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Frequency distributions of solar proton events

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Abstract

A study has been coordinated of 147 solar proton events (SPEs) with proton energies >10 MeV and peak intensities >10 protons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ "particle flux units (pfu)" at the Earth's orbit that were measured between 1976 and 1999. This study has been done in association with other related activities such as sunspot numbers, solar flare index, H-alpha solar flares, magnetic field of the Sun, high-speed solar wind streams, and galactic cosmic-rays. The time frequency and size distributions of the peak intensities of the SPEs have been obtained over the entire period and over the ascending–descending phases of each solar activity cycle. For the threshold intensity of >10 pfu the differential size distributions have a power-law form with a slope of -1.3 ± 0.2 with no evidence of any change with time, which is in agreement with the results of other authors in different time intervals.

An updated catalogue of the solar proton events with energy >10 MeV and peak flux >10 pfu is presented. It is based on the Moscow University catalogue (Catalogue of Solar Proton Events 1987–1996, Moscow University, Moscow) for the period 1987–1996. The events are separated into two categories (ordinary and anomalous) with respect to their sources at the Sun, their peak intensity, and their ground level enhancements. The relation between high-energy H-alpha flares and proton events associated with neutron monitor enhancements is discussed in order to be useful for the determination of acceleration processes at the flare site and in very rare interplanetary magnetic conditions.

Keywords: Solar cycle; Solar flares; Neutron monitor

1. Introduction

Solar flare proton events, studied in depth since 1956 (Malitson and Webber, 1962), show a solar cycle variation in the rate of events with large integrated fluxes. It has also been reported that the total solar cycle integrated flux is greater during solar cycles with larger maximum sunspot number (King, 1974). The statistical distribution of the intensities of the event at integrated fluxes (fluences) has been compared to log-normal distributions for several different time periods. King (1974) in an attempt to predict solar proton fluences with a log-normal distribution for space missions noted that the possibility of getting an event as large as the August 1972 event was extremely small (Feynman et al., 1990a). Data on event frequency distributions extensively reported for various solar flare phenomena are of great interest for resolving problems of particle acceleration at or near the Sun.

In particular, it is very important to estimate a fraction of the total flare energy budget for protons with energies <20 MeV in the context of a probable existence of threshold effects. A set of studies has been carried out on the size distributions of radio bursts, soft and hard X-rays flares, and interplanetary particle events (Kurt, 1990; Crosby et al., 1993). They all show distributions above the sensitivity threshold that can be fitted with power laws. The proton peak distributions at the Earth's orbit turn out to be significantly flatter than those obtained for other parameters more representative of total flare energy (Van Hollebeke et al., 1975; Feynman et al., 1990a,b; Mendoza et al., 1997).

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The purpose of this work is to study the frequency distribution of peak intensities of solar proton events (SPEs) over the period 1976–1999 using data from the National Oceanic and Atmospheric Administration of the Space Environment Services Center (NOAA SESC). We want to determine their association with other related activities and to identify possible sources at or near the Sun. An updated catalogue of SPEs based on the Moscow University catalogue gives the opportunity to study acceleration processes in the interplanetary medium. A first study of the biggest solar energetic events associated with ground-level enhancements is attempted.

