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Solar Proton Events in Solar Activity Cycles 21–24

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Abstract—It is shown that the number of solar proton events (SPEs) with proton energies (E) higher than 10 and 100 MeV in the current solar cycle (cycle 24) differs slightly from the number of the same events in earlier cycles (cycles 21–23), even though solar activity was low during the growth and maximum phase in cycle 24. A deficit was in this case observed for the most powerful GLE events, which are characterized by high proton fluxes with $E > 100$ MeV. The ratio of the number of SPEs with $E > 10$ and 100 MeV to the number of sunspots in cycle 24 doubled, compared to the same ratio in cycles 21–23, and the relative number of GLEs fell by more than half. The characteristics of flares and coronal mass ejections associated with proton events with $E > 100$ MeV in cycle 24 were virtually the same as the analogous parameters in cycle 23.

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INTRODUCTION

Energetic solar particles (solar cosmic rays (SCRs)) are registered in interplanetary and near-Earth space after powerful explosive releases of energy on the Sun. The energy of SCRs is many times higher than that of other solar particles and emissions, sometimes reaching 10 GeV or more. In this case, SCRs generate cascades in the Earth's atmosphere and are registered by ground-based devices. These belong to the class of SCR events referred to as ground level enhancements (GLEs). Such events are of great interest both in studying the mechanisms by which charged particles are accelerated and propagate on the Sun and in the interplanetary medium and in determining the danger posed by radiation in near-Earth space. The current solar activity cycle (cycle 24) is characterized by a deficit of GLEs. Two such events had been registered by April 2014 (month 64 from the beginning of cycle 24), on May 17, 2012, and January 6, 2014 [1, 2], while 7 to 13 events were registered during the same period in the previous cycles. In this work, we analyze SPEs and the accompanying phenomena on the Sun during cycles 21–24, paying attention to most powerful events.

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SPE STATISTICS

Solar proton events in which protons with energies of $E > 10$ MeV and fluxes of $J \geq 1$ pfu (1 pfu = 1 cm^{-2} s^{-1} sr^{-1}) have been recorded in the catalogs edited by Yu. I. Logachev [3] ever since 1970. These catalogs also contain data on parent flares and other accompanying phenomena. They are also homogeneous data series, as the event selection criteria have remained unchanged in compiling the catalogs since the beginning of the 1980s. The homogeneity of long time series is a necessary condition for statistical studies, so this work is based on [3], even though data from other catalogs [4–7] are used for comparison. In addition to the catalog data, this work contains the results from the authors' current efforts, in which events in cycles 23 and 24 that occurred from 1997 to April 2014 (month 64 of cycle 24) are analyzed.

The first event in cycle 24 with a solar proton flux of $J(>10$ MeV$) \geq 1$ pfu at the time profile maximum occurred in August 2010 (month 20 from the start of the cycle). For comparison, SCR activity started in month 3 from the start of cycle 21 and in months 8 and 19 in cycles 22 and 23, respectively. Sunspot formation activity in cycle 24 was low, compared to the previous cycles; nevertheless, the number of SPEs with >10 and

Table 1. SPE statistics for the first 64 months of cycles 21–24

	Onset	Month 64	Number of events over 64 months		
			GLE	N(>100 MeV)	N(>10 MeV)
21	1976.5	1981.71	8	37	84
22	1986.8	1992.04	13	55	105
23	1996.4	2001.63	7	30	50
24	2009.0	2014.29	2	37	64

>100 MeV protons, N(>10 MeV) and N(>100 MeV), during cycle 24's growth phase and maximum was quite comparable to the analogous number in the previous cycles, while the number of GLEs was much lower. Data on solar activity and the number of SPEs for the first 64 months of cycles 21–24 are presented in Tables 1 and 2.

