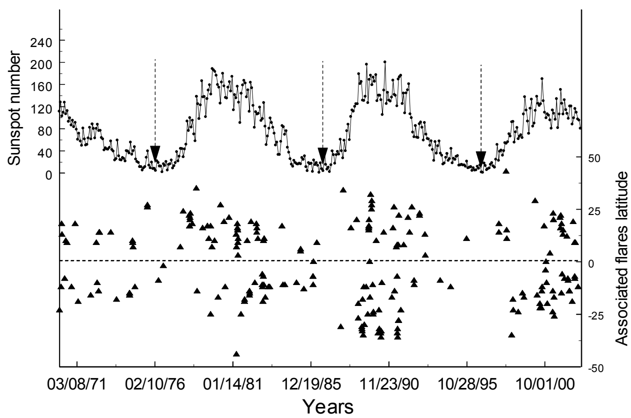

Fig. 5. "Butterfly diagram" of the associated with SPEs flares for the interval 1970–2002 is presented in the lower curve. Time profile of the sunspot number is also given in the upper curve.

with the high-energy particle production, but this fact is remarkable. From the other side it is natural to assume that solar activity with soft X-rays of importance ≥M4 have an ability to emit into interplanetary space protons sufficient to be registered near the Earth's vicinity as SPEs (Kurt, 1990; Belov et al., 2001).

The interplanetary magnetic field lines constitute an Archimedian spiral in a coordinate system with a fixed Earth-Sun line. An Archimedian spiral leading back to the Sun is located between 30°W÷80°W for a solar wind speed from 700 km/s^{-1} to 300 km/s^{-1}, respectively. A priori, if the "associated" flare is situated inside or near this longitudinal interval, the protons have the highest probability to be registered near the Earth's orbit.

The longitudinal distribution of the associated SPE flares and the distribution of the flares connected with GLEs are presented in Fig. 6. The associated flares are more widely distributed from the east limb to 120°W and centered within the longitude interval 40E÷80 W, that is in accordance with previous works (Van Hollebeke et al., 1975; Sladkova and Bazilevskaya, 2000). In our case longitudinal distribution of the associated flare number, as well as of the mean flux of the corresponded SPEs, demonstrate that most of the SPEs originate from flares located western to 70°W. It is interesting that only one of the GLEs has been registered from a flare located at the solar longitude 30°E. All the others are created from flares located near the west limb. It is noteworthy that ten of the forty-two GLEs examined here are caused by "over the limb flares.

3.2 Time delay

It is known from γ-line observations that protons can be accelerated up to 10–30 MeV energy during the rising phase of the flare and near the time of the flare maximum (Ramaty and Mandzhavidze, 1993; Chupp, 1987; 1996). There are evidences that additional prolonged acceleration takes place when the magnetic field in the flare region undergoes its restoration after the mass ejection and shock wave formation in the lower corona (e.g. Akimov et al., 1996). The exact time of the escaping of accelerated protons from the Sun into interplanetary space is unknown. It means that the zero value (T_0=Tescaping) of a time scale cannot be defined unambiguously. A suggestion was made that the time of the Hα flare onset (Table 1, column 6) is taken as T_0 for our time rule. Then, using the time maximum of the SPE as Tmax (Table 1, column 4), the time delay ΔT between the proton event maximum and the onset time of the Hα "associated