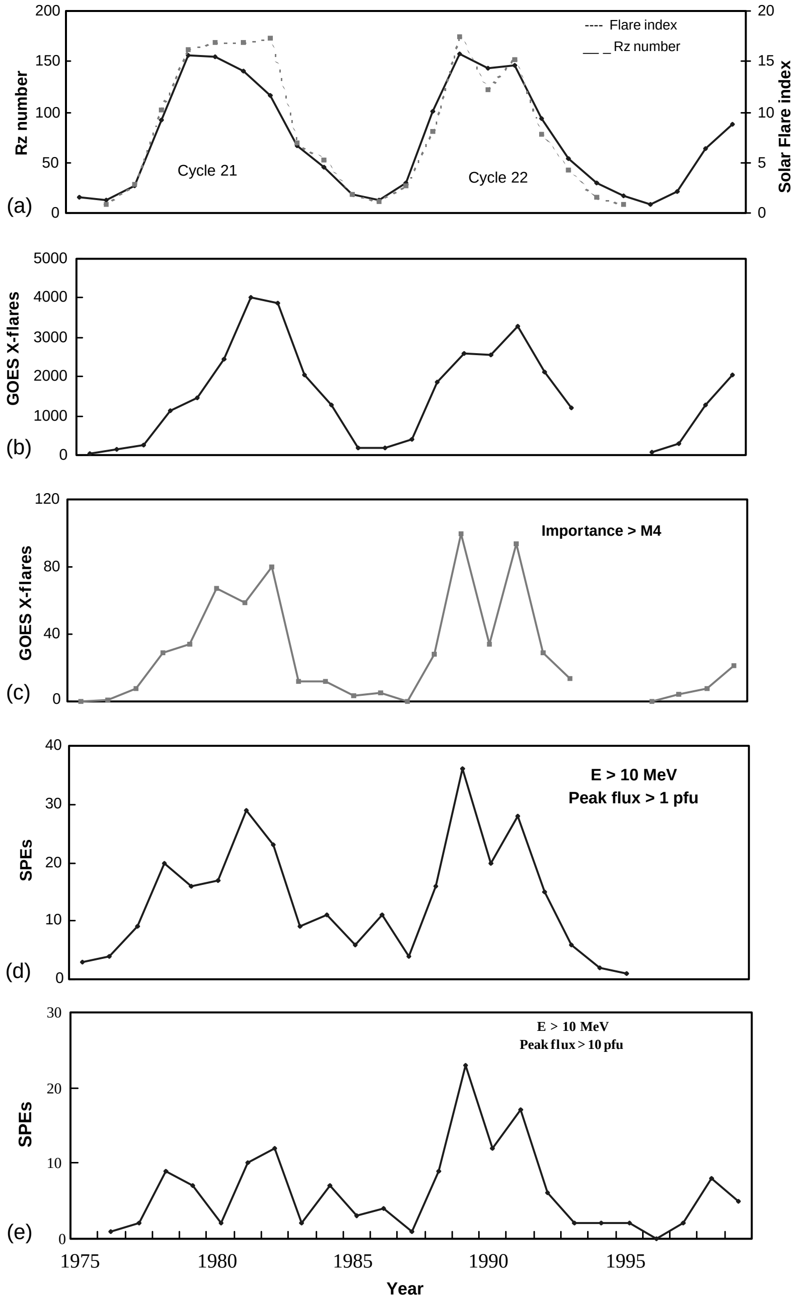


Fig. 1. Time distributions of the yearly values of (a) sunspot number R_z and solar flare index, (b) GOES flare number, (c) GOES flare number with importance $>$M4 and (d), (e) proton event number with $E > 10$ MeV and peak intensity > 1 and > 10 pfu, respectively, during the two solar cycles 21 and 22, and a part of cycle 23.

2. Proton event data

To select SPEs, we used a standard threshold integral intensity >10 particle flux units (pfu) at the peak time of the event and a threshold energy >10 MeV. These data are taken from issues of NOAA SESC (2000) for the time period from January 1976 to December 1999 covering over two solar cycles (21, 22 and a part of 23). According to this list, proton fluxes are integral 5-min averages for energies >10 MeV given in particle flux units measured by a GOES spacecraft in geosynchronous orbit. The start of a proton event is defined by the first three consecutive data points with fluxes $\geqslant 10$ pfu. The end of an event is the last time that the flux was $\geqslant 10$ pfu. This definition, motivated by SESC customer needs, allows multiple proton flares and/or interplanetary shock proton increases to occur within one SESC proton event.

In order to identify possible sources of the proton events, we examine the relationship between the proton event number and some other related activities such as sunspot number, solar X-ray flares registered by GOES, solar flare index (total energy emitted by the flares), and the solar X-ray flares with importance $>$M4. All of flare data are extracted from the NOAA SESC. The time distributions of these parameters and of solar proton events number with energies >10 MeV and peak intensities >1 and 10 pfu (Sladkova et al., 1998) are presented in Fig. 1. From this figure it can be seen that all these parameters follow the flare index maximum that is different from the sunspot number one. The large number of powerful solar flares with importance $\geqslant$ M4 characterizing solar cycle 22 results in an increasing occurrence rate of proton events during this cycle. Cane et al. (1999) reported that there is a kind of connection between the evolution of solar activity, the magnetic field of the Sun as a star, and the efficiency of powerful proton production.

