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Quantitative analysis of CME-Flare Coupling and their influence on Solar Energetic Particle Events (1997-2024)

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Solar energetic particles (SEPs) are major contributors to space weather conditions, especially protons with energies greater than 10 MeV, because they provide a critical scientific insight about the solar interplanetary processes. the relation between SEP flux and solar drivers (i.e., coronal mass ejections (CMEs) and solar flares) is discussed. For this, data collected between 1997-2024 were used; a total of 140 events were identified during this period, out of which around 75 % SEP events are linked with Halo CMEs. SC 23 has the most SEP events (87), followed by SC 24 (40) and SC 25 (13). Also, the study of the occurrence of SEP events with CME speed reveals that approximately 52 % SEP events were associated with fast CMEs (Speed>1400 km/s), 28 % with moderate CMEs (1000–1400 km/s), and approximately 20 % with slow-speed CMEs (Speed<1000 km/s). When the relationship between SEP events and CME-associated solar flares was investigated, it was found that more than 70 % of SEP-flare-related events originated from the western solar hemisphere, 30 % originated from the eastern hemisphere, and almost equal numbers of the SEP events are associated with northern and southern hemisphere-oriented solar flares. It was also found that approximately 50 % of SEP events are associated with M-class solar flares, 29 % with X-class solar flares and only 21% with C-class solar flares. Finally, Regression and correlation analyses were conducted between the CME speeds and SEP Flux intensities, and separate fitted regression lines for each cycle indicate that they are in favour of the evident trend of a larger SEP flux with a faster CME speed and reflect a progressively stronger correlation. These findings illustrate that the CME dynamics and flare properties play a strong role in SEP production and propagation. For efficient space weather forecasting and satellite protection, it is important to monitor the real-time solar flare locations and CME parameters.

Keywords: Solar energetic particles (SEP), Coronal mass ejection (CME), Solar flares

1 Introduction

For advancements in the field of space weather exploration and for the safe expansion of humans in space, accurate forecasting and monitoring of SEP events are critical. Extensive research has been conducted in this field to understand the relationship between SEP events and solar activities. SEPs mainly originate from two phenomena (CMEs and solar flares).

A large explosion of plasma and magnetic field takes place at the Sun's Corona, which travels into interplanetary space with solar wind known as coronal mass ejection[1], and the velocity of CMEs can exceed 2000 Km/Sec. SEP events and CME are closely associated with each other[2-3]. Many researchers suggest that the intensity of the SEP event is well correlated with CME speed. Those CMEs that are directed towards the Earth, known as halo CMEs, because they appear as a halo around the Sun in coronograph images, usually halo CMEs have very high energy. When the CME speed is greater than magnetoionic speed of the surrounding plasma it produces a large scale shock wave, and these shock waves serve as the accelerators for energetic solar particles and it accelerate these particles up to the relativistic speed, the intensity of SEP events also related to the CMEs width[4] when the intensity of SEP event is greater than 10 pfu these events are known as large SEP events because, owing to their high energy, they become extremely important for nears-Earth radiation and affect magnetosphere conditions[5]. While some SEPs are associated with magnetic reconnection, mostly high-energy SEPs are associated with CME-driven shock. The intensity of SEPs depends on various CME properties such as speed, width and orientation. The interaction of CME-driven shocks[6] with preceding CMEs is also linked with higher SEP intensity. The relationship between CMEs and SEPs is crucial since CME-driven SEPs pose hazard effects on spacecraft aviation systems during polar flights[7] and SEPs can damage satellite electric components[8]. The correlation between CME speed

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and SEP flux and the hemispherical flare association of SEP events across solar cycles 23-25 was found in this paper to develop accurate space weather forecasting models. It is important to study these relationships.

Solar flares are sudden bursts of electromagnetic radiation due to the release of magnetic energy stored in the Sun's corona. Solar flares occur around sunspots when the magnetic field is very strong, and due to the magnetic reconnection, sudden eruptions of solar plasma take place, known as solar flares. SEPs are high-energy particles (protons, electrons, and heavy ions) that are accelerated by solar flares and reach Earth's atmosphere within a few minutes. During the impulsive phase of solar flares, SEPs are rapidly accelerated by magnetic reconnection[9-10]. From previous studies, it is suggested that when Solar flares accelerate SEP's, various electromagnetic bursts are produced due to interaction with the interplanetary medium. Various studies have shown that SEPs are most likely associated with western solar flares (originating in the western hemisphere of the Sun). The association of SEPs with solar flares is important to study because flares are important for real-time forecasting.

