



The Origin of Energetic Solar Protons: Comparative Analysis of Ground-level Enhancement (GLE) Events and Non-GLE Solar Energetic Particle Events

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Received 2025 January 18; revised 2025 November 1; accepted 2025 November 2; published 2025 December 15

Abstract

This study explores the acceleration origins of solar energetic particles (SEPs) by analyzing the energy spectral characteristics of particles in ground-level enhancement (GLE) events and common SEP (non-GLE) events, as well as the correlations of the peak intensities of energetic particles with flare and coronal mass ejection (CME) diagnostic parameters. By examining the peak energy spectra of protons, for protons with energies >66 MeV, the peak intensities in most GLE events are significantly higher than those in SEP events, establishing an energy threshold distinguishing GLE from non-GLE events. Given the strong correlation between energetic electrons and protons, radio bursts and soft X-rays (SXR) produced by energetic electrons can be used to study acceleration regions of GLE. Based on data from solar cycles 23 and 24, multifrequency radio data (5, 8.8, and 15.4 GHz) and SXR intensity analysis reveal the heights of particle acceleration. The results indicate that protons with energies >66 MeV in GLE events are closely associated with flare-related acceleration in the low corona, although a contribution from CME-driven shock acceleration cannot be excluded. In contrast, lower-energy protons (<10 MeV) are primarily accelerated by CME-driven shocks. Moreover, SEPs at intermediate energies exhibit a mixed origin, which includes particles accelerated by both flares and CME-driven shocks. These findings provide key insights into the mechanisms of particle acceleration in solar events.

Unified Astronomy Thesaurus concepts: [Solar energetic particles \(1491\)](#); [Solar flares \(1496\)](#); [Solar activity \(1475\)](#); [Solar coronal mass ejections \(310\)](#); [Solar coronal mass ejection shocks \(1997\)](#)

1. Introduction

Prior to the discovery of coronal mass ejections (CMEs) in the early 1970s, early studies attributed the mechanism of solar energetic particle (SEP) production to “flare acceleration.” However, by the late 1980s, the acceleration of particles by CME-driven shocks was gradually emphasized. Compared with flares, CME-driven shocks have large scales and long acceleration durations. Typical gradual SEP events can last from several days to more than 10 days, which is much longer than the acceleration time of flares, and therefore the mainstream view is that the continuous acceleration of the shock leads to gradual events (S. W. Kahler 1982; D. V. Reames 1999). From observations, the acceleration ability of the shocks is different for energetic particles in different energy channels. Data from the 1 au spacecraft show that the interplanetary shock is capable of significantly accelerating energetic protons in the energy range of a few tens of keV to a few MeV. When the interplanetary shock passes through the spacecraft, the spacecraft often observes a significant peak in the intensity of particles, forming the so-called energetic storm particle (ESP) event. However, for >10 MeV energetic protons, there is no significant enhancement of the particle intensity when the interplanetary shock passes through the spacecraft in most events.

To explain the origin of >10 MeV proton events, H. V. Cane et al. (1988) analyzed a large amount of data from observations of the 1 au spacecraft and proposed that the theory of interplanetary shock acceleration can explain gradual proton events. This theory was widely accepted by the SEP community, and has become the classical paradigm dominating the study of gradual events in the past few decades. However, there are controversies about the interplanetary shock acceleration model proposed by H. V. Cane et al. (1988). For example, Y. Wang & G. Qin (2023) proposed that in many events, spacecraft at different longitudes can observe the same energetic particle event, which is caused by perpendicular diffusion of particles accelerated by solar source regions (flares or coronal shocks), while the acceleration of interplanetary shocks is unimportant. Using the perpendicular diffusion mechanism of particles (Y. Wang & G. Qin 2023), not only the reservoir phenomenon but also the equal relation among the peaks of >10 MeV proton intensities at different locations can be explained.

Ground-level enhancement (GLE) events are the most energetic gradual energetic particle events. In this paper, we use “non-GLE” to represent common SEP events other than GLE events. In GLE events, a large number of ions with a rigidity exceeding 1 GV are produced, so that ground-based neutron monitors are able to detect signals above the cosmic-ray background. The acceleration process of energetic protons with a rigidity of 1 GV occurs mainly in the solar source region and is produced by solar flares and coronal shocks. Although the association of GLE events with solar flares and



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coronal shocks is well recognized, there remains a problem as to whether the site of particle acceleration is situated at the coronal flare magnetic reconnection region or at the coronal shocks, or whether both locations make significant contributions to the acceleration. To address this question, a large number of statistical studies have analyzed in detail the characteristics of flares, active regions, and CMEs, and attempted to examine the acceleration processes of flares and coronal shocks from different perspectives. These studies from different perspectives can be categorized as follows. First, time-series and correlation analyses are used to infer acceleration mechanisms by examining the temporal relations and statistical correlations between GLE events and associated solar activities, such as solar flares and CMEs (M. J. Aschwanen 2012; H. Moraal & K. G. McCracken 2012; K. A. Firoz et al. 2019; G.-M. Le et al. 2017). Second, energy spectral and compositional analyses aim to distinguish acceleration source regions by investigating particle energy spectra, elemental abundance ratios, and charge states in GLE events (S. W. Kahler et al. 2012; R. A. Mewaldt et al. 2012; V. I. Kiselev et al. 2022). Third, studies of magnetic topology and acceleration locations focus on the magnetic field configuration, magnetic connectivity, and the specific altitudes at which particle acceleration occurs in the source regions (N. Gopalswamy et al. 2012; G. Li et al. 2012; N. V. Nitta et al. 2012). Finally, anisotropy and propagation characteristics are examined to infer acceleration mechanisms from the anisotropic distribution and propagation properties of energetic particles in GLE events (H. Moraal & K. G. McCracken 2012; M. A. Shea & D. F. Smart 2012; C. O. G. Waterfall et al. 2023).

There are also studies that focus on specific GLE events. In recent years, A. Kouloumvakos et al. (2024) analyzed the GLE that occurred on 2021 October 28 (GLE 73). They suggested that in the event, the CME shock dominated the particle acceleration process. Similarly, X. Li et al. (2022) explored the relation between the characteristics of CMEs and the production of energetic particles in GLE 73, finding that CME-driven shocks are the key mechanism for particle acceleration, with interacting CMEs enhancing shock acceleration efficiency and resulting in intense energetic particle events. In another study, E. Palmerio et al. (2021) studied the GLE on 2012 May 17 (GLE 71), and found that the preceding CME promoted the acceleration of energetic particles. V. V. Grechnev et al. (2024) suggested that magnetic reconnection plays a significant role in the development of CMEs and flares in this event. Additionally, S. Dalla et al. (2020) used three-dimensional modeling to study the propagation of solar energetic protons in interplanetary space during GLE events and assessed the role of propagation effects in the formation of GLE events. So far, there is still a controversy in the SEP community about whether the acceleration region of energetic protons in GLE events is located at the magnetic reconnection region in flares or at the coronal shocks.

In this work, we perform a statistical study of GLE events together with non-GLE events, seeking different parameters used to distinguish between the two. We use radio bursts in different frequency bands, soft X-rays (SXR), and CME speed to study the acceleration of energetic protons and energetic electrons in GLE events. Since it is only from the 23rd solar cycle that we have complete CME observations, this

study focuses on data from the 23rd and 24th solar activity cycles. According to NOAA's definition of solar proton events, and subsequent to our screening, a total of 170 events were counted during this period, encompassing 152 SEP events and 18 GLE events. In this work, we find that determining whether an event is a GLE event does not require the use of several hundred MeV of protons in the vast majority of cases, but only the peak intensity of >66 MeV protons. The lower the energy, the larger the number of corresponding events. Only if the number of energetic particle events is large enough, the results of the statistical analysis are significant. Therefore, we do not limit the study to energetic protons of a few hundred MeV, but rather investigate the variation of the intensities of proton peaks in different energy ranges with various physical quantities, such as radio intensity, SXR flux, and CME speed.

2. Data Sources

We study the SEP events in the 23rd and 24th solar cycles, including GLE events and non-GLE events, and the list of the events is mainly referred to on the website <http://www.wdcb.ru/stp/data/SPE/>, which contains a variety of characteristics of solar energetic proton events (SPEs). The CME speed and radio information is referenced from https://cdaw.gsfc.nasa.gov/CME_list/ and <https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-radio/rstn-1-second/>. The solar sources of GLE and non-GLE events are characterized primarily by SXR emission, radio bursts at 5, 8.8, and 15.4 GHz, and CME speed. The CME speed refers to the projected motion on the sky of CMEs ejected into interplanetary space, as measured in the online CME catalog of the Coordinated Data Analysis Workshop (CDAW; S. Yashiro et al. 2004). Table 1 summarizes the corresponding solar radio flux, flare class, and CME speed.

The energetic proton data are from the European Space Agency (ESA) Solar Energetic Particle Environment Modelling (SEPTEM) database (<http://sepem.eu>), which is a cross-calibrated set of observations from multiple spacecraft (N. Crosby et al. 2015). The SEPTEM database provides energetic proton data in 11 energy channels ranging from 5 to 289.2 MeV, namely pE1 (5.00–7.23 MeV), pE2 (7.23–10.46 MeV), pE3 (10.46–15.12 MeV), pE4 (15.12–21.87 MeV), pE5 (21.87–31.62 MeV), pE6 (31.62–45.73 MeV), pE7 (45.73–66.13 MeV), pE8 (66.13–95.64 MeV), pE9 (95.64–138.3 MeV), pE10 (138.3–200.0 MeV), and pE11 (200.0–289.2 MeV). The energetic electron data are partly from the deflected electrons detector of the EPAM instrument on the Advanced Composition Explorer (ACE) spacecraft, with four energy channels, eE1 (0.038–0.053 MeV), eE2 (0.053–0.103 MeV), eE3 (0.103–0.175 MeV), and eE4 (0.175–0.315 MeV). The other part of the energetic electron data comes from the EPHIN instrument data of the Solar and Heliospheric Observatory (SOHO) spacecraft with three energy channels, eE5 (0.25–0.70 MeV), eE6 (0.67–3.00 MeV), and eE7 (2.64–10.4 MeV). It should be noted that the electron data from the ACE and SOHO spacecraft observations are not cross-calibrated, and thus the peak electron intensities from the ACE and SOHO observations cannot be directly compared. As our study primarily involves correlational analysis of statistical events, the lack of cross calibration does not impact our conclusions. The peak intensities of energetic particles are listed in Table 2. In this study, all particle intensities

Table 1
Parameters of Flares and CME Shocks

No.	Date	Longitude	Flare Class	CME-v (km s ⁻¹)	5 GHz (sfu)	8.8 GHz (sfu)	15.4 GHz (sfu)
1	19971104	W34	X2.1	785	636	638	...
2	19980420	W90	M1.4	1863	...	...	...
3	19980430	E22	M6.8	1374	208	62	62
4	19980509	W90 ^a	M7.7	2331	...	...	...
5	19980616	W90 ^a	M1.0	1484	...	...	...
6	19980822	E51	M9.0	...	...	...	...
7	19980930	W78	M2.8	...	...	...	...
8	19981106	W18	M8.4	1118	879	839	530
9	19981107	W43	M2.4	632	...	...	...
10	19981114	W90 ^a	C1.3	...	...	...	...
11	19981122	W82	X3.7	...	368	1253	3095
12	19990120	E90 ^a	M5.2	...	130	...	...
13	19990504	E32	M4.4	1584	80	94	65
14	19990509	W90 ^a	M7.6	615	251	370	658
15	19990604	W72	M3.9	2230	1445	1526	1329
16	19991117	E21	M7.4	...	...	...	...
17	20000218	E07	M1.3	728	...	...	...
18	20000404	W66	C9.7	1188	284	181	111
19	20000607	E18	X2.3	1119	2712	3414	1596
20	20000610	W39	M5.2	1108	704	347	146
21	20000617	W72	M3.5	857	65	97	43
22	20000625	W55	M1.9	1617	40	38	...
23	20000722	W56	M3.7	1230	...	...	...
24	20000728	W78	M1.2	447	...	...	...
25	20000912	W08	M1.0	1550	38	36	48
26	20001016	W90 ^a	M2.5	1336	...	...	...
27	20001025	W80	C4.0	770	...	...	...
28	20001031	E08	C6.0	...	...	...	...
29	20001108	W66	M7.4	1738	417	232	87
30	20001124A	W05	X2.0	1298	...	...	...
31	20001124B	W08	X2.3	1454	2388	7097	13,532
32	20010128	W59	M1.5	916	36	30	35
33	20010226	W90 ^a	C1.6	851	...	...	...
34	20010326	E27	M2.2	541	52	52	44
35	20010329	W12	X1.7	942	8867	12,141	7634
36	20010402	W82	-X20.7-	2505	5381	7093	11,684
37	20010409	W04	M7.9	1192	3732	5256	5611
38	20010410	W09	X2.3	2411	5985	6937	5084
39	20010412	W42	X2.0	1184	...	...	...
40	20010520	W90 ^a	M6.4	546	400	333	270
41	20010915	W49	M1.5	478	262	198	127
42	20010924	E26	X2.6	2402	...	...	...
43	20011001	W80 ^a	M9.1	1405	...	...	...
44	20011019	W18	X1.6	558	585	1019	719
45	20011022	E16	X1.2	618	1713	2382	3748
46	20011117	E42	M2.8	1379	115	91	75
47	20011122	W38	M9.9	1437	1083	785	320
48	20011230	W90	M1.8	819	...	...	...
49	20020110	E90 ^a	...	...	...	...	...
50	20020115	W90 ^a	M4.4	1492	...	...	...
51	20020220	W72	M5.1	952	160	196	...
52	20020316	W03	M2.2	957	163	128	...
53	20020318	E16	M4.0	823	798	1005	950
54	20020417	W36	M2.6	1240	4348	2586	1000
55	20020421	W84	X1.5	2393	2975	2848	1527
56	20020722	E90 ^a	X3.3	1941	...	...	...
57	20020814	W54	M2.3	1309	150	175	148
58	20020817	E20	M5.2	1585	2375	1924	1088
59	20020818	W20	M2.2	682	1464	1367	1108
60	20020820	W35	M5.0	961	186	133	477
61	20020822	W62	M5.4	998	501	259	172
62	20030528	W20	X3.6	1366	3715	5225	5812
63	20030531	W65	M9.3	1835	3485	7198	8377

Table 1
(Continued)

No.	Date	Longitude	Flare Class	CME-v (km s ⁻¹)	5 GHz (sfu)	8.8 GHz (sfu)	15.4 GHz (sfu)
64	20030618	E60 ^a	M6.8	1813	3799	3419	2561
65	20031026	W38	X1.2	1537	3603	4194	3149
66	20031104	W83	-X30.2-	2657	21,436	27,724	55,457
67	20031120	W08	M9.6	669	2342	2147	1498
68	20031121	W17	M5.8	494	972	477	198
69	20031202	W90 ^a	C7.2	1393	...	...	...
70	20040411	W47	C9.6	1645	586	492	236
71	20040722	E25 ^a	M9.1	492	319	342	308
72	20040723	E04	M1.6	448	...	...	...
73	20040725	W33	M1.1	1333	125	78	66
74	20040801	W90 ^a	C8.4	1192	...	...	...
75	20040913	E42	M4.8	1328	2823	1395	662
76	20040919	W60 ^a	M1.9	...	492	186	95
77	20041101	W49	M1.1	925	...	...	...
78	20041107	W15 ^a	X2.0	1759	8349	6587	3599
79	20041110	W51	M8.9	2000	2060	1632	911
80	20050115	E06	M8.6	2049	2968	2395	1563
81	20050116	W08 ^a	X2.6	2861	10,408	10,475	12,966
82	20050616	W87	M4.0	...	402	226	102
83	20050713	W80	M5.0	1423	5087	5064	5404
84	20050714	W90 ^a	X1.2	2115	2720	5329	5747
85	20050731	E61	X1.3	1968	4141	3215	2376
86	20050822	W48	M2.6	1194	1729	1375	772
87	20050822a	W60	M5.6	2378	9884	9866	8485
88	20050914	E10 ^a	X1.5	1866	15,695	21,044	15,562
89	20061205	E79	-X9.2-	...	4121	6877	9895
90	20061206	E63	X6.5	...	9923	13071	12311
91	20061214	W46	X1.5	1042	1556	2561	1652
92	20100814	W52	C4.4	1205	...	...	...
93	20100818	W88	C4.5	1471	...	...	...
94	20110215	W15	X2.2	669	1347	1019	131
95	20110307	W67	M3.7	2125	...	...	...
96	20110321	E87	C4.2	963	...	...	...
97	20110607	W54	M2.5	1255	720	901	90
98	20110802	W15	M1.4	852	222	236	17
99	20110804	W36	M9.3	1315	728	1352	248
100	20110809	W69	-X7.5-	1610	700	1094	150
101	20110906	W07	M5.3	782	71	226	33
102	20110907	W18	X2.1	575	...	...	...
103	20111022	W77	M1.3	1005	...	...	...
104	20111104	E63	X1.9	991	301	760	133
105	20111126	W49	C1.2	933	...	...	...
106	20111225	W26	M4.0	366	121	151	40
107	20120120	E30	M3.2	1120	107	79	...
108	20120123	W21	M8.7	2175	3663	6848	695
109	20120127	W71	X1.7	2508	819	1101	83
110	20120304	E61	M2.0	1306	2502	1883	127
111	20120307	E27	X5.4	2684	5521	11,555	2036
112	20120313	W59	M7.9	1884	992	2803	495
113	20120706	W59	X1.1	1828	513	821	191
114	20120708	W83	M6.9	1495	718	934	100
115	20120712	W01	X1.4	885	808	478	43
116	20120717	W75	M1.7	958	...	...	...
117	20120719	W90	M7.7	1631	1049	1349	114
118	20120901	E42	C8.4	1442	...	...	...
119	20130116	W87	C2.2	648	...	...	...
120	20130411	E12	M6.5	861	474	307	22
121	20130515	E64	X1.2	1366	483	1317	147
122	20130522	W70	M5.0	1466	...	...	...
123	20130621	E73	M2.9	1900	5388	104	10
124	20131028	W66	X1.0	695	116	821	277
125	20131030	W89	X2.3	1001	79	645	343
126	20131107	W88	M1.9	1033	...	...	...