The frequency distribution of the total number of SPEs (1976–1999) at threshold proton energy >10 MeV and peak intensity >10 pfu represented by a power-law at the form $\mathrm{d}N/\mathrm{d}I = I^{-a}$, where N is the number of events per flux interval and I is the mean particle flux in that interval at energy >10 MeV, is presented in Fig. 2.

Using least-squares fitted power-law functions, we have calculated the slope of the distribution to be 1.3 ± 0.2. Each point is a weighted fit of all the events in that interval with the actual values used given in the tables of Fig. 2. It is noteworthy that this slope is in agreement with that calculated by Mendoza et al. (1997) for the time interval 1955–1993. We can compare this value with those of frequency distributions of solar flares at different wavelengths, such as in radio, soft X-rays, or hard X-rays being 1.7–1.8 for the peak count rate, 1.4–1.6 for flare energies, and 2.0 for flare durations (Crosby et al., 1993). Van Hollebeke et al. (1975) have found that the size distribution of flare associated particle events is represented also by a power-law form at a given energy of 20–80 MeV with a slope $a = 1.15 \pm 0.05$, which is consistent with the value of 1.3 ± 0.2 found in this paper within uncertainties.

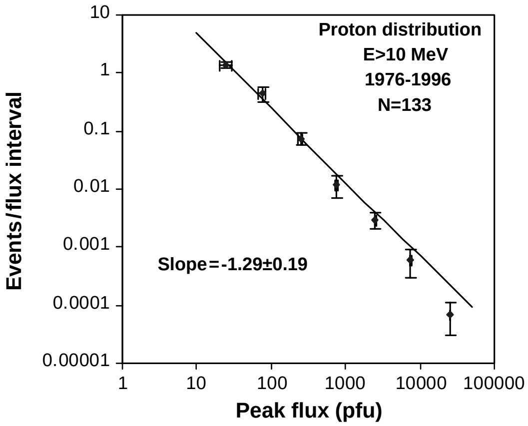
A similar procedure was performed with the SPEs that occurred on the ascending and descending phases of the 21st and 22nd solar cycles for proton energy >10 MeV and peak intensity >10 pfu. The slopes are 1.30 ± 0.23 and 1.28 ± 0.18 for the ascending and descending phases, respectively (Fig. 2). We noticed that the slight difference in slope between the two phases is not statistically significant. Two specific problems in these size distributions have already encountered, like the detection of low intensity events and the difference from the power-law fitting in the high-intensity ranges constructed with pure statistics.

3. Energetic proton events

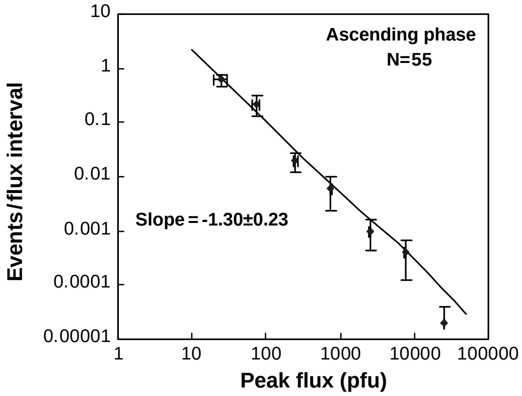
An updated catalogue of the solar proton events with energy >10 MeV and peak flux >10 pfu for the period 1987–1996 is presented in Table 1.

It is based on the catalogue of SPEs of the Institute of Nuclear Physics of Moscow University (Sladkova et al., 1998). The integral proton energy spectrum and intensity–time profiles of proton fluxes in several energy bands for each event as well as information on the possible SPE sources have been used. A typical example is given in Fig. 3. The particle flux data were derived from original observations from the Meteor satellite (Fedorov Institute of Applied Geophysics), the GOES and IMP spacecraft, and balloon measurements (Lebedev Physical Institute of Russian Academy of Sciences) (Sladkova et al., 1998). The Neutron Monitor data were taken from Ground Level Enhancement Database for Cycle 22 (Solar Geophysical Data 1987–1996). A total of 69 well-defined proton events are reported between 1987 and 1995 with 50% recorded as anomalous (A), and 12 associated with ground level enhancements (GLEs) as seen from Neutron Monitor increases. A previous catalogue published by Feynman et al. (1990b) for the period 1965–1985 did not include such a classification of the events. It is noteworthy that 73% of these events were reported during the 3 years at the maximum of this cycle, consistent with the result of Shea and Smart (1995).