In 2009, a prewarning model ESPERTA (Empirical Solar Proton Event Real Time Alert) was developed that uses the flare location, flare size and time-integrated intensity of type III radio emission at 1 MHz to predict SEP events[11]. Various studies show the importance of an empirical model in forecasting SEP events[12]. Recent studies have improved the understanding of transportation and acceleration processes of SEPs. From these studies, it was found that the intensity of SEPs depends on CME kinematics and magnetic connectivity[13,] also, it highlights that SEP occurrence probability increases with CME Speed. A comprehensive analysis presented in Universe 2020 examine relation between CME dynamics[14], solar eruption and SEP intensity for various solar cycles, these studies shows that SEP intensity influence by multiple factors like, shock strength, CME width and interplanetary magnetic field configurations, more advance model provide new insights about SEP acceleration and transportation, researchers develop a data driven particle transportation model which couples CME shock with magnetohydrodynamics simulations of coronal and hemispheric magnetic field[15]. In addition to this, observational studies show asymmetries in SEP detection related to hemispheric magnetic correlation. It reported that SEP intensity shows a strong longitudinal dependence, mainly due to particle transport along the Parker spirals[16].

2 Data Analysis and Methods

SEP events with energies >10 MeV and proton density >10puf (Gopalswamy *et al*., 2003) observed by GOES (Geostationary Operational Environmental satellite) for SC 23, 24 and 25 are used for the study. The GOES use geosynchronous satellites, which are a fundamental component of weather forecasting and monitoring in the United States it facilitates meteorological research, storm tracking and weather forecasting. The SEPs (Energy>10 MeV, Proton density >10puf) are chosen because it has a significant impact on space weather conditions. Although the total number of SEP events is large during this period, applying the above intensity threshold, only those events with a strong geomagnetic impact are included for analysis. Using the intensity criteria, a total of 140 SEP events is observed. The data is taken from the CWE website (http://cdaw.gsfc.nasa.gov/CME_list/sepe/), which includes CME speed and Solar-Flare location connected with SEP events.

Regression and correlation analysis is performed between CME speed and SEP flux for all the solar cycles 23, 24, and 25. Also, use statistical techniques to compare parameters and their possible relationship. A complete table containing all the SEP flux and CME associated solar flare data is given in the Table 1, in which the first and second columns contain onset date and SEP flux respectively, column 3 represents the associated CME speed and column 4 represents the solar flares location and the class of associated CMEs associated with solar flares.

3 Results and Discussion

From the study of SEP events (from 1997- 2024) a total of 140 events were identified, approximately 75 % of which were associated with halo CMEs. The year-wise distribution of SEP events is shown in (Fig. 1) , which reveals that the maximum number of SEP events takes place in SC 23 (87 events) than SC 24 (40 events) and in SC 25 (13 events), and during the starting and ending phase of the SC, very few or no SEP events take place, whereas during solar maxima the number of SEP events is high for all solar cycles.