Table 1
(Continued)

No.	Date	Longitude	Flare Class	CME-v (km s ⁻¹)	5 GHz (sfu)	8.8 GHz (sfu)	15.4 GHz (sfu)
127	20131119	W69	X1.0	740	...	...	...
128	20140106	W90 ^a	C2.1	1402	...	...	...
129	20140107	W11	X1.2	1830	8320	2209	190
130	20140220	W73	M3.0	948	398	435	27
131	20140225	E82	X4.9	2147	3774	6316	1314
132	20140228	W63	C4.2	...	...	...	...
133	20140329	W32	X1.0	528	367	656	118
134	20140418	W34	M7.3	1203	1004	1101	87
135	20140825	W36	M2.0	555	172	180	14
136	20140910	E02	X1.6	1267	1366	2785	247
137	20141101	E52	C2.7	1628	...	...	...
138	20141221	W25	M1.0	669	...	...	...
139	20141223	W71	C5.7	...	...	...	...
140	20150315	W25	C9.1	719	...	...	...
141	20150316	W32	M1.2	284	...	...	...
142	20150512	W83	C2.6	772	...	...	...
143	20150618	W81	M1.3	1714	...	...	...
144	20150625	W42	M7.9	1627	3856	5338	1010
145	20150920	W24	M2.1	1239	332	256	17
146	20151109	E41	M3.9	1041	...	673	616
147	20151228	W11	M1.8	1212	...	366	189
148	20160101	W82	M2.3	1730	...	...	...
149	20160418	W62	M6.7	1084	...	...	...
150	20160515	W62	C3.2	1118	...	...	...
151	20170714	W29	M2.4	1200	...	481	300
152	20170904	W16	M5.5	1418	...	...	...
G55	19971106	W63	X9.4	1556	6140	8385	10684
G56	19980502	W15	X1.1	938	2050	3650	1639
G57	19980506	W64	X2.7	1099	1048	2026	1482
G58	19980824	E09	X1.0	...	3167	2106	1176
G59	20000714	W07	X5.7	1674	...	...	...
G60	20010415	W84	-X14.8-	1199	2331	1511	5104
G61	20010418	W116	C2.2	2465	461	165	80
G62	20011104	W19	X1.0	1810	2833	2909	1632
G63	20011226	W54	M7.1	1446	3954	3922	1829
G64	20020824	W81	X3.1	1913	5942	9795	18,219
G65	20031028	E08	-X18-	2459	42,858	56,039	47,739
G66	20031029	W02	-X10.8-	2029	13,090	14,449	20,633
G67	20031102	W56	-X9.3-	2598	12,314	16,659	40,127
G68	20050117	W24	X3.8	2547	21,267	16,118	14,841
G69	20050120	W58	X7.1	...	19,147	47,997	50,019
G70	20061213	W24	X3.4	1774	4712	7165	9956
G71	20120517	W76	M5.1	1582	538	745	63
G72	20170910	W88	-X9.1-	3163	...	1996	3530

Notes. Flare classes in double hyphens (e.g., -X20.7-) are from H. Hudson et al. (2024). ... indicates no data.

^a Indicates the probable localization of the flare event.

are measured in (cm² s sr MeV)⁻¹, and all radio fluxes are measured in solar flux units (sfu).

In this work, a total of 170 events of the 23 and 24 solar active cycles are studied, among which there are 18 GLE events during this period. The magnetic connectivity between the spacecraft and solar source has an important effect on the intensity of energetic particles, so we differentiate the magnetic connectivity according to the longitude position of the source region, and define an event with the source region in W20°–W90° as the well-connected event. For the selection of peak intensities, we note the effect of local acceleration by interplanetary shocks on the peak intensities. Some shocks can significantly accelerate energetic protons to form ESP events, such as the second shock in Figure 1.

When the second shock passes through the spacecraft, the second peak of intensity is formed, as shown by the black dot in Figure 1. In most SEP events, the interplanetary shock acceleration process mainly affects the intensity of protons with energies <10 MeV. To study the acceleration near the solar source region (flares and coronal shocks), we filter for the first peak after the onset of the energetic particle event, as shown by the red dots in Figure 1. During the selection of the peak intensities of particle events, we check the time difference between the onset time of the particle intensity and the solar eruption and refer to the previous list of events (A. Papaioannou et al. 2016; R. Miteva et al. 2018) to ensure that the energetic particle events could be accurately matched to the source region.

Table 2
Statistical Results of Energetic Proton/Electron Peak Intensity

No.	Date	Peak Particle Intensity (cm ² s sr MeV) ⁻¹																	
		PE1	PE2	PE3	PE4	PE5	PE6	PE7	PE8	PE9	PE10	PE11	eE1	eE2	eE3	eE4	eE5	eE6	eE7
1	19971104	1.21 × 10 ¹	6.50	3.78	2.15	9.07 × 10 ⁻¹	4.76 × 10 ⁻¹	2.20 × 10 ⁻¹	6.61 × 10 ⁻²	1.85 × 10 ⁻²	4.82 × 10 ⁻³	1.54 × 10 ⁻³	2.24 × 10 ⁵	5.53 × 10 ⁴	1.89 × 10 ⁴	4.87 × 10 ³	1.50 × 10 ⁴	5.00 × 10 ¹	2.15
2	19980420	1.33 × 10 ²	1.04 × 10 ²	7.99 × 10 ¹	5.91 × 10 ¹	2.39 × 10 ¹	9.80	2.66	3.72 × 10 ⁻¹	4.88 × 10 ⁻²	5.12 × 10 ⁻³	...	1.35 × 10 ⁶	5.79 × 10 ⁵	3.44 × 10 ⁵	1.27 × 10 ⁵	4.18 × 10 ⁵	1.93 × 10 ³	9.79 × 10 ¹
3	19980430	1.05 × 10 ¹	1.48	2.33 × 10 ⁻¹	5.55 × 10 ⁻²	...	...	...	...	...	...	...	2.01 × 10 ⁵	2.94 × 10 ⁴	5.50 × 10 ³	7.07 × 10 ²	8.09 × 10 ²	2.68	4.29 × 10 ⁻²
4	19980509	4.69	2.21	9.72 × 10 ⁻¹	3.15 × 10 ⁻¹	1.20 × 10 ⁻¹	4.51 × 10 ⁻²	1.69 × 10 ⁻²	...	...	...	...	2.05 × 10 ⁴	5.89 × 10 ³	2.71 × 10 ³	8.63 × 10 ²	2.34 × 10 ³	1.60 × 10 ¹	1.68 × 10 ⁻¹
5	19980616	1.57	5.34 × 10 ⁻¹	1.87 × 10 ⁻¹	6.49 × 10 ⁻²	3.28 × 10 ⁻²	...	...	...	...	...	...	8.96 × 10 ³	1.74 × 10 ³	5.61 × 10 ²	1.34 × 10 ²	2.24 × 10 ²	7.05 × 10 ⁻¹	9.73 × 10 ⁻³
6	19980822	3.74	1.17	3.05 × 10 ⁻¹	7.17 × 10 ⁻²	...	...	...	...	...	...	...	2.45 × 10 ⁴	4.20 × 10 ³	1.15 × 10 ³	2.55 × 10 ²	...	...	...
7	19980930	3.48 × 10 ²	1.65 × 10 ²	8.11 × 10 ¹	3.81 × 10 ¹	1.01 × 10 ¹	3.26	7.98 × 10 ⁻¹	1.26 × 10 ⁻¹	2.16 × 10 ⁻²	5.01 × 10 ⁻³	1.23 × 10 ⁻³	8.38 × 10 ⁵	2.23 × 10 ⁵	8.51 × 10 ⁴	2.16 × 10 ⁴	...	...	...
8	19981106	3.42 × 10 ¹	6.48	9.54 × 10 ⁻¹	9.91 × 10 ⁻²	3.70 × 10 ⁻²	1.37 × 10 ⁻²	...	...	...	...	...	5.03 × 10 ³	9.94 × 10 ²	3.24 × 10 ²	7.34 × 10 ¹	...	...	...
9	19981107	1.60 × 10 ¹	4.37	9.87 × 10 ⁻¹	2.28 × 10 ⁻¹	6.86 × 10 ⁻²	2.39 × 10 ⁻²	...	...	...	...	...	1.87 × 10 ⁴	4.47 × 10 ³	1.57 × 10 ³	3.18 × 10 ²	4.91 × 10 ²	9.08 × 10 ⁻¹	1.00 × 10 ⁻²
10	19981114	5.99 × 10 ¹	3.45 × 10 ¹	1.86 × 10 ¹	9.40	4.23	1.87	6.53 × 10 ⁻¹	1.73 × 10 ⁻¹	4.33 × 10 ⁻²	7.98 × 10 ⁻³	1.22 × 10 ⁻³	4.81 × 10 ⁵	1.59 × 10 ⁵	7.18 × 10 ⁴	2.21 × 10 ⁴	8.60 × 10 ⁴	3.40 × 10 ²	1.25 × 10 ¹
11	19981122	6.11 × 10 ⁻¹	3.62 × 10 ⁻¹	1.99 × 10 ⁻¹	9.90 × 10 ⁻²	5.68 × 10 ⁻²	3.17 × 10 ⁻²	1.55 × 10 ⁻²	...	...	...	...	3.08 × 10 ³	7.45 × 10 ²	2.93 × 10 ²	9.07 × 10 ¹	...	...	...
12	19990120	5.84	1.68	3.79 × 10 ⁻¹	1.31 × 10 ⁻¹	5.79 × 10 ⁻²	3.16 × 10 ⁻²	1.38 × 10 ⁻²	...	...	...	...	1.89 × 10 ⁴	4.61 × 10 ³	1.88 × 10 ³	5.89 × 10 ²	...	...	...
13	19990504	2.56 × 10 ¹	6.07	1.34	2.10 × 10 ⁻¹	6.51 × 10 ⁻²	...	...	...	...	...	...	1.10 × 10 ⁵	2.00 × 10 ⁴	4.43 × 10 ³	6.96 × 10 ²	1.01 × 10 ³	1.92	6.43 × 10 ⁻³
14	19990509	9.54 × 10 ⁻¹	3.71 × 10 ⁻¹	1.64 × 10 ⁻¹	7.05 × 10 ⁻²	3.28 × 10 ⁻²	...	...	...	...	...	...	1.06 × 10 ⁵	1.51 × 10 ⁴	2.22 × 10 ³	3.46 × 10 ²	5.29 × 10 ²	1.13	6.18 × 10 ⁻³
15	19990604	4.37 × 10 ¹	1.43 × 10 ¹	5.37	1.57	3.84 × 10 ⁻¹	9.18 × 10 ⁻²	2.28 × 10 ⁻²	...	...	...	...	1.60 × 10 ⁵	4.72 × 10 ⁴	1.99 × 10 ⁴	5.51 × 10 ³	1.14 × 10 ⁴	4.34 × 10 ¹	2.52 × 10 ⁻¹
16	19991117	9.46 × 10 ⁻¹	3.41 × 10 ⁻¹	1.10 × 10 ⁻¹	...	...	...	...	...	...	...	...	1.21 × 10 ⁴	2.82 × 10 ³	9.77 × 10 ²	2.05 × 10 ²	...	...	...
17	20000218	4.40	2.31	1.03	3.66 × 10 ⁻¹	1.69 × 10 ⁻¹	7.08 × 10 ⁻²	3.08 × 10 ⁻²	8.96 × 10 ⁻³	3.00 × 10 ⁻³	...	...	2.03 × 10 ⁵	7.79 × 10 ⁴	3.56 × 10 ⁴	8.84 × 10 ³	5.63 × 10 ³	2.82 × 10 ¹	1.47 × 10 ⁻¹
18	20000404	9.24 × 10 ¹	2.61 × 10 ¹	5.38	7.10 × 10 ⁻¹	1.44 × 10 ⁻¹	2.64 × 10 ⁻²	6.93 × 10 ⁻³	...	...	...	...	1.47 × 10 ⁵	3.52 × 10 ⁴	6.94 × 10 ³	9.53 × 10 ²	1.22 × 10 ³	3.51	1.24 × 10 ⁻²
19	20000607	1.15 × 10 ²	2.89 × 10 ¹	6.13	1.02	1.87 × 10 ⁻¹	3.63 × 10 ⁻²	8.17 × 10 ⁻³	...	...	...	...	3.02 × 10 ⁴	6.85 × 10 ³	2.27 × 10 ³	4.94 × 10 ²	9.80 × 10 ²	3.87	3.89 × 10 ⁻²
20	20000610	1.46 × 10 ¹	6.68	3.07	1.41	6.55 × 10 ⁻¹	3.07 × 10 ⁻¹	1.43 × 10 ⁻¹	4.16 × 10 ⁻²	1.17 × 10 ⁻²	2.55 × 10 ⁻³	5.45 × 10 ⁻⁴	5.56 × 10 ⁵	1.28 × 10 ⁵	2.95 × 10 ⁴	5.83 × 10 ³	6.34 × 10 ³	3.45 × 10 ¹	6.53 × 10 ⁻¹
21	20000617	4.25 × 10 ⁻¹	2.16 × 10 ⁻¹	7.85 × 10 ⁻²	3.24 × 10 ⁻²	1.54 × 10 ⁻²	...	...	...	...	...	...	1.66 × 10 ⁵	3.33 × 10 ⁴	7.20 × 10 ³	8.98 × 10 ²	1.29 × 10 ³	2.33	9.53 × 10 ⁻³
22	20000625	9.56	2.22	4.39 × 10 ⁻¹	5.58 × 10 ⁻²	2.06 × 10 ⁻²	8.51 × 10 ⁻³	...	...	...	...	...	1.27 × 10 ⁴	2.07 × 10 ³	5.85 × 10 ²	1.24 × 10 ²	2.97 × 10 ²	9.30 × 10 ⁻¹	9.31 × 10 ⁻³
23	20000722	6.49	2.72	1.16	5.90 × 10 ⁻¹	2.33 × 10 ⁻¹	1.05 × 10 ⁻¹	3.88 × 10 ⁻²	9.54 × 10 ⁻³	2.47 × 10 ⁻³	...	...	4.17 × 10 ⁴	1.14 × 10 ⁴	4.64 × 10 ³	1.37 × 10 ³	2.42 × 10 ³	9.75	6.50 × 10 ⁻²
24	20000728	2.49	1.43	8.92 × 10 ⁻¹	3.60 × 10 ⁻¹	1.01 × 10 ⁻¹	2.61 × 10 ⁻²	6.92 × 10 ⁻³	...	...	...	...	1.93 × 10 ⁴	5.45 × 10 ³	2.17 × 10 ³	5.58 × 10 ²	...	...	...
25	20000912	2.64 × 10 ²	9.92 × 10 ¹	2.92 × 10 ¹	6.09	1.18	2.36 × 10 ⁻¹	4.90 × 10 ⁻²	1.25 × 10 ⁻²	2.99 × 10 ⁻³	...	...	3.17 × 10 ⁵	6.57 × 10 ⁴	1.98 × 10 ⁴	4.54 × 10 ³	1.83 × 10 ⁴	7.52 × 10 ¹	6.63 × 10 ⁻¹
26	20001016	4.75	2.45	1.10	4.87 × 10 ⁻¹	1.88 × 10 ⁻¹	9.07 × 10 ⁻²	3.86 × 10 ⁻²	9.12 × 10 ⁻³	2.03 × 10 ⁻³	...	...	4.54 × 10 ⁴	8.03 × 10 ³	2.32 × 10 ³	5.41 × 10 ²	1.08 × 10 ³	3.29	3.64 × 10 ⁻²
27	20001025	1.51 × 10 ¹	4.38	1.38	3.49 × 10 ⁻¹	9.79 × 10 ⁻²	2.81 × 10 ⁻²	8.11 × 10 ⁻³	...	...	...	...	3.59 × 10 ⁴	7.46 × 10 ³	2.48 × 10 ³	5.79 × 10 ²	1.32 × 10 ³	4.48	3.01 × 10 ⁻²
28	20001031	7.03	1.84	4.19 × 10 ⁻¹	7.17 × 10 ⁻²	2.51 × 10 ⁻²	9.97 × 10 ⁻³	...	...	...	...	...	2.74 × 10 ⁴	5.60 × 10 ³	1.73 × 10 ³	3.68 × 10 ²	6.45 × 10 ²	1.77	...
29	20001108	1.57 × 10 ³	1.07 × 10 ³	7.80 × 10 ²	5.37 × 10 ²	2.21 × 10 ²	1.10 × 10 ²	4.50 × 10 ¹	1.11 × 10 ¹	2.42	3.45 × 10 ⁻¹	5.00 × 10 ⁻²	3.39 × 10 ⁶	1.22 × 10 ⁶	8.17 × 10 ⁵	3.37 × 10 ⁵	6.89 × 10 ⁵	5.08 × 10 ³	9.17 × 10 ²
30	20001124A	2.04	1.17	5.43 × 10 ⁻¹	2.56 × 10 ⁻¹	1.18 × 10 ⁻¹	5.36 × 10 ⁻²	2.28 × 10 ⁻²	8.26 × 10 ⁻³	2.88 × 10 ⁻³	1.01 × 10 ⁻³	...	3.11 × 10 ⁴	8.54 × 10 ³	3.64 × 10 ³	1.03 × 10 ³	1.91 × 10 ³	7.66	4.53 × 10 ⁻²
31	20001124B	4.40 × 10 ¹	2.02 × 10 ¹	7.54	2.54	9.29 × 10 ⁻¹	3.45 × 10 ⁻¹	1.12 × 10 ⁻¹	3.26 × 10 ⁻²	9.01 × 10 ⁻³	2.38 × 10 ⁻³	6.86 × 10 ⁻⁴	2.35 × 10 ⁵	6.14 × 10 ⁴	2.45 × 10 ⁴	6.95 × 10 ³	2.35 × 10 ⁴	6.31 × 10 ¹	1.06
32	20010128	7.60 × 10 ¹	1.49 × 10 ¹	3.99	1.14	3.46 × 10 ⁻¹	1.52 × 10 ⁻¹	5.12 × 10 ⁻²	1.06 × 10 ⁻²	...	...	...	6.67 × 10 ⁴	1.53 × 10 ⁴	6.76 × 10 ³	1.96 × 10 ³	4.62 × 10 ³	1.96 × 10 ¹	1.36 × 10 ⁻¹
33	20010226	3.14	8.75 × 10 ⁻¹	2.08 × 10 ⁻¹	2.82 × 10 ⁻²	1.30 × 10 ⁻²	...	...	...	...	...	...	7.53 × 10 ³	2.08 × 10 ³	9.00 × 10 ²	2.51 × 10 ²	6.18 × 10 ²	2.11	6.14 × 10 ⁻³
34	20010326	1.64 × 10 ¹	2.75	4.04 × 10 ⁻¹	5.50 × 10 ⁻²	2.05 × 10 ⁻²	...	...	...	...	...	...	5.60 × 10 ⁴	7.11 × 10 ³	1.16 × 10 ³	1.51 × 10 ²	2.33 × 10 ²	3.86 × 10 ⁻¹	...
35	20010329	1.66 × 10 ¹	6.73	2.68	1.01	2.97 × 10 ⁻¹	9.89 × 10 ⁻²	3.08 × 10 ⁻²											

