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Major solar proton events observed by IMP-8 (from November 1973 to May 2001)

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Abstract. The ongoing mission of the IMP-8 spacecraft has generated a uniform and nearly time-continuous database of energetic particle events through solar cycles 21, 22, and the rising phase of solar cycle 23. In this paper we use energetic (48.0–96.0 MeV) proton intensities from the CPME instrument to identify the major solar energetic proton (SEP) events observed during a 27.5-year period (November 1973 – May 2001). We examine their time-intensity profiles and their temporal distribution within the sunspot solar cycles. We compare the two largest SEP events observed so far in solar cycle 23 (i.e., the Bastille Day 2000 event and the November 9, 2000 event) with the other major SEP events observed over the last two solar cycles. The two SEP events in 2000 show the highest intensities ever observed by IMP-8. These data allow us to establish an upper limit on the ∼50–100 MeV SEP intensities observed at 1 AU during the past 27.5 years.

1 Introduction

The IMP-8 spacecraft has monitored SEP intensities for nearly 28 years. In this paper we examine IMP-8 observations of major proton intensity increases during the last 2.5 solar cycles. We determine the maximum intensities reached by ∼50–100 MeV solar energetic protons observed at 1 AU and also determine the occurrence times of these major events during the solar activity cycles.

2 Event selection

Data used in this paper are intensities of protons with energies 48.0–96.0 MeV, as measured by a channel of the Charged Particle Measurement Experiment (CPME) on the earth-orbiting satellite IMP-8 (Sarris et al., 1976). We focus on this energy range because this CPME channel has shown no susceptibility to instrumental saturation at even the highest intensities, and because SEPs in the ∼50–100 MeV range are of particular concern during inclement space weather conditions (e.g., during Polar Cap Absorption events and manned space flights). We scanned these data for the period November 1, 1973 to May 1, 2001 and selected all events with 48.0–96.0 MeV proton intensities > 1 $(\mathrm{cm^2 sr\, s\, MeV})^{-1}$. This restrictive criterion reduces our sample of SEP events to those with very high intensities. Table 1 lists the 21 periods that satisfy this condition during the above period. We have associated each SEP event with a specific solar event (i.e., flare and/or CME) using published studies (last column of Table 1). Observations of coronal mass ejections (CMEs) were confined to the operational periods of the SMM and LASCO coronagraphs, as described in the respective references. When it was possible to compute the plane-of-sky (POS) speeds of these CMEs, they were always higher than 1100 km s^{-1}.

Figure 1 shows the time-intensity profiles for 15 of these events. Vertical solid lines mark the arrival of interplanetary shocks at 1 AU. For those periods with an IMP-8 data gap, we use the occurrence of Sudden Storm Commencements (SSCs) as a proxy for the arrival of interplanetary shocks at the earth (these cases are indicated by an asterisk in the seventh column of Table 1). Note that the shock for the second event in Aug’89 was not associated with the main solar event responsible for the SEP event at the earth (Richardson et al., 1994). The events in Mar’91, Jun’91 and Aug’89 occurred during periods of intense solar activity and, most probably, some additional solar events (not specified in Table 1) contributed to observed proton intensities (Shea and Smart, 1993; Richardson et al., 1994).

Most of SEP events in Table 1 were associated with flares that occurred at or near the Sun’s western limb. Those with large proton fluences (see Figure 1) were associated with solar events near the Sun’s central meridian (Shea and Smart, 1996). For these latter SEP events, a strong interplanetary shock was usually observed at the earth. These events have the largest fluences because particles are accelerated continually during the shock’s transit time from the Sun to 1 AU and the observer connects to stronger regions of the shock front as it moves away from the Sun (Lario et al., 1998).