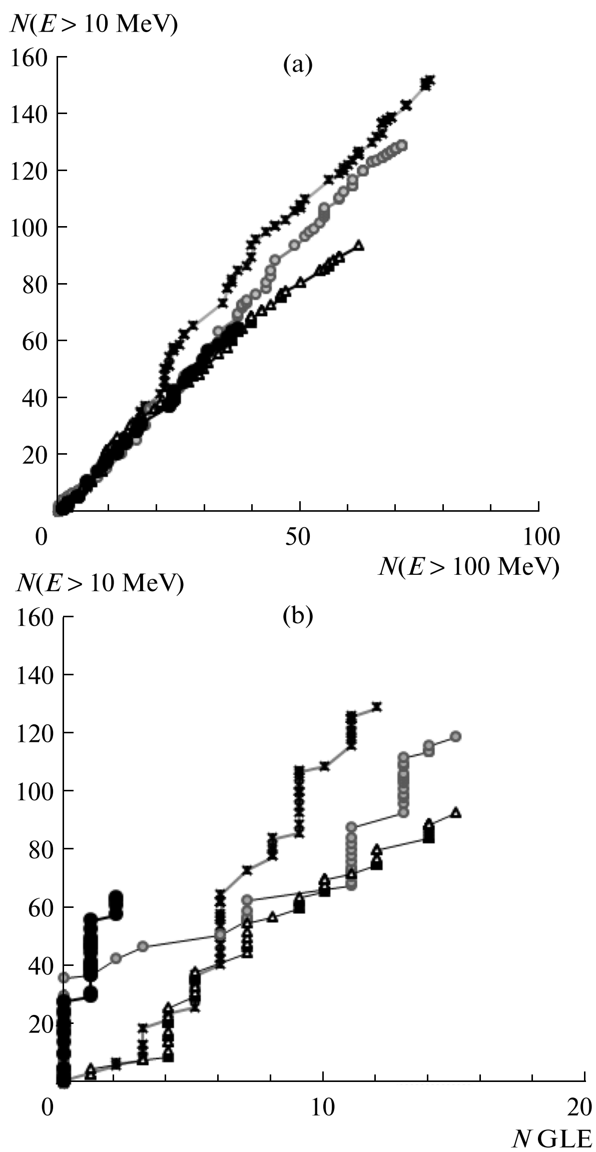

Fig. 1. (a) Relationship between the number of events with $E > 10$ and 100 MeV in cycles 21 (crosses), 22 (gray dots), 23 (white triangles), and 24 (black dots). Data prior to April 2014 were used for cycle 24. (b) The same, but for events with $E > 10$ MeV protons and the number of GLEs.

To account for cycle 24 being weaker than the previous cycles with respect to the number of sunspots (R_z) [12], we can use the ratio of the numbers of SPEs and sunspots accumulated over 64 months (ΣR_z). The number of events accumulated in a given month is the sum of events during the period from the start of the cycle. The results are given in Table 2. It is evident that the relative number of SPEs with $E > 10$ and 100 MeV grew remarkably in cycle 24, while the number of GLEs declined.

The relationship between the accumulated numbers of SPEs with $E > 10$ and 100 MeV in cycles 21–24 is shown in Fig. 1a. It is clear that all cycles are quite similar and cycle 24 was similar to the previous cycles in this parameter. Events with $E > 10$ and 100 MeV begin at approximately the same time, the difference being less than half a year, and the relationship between them remains the same during a cycle. GLEs began 15, 33, 18, and 40 months after the start of cycles 21–24, respectively. This can be seen in Fig. 1b, where the relationship between the accumulated numbers of SPEs with $E > 10$ MeV and GLEs is presented. It is clear that this relationship is similar for cycles 21 and 23, and that GLE generation lagged behind SPEs ($E > 10$ MeV). In cycle 22, when there were no GLEs for a long period of time, the relationship between these events and SPEs ($E > 10$ MeV) rapidly reached a value close to the ones in cycles 21 and 23. In cycle 24, the first SCR GLE occurred in month 41, while the second event was registered by month 64. Only event on May 17, 2012 (month 41), is officially acknowledged as GLE.