Table 2
(Continued)

No.	Date	Peak Particle Intensity (cm ² s sr MeV) ⁻¹																	
		PE1	PE2	PE3	PE4	PE5	PE6	PE7	PE8	PE9	PE10	PE11	eE1	eE2	eE3	eE4	eE5	eE6	eE7
60	20020820	1.31	4.83 × 10 ⁻¹	1.82 × 10 ⁻¹	7.63 × 10 ⁻²	3.12 × 10 ⁻²	1.33 × 10 ⁻²	...	...	...	...	...	4.97 × 10 ⁵	1.11 × 10 ⁵	4.43 × 10 ⁴	1.33 × 10 ⁴	4.63 × 10 ⁴	9.91 × 10 ¹	4.35 × 10 ⁻¹
61	20020822	4.00	2.77	1.80	1.06	5.34 × 10 ⁻¹	2.95 × 10 ⁻¹	1.29 × 10 ⁻¹	4.11 × 10 ⁻²	1.23 × 10 ⁻²	2.96 × 10 ⁻³	6.60 × 10 ⁻⁴	1.96 × 10 ⁵	3.66 × 10 ⁴	9.97 × 10 ³	2.10 × 10 ³	4.29 × 10 ³	2.22 × 10 ¹	3.94 × 10 ⁻¹
62	20030528	2.52 × 10 ¹	7.52	2.17	6.16 × 10 ⁻¹	1.50 × 10 ⁻¹	3.94 × 10 ⁻²	1.08 × 10 ⁻²	...	...	...	...	6.08 × 10 ⁴	1.61 × 10 ⁴	6.08 × 10 ³	1.64 × 10 ³	4.07 × 10 ³	1.59 × 10 ¹	5.31 × 10 ⁻²
63	20030531	1.59 × 10 ¹	4.63	1.78	7.78 × 10 ⁻¹	3.52 × 10 ⁻¹	1.61 × 10 ⁻¹	6.38 × 10 ⁻²	2.07 × 10 ⁻²	6.40 × 10 ⁻³	1.61 × 10 ⁻³	...	5.73 × 10 ⁵	1.29 × 10 ⁵	4.46 × 10 ⁴	1.04 × 10 ⁴	3.09 × 10 ⁴	7.35 × 10 ¹	1.35
64	20030618	4.24 × 10 ¹	1.27 × 10 ¹	3.82	6.84 × 10 ⁻¹	1.27 × 10 ⁻¹	2.17 × 10 ⁻²	...	...	...	...	...	3.43 × 10 ⁵	7.36 × 10 ⁴	1.94 × 10 ⁴	3.46 × 10 ³	4.46 × 10 ³	6.31	1.34 × 10 ⁻²
65	20031026	2.29 × 10 ²	1.16 × 10 ²	5.89 × 10 ¹	1.78 × 10 ¹	4.52	1.11	2.49 × 10 ⁻¹	4.17 × 10 ⁻²	7.59 × 10 ⁻³	1.52 × 10 ⁻³	...	5.40 × 10 ⁵	1.31 × 10 ⁵	4.66 × 10 ⁴	1.48 × 10 ⁴	1.06 × 10 ⁵	4.53 × 10 ²	1.29 × 10 ¹
66	20031104	1.56 × 10 ²	7.01 × 10 ¹	3.32 × 10 ¹	1.34 × 10 ¹	4.73	1.50	3.53 × 10 ⁻¹	5.39 × 10 ⁻²	8.81 × 10 ⁻³	1.80 × 10 ⁻³	...	1.12 × 10 ⁵	3.72 × 10 ⁴	1.93 × 10 ⁴	6.73 × 10 ³	2.37 × 10 ⁴	9.46 × 10 ¹	2.54
67	20031120	1.41 × 10 ¹	3.10	9.28 × 10 ⁻¹	1.90 × 10 ⁻¹	6.02 × 10 ⁻²	2.15 × 10 ⁻²	...	...	...	...	...	1.54 × 10 ⁵	3.28 × 10 ⁴	1.15 × 10 ⁴	2.80 × 10 ³	5.74 × 10 ³	2.13 × 10 ¹	7.42 × 10 ⁻²
68	20031121	2.08 × 10 ¹	6.33	2.10	5.40 × 10 ⁻¹	1.40 × 10 ⁻¹	3.12 × 10 ⁻²	...	...	...	...	...	2.58 × 10 ⁵	6.08 × 10 ⁴	2.50 × 10 ⁴	6.37 × 10 ³	1.42 × 10 ⁴	1.78 × 10 ¹	5.40 × 10 ⁻²
69	20031202	1.34 × 10 ²	4.48 × 10 ¹	1.59 × 10 ¹	3.34	5.42 × 10 ⁻¹	7.37 × 10 ⁻²	1.14 × 10 ⁻²	...	...	...	...	4.25 × 10 ⁴	7.05 × 10 ³	1.82 × 10 ³	3.67 × 10 ²	2.71 × 10 ³	1.46 × 10 ¹	6.88 × 10 ⁻²
70	20040411	9.97 × 10 ¹	2.26 × 10 ¹	6.66	1.03	1.93 × 10 ⁻¹	4.82 × 10 ⁻²	1.04 × 10 ⁻²	...	...	...	...	7.79 × 10 ⁴	1.56 × 10 ⁴	5.64 × 10 ³	1.49 × 10 ³	4.09 × 10 ³	2.20 × 10 ¹	1.59 × 10 ⁻¹
71	20040722	4.41	1.14	4.65 × 10 ⁻¹	1.12 × 10 ⁻¹	4.51 × 10 ⁻²	1.89 × 10 ⁻²	...	...	...	...	...	9.64 × 10 ⁴	2.09 × 10 ⁴	8.43 × 10 ³	2.58 × 10 ³	6.89 × 10 ³	5.31 × 10 ¹	2.66 × 10 ⁻¹
72	20040723	9.78	1.79	5.59 × 10 ⁻¹	1.54 × 10 ⁻¹	5.92 × 10 ⁻²	2.31 × 10 ⁻²	...	...	...	...	...	1.23 × 10 ⁵	1.98 × 10 ⁴	5.77 × 10 ³	1.16 × 10 ³	1.94 × 10 ³	6.55	3.34 × 10 ⁻²
73	20040725	8.88 × 10 ¹	3.03 × 10 ¹	1.59 × 10 ¹	4.39	8.92 × 10 ⁻¹	1.49 × 10 ⁻¹	2.64 × 10 ⁻²	...	...	...	...	1.21 × 10 ⁵	3.03 × 10 ⁴	1.27 × 10 ⁴	3.77 × 10 ³	8.35 × 10 ³	5.13 × 10 ¹	3.12 × 10 ⁻¹
74	20040801	8.62	2.45	1.16	3.04 × 10 ⁻¹	1.07 × 10 ⁻¹	3.31 × 10 ⁻²	...	...	...	...	...	3.28 × 10 ⁵	6.83 × 10 ³	2.06 × 10 ³	4.33 × 10 ²	8.41 × 10 ²	2.61	1.36 × 10 ⁻²
75	20040913	3.48 × 10 ⁻¹	2.76 × 10 ⁻¹	3.19 × 10 ⁻¹	1.70 × 10 ⁻¹	7.41 × 10 ⁻²	1.94 × 10 ⁻²	...	...	...	...	...	6.79 × 10 ³	1.52 × 10 ³	5.64 × 10 ²	1.61 × 10 ²	3.44 × 10 ²	1.33	7.47 × 10 ⁻³
76	20040919	2.27 × 10 ¹	1.15 × 10 ¹	6.50	2.20	7.29 × 10 ⁻¹	2.31 × 10 ⁻¹	6.04 × 10 ⁻²	1.39 × 10 ⁻²	...	...	...	1.32 × 10 ⁵	4.39 × 10 ⁴	2.24 × 10 ⁴	7.89 × 10 ³	...	...	...
77	20041101	1.24 × 10 ¹	6.69	5.42	2.33	1.05	4.29 × 10 ⁻¹	1.73 × 10 ⁻¹	4.08 × 10 ⁻²	1.05 × 10 ⁻²	2.28 × 10 ⁻³	...	3.38 × 10 ⁵	7.87 × 10 ⁴	2.61 × 10 ⁴	6.36 × 10 ³	1.03 × 10 ⁴	5.52 × 10 ¹	7.52 × 10 ⁻¹
78	20041107	4.60 × 10 ²	1.78 × 10 ²	6.86 × 10 ¹	1.85 × 10 ¹	3.78	6.38 × 10 ⁻¹	1.17 × 10 ⁻¹	2.22 × 10 ⁻²	3.65 × 10 ⁻³	...	...	5.58 × 10 ⁵	1.05 × 10 ⁵	2.78 × 10 ⁴	5.16 × 10 ³	2.29 × 10 ⁴	1.38 × 10 ²	2.65
79	20041110	6.24 × 10 ¹	2.73 × 10 ¹	1.21 × 10 ¹	2.91	6.84 × 10 ⁻¹	1.41 × 10 ⁻¹	2.75 × 10 ⁻²	...	...	...	...	4.91 × 10 ⁵	9.40 × 10 ⁴	2.48 × 10 ⁴	4.69 × 10 ³	2.51 × 10 ⁴	1.14 × 10 ²	4.66
80	20050115	9.65	2.73	1.19	3.14 × 10 ⁻¹	1.14 × 10 ⁻¹	4.64 × 10 ⁻²	1.75 × 10 ⁻²	...	...	...	...	2.73 × 10 ⁴	5.02 × 10 ³	1.48 × 10 ³	3.52 × 10 ²	8.30 × 10 ²	3.30	5.24 × 10 ⁻²
81	20050116	3.84 × 10 ²	1.12 × 10 ²	3.74 × 10 ¹	1.36 × 10 ¹	4.20	1.35	3.06 × 10 ⁻¹	4.11 × 10 ⁻²	4.71 × 10 ⁻³	...	...	9.40 × 10 ⁵	1.89 × 10 ⁵	6.00 × 10 ⁴	1.36 × 10 ⁴	3.97 × 10 ⁴	1.62 × 10 ²	5.37
82	20050616	7.13	4.18	3.15	1.54	8.10 × 10 ⁻¹	4.07 × 10 ⁻¹	1.97 × 10 ⁻¹	6.61 × 10 ⁻²	2.05 × 10 ⁻²	5.57 × 10 ⁻³	1.46 × 10 ⁻³	1.28 × 10 ⁵	4.05 × 10 ⁴	1.92 × 10 ⁴	6.14 × 10 ³	1.43 × 10 ⁴	9.14 × 10 ¹	1.24
83	20050713	1.77 × 10 ¹	5.09	1.84	4.40 × 10 ⁻¹	1.24 × 10 ⁻¹	3.22 × 10 ⁻²	...	...	...	...	...	2.79 × 10 ⁵	5.67 × 10 ⁴	1.43 × 10 ⁴	2.39 × 10 ³	4.52 × 10 ³	1.71 × 10 ¹	2.58 × 10 ⁻²
84	20050714	4.62 × 10 ¹	2.38 × 10 ¹	1.33 × 10 ¹	5.45	1.47	3.66 × 10 ⁻¹	7.55 × 10 ⁻²	1.08 × 10 ⁻²	...	...	...	2.69 × 10 ⁵	6.76 × 10 ⁴	2.46 × 10 ⁴	6.01 × 10 ³	9.48 × 10 ³	3.29 × 10 ¹	2.01 × 10 ⁻¹
85	20050731	6.42 × 10 ¹	1.57 × 10 ¹	4.50	7.23 × 10 ⁻¹	1.52 × 10 ⁻¹	3.23 × 10 ⁻²	...	...	...	...	...	3.58 × 10 ⁵	8.59 × 10 ⁴	3.04 × 10 ⁴	7.57 × 10 ³	2.19 × 10 ⁴	4.13 × 10 ¹	1.70 × 10 ⁻¹
86	20050822A	9.53	2.85	9.97 × 10 ⁻¹	2.76 × 10 ⁻¹	7.76 × 10 ⁻²	2.22 × 10 ⁻²	...	...	...	...	...	1.27 × 10 ⁵	2.56 × 10 ⁴	7.03 × 10 ³	1.46 × 10 ³	3.49 × 10 ³	2.49 × 10 ¹	8.14 × 10 ⁻²
87	20050822B	2.67 × 10 ²	1.08 × 10 ²	4.43 × 10 ¹	1.27 × 10 ¹	3.15	6.80 × 10 ⁻¹	1.22 × 10 ⁻¹	1.78 × 10 ⁻²	...	...	...	8.56 × 10 ⁵	1.91 × 10 ⁵	5.96 × 10 ⁴	1.34 × 10 ⁴	5.66 × 10 ⁴	2.13 × 10 ²	2.55
88	20050914	1.24 × 10 ²	5.07 × 10 ¹	2.27 × 10 ¹	7.17	1.68	3.05 × 10 ⁻¹	5.16 × 10 ⁻²	8.94 × 10 ⁻³	...	...	...	2.10 × 10 ⁵	5.13 × 10 ⁴	2.00 × 10 ⁴	5.37 × 10 ³	...	...	...
89	20061205	1.77	9.97 × 10 ⁻¹	8.07 × 10 ⁻¹	3.26 × 10 ⁻¹	1.41 × 10 ⁻¹	5.49 × 10 ⁻²	...	...	...	...	...	1.08 × 10 ⁴	3.29 × 10 ³	1.53 × 10 ³	4.76 × 10 ²	...	...	...
90	20061206	1.06 × 10 ³	4.59 × 10 ²	2.12 × 10 ²	7.51 × 10 ¹	2.76 × 10 ¹	9.25	2.60	5.65 × 10 ⁻¹	1.29 × 10 ⁻¹	3.17 × 10 ⁻²	8.03 × 10 ⁻³	7.55 × 10 ⁶	2.37 × 10 ⁶	1.20 × 10 ⁶	3.89 × 10 ⁵	6.73 × 10 ⁵	3.77 × 10 ³	1.05 × 10 ²
91	20061214	6.27 × 10 ¹	3.71 × 10 ¹	2.19 × 10 ¹	8.68	3.29	1.01	3.05 × 10 ⁻¹	7.04 × 10 ⁻²	1.62 × 10 ⁻²	4.26 × 10 ⁻³	1.14 × 10 ⁻³	1.07 × 10 ⁵	2.81 × 10 ⁴	1.14 × 10 ⁴	2.94 × 10 ³	6.11 × 10 ³	2.78 × 10 ¹	3.87 × 10 ⁻¹
92	20100814	4.71	2.29	1.90	5.55 × 10 ⁻¹	1.72 × 10 ⁻¹	4.65 × 10 ⁻²	...	...	...	...	...	3.60 × 10 ⁴	6.49 × 10 ³	1.80 × 10 ³	3.74 × 10 ²	7.46 × 10 ²	1.79	1.55 × 10 ⁻²
93	20100818	3.16	1.16	5.85 × 10 ⁻¹	1.02 × 10 ⁻¹	4.34 × 10 ⁻²	...	...	...	...	...	...	4.24 × 10 ⁴	1.08 × 10 ⁴	4.03 × 10 ³	1.02 × 10 ³			