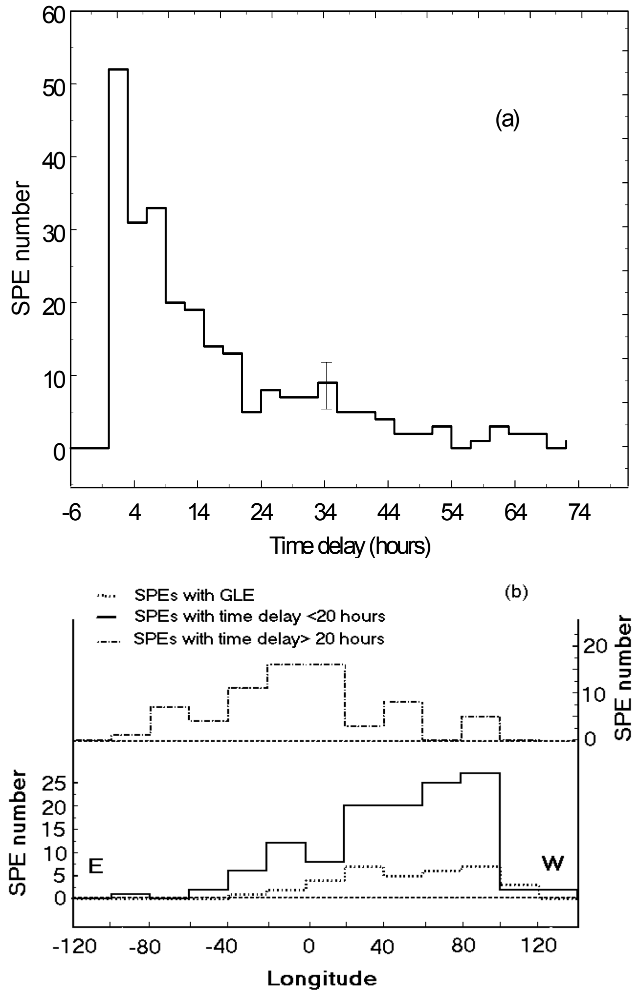

Fig. 7. (**a**) The SPEs number with respect the time delay between the proton event maximum and the onset time of the Ha "associated flares" is presented. (**b**) The longitudinal distribution of the SPEs in three cases (with GLE, with time delay $<$20 h and with time delay $>$20 h) is also illustrated.

Table 2. SPEs number and Imean in latitudes $>20°$ and $<20°$.

Latitude	SPEs number	Imean (pfu)
> 20°	59	3524
< 20°	162	790

flare" $\Delta T = T_{max} - T_0$ was calculated. Of course the choice of T_0 is not physically correct, but it is acceptable, as the time resolution of our analysis is greater or equal to one hour.

3.3 Associated solar flares

A number of 231 Hα/SXR flares have been identified with respect to the solar proton events of our catalogue, named as "associated" flares of SPEs. From the rest of the SPEs some of them can possibly be connected with "over the limb" flares, in some cases the identification could not be done definitely, while some others are related to CMEs, not associated with flares.

Thus, a "butterfly" diagram–that means a time dependence of the solar latitudinal distribution of the "associated flares" is presented in Fig. 5. Monthly values of sunspot number are also given in this Figure, and the arrows indicate the start of each cycle. It is known that solar flares follow the "butterfly" diagram, by which every cycle starts with flares at high latitudes (greater than 35°, while it ends with flares at low latitudes. It is interesting to note, that in our case the latitudinal distribution of the associated flares seems to have a similar distribution to total flares and sunspot number. However, the sources of SPEs with large fluxes are often located at high latitudes greater than 20° (Table 2). Apparently, the protons can propagate easily from relatively high latitudes to the ecliptic plane.

The result of our treatment on SPEs with respect to the calculated time delay ΔT is demonstrated in Fig. 7a. One can see a very pronounced maximum in the time delay ΔT from 3 to 9 h, followed by a long lasting tail. SPEs can be separated into two groups depending on ΔT values: the first one includes events with $\Delta T \leq 20$ h and the second one regarding events with $\Delta T \geq 20$ h. Longitudinal distributions of the "associated flares" in these two groups are depicted in Fig. 7b. The distribution of GLEs is also presented in the same figure. "Associated flares" in the first group obviously exhibit the same longitudinal distribution as those associated with GLEs, with most of them located in the Western Hemisphere.

This SPEs separation with respect to the time delay between the flare onset and the event maximum was found in accordance with the main properties of the proton's interplanetary transport. If an event has $\Delta T \leq 20$ h, we may be sure that the registered event is "prompt", that means the proton transport is mainly caused by diffusion (Miroshnichenko, 2001). For the events of the second group an influence of shock waves and CMEs on the particle propagation and acceleration is noticeable. Sometimes the events with ΔT between 20÷30 h are of "prompt" increases. In some cases the time of the peak maximum Tmax was coincided with a very fast shock arrival at 1 AU. Careful examination of the events with $\Delta T \geq 30$ h shows that these are shock-related events.