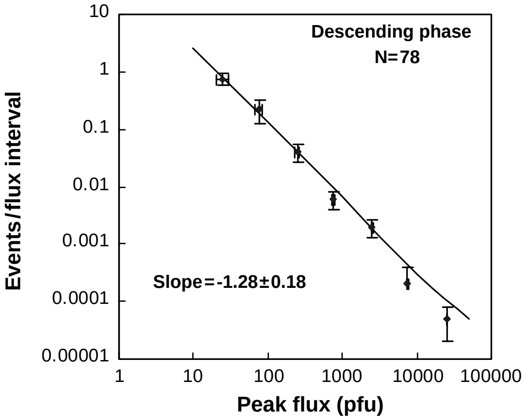
For a better understanding of the interest for proton events, some of the most typical energetic events of the Table 1 are mentioned, such as those of October 1989, May 1990, etc. The October 1989 type of event occurs very rare. This event was characterized by an extremely anisotropic “spike” and the absence of a worldwide sudden commencement geomagnetic field perturbation following this event (Shea and Smart, 1998). The relativistic SPE in May 1990 has also exhibited some unusual effects. This event was associated with impulsive short solar X-ray flares, but similar to the event of October 1989, no geomagnetic disturbance was recorded. The energy spectra, the time distribution and the cosmic-ray intensity registered at Inuvik, Deep River and Goose Bay Neutron Monitor stations for this event are presented in



Flux interval pfu	Events > 10 MeV	Events/flux interval
10-50	55	1.375±0.139
50-100	22	0.440±0.130
100-500	30	0.075±0.017
500-1000	6	0.012±0.005
1000-5000	14	0.003±0.001
5000-10000	3	0.0006±0.0003
10000-50000	3	0.00007±0.00004



Flux interval pfu	Events > 10 MeV	Events/flux interval
10-50	25	0.625±0.160
50-100	11	0.220±0.092
100-500	8	0.020±0.008
500-1000	3	0.006±0.004
1000-5000	5	0.001±0.0006
5000-10000	2	0.0004±0.0003
10000-50000	1	0.00002±0.00002



Flux interval pfu	Events > 10 MeV	Events/flux interval
10-50	30	0.750±0.163
50-100	11	0.220±0.092
100-500	22	0.050±0.014
500-1000	3	0.006±0.002
1000-5000	9	0.002±0.001
5000-10000	1	0.0002±0.0002
10000-50000	2	0.00005±0.00003

Fig. 2. The upper panel is the size distribution of solar proton events with energies $E > 10$ MeV and peak intensity > 10 pfu for the period 1976–1997. The values of each point of this distribution are given in the nearby table. The size distributions for the ascending and descending phases of the solar cycles 21 and 22 are given in the next two panels.

Fig. 3. This was captured by the LASCO detector on SOHO. During the current cycle the first solar energetic events occurred in early (3–9) November, 1997. For the first time, such events were observed by the new generation of spacecraft, including SOHO and a number of other spacecraft such as GOES (Daly and Nieminen, 1998). Especially the event of November 6, 1997 was so large and energetic that it could be measured at ground level. During the event of October

Table 1
List of solar proton events for the period 1987–1995[a]