Assuming that cycle 23 was typical with respect to SPE characteristics and is most completely provided with the data on possible solar proton sources, we now consider only cycles 23 and 24. Let us concentrate on SPEs with $E > 100$ MeV protons (which include GLEs) and try to find differences in the SPE(>100 MeV) characteristics for cycles 23 and 24. The distribution of events over the flux size for J(>100 MeV) turned out to be steeper in cycle 24 ($\propto J^{-1.3}$) than in cycle 23 ($\propto J^{-1.1}$). In addition, there were no events with J(>100 MeV) > 100 pfu in cycle 24. We should note that it is GLEs that are characterized by higher J(>100 MeV). The deficit of GLEs in cycle 24 would thus seem to reflect the absence of intense proton fluxes with $E > 100$ MeV.

FLARES AND CMES RELATED TO EVENTS IN WHICH PROTONS WITH $E > 100$ MeV ARE OBSERVED

It is known (e.g., [9, 10]) that flares and CMEs are the most likely sources of accelerated particles registered after explosive releases of energy on the Sun. Particles are as a rule generated by >M5 X-ray flares [11, 12]. The numbers of such flares have fallen since cycle 23. The maximum numbers of M flares in cycles 22 and 23, smoothed over seven months, were ~50 and ~30, and for the X ball flares they were approximately 6 and 2, respectively. During the first 64 months, the maximum smoothed numbers of M and X flares were approximately 9 and 0.6, respectively [13]. The flare characteristics related to the generation of >100 MeV protons in this case remained virtually the same: the average magnitudes of X-ray flares during the first 64 months were M5 and M8 for cycles 23 and 24, respectively.

CMEs associated with SPEs with $E > 100$ MeV have high velocities (>1200 km/s on average) and wide beam angles (around 70% of these CMEs are halos). The fraction of CMEs with velocities greater than 1200 km/s is very small. According to the measurements in [14], this fraction was 1.87% in cycle 23 and 0.73% during the first 64 months of cycle 24; i.e., it fell by a factor of 2.5. At the same time, the parameters of CMEs related to SPEs with $E > 100$ MeV protons varied only slightly during the first 64 months of cycles 23 and 24: the average velocity was 1460 ± 73 and 1235 ± 89 km/s in cycles 23 and 24, respectively. The authors of [15] assumed that the smaller number of GLEs upon the simultaneous comparatively slight reduction in the total number of SPEs in cycle 24 was related to an increase in the CME beam angle, caused by a drop in the total (magnetic and plasma) pressure in the environment. Shocks form more easily as a result of the slower Alfvén velocity, but the efficiency of particle acceleration diminishes. However, our analysis of events with >100 MeV protons indicates that the average CME beam angle for these events was 305.2° ± 10.5° and 301.6° ± 17.5° in cycles 23 and 24, respectively. In other words, these angles virtually coincide.