Table1 — Data table

Max Time	EvnMax	Speed	Location	Class
04-11-1997	72	785	S14W33	X2.1/2B
07-11-1997	495	1556	S18W63	X9.4/2B
21-04-1998	1700	1863	S22W90	M1.4/--
02-05-1998	146	938	S15W15	X1.1/3B
06-05-1998	207	1099	S11W65	X2.7/1N
09-05-1998	11	2331	S14W89	M7.7/--
26-08-1998	665	----	N35E09	X1.0/3B
25-09-1998	44	----	N18E09	M7.1/3B
01-10-1998	1160	----	N23W81	M2.8/2N
14-11-1998	314	----	N28W90	C1.3/--
23-01-1999	14	----	N27E90	M5.2/--
05-05-1999	14	1584	N15E32	M4.4/2N
04-06-1999	64	2230	N17W69	M3.9/2B
05-04-2000	55	1188	N16W66	C9.7/2F
08-06-2000	84	1119	N20E18	X2.3/--
10-06-2000	46	1108	N22W38	M5.2/3B
15-07-2000	24000	1674	N22W07	X5.7/3B
23-07-2000	17	1230	N14W56	M3.7/2N
13-09-2000	321	1550	S19W06	M1.0/2N
16-10-2000	15	1336	N03W90	M2.5/--
26-10-2000	15	770	N09W63	C4.0/--
09-11-2000	14800	1738	N10W77	M7.4/3F
24-11-2000	94	1245	N22W07	X2.3/2B
29-01-2001	49	916	S04W59	M1.5/1N
30-03-2001	35	942	N20W19	X1.7/1F
03-04-2001	1110	2505	N19W72	X20./--
11-04-2001	355	2411	S23W09	X2.3/3B
12-04-2001	51	1184	S19W43	X2.0/--
15-04-2001	951	1199	S20W85	X14./2B
28-04-2001	57	1006	N20W05	M1.7/--
15-09-2001	12	478	S21W49	M1.5/1N
25-09-2001	12900	2402	S16E23	X2.6/--
02-10-2001	2360	1405	S24W81	M9.1/--
19-10-2001	12	901	N15W29	X1.6/2B
22-10-2001	24	1336	S21E18	M6.7/2N
06-11-2001	31700	1810	N06W18	X1.0/3B
20-11-2001	34	1379	S13E42	M2.8/1N
23-11-2001	25	1443	S25W67	M3.8/2B
23-11-2001	4800	1437	S17W36	M9.9/--
26-12-2001	780	1446	N08W54	M7.1/1B
29-12-2001	76	2216	S26E90	X3.4/--
15-01-2002	15	1492	S28W83	M4.4/--
20-02-2002	13	952	N12W72	M5.1/1N
17-03-2002	13	957	S08W03	M2.2/1F
19-03-2002	53	989	S10W30	M1.0/--
23-03-2002	16	1750	S09W90	M1.6/--
17-04-2002	24	1240	S14W34	M2.6/2N
21-04-2002	2520	2393	S14W84	X1.5/1F
23-05-2002	820	1557	S30W34	C5.0/--
07-07-2002	23	1423	S19W90	M1.0/--
17-07-2002	234	1300	N19W01	M1.8/--
23-07-2002	28	1941	S13E90	X3.3/--
14-08-2002	26	1309	N09W54	M2.3/1N
22-08-2002	36	998	S07W62	M5.4/2B
24-08-2002	317	1913	S02W81	X3.1/1F
07-09-2002	208	1748	N09E28	C5.2/SF
10-11-2002	404	1838	S12W29	M4.6/2B

(*Contd.*)

Table1 — Data table (*Contd.*)

Max Time	EvnMax	Speed	Location	Class
29-05-2003	121	1366	S07W20	X3.6/--
31-05-2003	27	1835	S07W65	M9.3/2B
19-06-2003	24	1813	S07E55	M6.8/--
26-10-2003	466	1537	N02W38	X1.2/1N
29-10-2003	29500	2459	S16E08	X17./--
30-10-2003	3300	2029	S15W02	X10./2B
03-11-2003	1570	2598	S14W56	X8.3/2B
05-11-2003	353	2657	S19W83	X28./3B
22-11-2003	14	669	N01W08	M9.6/2B
02-12-2003	89	1393	S11W90	C8.0/--
11-04-2004	35	1645	S14W47	C9.6/1F
26-07-2004	2090	1333	N08W33	M1.1/1F
14-09-2004	273	1328	N03E49	M4.8/2N
20-09-2004	57	----	N03W58	M1.9/--
08-11-2004	495	1759	N09W17	X2.0/--
09-11-2004	82	2000	N08W51	M8.9/2N
10-11-2004	424	3387	N09W49	X2.5/3B
16-01-2005	365	2861	N15W05	X2.6/--
17-01-2005	5040	2547	N15W25	X3.8/--
20-01-2005	1860	882	N14W61	X7.1/2B
15-05-2005	3140	1689	N12E11	M8.0/2B
17-06-2005	44	----	N08W90	M4.0/SF
15-07-2005	134	2115	N11W90	X1.2/--
29-07-2005	41	1787	N11E90	M3.7/--
23-08-2005	337	2378	S13W65	M5.6/1N
11-09-2005	1880	----	S11E77	X17./3B
14-09-2005	183	1866	S09E10	X1.5/2B
07-12-2006	1980	----	S05E64	X6.5/3B
13-12-2006	698	1774	S06W23	X3.4/4B
15-12-2006	215	1042	S06W46	X1.5/--
14-08-2010	14		N17W52	C4.4/--
08-03-2011	50		N31W53	M3.7/--
07-06-2011	72		S21W54	M2.5/2N
05-08-2011	96		N19W36	M9.3/2B
09-08-2011	26		N17W69	X6.9/2B
26-09-2011	35		N09E89	X1.4/--
27-11-2011	80		N17W49	C1.2/--
24-01-2012	6310		N28W21	M8.7/--
28-01-2012	795	2508	N27W71	X1.7/1F
08-03-2012	6530	2684	N17E27	X5.4/--
13-03-2012	469	1884	N17W66	M7.9/--
17-05-2012	255	1582	N11W76	M5.1/1F
16-06-2012	15	987	S17E06	M1.9/1N
07-07-2012	25	1828	S13W59	X1.1/--
09-07-2012	19	1497	S17W74	M6.9/1N
12-07-2012	96	885	S15W01	X1.4/--
18-07-2012	136	958	S28W65	C9.9/1F
19-07-2012	80	1631	S13W88	M7.7/--
02-09-2012	60	1442	S25E59	C8.1/2F
28-09-2012	28	947	N06W34	C3.7/1F
17-03-2013	16	1063	N11E12	M1.1/1F
11-04-2013	114	861	N09E12	M6.5/3B
17-05-2013	42	1366	N12E64	X1.2/2N
23-05-2013	1660	1466	N15W70	M5.0/--
24-06-2013	14	1900	S16E73	M2.9/1F
30-09-2013	182	1179	N17W29	C1.3/--
06-01-2014	42	1402	S15W112	C2.1/--
09-01-2014	1026	1830	S15W11	X1.2/2N