Event	Date (YY/MM/DD)	Peak duration (DD:HH/DD:HH)	Peak flux (pfu)	Flares		Neutron monitor increase (%)	Type
				Imp	Region		
1	87/11/08	08:10/08:12	60	1N	4875[a]	No	O
2	88/01/03	03:09/03:11	60	3N	4912	No	O
3	88/03/25	25:23/26:01	38	No flare	4964[a]	No	O
4	88/06/30	30:11/30:15	10	2B	5060	No	O
5	88/11/08	08:16/09:02	15	2N	5222	No	O
6	88/12/14	15:03/15:08	10	1N	5278[a]	No	O
7	88/12/16	16:18/17:13	18	2B	5278	No	O
8	89/03/07	09:10/10:02	150	3B	5395	No	A
9	89/03/10	13:07/13:09	780	3B	5395	No	A
10	89/03/17	18:08/18:11	1000	2B	5395	No	A
11	89/03/23	23:21/23:24	30	3B	5409	No	O
12	89/04/11	12:00/12:04	500	No flare	No flare	No	A
13	89/05/05	05:11/05:14	40	2B	5470[b]	No	O
14	89/05/20	23:13/23:15	20	2B	5497[b]	No	O
15	89/06/18	18:17/18:20	10	SF	5536[a]	No	O
16	89/07/25	25:09/25:14	30	1B	5603	No	O
17	89/08/12	13:04/13:09	6309	2B	5629	No	A
18	89/08/15	15:17/15:23	316	1N	5629	No	A
19	89/08/16	16:03/16:09	1000	2N	5629	10–100%	A
20	89/08/17	17:10/17:17	631	SN	5629	No	A
21	89/08/19	20:03/20:04	250	1N	5645[c]	No	A
22	89/08/22	22:18/23:03	60	No flare	No flare	No	O
23	89/09/12	13:08/13:11	30	2N	5687[b]	No	O
24	89/09/29	29:13/29:24	1995	2N	5698	>100%	A
25	89/10/19	20:15/20:18	25119	3B	5747	10–100%	A
26	89/10/22	22:18/23:07	2512	1N	5747	>100%	A
27	89/10/24	24:20/25:03	63096	2N	5747	>100%	A
28	89/10/29	29:08/29:12	55	No flare	No	No	O
29	89/11/15	15:07/15:11	58	2B	5786	10/100%	O
30	89/11/26	28:12/28:13	130	2B	5800[c]	No	A
31	89/11/30	01:01/01:15	1995	2N	5800	No	A
32	90/02/03	03:03/03:08	18	1N	5917	No	O
33	90/03/19	19:17/20:01	700	1N	5969	No	A
34	90/04/15	17:11/17:13	10	2B	6022	No	O
35	90/04/28	28:18/28:20	100	No flare	No flare	No	O
36	90/05/21	21:23/22:08	199	2B	6063	10–100%	A
37	90/05/24	24:21/25:03	199	1B	6063	10–100%	A
38	90/05/26	26:22/27:04	158	No flare	No flare	10–100%	A
39	90/05/28	28:08/29:02	100	No flare	No flare	3–10%	A
40	90/06/12	12:14/12:20	70	2B	6089	No	O
41	90/07/25	26:04/26:10	10	2N	6174	No	O
42	90/07/30	01:17/01:22	200	2N	6180	No	A
43	91/01/31	31:15/31:20	200	2B	6462	No	A
44	91/03/22	24:04/24:06	10^4	3B	6555	No	A
45	91/04/03	04:05/04:12	48	2N	6562	No	O
46	91/05/13	13:04/13:11	300	SN	6615	No	A
47	91/05/31	31:09/31:17	20	1B	6654[b]	No	O
48	91/06/02	02:19/02:23	18	2B	6652[b]	No	O
49	91/06/04	07:06/08:17	280	3B	6659[b]	No	A
50	91/06/11	11:13/11:16	1995	2B	6659	3–10%	A
51	91/06/15	15:09/15:17	1000	3B	6659	10–100%	O
52	91/06/29	30:13/01:01	25	SN	6693[b]	No	O
53	91/07/01	01:19/02:01	100	1N	6703	No	A
54	91/07/07	08:05/08:07	1000	3B	6703	No	A
55	91/07/10	11:05/11:07	20	2N	6718	No	O
56	91/08/25	27:17/27:21	200	2B	6805	No	A

Table 1 (*continued*)