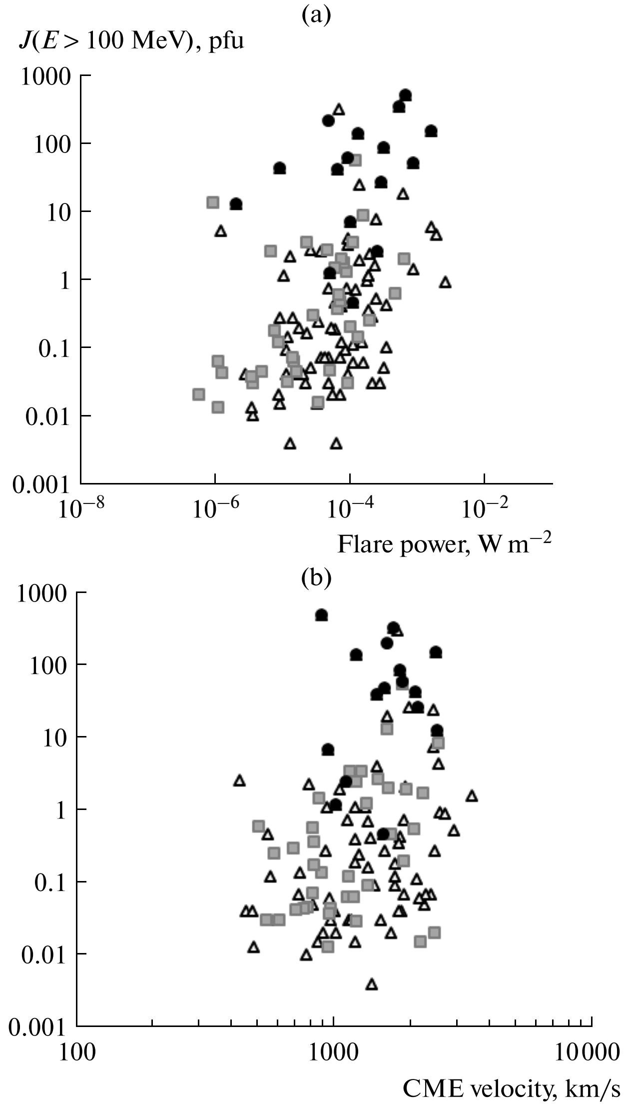

Fig. 2. (a) Flux of solar protons with $E > 100$ MeV at SPE time profile maximum, depending on the parent flare power for cycles 23 (white triangles) and 24 (gray squares). GLEs are marked by black dots. Data prior to April 2014 were used for cycle 24. (b) The same, but depending on the CME velocity.

The relationship between the J(>100 MeV) values and the importance of the X-ray flares associated with these values is shown in Fig. 2a; a similar relationship

Table 2. Number of SPEs, divided by the number of sunspots for the first 64 months of the solar cycle

Cycle	Month 64	R_z	ΣR_z for 64 months	Ratio of the number of SPEs to ΣR_z, multiplied by 100		
				GLE	N(>100 MeV)	N(>10 MeV)
21	1981.71	167	6481	0.12	0.57	1.3
22	1992.04	150	7108	0.18	0.77	1.48
23	2001.63	107	4471	0.16	0.67	1.12
24	2014.29	85	2731	0.07	1.35	2.34

between J(>100 MeV) and the CME velocity is shown in Fig. 2b. It is clear that the J(>100 MeV) distributions over the above source parameters for cycles 23 and 24 are similar. Although GLEs are associated with more powerful flares and faster CMEs, these events do not form a distinguishable group in the distributions shown in Fig. 2.

CONCLUSIONS

Analysis of a series of homogeneous SCR events cataloged in [3–7] surprisingly revealed that the number of SCRs with proton energies higher than 10 and 100 MeV in cycle 24 differed only slightly from the analogous number for the first 64 months of cycles 21–23, even though solar activity during cycle 24's growth phase and maximum was low. However, a deficit of GLEs was observed. The relative increase in comparatively low-energy SPEs is worthy of further study. The ratio of the number of SPEs with $E > 10$ and 100 MeV protons to the total (accumulated) number of sunspots for the first 64 months in cycle 24 was almost twice as high as the analogous ratio in the previous cycles, while the same ratio was more than 50% lower for GLEs.

Although the ratio of the number of events with $E >$ 10 MeV to the analogous number of $E > 100$ MeV events in cycle 24 was the same as in the previous three cycles, the $E > 100$ MeV events in cycle 24 were characterized by lower proton intensity at the SPE maximum.

The power of the X-ray flares associated with SCRs and the CME velocity and beam angle differed only slightly for the >100 MeV events in cycles 23 and 24.

Our results cannot be considered surprising. The relation of SPEs to flares and CMEs is neither simple nor clear-cut [16, 17]. Cycles 21–24 must be compared in more detail with respect to the factors that accompany SPEs (e.g., active region singularities, the radioemissions associated with flares, and the presence of several CMEs in the corona and in the interplanetary medium).

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