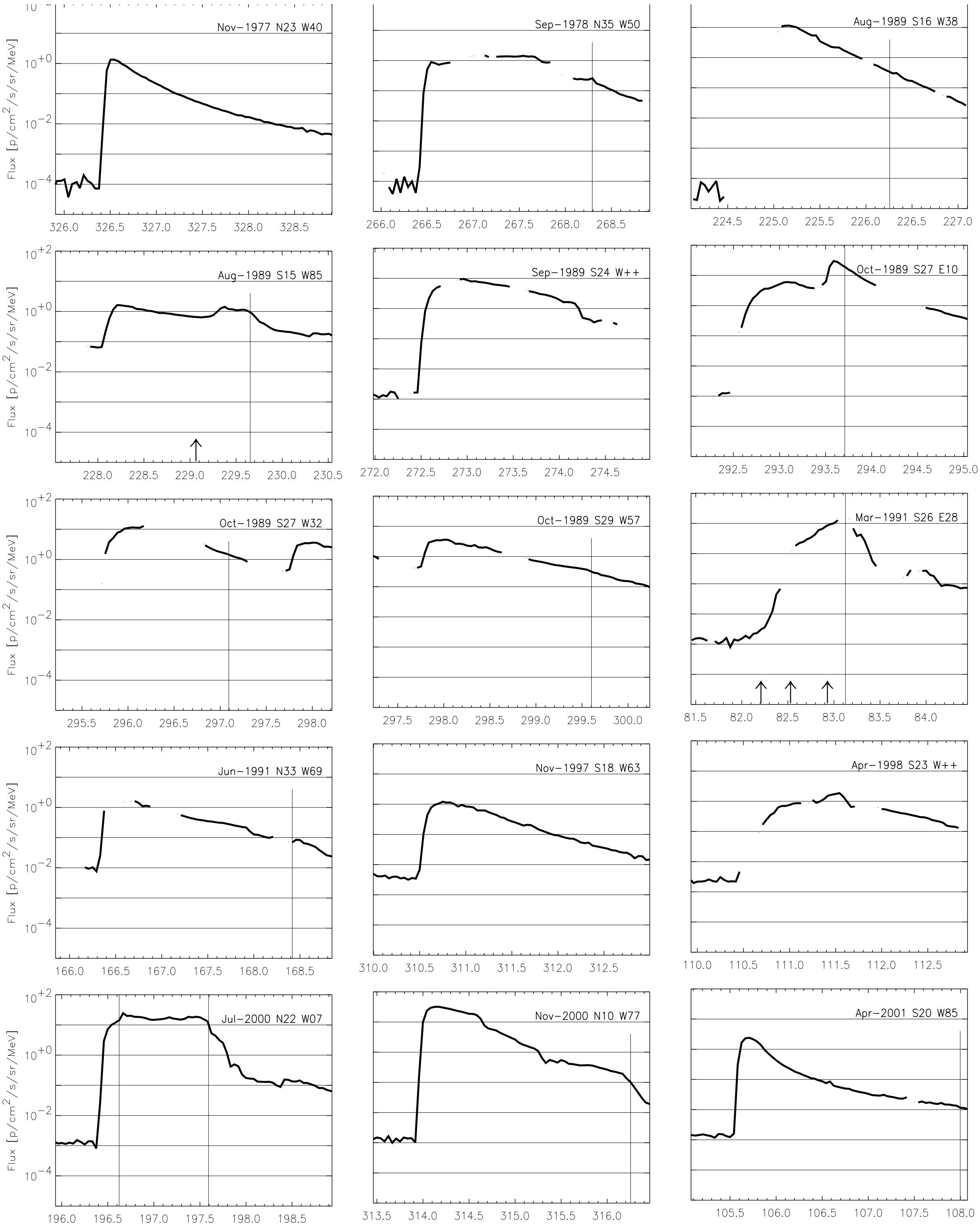

Fig. 1. Intensity time profiles as measured by the 48.0–96.0 MeV proton channel of the CPME instrument on board the IMP-8 spacecraft for 15 of the 21 SEP events described in Table 1.

3 Distribution of the major solar proton events over the sunspot solar cycles

Figure 2 shows the temporal distribution of the 21 solar proton events in Table 1. The following features are noteworthy. Major events (as per our definition) tend to occur during the rising, maximum and decaying phases of the solar cycles, being completely absent during the years of sunspot minima. A relatively long period devoid of major SEP events occurred during the maximum of the solar cycle 21. Solar cycle 22

Table 1. Major solar proton events observed by IMP-8. References: [1] Burlaga et al. (1980); [2] Cane (1985); [3] Richardson et al. (1991); [4] Cane et al. (1986); [5] Kahler et al. (1990); [6] Kahler (1993); [7] Richardson et al. (1994); [8] Kahler (1994); [9] Klein et al. (1999); [10] Lario and Decker (2001); [11] Cane and Richardson (1995); [12] Shea and Smart (1993); [13] Kocharov et al. (1994); [14] Lario et al. (2000); [15] Reames et al. (2001). IMP-8 located at the magnetotail [T], magnetosheath [S] or solar wind [SW]. $*$ Arrival time of the shock based on the occurrence of a SSC. † Peak flux evaluated outside the ESP event.