(*Contd.*)

Table1 — Data table (*Contd.*)

Max Time	EvnMax	Speed	Location	Class
20-02-2014	22	948	S15W73	M3.0/SN
26-02-2014	24	2147	S12E82	X4.9/2B
19-04-2014	58	1203	S20W34	M7.3/--
12-09-2014	126	1267	N14E02	X1.6/2B
18-06-2015	17	1714	S16W81	M1.2/--
22-06-2015	1066	1366	N12E16	M2.6/--
27-06-2015	22	1627	N09W42	M7.9/3B
02-01-2016	22	1730	S25W82	M2.3/--
14-07-2017	22	1200	S06W29	M2.4/1N
05-09-2017	210	1418	S10W12	M5.5/--
07-09-2017	844	1571	S08W33	X9.3/--
11-09-2017	1490	3163	S09W92	X8.2/--
29-05-2021	16	971	N21W63	C9.4/1F
29-10-2021	29	1519	S28W01	X1.0/--
20-01-2022	23	1431	N08W68	M5.5/1F
28-03-2022	19	702	N14W04	M4.0/--
31-03-2022	11	641	N13W31	X1.3/--
02-04-2022	32	1433	N12W68	M3.9/--
27-08-2022	24	1284	S19W58	M4.8/SF
25-02-2023	59	1170	N26W43	M6.3/--
10-05-2023	83	1209	N13W31	M4.2/1B
18-07-2023	620	1385	S26W78	M5.7/--
29-07-2023	154	1896	N23W105	M4.1/--
05-08-2023	19	1000	N07W63	M1.6/--
09-08-2023	48	1851	N14W103	X1.5/--