Table 2
(Continued)

No.	Date	Peak Particle Intensity (cm ² s sr MeV) ⁻¹																	
		PE1	PE2	PE3	PE4	PE5	PE6	PE7	PE8	PE9	PE10	PE11	eE1	eE2	eE3	eE4	eE5	eE6	eE7
119	20130116	3.79	1.07	2.87 × 10 ⁻¹	6.44 × 10 ⁻²	2.20 × 10 ⁻²	...	...	...	...	...	...	6.76 × 10 ³	1.05 × 10 ³	2.98 × 10 ²	6.76 × 10 ¹	7.14 × 10 ¹	1.75 × 10 ⁻¹	...
120	20130411	2.92 × 10 ¹	1.36 × 10 ¹	9.08	4.37	1.61	5.34 × 10 ⁻¹	1.62 × 10 ⁻¹	4.42 × 10 ⁻²	1.18 × 10 ⁻²	3.32 × 10 ⁻³	9.14 × 10 ⁻⁴	9.73 × 10 ⁴	2.50 × 10 ⁴	9.91 × 10 ³	2.80 × 10 ³	7.39 × 10 ³	5.59 × 10 ¹	7.54 × 10 ⁻¹
121	20130515	2.97 × 10 ¹	1.11 × 10 ¹	4.63	1.21	2.73 × 10 ⁻¹	5.49 × 10 ⁻²	1.25 × 10 ⁻²	...	...	...	...	3.39 × 10 ⁵	9.75 × 10 ⁴	4.11 × 10 ⁴	1.18 × 10 ⁴	3.73 × 10 ⁴	8.57 × 10 ¹	5.96 × 10 ⁻¹
122	20130522	4.53 × 10 ²	2.56 × 10 ²	1.64 × 10 ²	7.05 × 10 ¹	1.69 × 10 ¹	2.99	5.04 × 10 ⁻¹	8.68 × 10 ⁻²	2.19 × 10 ⁻²	6.13 × 10 ⁻³	1.65 × 10 ⁻³	1.66 × 10 ⁶	3.94 × 10 ⁵	1.31 × 10 ⁵	2.98 × 10 ⁴	7.67 × 10 ⁴	5.65 × 10 ²	2.90 × 10 ¹
123	20130621	4.78	1.65	8.27 × 10 ⁻¹	2.64 × 10 ⁻¹	7.84 × 10 ⁻²	2.16 × 10 ⁻²	...	...	...	...	...	1.83 × 10 ⁴	4.42 × 10 ³	1.62 × 10 ³	3.91 × 10 ²	9.09 × 10 ²	3.62	4.83 × 10 ⁻²
124	20131028	4.45	1.43	5.49 × 10 ⁻¹	1.53 × 10 ⁻¹	5.29 × 10 ⁻²	2.19 × 10 ⁻²	...	...	...	...	...	3.75 × 10 ⁵	7.70 × 10 ⁴	2.22 × 10 ⁴	4.26 × 10 ³	6.48 × 10 ³	1.69 × 10 ¹	1.43 × 10 ⁻¹
125	20131030	2.63	9.55 × 10 ⁻¹	4.35 × 10 ⁻¹	1.60 × 10 ⁻¹	7.01 × 10 ⁻²	2.80 × 10 ⁻²	...	...	...	...	...	...	...	...	...	...	...	...
126	20131107	7.60	2.19	8.70 × 10 ⁻¹	2.38 × 10 ⁻¹	7.10 × 10 ⁻²	1.82 × 10 ⁻²	...	...	...	...	...	9.83 × 10 ⁴	1.82 × 10 ⁴	3.91 × 10 ³	5.57 × 10 ²	5.12 × 10 ²	9.68 × 10 ⁻¹	2.45 × 10 ⁻²
127	20131119	1.95	6.81 × 10 ⁻¹	4.34 × 10 ⁻¹	1.41 × 10 ⁻¹	5.56 × 10 ⁻²	2.04 × 10 ⁻²	...	...	...	...	...	9.22 × 10 ³	1.91 × 10 ³	6.24 × 10 ²	1.67 × 10 ²	3.36 × 10 ²	2.04	4.09 × 10 ⁻²
128	20140106	1.62 × 10 ¹	7.13	3.40	1.52	7.22 × 10 ⁻¹	4.44 × 10 ⁻¹	2.21 × 10 ⁻¹	7.85 × 10 ⁻²	2.67 × 10 ⁻²	8.83 × 10 ⁻³	3.50 × 10 ⁻³	8.58 × 10 ⁴	1.93 × 10 ⁴	7.10 × 10 ³	1.90 × 10 ³	3.62 × 10 ³	2.17 × 10 ¹	6.03 × 10 ⁻¹
129	20140107	1.05 × 10 ²	8.35 × 10 ¹	6.61 × 10 ¹	4.10 × 10 ¹	1.66 × 10 ¹	5.19	1.07	1.33 × 10 ⁻¹	2.58 × 10 ⁻²	5.04 × 10 ⁻³	8.99 × 10 ⁻⁴	1.29 × 10 ⁶	3.03 × 10 ⁵	1.32 × 10 ⁵	3.88 × 10 ⁴	1.34 × 10 ⁵	6.67 × 10 ²	3.75 × 10 ¹
130	20140220	8.39	3.56	2.17	8.88 × 10 ⁻¹	4.22 × 10 ⁻¹	1.90 × 10 ⁻¹	8.31 × 10 ⁻²	1.97 × 10 ⁻²	4.77 × 10 ⁻³	...	...	1.38 × 10 ⁵	4.63 × 10 ⁴	1.78 × 10 ⁴	4.59 × 10 ³	4.20 × 10 ³	1.32 × 10 ¹	3.53 × 10 ⁻¹
131	20140225	3.98	2.40	1.79	8.75 × 10 ⁻¹	3.92 × 10 ⁻¹	1.61 × 10 ⁻¹	6.19 × 10 ⁻²	2.05 × 10 ⁻²	6.63 × 10 ⁻³	2.01 × 10 ⁻³	...	5.01 × 10 ⁴	1.44 × 10 ⁴	6.11 × 10 ³	1.62 × 10 ³	3.42 × 10 ³	1.73 × 10 ¹	3.03 × 10 ⁻¹
132	20140228	8.21 × 10 ¹	3.29 × 10 ¹	1.42 × 10 ¹	3.86	8.11 × 10 ⁻¹	1.40 × 10 ⁻¹	2.74 × 10 ⁻²	...	...	...	...	7.60 × 10 ⁵	1.62 × 10 ⁵	4.49 × 10 ⁴	7.63 × 10 ³	1.63 × 10 ⁴	3.41 × 10 ¹	5.48 × 10 ⁻¹
133	20140329	6.10 × 10 ⁻¹	2.91 × 10 ⁻¹	2.06 × 10 ⁻¹	1.08 × 10 ⁻¹	5.33 × 10 ⁻²	2.00 × 10 ⁻²	...	...	...	...	...	3.49 × 10 ⁴	9.01 × 10 ³	3.64 × 10 ³	1.06 × 10 ³	2.39 × 10 ³	8.05	6.27 × 10 ⁻²
134	20140418	5.70 × 10 ¹	2.05 × 10 ¹	7.86	2.18	5.40 × 10 ⁻¹	1.54 × 10 ⁻¹	4.33 × 10 ⁻²	1.39 × 10 ⁻²	4.77 × 10 ⁻³	1.75 × 10 ⁻³	7.02 × 10 ⁻⁴	8.88 × 10 ⁴	1.80 × 10 ⁴	5.92 × 10 ³	1.41 × 10 ³	2.38 × 10 ³	1.06 × 10 ¹	1.47 × 10 ⁻¹
135	20140825	7.53 × 10 ⁻¹	3.15 × 10 ⁻¹	2.01 × 10 ⁻¹	4.50 × 10 ⁻²	1.64 × 10 ⁻²	...	...	...	...	...	...	1.14 × 10 ⁴	1.92 × 10 ³	4.17 × 10 ²	7.71 × 10 ¹	1.15 × 10 ²	3.79 × 10 ⁻¹	8.43 × 10 ⁻³
136	20140910	9.12	3.80	1.96	1.06	5.19 × 10 ⁻¹	2.29 × 10 ⁻¹	8.50 × 10 ⁻²	2.39 × 10 ⁻²	6.55 × 10 ⁻³	...	...	5.67 × 10 ⁴	1.80 × 10 ⁴	8.73 × 10 ³	2.80 × 10 ³	6.70 × 10 ³	5.41 × 10 ¹	1.38
137	20141101	1.39 × 10 ¹	3.86	1.46	3.79 × 10 ⁻¹	1.09 × 10 ⁻¹	3.01 × 10 ⁻²	...	...	...	...	...	4.54 × 10 ⁴	8.57 × 10 ³	2.30 × 10 ³	4.29 × 10 ²	7.50 × 10 ²	2.12	3.61 × 10 ⁻²
138	20141221	7.99	1.88	4.99 × 10 ⁻¹	9.09 × 10 ⁻²	3.30 × 10 ⁻²	...	...	...	...	...	...	1.06 × 10 ⁵	2.30 × 10 ⁴	7.96 × 10 ³	1.73 × 10 ³	2.86 × 10 ³	6.27	5.08 × 10 ⁻²
139	20141223	3.78	1.02	3.93 × 10 ⁻¹	7.39 × 10 ⁻²	...	...	...	...	...	...	...	6.87 × 10 ⁴	1.37 × 10 ⁴	4.23 × 10 ³	8.59 × 10 ²	...	...	...
140	20150315	6.90	2.04	6.21 × 10 ⁻¹	1.15 × 10 ⁻¹	3.54 × 10 ⁻²	...	...	...	...	...	...	2.66 × 10 ⁴	4.72 × 10 ³	1.22 × 10 ³	2.26 × 10 ²	...	...	...
141	20150316	1.34 × 10 ²	1.93 × 10 ¹	3.04	1.51 × 10 ⁻¹	3.03 × 10 ⁻²	...	...	...	...	...	...	2.48 × 10 ⁵	4.70 × 10 ⁴	1.22 × 10 ⁴	1.98 × 10 ³	4.61 × 10 ³	4.53	4.92 × 10 ⁻²
142	20150512	3.36	1.25	6.11 × 10 ⁻¹	2.21 × 10 ⁻¹	8.55 × 10 ⁻²	3.03 × 10 ⁻²	1.03 × 10 ⁻²	...	...	...	...	1.39 × 10 ⁴	2.98 × 10 ³	9.92 × 10 ²	2.36 × 10 ²	2.81 × 10 ²	1.03	1.62 × 10 ⁻²
143	20150618	7.64	3.10	1.74	7.18 × 10 ⁻¹	1.96 × 10 ⁻¹	3.82 × 10 ⁻²	...	...	...	...	...	2.57 × 10 ⁴	6.34 × 10 ³	2.56 × 10 ³	7.05 × 10 ²	1.56 × 10 ³	5.78	3.05 × 10 ⁻¹
144	20150625	1.20 × 10 ¹	4.88	2.09	6.12 × 10 ⁻¹	1.44 × 10 ⁻¹	...	...	...	...	...	...	7.65 × 10 ⁴	1.68 × 10 ⁴	4.82 × 10 ³	8.62 × 10 ²	1.35 × 10 ³	3.14	2.98 × 10 ⁻²
145	20150920	1.60	5.91 × 10 ⁻¹	3.43 × 10 ⁻¹	9.81 × 10 ⁻²	4.02 × 10 ⁻²	1.48 × 10 ⁻²	...	...	...	...	...	3.17 × 10 ⁵	9.17 × 10 ⁴	1.95 × 10 ⁴	2.40 × 10 ³	1.73 × 10 ³	5.61	2.68 × 10 ⁻²
146	20151109	1.22	6.43 × 10 ⁻¹	3.71 × 10 ⁻¹	1.20 × 10 ⁻¹	4.33 × 10 ⁻²	1.66 × 10 ⁻²	...	...	...	...	...	6.52 × 10 ³	1.01 × 10 ³	2.85 × 10 ²	6.78 × 10 ¹	7.17 × 10 ¹	2.40 × 10 ⁻¹	1.99 × 10 ⁻²
147	20151228	7.16	2.24	7.29 × 10 ⁻¹	8.80 × 10 ⁻²	2.52 × 10 ⁻²	...	...	...	...	...	...	1.02 × 10 ⁴	1.94 × 10 ³	5.40 × 10 ²	1.23 × 10 ²	1.86 × 10 ²	7.39 × 10 ⁻¹	1.69 × 10 ⁻²
148	20160101	2.53 × 10 ¹	7.76	3.69	6.56 × 10 ⁻¹	1.45 × 10 ⁻¹	3.28 × 10 ⁻²	9.67 × 10 ⁻³	3.27 × 10 ⁻³	...	...	...	5.59 × 10 ⁴	1.06 × 10 ⁴	2.96 × 10 ³	5.51 × 10 ²	9.67 × 10 ²	3.42	1.96 × 10 ⁻¹
149	20160418	6.07 × 10 ⁻¹	2.15 × 10 ⁻¹	1.44 × 10 ⁻¹	3.11 × 10 ⁻²	...	...	...	...	...	...	...	1.45 × 10 ⁴	1.82 × 10 ³	3.49 × 10 ²	6.37 × 10 ¹	6.25 × 10 ¹	1.68 × 10 ⁻¹	...
150	20160515	4.35	1.35	5.51 × 10 ⁻¹	6.58 × 10 ⁻²	2.22 × 10 ⁻²	...	...	...	...	...	...	1.61 × 10 ⁴	3.65 × 10 ³	1.37 × 10 ³	3.34 × 10 ²	4.89 × 10 ²	1.24	9.64 × 10 ⁻³
151	20170714	1.16 × 10 ¹	5.26	2.39	6.15 × 10 ⁻¹	1.66 × 10 ⁻¹	4.23 × 10 ⁻²	9.77 × 10 ⁻³	...	...	...	...	2.18 × 10 ⁴	5.69 × 10 ³	1.94 × 10 ³	4.16 × 10 ²	6.04 × 10 ²	1.24	5.92 × 10 ⁻²
152	20170904	1.23 × 10 ²	4.69 × 10 ¹	1.84 × 10 ¹	3.54	5.10 × 10 ⁻¹	5.33 × 10 ⁻²	...	...	...	...	...	2.40 × 10 ⁵	4.86 × 10 ⁴	1.60 × 10 ⁴	4.38 × 10 ³	8.34 × 10 ³	3.45 × 10 ¹	1.41
G55	19971106	2.89 × 10 ¹	2.45 × 10 ¹	1.93 × 10 ¹	1.33 × 10 ¹	7.62	4.30	2.25	9.08 × 10 ⁻¹	3.58 × 10 ⁻¹	1.23 × 10 ⁻¹	5.26 × 10 ⁻²	5.16 × 10 ⁵	1.88 × 10 ⁵	1.01 × 10 ⁵	3.52 × 10 ⁴	1.21 × 10 ⁵	5.04 × 10 ²	3.24 × 10 ¹
G56	19980502	2.68 × 10 ¹	1.63 × 10 ¹	8.93	5.20	2.31	1.09	4.76 × 10 ⁻¹	1.92 × 10 ⁻¹	7.38 × 10 ⁻²	2.48 × 10 ⁻²	1.17 × 10 ⁻²							

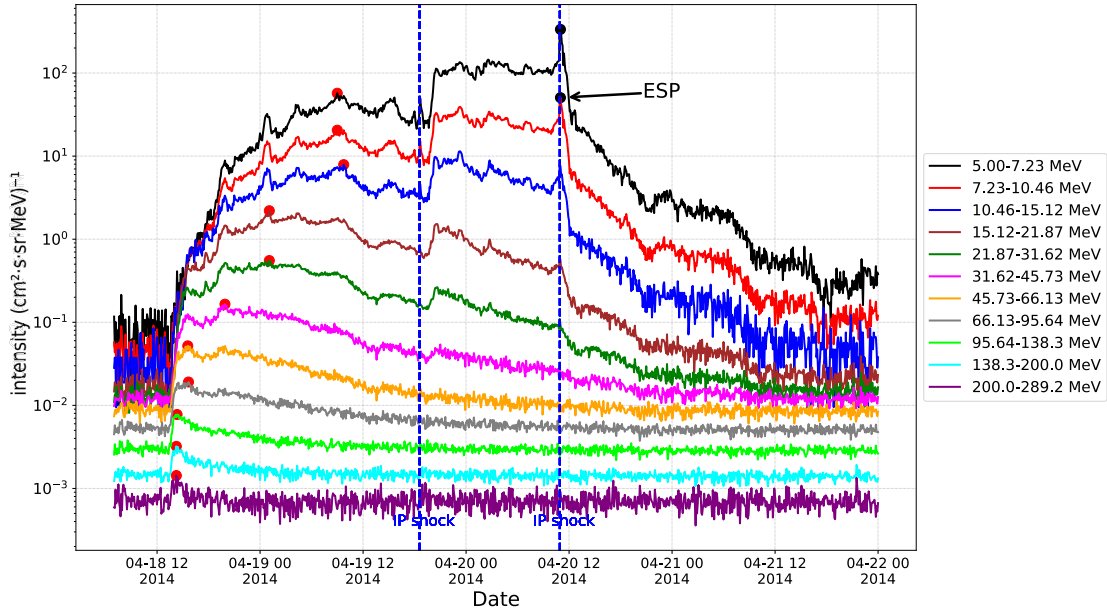


Figure 1. The 2014 April 18 energetic proton event. The two dashed vertical lines represent the moments when the interplanetary shocks passed the spacecraft. The red dots represent the first peaks of particle intensities, and the black dots represent the second peaks that were accompanied by the second interplanetary shock.