SEP Event	Solar Flare			CME		Shock	Peak Flux	IMP-8	Refe-
	X-ray Maximum	Importance X-ray/Opt	AR Location	Speed POS [km s^{-1}]	Observation Time [UT]	at 1 AU	48.0-96.0 MeV [cm^{2}sr s MeV]$^{-1}$	Loca-tion	rences
Nov'77	326/1006	X1/2B	N23W40	-	-	329/1213	1.34	S	[1]
Sep'78	266/1023	X1/3B	N35W50	-	-	268/0718*	1.56	SW	[2]
Oct'81	285/0627	X3/2B	S17E30	-	-	286/2240*	1.33	T	[3]
Dec'82	341/2354	X2/1B	S19W86	-	-	NO	1.44	SW	[4]
Feb'84	047/0858	–	∼S12W130	1260	047/0844	NO	>0.87	T	[5]
Aug'89	224/1427	X2/2B	S16W38	>1200	224/<1445	226/0612*	11.5	T	[6,7]
Aug'89	228/0107	X20/2N	S15W85	1377	228/∼0050	229/1540*	1.63	SW	[7,8]
Sep'89	272/1133	X9/1B	∼S24W105	1828	272/1122	?	9.54	T	[8,9]
Oct'89	292/1258	X13/4B	S27E10	-	-	293/∼1650	6.04†	SW	[10]
Oct'89	295/1755	X2/1N	S27W32	-	295/<1917	297/0215*	12.8	SW	[8,11]
Oct'89	297/1831	X5/2N	S29W57	1453	297/1756	299/1427*	3.60	T	[8,11]
Mar'91	082/2247	X9/3B	S26E28	-	-	083/0342*	>14.2	T	[12]
Jun'91	162/0229	X12/3B	N31W17	-	-	164/0016*	4.92	T	
Jun'91	166/0821	X12/3B	N33W69	-	-	168/1018*	>1.63	SW	[13]
Oct'92	304/1816	X1/2B	S22W61	-	-	306/2146	>1.85	SW	–
Nov'92	307/0308	X9/2B	S23W90	-	-	?	>1.11	S	–
Nov'97	310/1155	X9/2B	S18W63	1560	310/1210	313/1003	1.21	SW	[14]
Apr'98	110/1021	M1/	∼S23W125	1638	110/1007	113/1730	1.86	SW	[14]
Jul'00	196/1024	X5/3B	N22W07	>1450	196/1054	197/1415	24.5	SW	[15]
Nov'00	313/2304	M7/3F	N10W77	2035	313/2306	316/0605	32.0	S	
Apr'01	105/1350	X14/2B	S20W85	1160	105/<1406	107/2357(?)	2.40	SW	