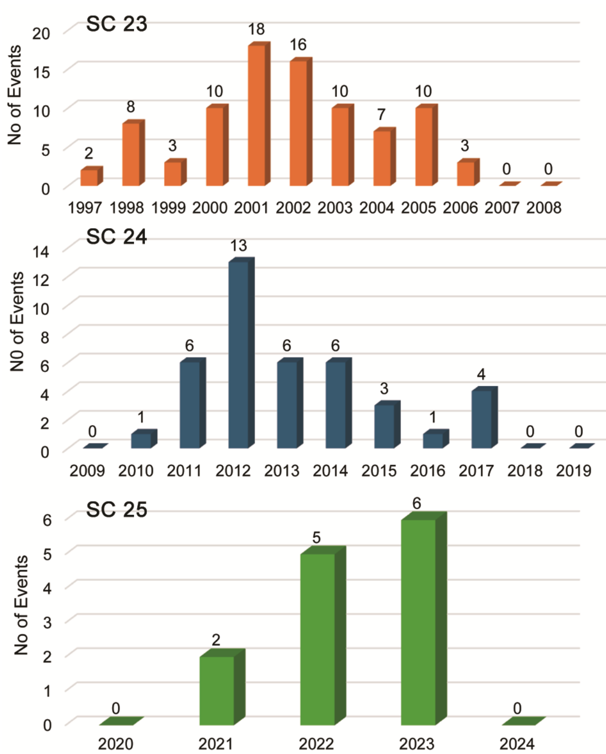

Fig. 1 — Yearly distribution of SEPs for SC 23, 24 and 25

3.1 CME Speed and Associated SEP Events

Coronal mass ejection and SEP events are closely related phenomena; CMEs act as an accelerator for SEPs. The intensity of SEPs also depends on the CME speed; mostly, the intense SEPs are associated with fast CMEs. When multiple CMEs connect or merge, they create a complex magnetic structure that leads to prolonged intense SEP events[17]. The study investigated SEP events associated with CMEs and their speed. For the study, CMEs are divided into groups as fast CMEs (V>1400 Km/s), moderate CMEs (1000<v<1400 km/sec) and slow CMEs (V<600 km/sec). The study found that the occurrence probability of SEP events increases with the CME speed (Fig 2). SC 23 has the highest number of SEP events and the average CME speed is (1350 km/sec) SC 24 average speed (1000 km/sec) and for solar cycle 25 it is 850 km/sec, also from Fig 2 it found that for SC 23 approximately 52 % of SEP events are associated with fast CMEs, 21% with moderate CMEs and 27 % with slow CMEs and for SC 24 57% SEPs are associated with fast CMEs 25 % with Moderated CMEs and 18 % with slow CEMs. Similarly, for SC 25, 46 % of the SEPs are linked to fast CMEs, 39 % with moderated CMEs and 15 % are associated with slow CMEs.

3.2 CME Speed and SEP Flux Correlation

The relationship between the CME speed and SEP flux for Solar Cycles 23, 24 and 25 reveals a weak positive linear correlation between these parameters (Fig 3). The regression equation for SC 23 is $y =$

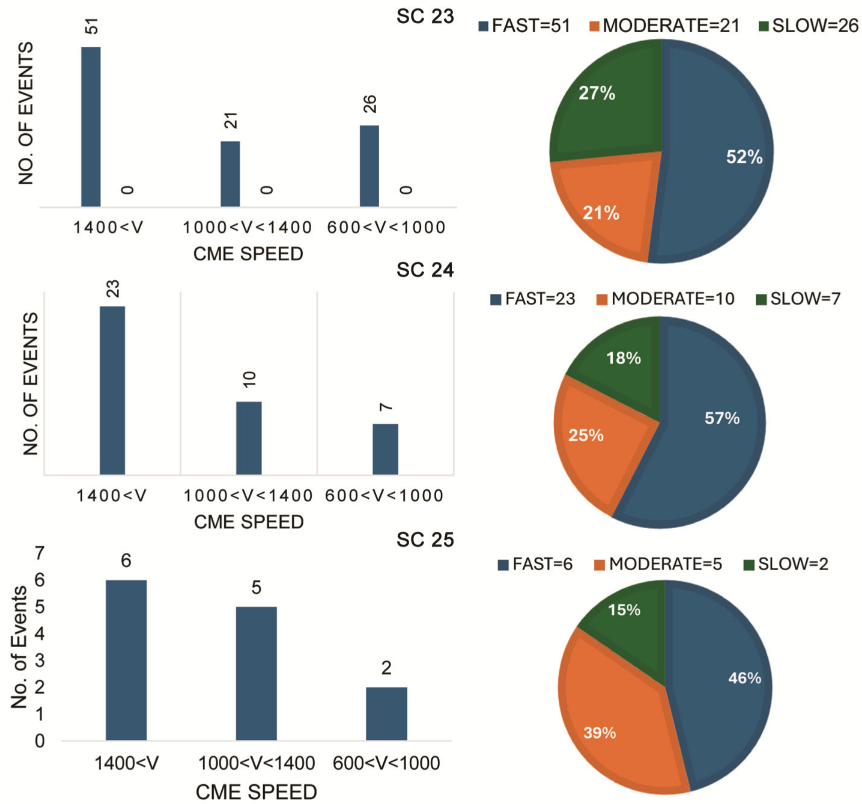

Fig. 2 — Solar energetic particles associated with the CME speed for SCs 23,24 and 25