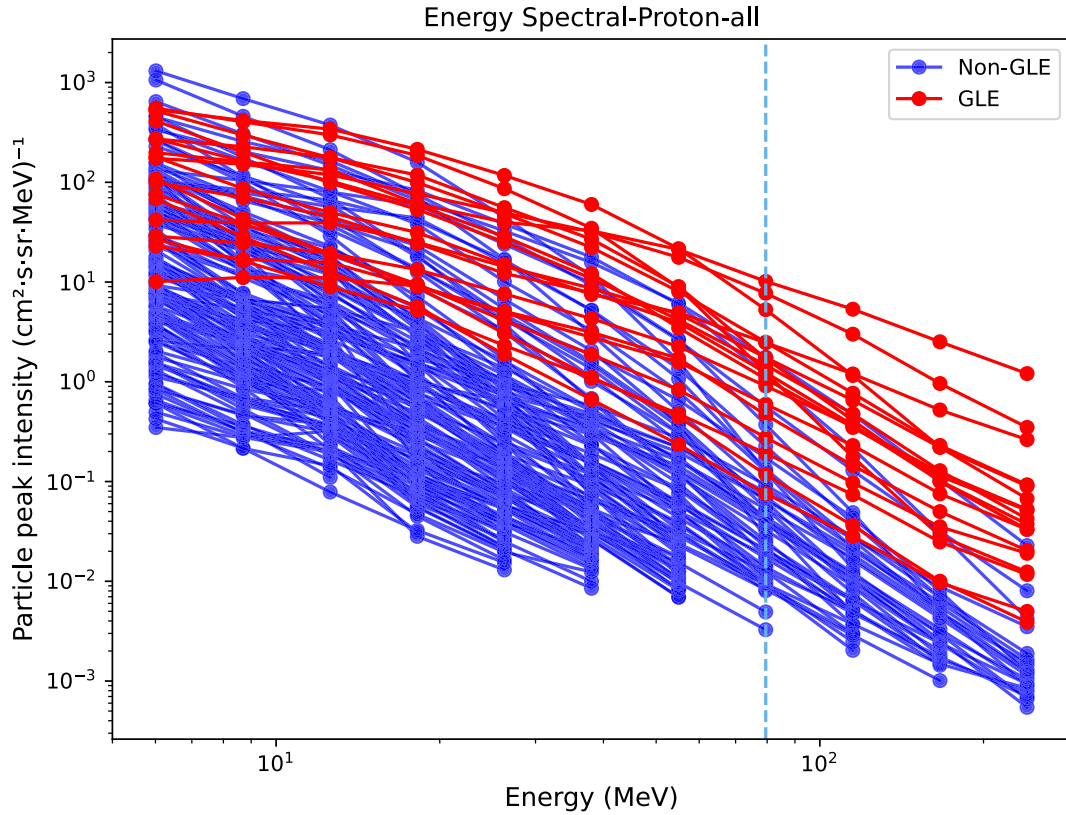


Figure 2. Energy spectra of the peak intensity of energetic protons in all non-GLE and GLE events. The vertical axis represents the peak intensities of energetic protons, and the horizontal axis represents the energy channels. Red dots represent GLE events and blue dots represent non-GLE events. The energy of 79.5 MeV (pE8: 66.13–95.64 MeV) is marked by a light blue vertical dashed line.

3. Peak Energy Spectrum of Energetic Particles

In the study of solar activity, the spectral characteristics of energetic particle events are crucial for understanding the acceleration mechanism of energetic particles. Based on the peaks of the particle intensities, we obtain the peak energy spectra of energetic particle events and compare the

differences in the energy spectra of GLE events with those of non-GLE events. Figure 2 shows the energy spectrum statistics of the energetic protons in all events, totaling 18 GLE and 152 non-GLE events. In Figure 2, the energy value is taken as the average of each energy channel, with the formula $\bar{E} = \sqrt{E_1 \cdot E_2}$. For example, for the energy channel pE8, with an energy range of 66.13–95.64 MeV, the value marked in the

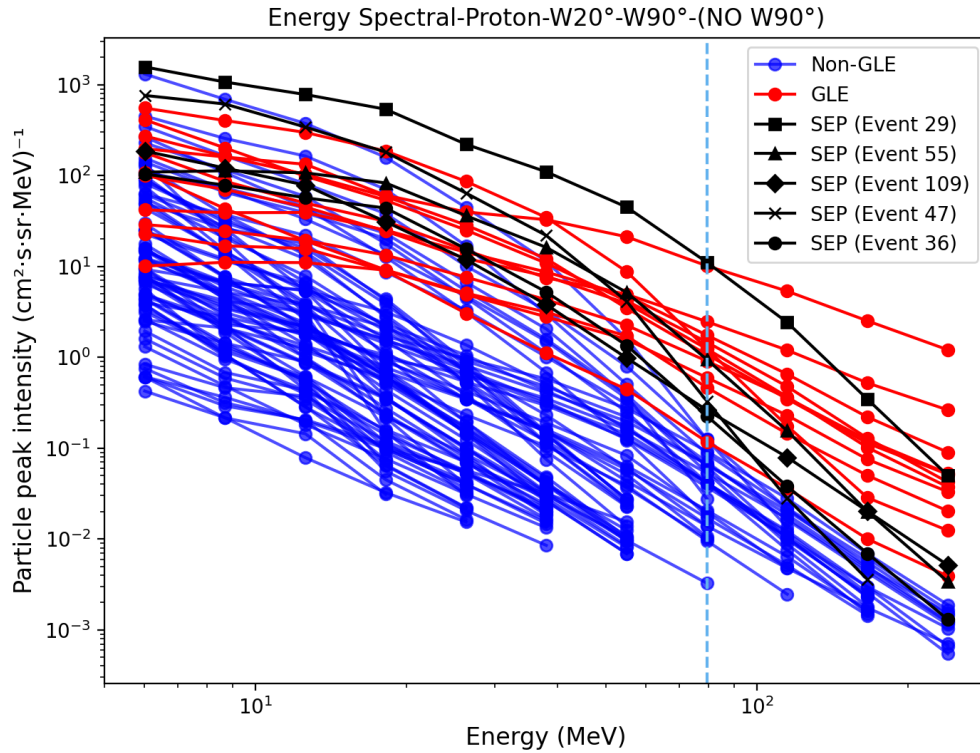


Figure 3. Energy spectra of the energetic proton peak intensity within the source region of W20°–W90° (NO W90°). The energy of 79.5 MeV (pE8: 66.13–95.64 MeV) is marked by a light blue vertical dashed line, and five non-GLE events that are indistinguishable from GLE events have been labeled with different symbols in the figure.

figure is 79.53 MeV. Figure 3 illustrates the statistics of the energy spectrum of energetic protons in events with good magnetic links W20°–W90° (NO W90°), a total of 11 GLE and 78 non-GLE events. “NO 90°” means that we do not include events on the western edge because of the inaccuracy of the source locations of such events. As shown in Figures 2 and 3, in the low-energy channel, e.g., 5.00–7.23 MeV, the peak intensities of protons in the GLE events are not significantly stronger than those in the non-GLE events. As the energy increases, the peak intensities of protons in GLE events gradually exceed those in non-GLE events. In Figure 3, using the pE8 energy channel as a reference, we can find that the GLE events are distinguishable from the non-GLE events except for five non-GLE events that are mixed with the GLE events, which we have labeled with different symbols in black; from top to bottom they are 2000 November 8, 2002 April 21, 2012 January 27, 2001 November 22, and 2001 April 2, respectively. This indicates that most GLE events can be effectively identified by analyzing their peak intensities starting from the 66.13–95.64 MeV energy channel (pE8) and beyond. The peak intensity of >66 MeV protons can be used as a signature to distinguish GLE events from non-GLE events. The advantage of this approach is that, compared to studying protons above 500 MeV, focusing on lower-energy ranges (such as >66 MeV) provides a larger sample of energetic particle events, leading to more statistically robust and reliable results.

It is worth noting that the intensities measured at the first peak of large SEP events (the prompt component) are constrained by an upper limit termed the streaming limit. Energetic particles propagating along interplanetary magnetic field lines amplify surrounding magnetohydrodynamic (MHD)

waves. These waves, in turn, scatter the energetic particles, thereby limiting their streaming transport. This effect results in a definite upper limit on the prompt component of particle intensities measured in large SEP events. In the five non-GLE events, the events of 2000 November 8 and 2001 November 22, analyzed in the study by D. Lario et al. (2009), were classified as “Event with prompt components above the previously determined streaming limit” and “Event with prompt components close to the streaming limit,” respectively. Consequently, the intensities of energetic particles observed near 1 au may have been modulated by these MHD waves in the two events.

In Figures A1 and A2, we compare the peak electron intensities with the peak proton intensities for all events (including GLE and non-GLE events). The lower-right corner of every panel shows the Pearson correlation coefficient and the total number of events (all GLE events + all non-GLE events). We find a strong correlation between the peak of the electron intensities and the peak of the proton intensities. It implies strong proton acceleration often accompanied by strong electron acceleration. Energetic electrons produce radio radiation and X-rays during propagation, so the peak intensities of energetic protons should also correlate with the peaks of radio and X-rays.

4. Flare Diagnostic Parameters

4.1. Fluxes of ≥ 5 GHz Radio Bursts

Energetic electrons accelerated during solar eruptions can produce considerable radio bursts. Depending on frequencies or locations, these bursts result from various mechanisms, such as the plasma emission, bremsstrahlung, and gyrosynchrotron,

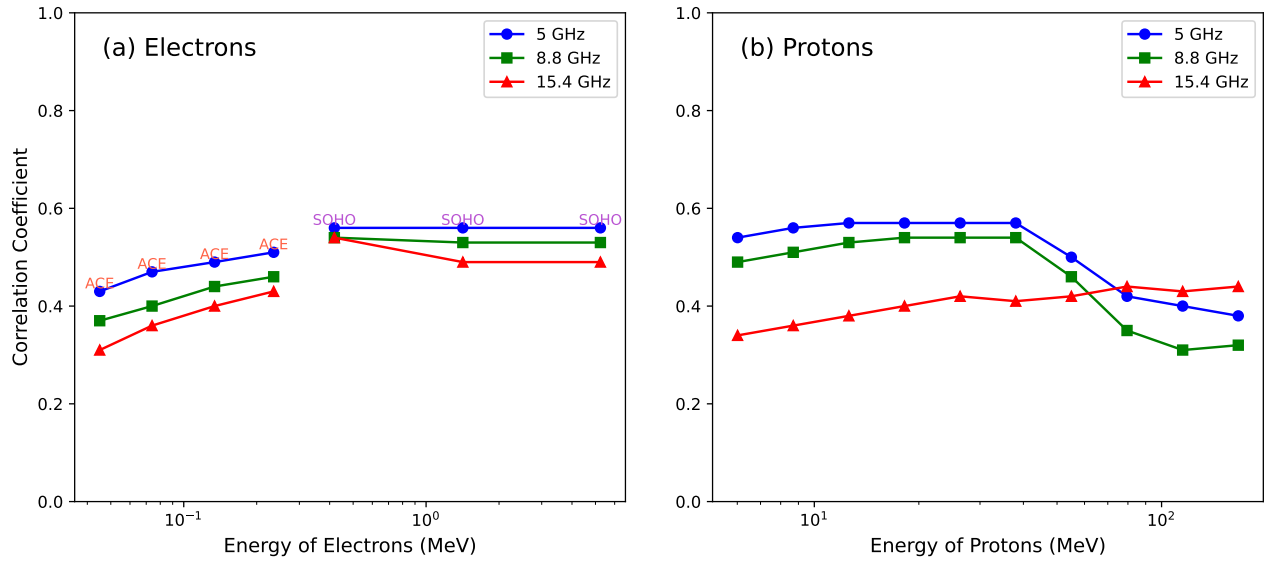


Figure 4. The correlation coefficients between the peak intensities of electrons and protons across different energy channels and the peak fluxes of radio frequencies at 5, 8.8, and 15.4 GHz. Panel (a) shows the correlation coefficients for electrons and panel (b) shows the correlation coefficients for protons.

and therefore could provide valuable insights into the acceleration of energetic particles. In this work, we focus on the radio emission associated with solar flares. We use ≥ 5 GHz radio emission to study the acceleration of electrons by the magnetic reconnection accompanying flares, and compare GLE events with non-GLE events to investigate the differences in the radio emission during flares between the two types of events. In the following study, we focus on well-connected events, and due to the insufficient number of energetic proton events, our analysis is limited to the pE10 energy channel. In the study by G. Trottet et al. (2015), the correlation between ≥ 1 GHz radio bursts in different frequencies and energetic particles was investigated. Here we will focus on the correlations between particle peak intensity and microwave peak flux at 5, 8.8, and 15.4 GHz. Emission at these frequencies are typically manifested around the turnover frequency and in the typical optically thin regime of microwave spectra, indicating pure gyrosynchrotron radiation emitted by flare-accelerated electrons. Events with peak flux exceeding 100 sfu are selected in our analysis, after subtracting quiet-Sun components by averaging values before or after the bursts.

Figures A3–A5 show scatter plots of peak intensities of energetic electrons versus peak fluxes of radio at 5, 8.8, and 15.4 GHz, respectively. The energetic electron data in the first four channels are from the ACE EPAM instrument, and the data in the last three channels are from the SOHO EPHIN instrument. The blue dots represent non-GLE events, while the red dots represent GLE events. In the figures, there are three blue dashed lines labeled 85% non-GLE, 90% non-GLE, and 95% non-GLE, representing the 85th, 90th, and 95th percentiles of radio intensity for non-GLE events, which help to distinguish the intensities and distribution characteristics of GLE and non-GLE events. Statistical results reveal that intense electron intensities are associated with intense radio fluxes. At 5 GHz, the mean and median of peak fluxes for GLE events are 7739 and 5327 sfu, respectively, significantly exceeding the corresponding values for non-GLE events (1994 and 718 sfu). This trend continues at higher frequencies: at 8.8 GHz (mean 10,574 versus 2423 sfu; median 7165 versus 918 sfu) and

15.4 GHz (mean 15,579 versus 2764 sfu; median 10,320 versus 310 sfu). Figures A6–A8 show scatter plots of peak intensities of energetic protons versus peak fluxes of radio at 5, 8.8, and 15.4 GHz, respectively. Most GLE events exceed the 85th percentile threshold of non-GLE events: 70% at 5 GHz, 55% at 8.8 GHz, and 80% at 15.4 GHz. The intensive radio fluxes associated with GLE events confirm the correlation between solar proton events and radio bursts.

Based on the results presented in Figures A1–A8, the following conclusions can be drawn:

(1) *Strong correlation between electron and proton acceleration.* A strong positive correlation (with correlation coefficients from 0.69 to 0.92) exists between the peak intensities of energetic electrons and protons in solar events (both GLE and non-GLE). This indicates that efficient proton acceleration is consistently accompanied by efficient electron acceleration.

(2) *Electron intensity correlates with radio flux.* There is a clear association between peak intensities of energetic electrons and peak radio fluxes at 5, 8.8, and 15.4 GHz. GLE events consistently exhibit significantly higher radio fluxes across all frequencies compared to non-GLE events, as confirmed by much higher mean and median of peak fluxes.

(3) *Proton intensity correlates with radio flux.* Radio fluxes in the majority of GLE events exceed that in the 85% non-GLE events, providing strong statistical evidence for a correlation between intense solar proton events and intense radio bursts.

In conclusion, the analysis of Figures A1–A8 consistently demonstrates that GLEs characterized by intense acceleration of both electrons and protons are strongly correlated with intense nonthermal radio emission across multiple microwave frequencies. For high-energy channels (pE8–pE10), microwave radio bursts at the three frequencies (5, 8.8, and 15.4 GHz) are consistent with an acceleration mechanism driven by flare-related magnetic reconnection in the low corona.