Event	Date (YY/MM/DD)	Peak duration (DD:HH/DD:HH)	Peak flux (pfu)	Flares Imp	Flares Region	Neutron monitor increase (%)	Type
57	91/10/28	28:14/28:17	25	2B	6891[a]	No	O
58	91/10/30	30:09/30:13	60	2N	6891	No	O
59	92/02/07	07:11/07:12	60	2B	7035	No	O
60	92/05/08	09:12/09:23	1585	2N	7154	No	A
61	92/06/25	25:23/26:09	300	1B	7205	No	A
62	92/06/28	28:15/29:05	20	SN	7205	No	O
63	92/10/30	31:02/31:08	63095	2N	7321	No	A
64	92/11/02	02:06/02:15	2000	2B	7321	No	A
65	93/03/04	04:14/04:18	15	1N	7434	No	O
66	93/03/12	12:21/13:04	30	3B	7440	No	O
67	94/02/20	21:07/21:11	2512	3B	7671	No	A
68	94/10/19	20:00/20:16	20	1F	7790[b]	No	O
69	95/10/20	20:08/120:15	40	1N	7912	No	O

Note: The first column indicates the proton events and the second one the date (year/month/day) of each one. The third column indicates the time of detection of the maximum in the particle fluxes and the symbols "/" separates the commencement and end of the time interval within which the maximum proton fluxes were observed (Sladkova et al., 1998). The fourth column gives the maximum value of the flux and the next two indicate the associated flares identified as certain, probable (a), possible (c) or contributing (b) sources of the proton events. The next column identifies the increase appearing or not appearing in the Neutron Monitor data. The last column presents the type of the event classified as ordinary (O) or anomalous (A).

[a] Probable.

[b] Contributing.

[c] Possible.

1989, which was the largest event of the last 20 years, the 10 MeV flux registered by GOES reached about 4×10^4 pfu compared to 5×10^2 pfu for the event of November 1997. A very large GLE also appeared during the last year on July 14, 2000. We can expect to see such events at the rate of about one every 6 months to a year during the solar cycle.

A detailed study of the biggest solar energetic events associated with ground level enhancements will be attempted in the next work.

4. Discussion and conclusions

Studying the well-defined SPEs from the NOAA SESC catalogue for the interval 1976–1999, we have separated 147 events with proton energy >10 MeV and peak intensity >10 pfu observed at 1 AU. The maximum number of the SPEs per year during the 22nd cycle is more than twice that recorded in Cycle 21, while this cycle is characterized by a strong flare activity in relation to the sunspot number (Fig. 1e). Statistical analysis of the SPEs with other related activities, such as sunspot numbers, grouped solar flares, high-speed solar-wind streams and galactic cosmic-rays shows systematic differences between the two cycles (Mavromichalaki et al., 1997).

The identified solar flare sources of the SPEs during the examined time interval present a longitudinal distribution and are located at the edges of the solar disk and especially in the west limb of the Sun. This is in agreement with the well-known result caused by the spiraling of the solar magnetic field between the Sun and the Earth.

We have also tried to obtain the SPE size distribution for the period 1976–1999 considering the total number of events and the events separated according to whether they occurred in the ascending and descending phases of the solar activity cycle. It is characteristic that the slopes of all three distributions have only small deviations, in spite of the different statistics of the events under study. These slopes are in agreement with the previous work of Mendoza et al. (1997) for the period 1955–1993. The same results have been obtained from the frequency distribution of flare electron events, which reveals a slope 1.30 ± 0.07 and 1.42 ± 0.04 in the energy interval 3.6 and 185 MeV, respectively (Kurt, 1990). The proton peak flux distributions at the Earth's orbit are significantly flatter than those obtained for other parameters more representative of total flare energy with a slope of 1.45 ± 0.15 (Kahler et al., 1991) for the energy intervals >10 and >25 MeV and a power-law slope of 1.53 ± 0.02 for the total energy in electrons (Crosby et al., 1993), while a slope of 1.15 ± 0.05 for solar flare associated particle events for 20–80 MeV is given by Van Hollebeke et al. (1975). It is noted that the slope value of 1.3 ± 0.2 presented in this paper for proton events with energy >10 MeV is consistent with this statement.