3.4 Peak-size distributions

The frequency distributions of our data set at the threshold proton energy of 10 MeV and peak intensity $>$10 pfu represented by power law as $dN/dI = I^{-\nu}$, where N is the number of events per flux interval and I is the mean particle flux in this interval at energy $>$10 MeV, are presented in Fig. 8. This figure includes differential frequency-size distributions of the peak value selected SPEs for three separate subsets. The first subset contains the total number of SPEs (upper panel), the second group contains the "prompt" SPEs with time delay $<$20 h (middle panel) and the third one presents

SPEs associated with GLEs (bottom panel). The first and second cases can be described by power law with exponent ν=-1.36±0.04 and ν= -1.30±0.02, respectively. The turnover near two bins (30<Imax<300 pfu) is seen in the peak-size distribution for the events with GLEs caused by threshold effects of the neutron monitors. The power law approximation outside the first bin (30< Imax<100 pfu) gives ν= 1.12 ± 0.16. It is noticeable that a difference in the slopes between the differential distributions at 10 MeV and >500 MeV(GLEs) has appeared. Hence, in our study the spectral indices vary from 1.12 to 1.36. Such a difference in the slopes of solar proton events in different energy channels (>10 MeV, > 30 MeV, > 60 MeV, >100 MeV, > 500 MeV) for the time period 1970–1995 is also reported by Kurt et al. (2002). It indicates the existence of a slope dependence on the proton energy under consideration (Miroschnishenko et al., 2001).

Our results are consistent with spectral indices of solar proton events published earlier, as 1.15±0.1 (Van Hollebeke, 1975), 1.45±0.15 (Belovsky and Ochelkov, 1979), 1.35±0.15 (Kurt, 1990), 1.3±0.12 (Gerontidou et al., 2002). In our case our results are based on the best statistics and give the verification of the spectral index that is very important for the models of flare energy release.

4 Discussion and conclusions

In this work the first attempt to accomplish an extended statistical analysis of solar proton events with energy >10 MeV and peak flux >10 pfu observed at 1 AU through January 1970 to December 2002 is performed. A catalogue of 253 events based upon satellites and ground level observations is created and presented. Solar proton event evolution steps, as time dependence over three solar cycles, longitudinal and latitudinal distributions of the parent flares and distribution of the time delay between the Ha flare onset and the SPE maximum are analyzed. The frequency peak flux distributions are also obtained.

Summing up the main results of this study we note that, together with appropriate results published since 1975, our findings provide new and important information about some features of the Sun's proton productivity and its relation to existing problems of particle acceleration at/near the Sun.

1. It is characteristic that the numbers of SPEs and SXR flares of importance >M4 are almost the same during the solar cycles 21 and 22. It is noted that one per six of these SXR flares is associated with an SPE. In the cycle 21 the number of SXR-flares of importance >M4 is 478 and the number of SPEs is 78, while during the solar cycle 22 the number of SXR-flares of importance >M4 is 460 and the number of SPEs is 73.

   The occurrence rate of SPEs and SXR flares >M4 in relation to other manifestations of solar activity seems to appear as a significant increase during the maximum of solar cycle 22. It means that solar activity with soft x-rays of importance >M4 have an ability to emit protons sufficient to be registered near the Earth's vicinity as SPEs, but not all of them are accompanied by a proton event.