Figure 4(a) shows the variations in the correlation between the peak fluxes of radio frequencies at 5, 8.8, and 15.4 GHz and electron intensities across different energy channels. The blue/green/red curves represent data at the 5, 8.8, and 15.4 GHz

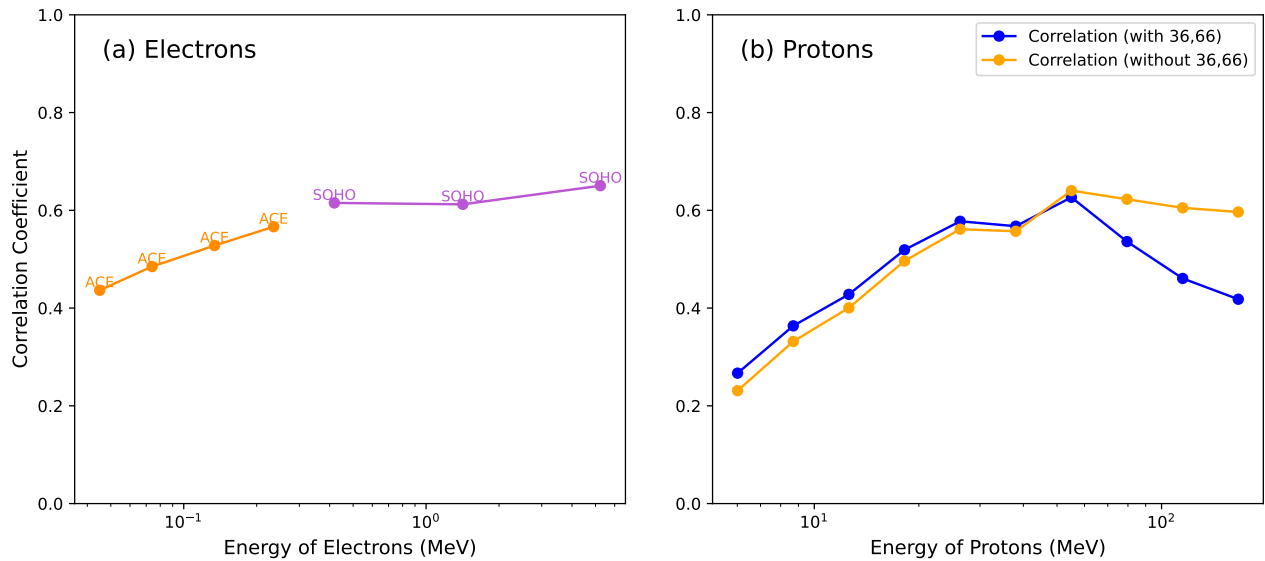


Figure 5. The correlation coefficients between the peak intensities of electrons and protons across different energy channels and the peak intensities of SXRs. Panel (a) shows the correlation coefficients for electrons and panel (b) is the correlation coefficients for protons.

frequencies, respectively. The data for the first four energy channels are observed by ACE, while the data for the next three higher-energy channels are observed by SOHO. The correlations between the peak radio fluxes and peak electron intensities vary from 0.43 to 0.56 for 5 GHz, from 0.37 to 0.53 for 8.8 GHz, and from 0.31 to 0.54 for 15.4 GHz, respectively. The correlation coefficients between electrons and radio bursts are higher for higher-energy electrons observed by SOHO than for lower-energy electrons observed by ACE. Figure 4(b) shows the correlation variations for protons across different energy channels. The correlation between radio peak flux and proton peak intensity varies from 0.38 to 0.57 for 5 GHz, from 0.31 to 0.54 for 8.8 GHz, and from 0.34 to 0.44 for 15.4 GHz. As proton energy increases, the correlation coefficients at frequencies of 5 and 8.8 GHz first rise and then gradually decrease starting from the pE7 energy. In contrast, the correlation at 15.4 GHz shows a different characteristic; as proton energy increases, the correlation coefficient gradually increases. For protons with energies above the pE8 channel, the correlation coefficients at 15.4 GHz are higher than those at 5 and 8.8 GHz. This difference in behavior at different frequencies may be due to the difference between optically thick and optically thin microwave emission, which we do not consider.

4.2. Soft X-Ray Fluxes

The peak SXR flux at 0.1–0.8 nm determines the flare class. We consider the flares ranging from C class to X class. Figures 5(a) and (b) show the correlation coefficients between the peak of SXR intensity and the peaks of electron and proton intensities, respectively. Figures A9 and A10 provide more detailed information. Figures 5(a) and A9 show the correlation coefficient between the electron intensity peak and the SXR intensity peak that gradually increases with increasing electron energy. Figures 5(b) and A10 show that in the pE1 energy channel, the correlation coefficient between the proton intensity peak and the SXR intensity peak is only 0.27, and the correlation coefficient gradually increases to more than 0.5 with the increase of energy. In the high-energy channels (pE8–pE10), where the number of energetic particle events is limited, particular attention should be paid to the potential

influence of individual outliers on the correlation coefficients. In pE8–pE10 channels, SEP events 36 (2001 April 2) and 66 (2003 November 4) are identified as deviation points in the statistics. The peak intensities of protons in these two events are relatively low and are marked with gray triangles. We perform separate fits for datasets including and excluding events 36 and 66 (denoted as Fit (with 36, 66) and Fit (without 36, 66), respectively). The fitting results indicate that SEP events 36 (2001 April 2) and 66 (2003 November 4) notably affect the correlation between the proton intensity peak and the SXR intensity peak in the pE8–pE10 channels. Specifically, for the dataset including events 36 and 66, the correlation coefficient decreases from 0.63 to 0.42, showing a declining trend in pE8–pE10. In contrast, the correlation coefficient for the dataset excluding events 36 and 66 shows little change, varying only from 0.64 to 0.60. In SEP event 36, the spacecraft was located inside an interplanetary coronal mass ejection (ICME; I. G. Richardson & H. V. Cane 2010; G. Trottet et al. 2015). When energetic particles reach the spacecraft, the magnetic field of the ICME may weaken the peak intensity of the SEP event. In SEP event 66, the eruption produced the most powerful flare of the 2003 “Halloween Solar Storms,” up to class X30.2 (H. Hudson et al. 2024). However, it is possible that the solar storm did not result in a GLE due to the highly disturbed near-Earth environment on that day, as indicated by the arrival of a considerable interplanetary disturbance observed by the ACE spacecraft on 2003 November 4 (day of the year 308) around 06:00 UT,⁴ and the geomagnetic disturbance characterized by a disturbance storm time index of −69 nT at 11:00 UT.⁵ This unregistered ICME might have played a role in preventing the GLE, analogous to the mechanism proposed for Event 36.

In Figures A9 and A10, the mean and median of SXR fluxes are 5.81×10^{-4} and $3.8 \times 10^{-4} \text{ W m}^{-2}$ for GLE events, compared with 1.32×10^{-4} and $3.7 \times 10^{-5} \text{ W m}^{-2}$ for non-GLE events. In addition, approximately 82% of GLE events exceed the 85th percentile threshold of non-GLE events,

⁴ https://izw1.caltech.edu/ACE/ASC/browse/view Browse_data.html

⁵ https://wdc.kugi.kyoto-u.ac.jp/dst_final/200311/index.html

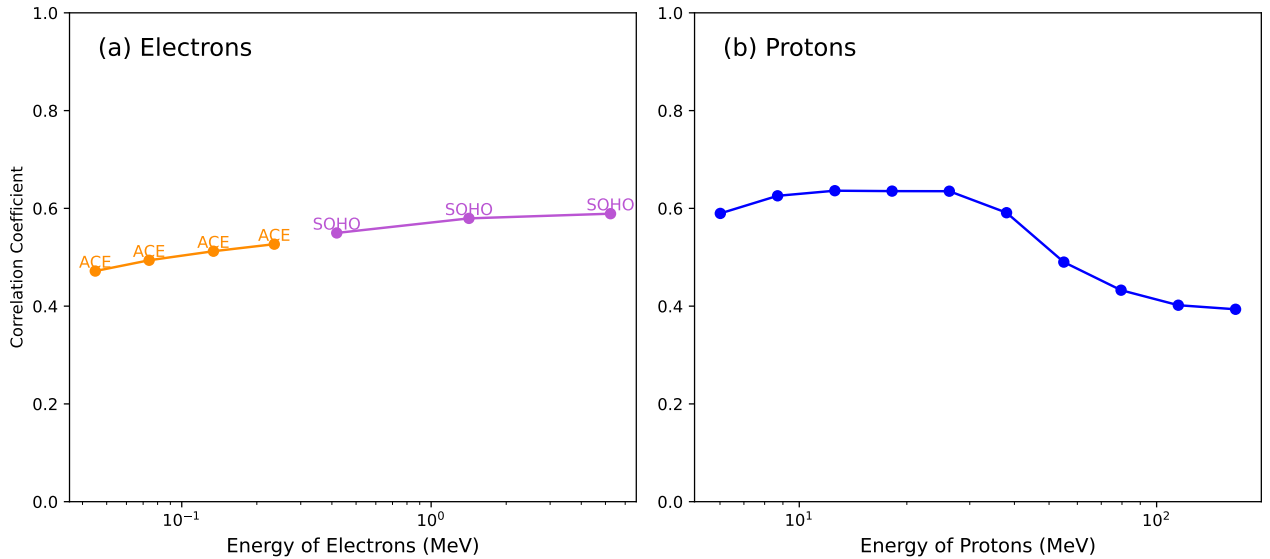


Figure 6. The correlation coefficients between the peak intensities of electrons and protons across different energy channels and CME-v. Panel (a) shows the correlation coefficients for electrons and panel (b) shows the correlation coefficients for protons.

further highlighting the stronger SXR emissions associated with GLE events. This correspondence implies that high-energy channels (pE8–pE10) of most GLE events correspond to intensive SXRs. Notably, the distinction between non-GLE and GLE events in the SXR data is more pronounced than that in ≥ 5 GHz radio data. Up to this point, we have analyzed ≥ 5 GHz radio and SXRs, both of which are characteristic parameters of the flare. We find that both ≥ 5 GHz radio and SXR emissions are correlated with energetic particle intensity.

The correlation variations between the peak of SXR fluxes and particle intensities across different energy channels are summarized in Figure 5, with panel (a) for electrons and panel (b) for protons. In panel (b), the correlation coefficients are presented in two curves: a blue line for data including points 36 and 66, and a gold line for data excluding them. The blue line shows an initial increase followed by a decline after its peak, while the gold line plateaus at a high correlation value, indicating a significant difference in the trend depending on the two specific events. From the pE1 to pE8 energy channels, the correlation coefficient between the proton intensity peak and the SXR intensity peak gradually increases with increasing energy, which is consistent with a flare-related origin of high-energy (>66 MeV protons) particles. We infer that in most GLE events, high-energy (>66 MeV protons) protons is mainly associated with flares, but does not exclude their shock-related origin.

5. CME-shock Diagnostic Parameter

5.1. CME Speeds

In addition to solar flares, another important source of SEPs is the CME shock. The CME speed (denoted as CME-v), a critical metric for measuring the acceleration capability of CME shocks, is essential for studying the relation between CME events and particle events. In this study, we use the plane-of-the-sky projected CME speeds measured in the online CDAW CME catalog (S. Yashiro et al. 2004).⁶ Figures A11 and A12 present scatter plots of the CME speed versus the

peak intensities of energetic electrons and energetic protons for events at W20°–W90° (including western limb events), respectively. GLE 69 is excluded due to its uncertain speed (N. Gopalswamy et al. 2005; G. M. Simnett 2006; V. V. Grechnev et al. 2008). In Figures A11 and A12, there is a substantial overlap between GLE and non-GLE events. Although the average CME speed for GLE events (mean 1852 km s^{-1} ; median 1774 km s^{-1}) is somewhat higher than that for non-GLE events (mean 1272 km s^{-1} ; median 1204 km s^{-1}), it remains difficult to clearly distinguish GLE events (red dots) from non-GLE events (blue dots) in the pE8 channel.

In Figure A11, the correlation between CME speeds and peak electron intensities is relatively stable across all energy channels, with a correlation coefficient around 0.55. In Figure A12, the correlation between the CME speeds and the peak proton intensities is higher at lower proton energies. However, as energy increases, the correlation gradually decreases, indicating that CME-shock acceleration is more effective for lower-energy protons and the acceleration capability drops notably at higher energies. The correlation variations between CME speed and particle intensities across different energy channels are summarized in Figure 6, with panel (a) for electrons and panel (b) for protons. It is also noticeable that the number of MeV electron events far exceeds that of hundred-MeV proton events, suggesting that MeV electrons are easier to accelerate. Compared to hundred-MeV protons, MeV electrons, due to their smaller mass, are more easily accelerated to relativistic speeds. MeV energetic electrons are probably accelerated by both magnetic reconnection in flares and CME shocks. CME shocks are more effective at accelerating low-energy protons, and their acceleration capability decreases with increasing proton energy. The correlations between CME speeds with >66 MeV protons are weak. It appears that CME shocks are not significantly effective at accelerating >66 MeV protons in GLE events.

In a previous study, K.-L. Klein & G. Trottet (2001) suggested that protons in the lower-energy range are predominantly accelerated by CME-driven shocks, whereas high-energy protons originate primarily from flare-associated

⁶ https://cdaw.gsfc.nasa.gov/CME_list/

processes. This interpretation is further substantiated by multiple independent studies, including M. Dierckxsens et al. (2015) and G.-M. Le et al. (2017). Our work aligns with a key finding from previous research by M. Dierckxsens et al. (2015), who statistically analyzed SEP events, solar flares (intensity, location), and CMEs (speed, angular width) during Solar Cycle 23. Specifically, their study revealed an energy-dependent pattern in correlations: the relationship between proton flux and flare intensity strengthens with increasing energy, while the correlation with CME speed weakens. Consequently, CME speed dominates correlations below 10 MeV, whereas flare intensity dominates above 50 MeV. Moreover, the origin of SEPs at intermediate energies is mixed, involving contributions from both flare and CME-shock acceleration. Based on an expanded dataset (Solar Cycles 23 and 24), our work confirms these fundamental patterns regarding energy-dependent correlations.

6. Conclusion

In energetic particle events, proton acceleration processes may differ in different energy ranges. In this study, a comparative analysis of particles at different energy channels in GLE and non-GLE events is conducted, examining the relation between particle peak intensities and various parameters of solar flares and CMEs. The variation trends of correlation coefficients with particle energy are used to distinguish the acceleration regions of energetic protons across different energy channels.

We classified the source locations of the events and compared the spectral characteristics of GLE and non-GLE events. For >66 MeV protons, the peak intensities of protons in most GLE events are significantly higher than those in non-GLE events, thus identifying the energy threshold distinguishing GLE from non-GLE events. By comparing the peak intensities of energetic electrons and protons, we find a strong correlation between them, suggesting that energetic electrons can be used to aid in studying the source regions of energetic protons. Energetic electrons move in magnetic fields, producing radio bursts and X-ray flares. Therefore, analyzing the correlations between these phenomena and energetic particles can help identify the acceleration source.

We investigate the correlation between the peaks of particle intensities and the maximum peaks of radio fluxes, as well as the SXR flux, to study the flare-related acceleration. By analyzing the correlation between the peak intensities of radio bursts at different frequencies (5, 8.8, 15.4 GHz) and the peak intensities of protons and electrons, we find that GLE events are associated with intensive ≥ 5 GHz radio bursts. Furthermore, we find a correlation between the peak of radio flux and the peak of SXR flux, and the SXR peak effectively distinguishes most GLE events from non-GLE events. These results suggest that >66 MeV protons in GLE events have a stronger correlation with flare-related acceleration.

CME-driven shocks are effective at accelerating protons below 10 MeV. The correlation between CME speeds and proton peak intensities decreases with increasing energy, and the correlation between CME speeds and >66 MeV peak proton intensities is relatively weak. This indicates that >66 MeV protons in GLE events are not primarily accelerated by CME-driven shocks but are instead closely associated with flare-related acceleration. The number of MeV electron events significantly exceeds that of hundred-MeV proton events. Compared to hundred-MeV protons, MeV electrons, due to their smaller mass, are accelerated to relativistic speeds more easily. For relativistic electrons, their production is attributed to a combination of magnetic reconnection acceleration during solar flares and acceleration by CME shocks.

Based on the above analysis, we conclude that in most GLE events, the acceleration of >66 MeV protons likely occurs primarily in the low corona and is closely associated with the acceleration mechanisms of solar flares. In contrast, the acceleration of the lower channel of energetic protons (<10 MeV) is related to CME-driven shocks. Moreover, the origin of SEPs at intermediate energies is mixed, arising from both flare acceleration and CME-driven shock acceleration. The results of our analysis of an extended dataset including Solar Cycle 24 confirm the conclusions drawn from previous solar cycle data (M. Dierckxsens et al. 2015) and provide indications of the sources of accelerated protons of different energies.