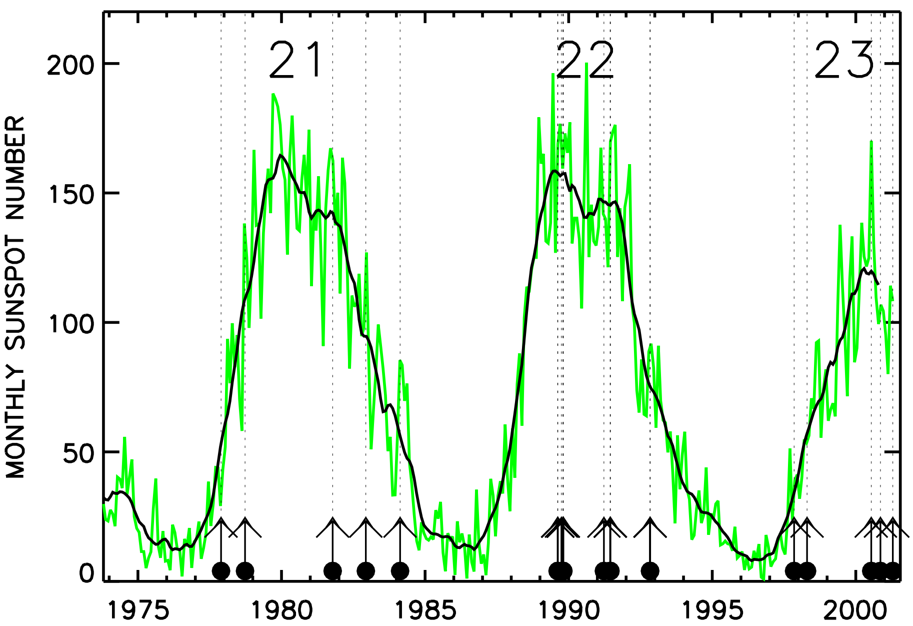

Fig. 2. Monthly sunspot number from November 1973 to May 2001. Vertical arrows mark the occurrence of the major proton events described in Table 1.

was marked by an absence of major events during its rising phase, and then a cluster of six major SEP events in the autumn of 1989; four of these events (Sep'89 and Oct'89) originated from the same active region (Bavassano et al., 1994).

Several major SEP events have occurred during solar cycle decay phases (the large event in Aug'72, not shown here, occurred during the declining phase of the solar cycle 20). Thus far, during the current solar cycle 23, two relatively small events occurred during its rising phase (Nov'97 and Apr'98). But, the two most intense events ever observed by IMP-8, i.e., the Bastille Day 2000 (Jul'00) and the November 2000 (Nov'00) events, occurred within just this past year. Note that the largest SEP events in solar cycle 21 were less intense, by at least a factor of ten (Table 1, Column 8), than those in cycles 22 and 23.

4 Maximum peak intensities

Column 8 of Table 1 contains the peak intensity (based on 1-hour averages) of 48.0–96.0 MeV protons for each of the 21 events. For those events with data gaps, we have supplemented the profiles with those from the GOES energetic particle detectors to infer a lower limit to the peak flux detected by IMP-8. Note that IMP-8 was in the solar wind for 11 of the 21 events (Table 1, Column 9).

The two SEP events in 2000 show the highest 48.0–96.0 MeV proton intensities. We note that the peak intensity for the first of the Oct'89 events was taken at the time before the arrival of the Energetic Storm Particle (ESP) event. This ESP event was due to an unusual sequence of interplanetary magnetic field structures as described by Lario and Decker (2001). However, the peak intensity for the Nov'00 event, which was observed during the prompt phase of SEP arrival, was even higher than the peak for the ESP event in Oct'89.

The Jul'00 (Bastille Day) event occurred just before the arrival of an interplanetary shock at earth on 196/1458 UT. The CME that generated the Jul'00 SEPs occurred at 196/$<$1054 UT. The trapping of particles between the first shock and that driven by the Jul'00 CME produced a plateau in the proton intensities that lasted longer than a day (Reames et al., 2001). By contrast, the prompt component of the Nov'00 SEP event arrived at 1 AU under relatively undisturbed conditions; therefore, the high proton intensities during this event were largely unaffected by particle trapping and/or reflection. Reames and Ng (1998) suggested that the physical process of wave generation by particles streaming outward early in a SEP event provides a self-regulation of the particle intensity observed at 1 AU that cannot exceed a given limit. As noted by Reames et al. (2001) the Jul'00 event showed proton intensities higher than the original streaming limit found previously by Reames and Ng (1998). We note that for the Nov'00 SEP event we observe an intensity of 48–96 MeV protons that is not only higher than initially predicted, but even higher than that observed during the Jul'00 event.

5 Conclusions

Using IMP-8/CPME observations from November 1973 to May 2001, we found 21 SEP events for which the intensity of 48.0–96.0 MeV protons exceeded 1 $(\mathrm{cm}^2 \mathrm{sr\,s\ MeV})^{-1}$. All these SEP events occurred during the interval from within two years before to four years after each solar maximum. The events were associated with fast CMEs that originated from central meridian or western longitudes on the Sun. The question "how intense an SEP event can the Sun produce ?" is of interest not only for historic research but also for space weather purposes. We emphasize ESP events are not the only phase of SEP time-intensity profiles where one observes unusually high intensities of high-energy protons — extremely high intensities can also be observed in the promptly arriving SEP component.

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