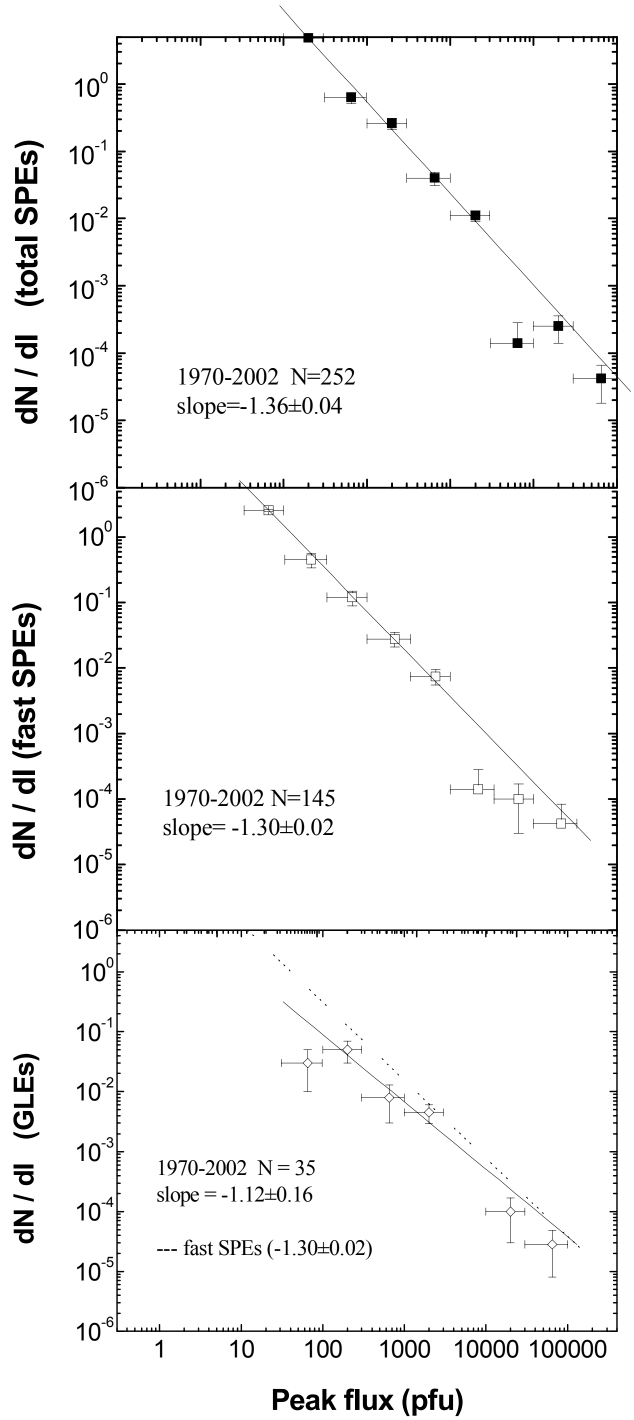

Fig. 8. Peak size distributions of the total number of SPEs with energies E>10 MeV (upper panel), of the fast SPEs (middle panel) and of the SPEs connected with GLEs (lower panel) that appeared.

2. Dependence of solar latitude distribution of parent flares of SPEs on the solar cycle seems to have the same behavior as the sunspot number. Every cycle starts with flares at high latitudes and ends with flares at low latitudes. The sources of SPEs with large fluxes are often located at high latitudes greater than 20°. Protons can propagate easily from relatively high latitudes to the ecliptic plane. On the other hand, the longitudinal distribution of the associated flares of SPEs shows a preferable connecting region within 40°E-80°W, which is consistent with previous results (Sladkova and Basilevskaya, 2000). The most of the SPEs are created by flares, located at solar longitude around 70° W. It is in agreement with the distribution of the GLE related flares.

3. The calculated time delay between the proton event maximum and the onset time of the Ha associated flare reveals a pronounced maximum of this time from 3 to 9 h. This maximum is connected with fast events ($\Delta T<20$ hours), where the proton transport is mainly caused by diffusion, while a long time delay is related to shock events.

4. The best power-law fit for the basic sample of 253 events is attained at a slope of 1.36 ± 0.04 over the entire range of proton intensities 10^1-10^5 pfu. The difference in the slopes between differential size distributions at >10 MeV and >500 MeV, obtained on the best statistic, indicates the existence of slope dependence on the proton energy. This result is consistent with other studies (Miroschnishenko et al., 2001; Gerontidou et al., 2002; Kurt et al, 2002).

5. The mechanisms responsible for proton acceleration and SPEs are widely discussed in the literature, with much controversy in particular over the role of flares. Our results not only confirm but give quantitative characteristics of the SPE relation to the flares that may be used for prediction of these events and radiation forecasting (Gabriel and Patrick, 2003).

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