Acknowledgments

We are grateful for the stimulating discussions with Xianzhi Ao, Bei Zhu, Yaodong Xu, Wenya Li, Binbin Tang, Xiaoshuai Zhu, and Peng Zou. We are partly supported by the National Natural Science Foundation of China (grant Nos. 42474220, 42074205, and 42374190), Guangdong Basic and Applied Basic Research Foundation (No. 2023A1515011626), National Key Research and Development Program of China (No. 2022YFA1604600), the Key-Area Research and Development Program of Guangdong Province (No. 2020B0303020001), and Shenzhen Key Laboratory Launching Project (No. ZDSYS20210702140800001). We would like to acknowledge and express our gratitude for the energetic particle data provided by ACE, SOHO, and the SEP-EM database. The CME catalog is generated and maintained by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA. We also thank the CDA, OMNI, and NOAA for maintaining the spacecraft data online.

Appendix

See Figures A1–A12 for more detailed data.

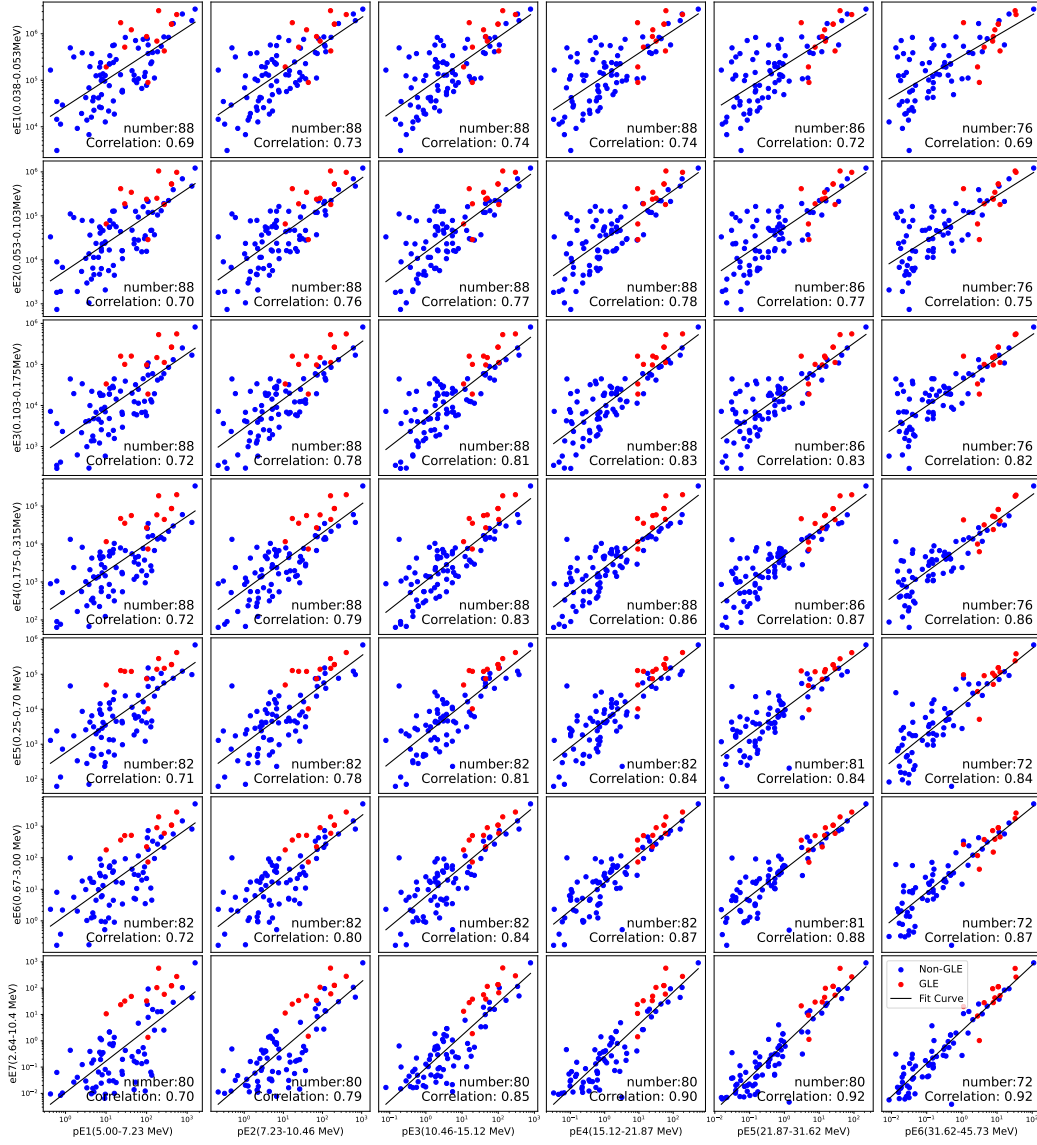


Figure A1. Scatter (log-log) plots of the peak intensities of energetic electrons versus the peak of the energetic protons in different energy channels. The vertical axes represent the peaks of energetic electron intensities and the horizontal axes represent the peaks of energetic proton intensities. The energy channels of protons in different panels from left to right become gradually larger, and the energy channels of electrons in different panels from top to bottom become gradually larger. Red dots represent GLE events and blue dots represent non-GLE events.

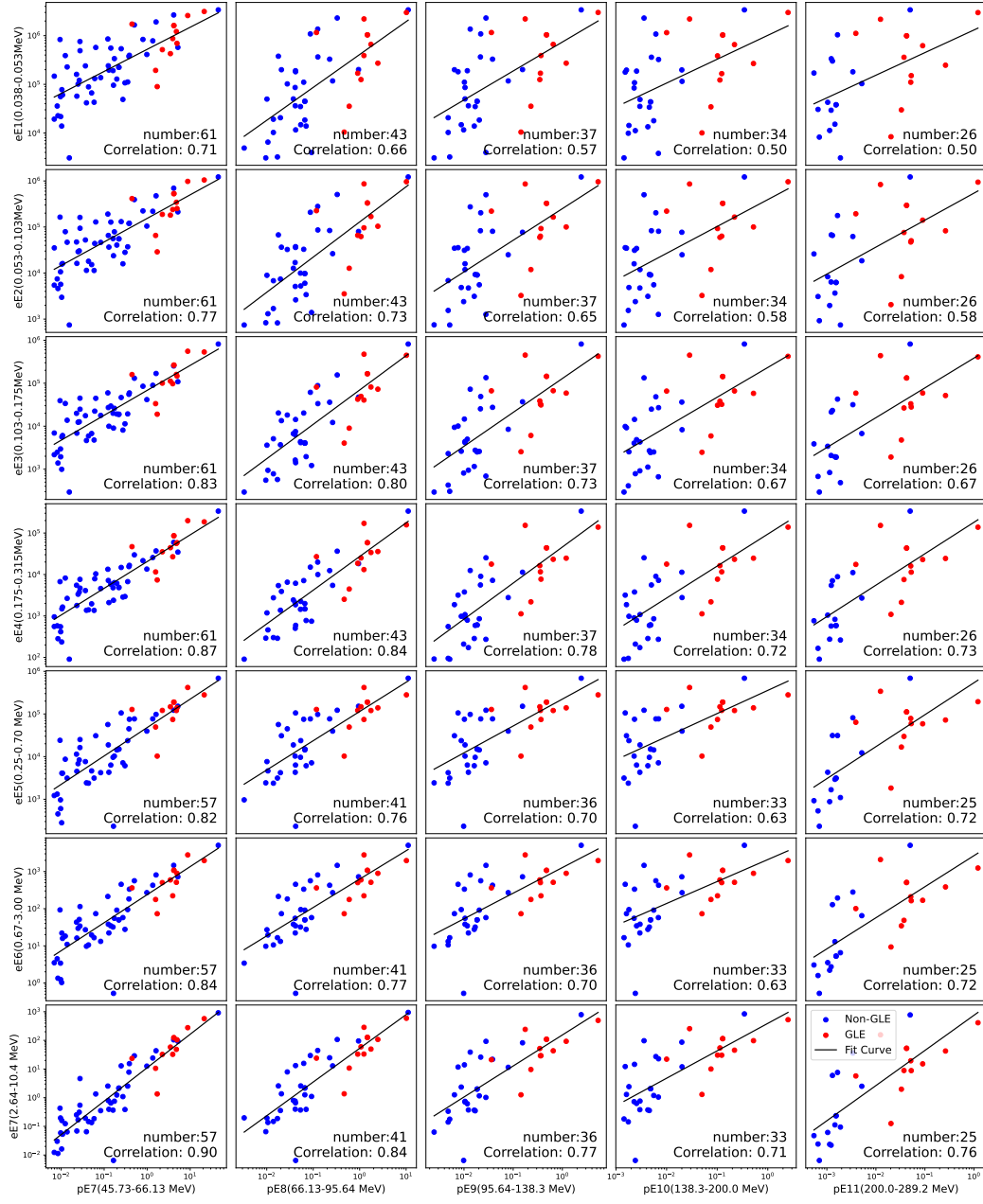


Figure A2. Scatter (log-log) plots of the peak intensities of energetic electrons versus the peak of the energetic protons in different energy channels, but with higher-energy channels for energetic protons.

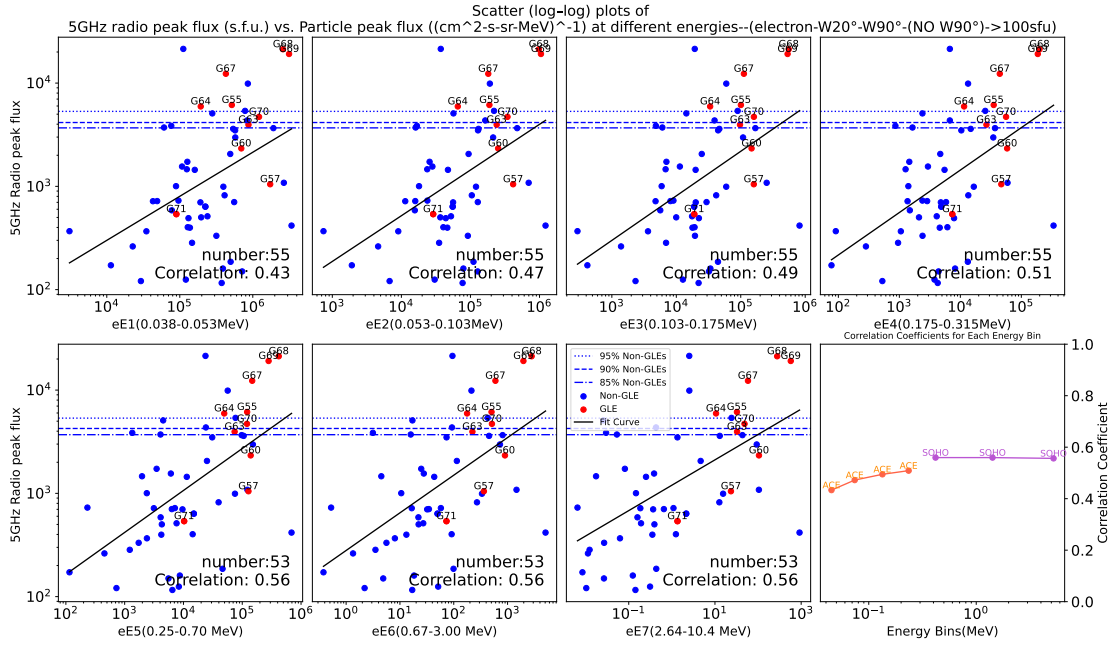


Figure A3. Scatter (log-log) plots of the 5 GHz radio peak fluxes versus the peak of the energetic electron intensities; the longitude range of the source region is limited to W20°–W90°. Different panels represent different energy channels of energetic electrons. The last panel shows the variation of the correlation coefficient with energy channel of energetic electrons. The meanings represented by the different points and curves are labeled in the eE7 panel.

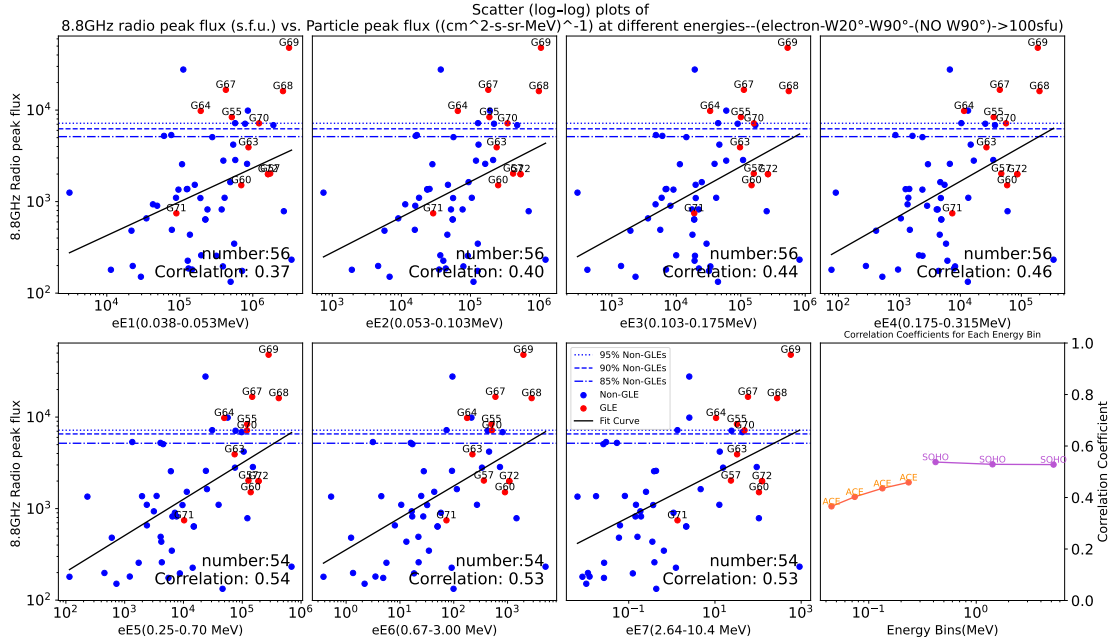
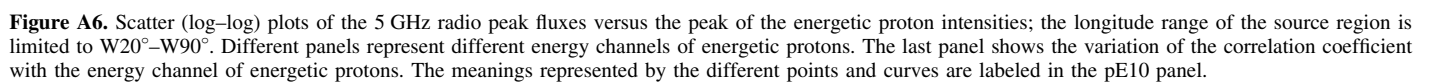
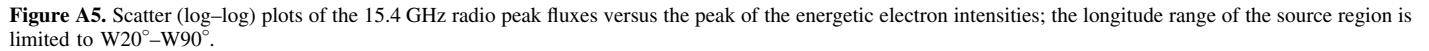


Figure A4. Scatter (log-log) plots of the 8.8 GHz radio peak fluxes versus the peak of the energetic electron intensities; the longitude range of the source region is limited to W20°–W90°.



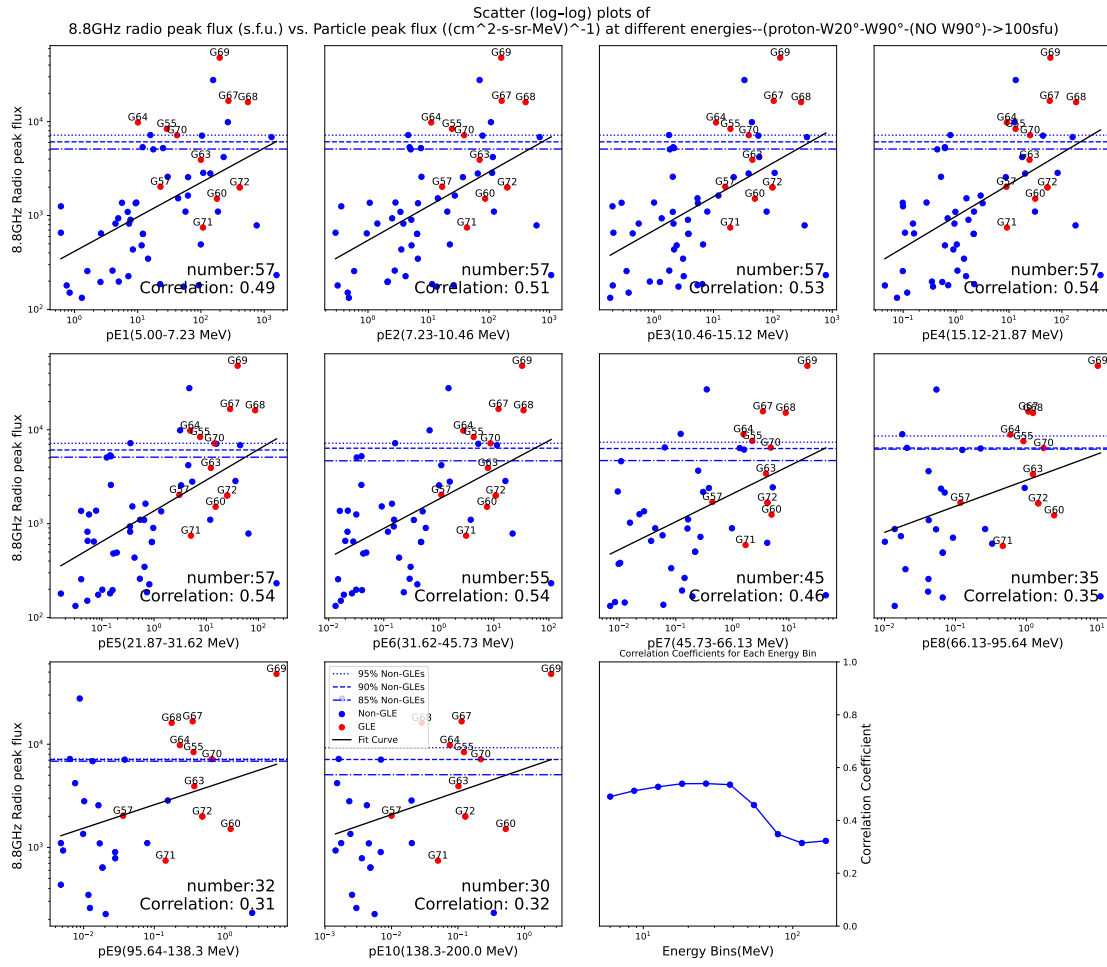


Figure A7. Scatter (log-log) plots of the 8.8 GHz radio peak fluxes versus the peak of the energetic proton intensities; the longitude range of the source region is limited to W20°–W90°.