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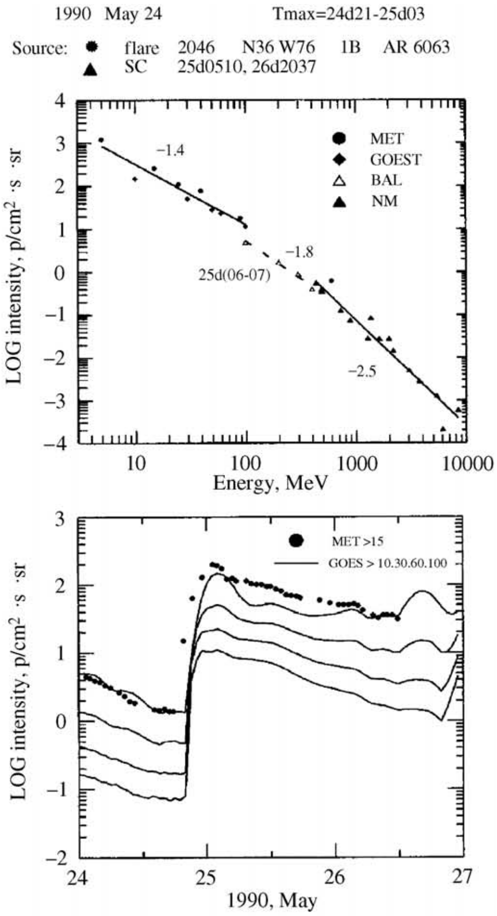
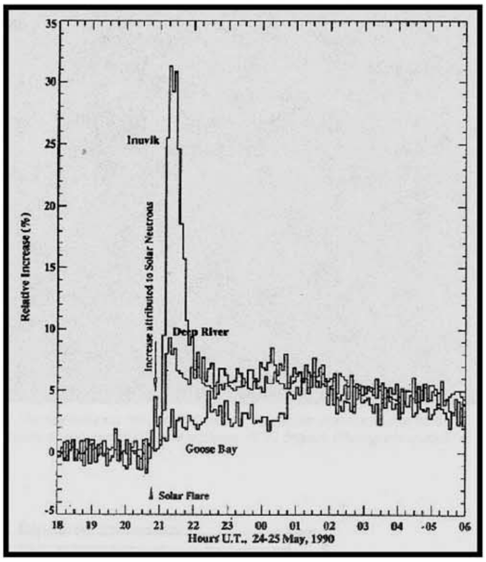
Fig. 3. A typical example of the large event of May 24, 1990 is presented. The proton energy spectra and the intensity time profile for this event are in the upper panels. The lower panel presents the big cosmic-ray intensity enhancement measured at Deep River, Inuvik and Goose Bay Neutron Monitor Stations (Houseman and Fehr, 1996).





A new catalogue of the solar proton events with energy > 10 MeV and peak flux > 10 pfu with a separation of the events into two categories (ordinary and anomalous) based on the Moscow University catalogue (1998) for the time period 1987–1996 is given in Table 1. As we can see 69 proton events took place during this period and 10 of them gave GLEs. The criteria for the separation of the events in categories (ordinary and anomalous) are their peak intensity, their sources at the Sun, and their GLEs.

A closer connection between the powerful flares and the occurrence rate of the proton events is observed in our study. Gabriel et al. (1990) reported a circa 154-day periodicity in the occurrence rate of solar proton events which exists also in the H-alpha flare data, while Das et al. (1996) found a periodicity of 74 days in the time series of the solar flare proton fluences measured in three ranges of energy (> 1, > 10 and > 100 MeV) in Cycle 22 indicating the intimate relationship of proton emission with solar activity. Searching for the manifestation of a fundamental causative mechanism for proton events, we examined the relation between proton events and powerful flares that are caused by the global changes of the solar magnetic field that is important for long term modulation (Cane et al., 1999). While in most cases a parent flare can be identified with the proton event, this is not always the case, because it can be associated with an erupting filament well away from any active region (Kahler et al., 1986). Many differing conclusions about this subject gives the result that perhaps flares and proton events are just different manifestations of the same more fundamental phenomenon, which can be the escape of magnetic field from the Sun.

A more detailed investigation of the well determined proton events associated with GLEs according to our catalogue will help us to find the flare sources of SPEs that can produce GLEs and to define a more general indicator of solar activity for a better understanding of the interplanetary conditions that define Space Weather.

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