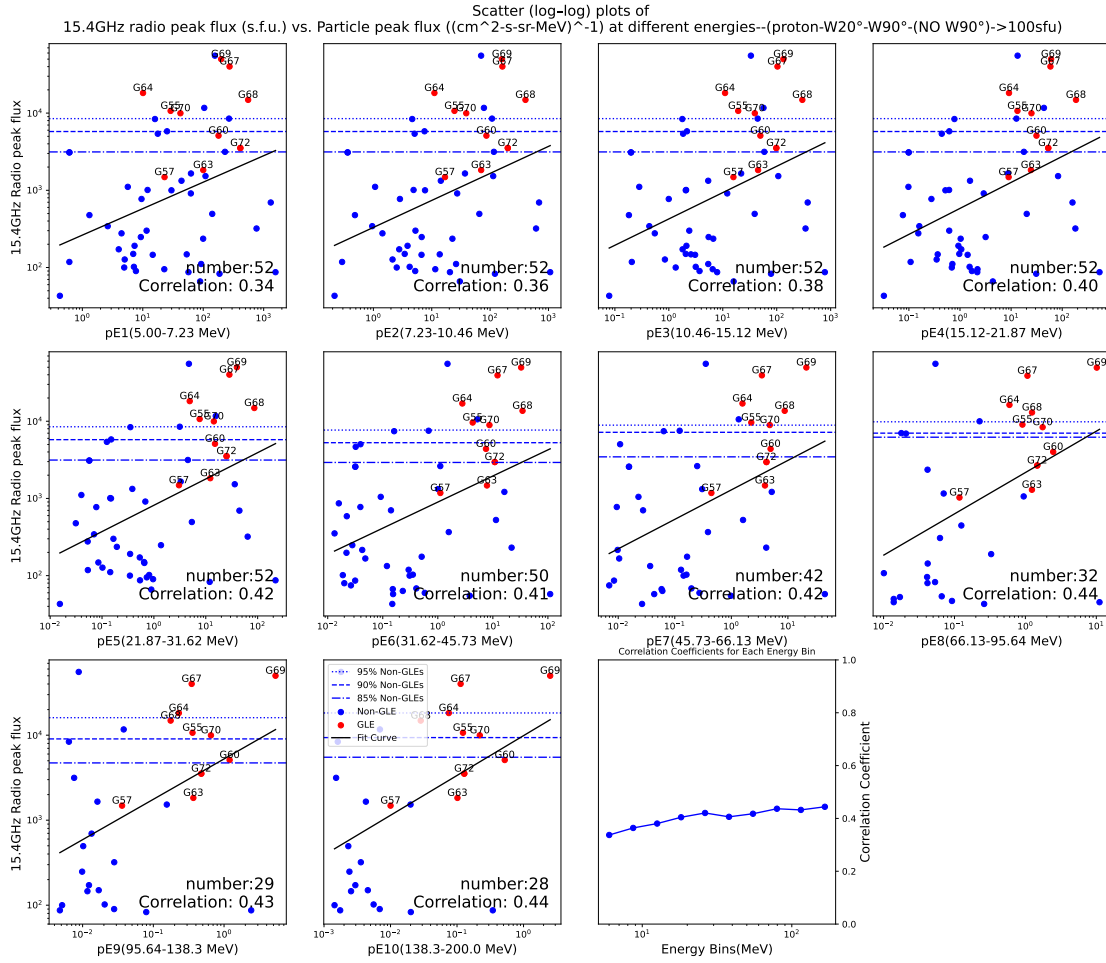


Figure A8. Scatter (log-log) plots of the 15.4 GHz radio peak fluxes versus the peak of the energetic proton intensities; the longitude range of the source region is limited to W20°-W90°.

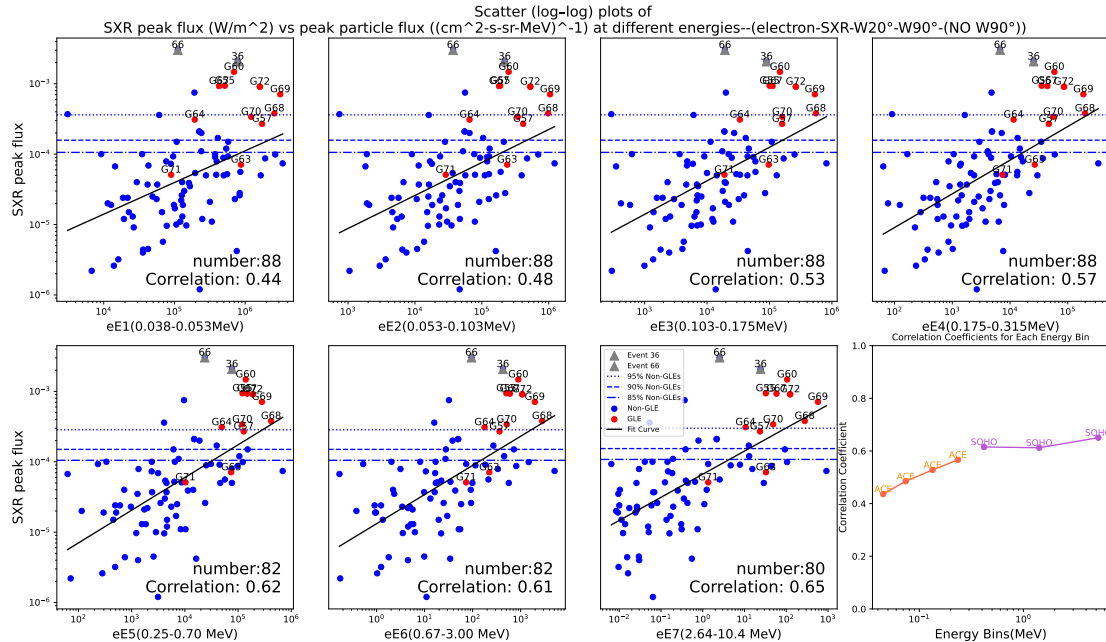


Figure A9. Scatter (log-log) plots of the peak of SXR fluxes versus the peak of the energetic electron intensities; the longitude range of the source region is limited to W20°-W90°. Different panels represent different energy channels of energetic electrons. The last panel shows the variation of the correlation coefficient with the energy channel of energetic electrons. The meanings represented by the different points and curves are labeled in the eE7 panel.

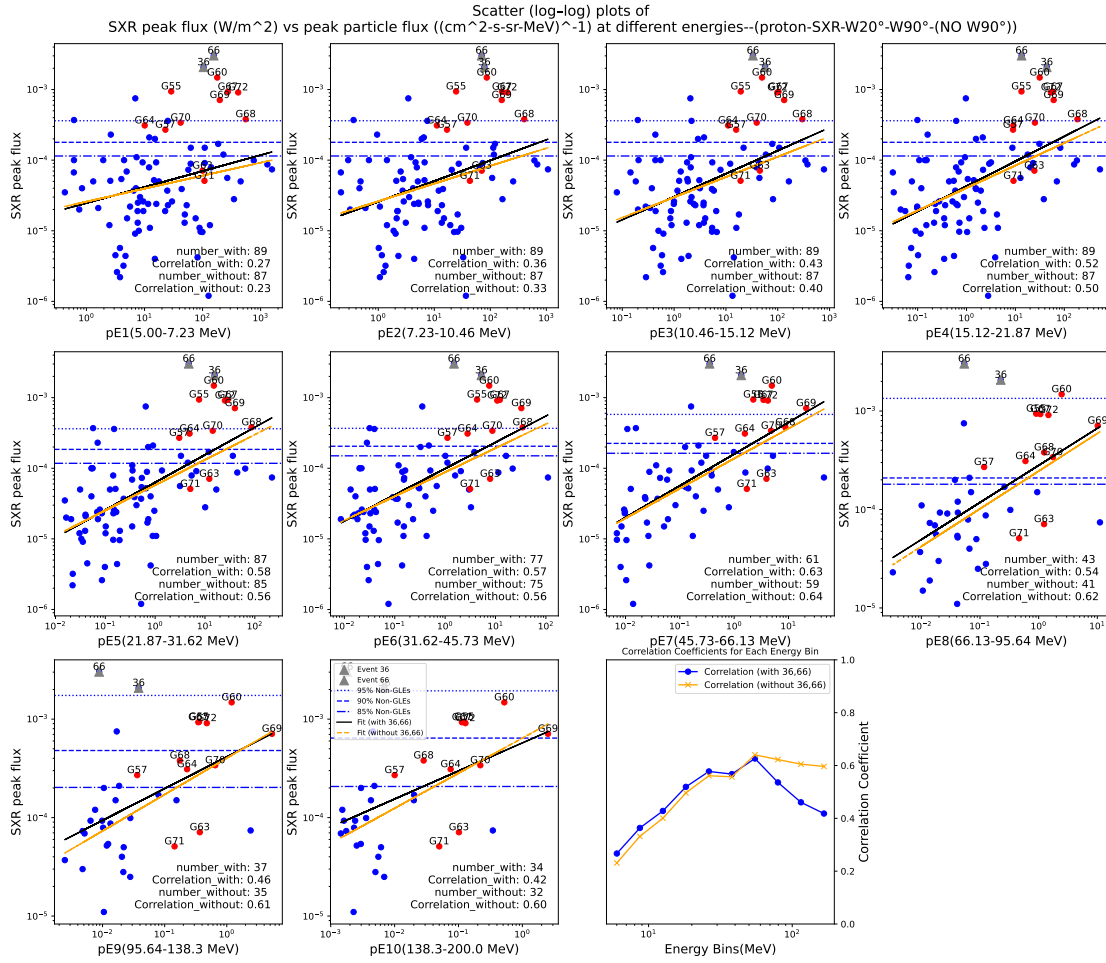


Figure A10. Scatter (log-log) plots of the peak of SXR fluxes versus the peak of the energetic proton intensities, the longitude range of the source region is limited to W20°–W90°. Different panels represent different energy channels of energetic protons. Two deviated points were marked and the data are fitted separately with and without these two points. The last panel shows the variation of the correlation coefficient with the energy points channel of energetic protons. The meanings represented by the different points and curves are labeled in the pE10 panel.

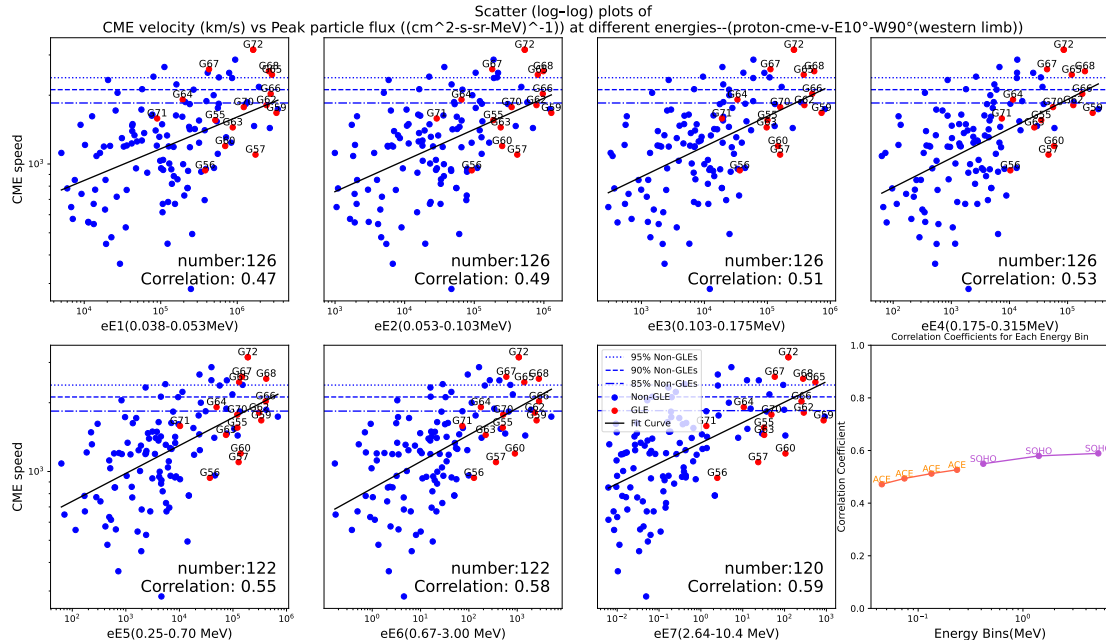


Figure A11. Scatter (log-log) plots of the CME speeds versus the peak of the energetic electron intensities; the longitude range of the source region is limited to E10°–W90°. The last panel shows the variation of the correlation coefficient with the energy channel of energetic electrons. The meanings represented by the different points and curves are labeled in the eE7 panel.

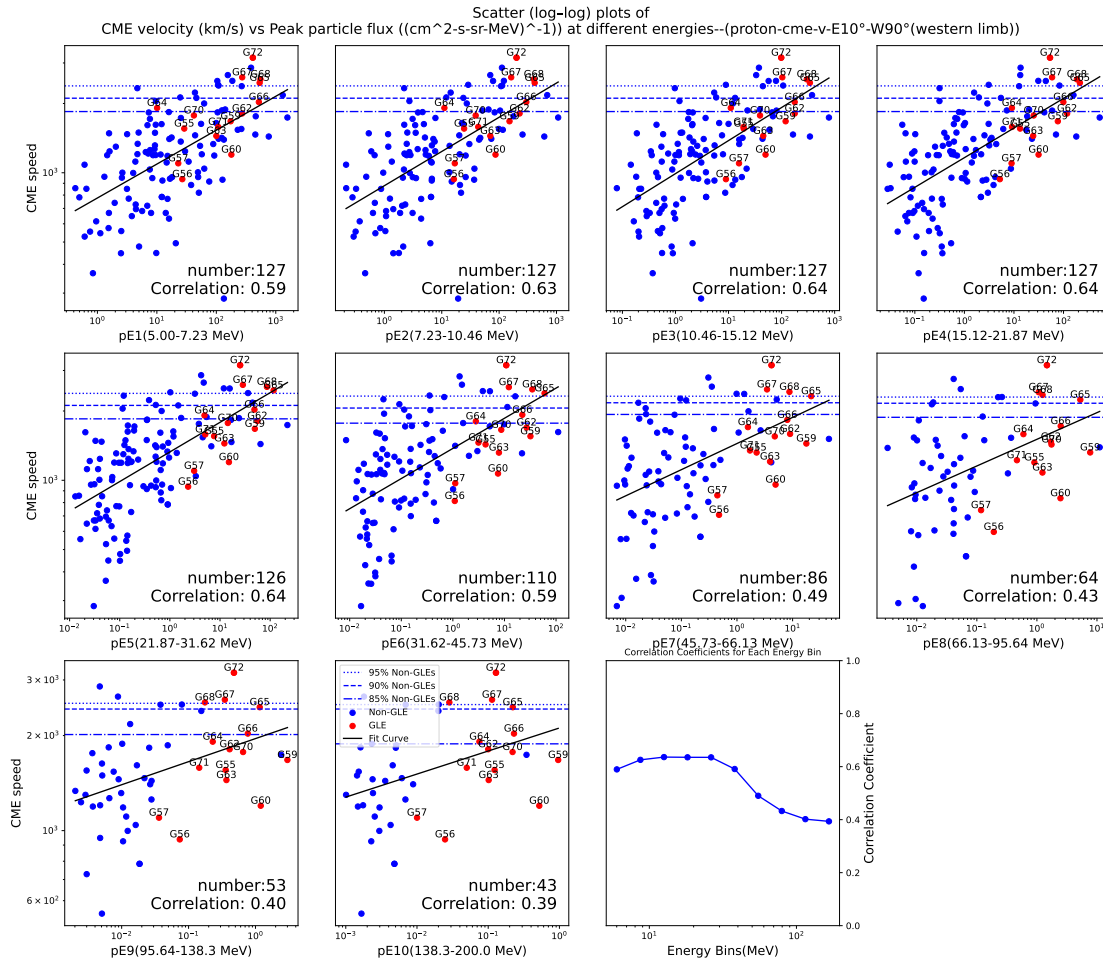


Figure A12. Scatter (log-log) plots of the CME speeds versus the peak of the energetic proton intensities; the longitude range of the source region is limited to E10°–W90°. The last panel shows the variation of the correlation coefficient with the energy channel of energetic protons. The meanings represented by the different points and curves are labeled in the pE10 panel.

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