$2.2722x - 1659.7$, with a coefficient of determination of $R^2 = 0.0489$, which means that approximately 4.9% of the variation in SEP flux can be explained by the CME speed alone. A similar trend appears in the third plot. The regression equation here is $y = 0.0999x - 39.323$ and $R^2 = 0.0538$, again indicating a very weak relationship. Modern SEP forecasting models based on a data-driven approach (Lei Cheng *et al.*, 2025) show that SEP acceleration in the inner heliosphere plays an important role in shaping the final SEP flux. So, the weak correlation between CME and SEP flux confirms the influence of additional factors like CME shock evolution, magnetic field connectivity and interplanetary transport process. The scatter of data points, especially in SC 23, is significant. Several high SEP flux outliers suggest that extreme events such as ground-level enhancements (GLEs) may have occurred. These extreme values impact the regression fit but limit the use of the CME speed as the only predictor of the SEP intensity.

3.3 CME-Associated Solar Flares and SEP Events

When the solar flare associated CME and SEP events were analysed, it was found that the maximum number of SEP events for all the SCs are associated with the western solar flare (more than 70%) and only few SEP events are associated to Eastern solar flare (Fig. 4), possibly because the Solar flares which originate from western hemisphere of the Sun connect with the Earth's magnetic field more difference efficiently, so the particles that accelerate during this period can easily travel and arrive the Earth's with higher intensity because they suffer very little scattering. Whereas almost equal percentages of SEP events are associated with northern and southern-originated solar flares. Based on the study, it can be concluded that western solar flares are most prominent in producing SEPs. The study also investigated SEP events associated with different classes of solar flares, and it found that most of the SEP events are linked with M-class solar flares. Further most of the SEP events associated with M-class solar flares are linked with fast CMEs (65 %), and a similar pattern is observed for X and C-class solar Flares (Fig. 5).

3.4 Ground Level Enhancement Events (GLEs)

GLE represents the most extreme solar energetic events that reach Earth's atmosphere and are detected by neutron monitor stations. These events typically

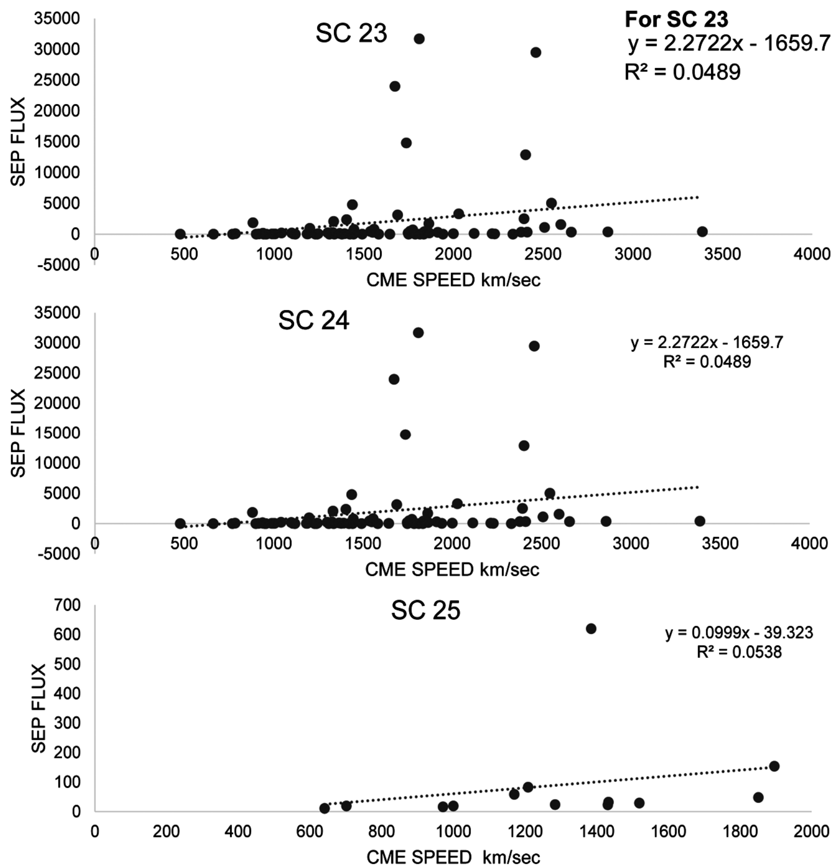

Fig. 3 — Scattering Curve between SEP flux and CME speed for SC 23, 24 and 25

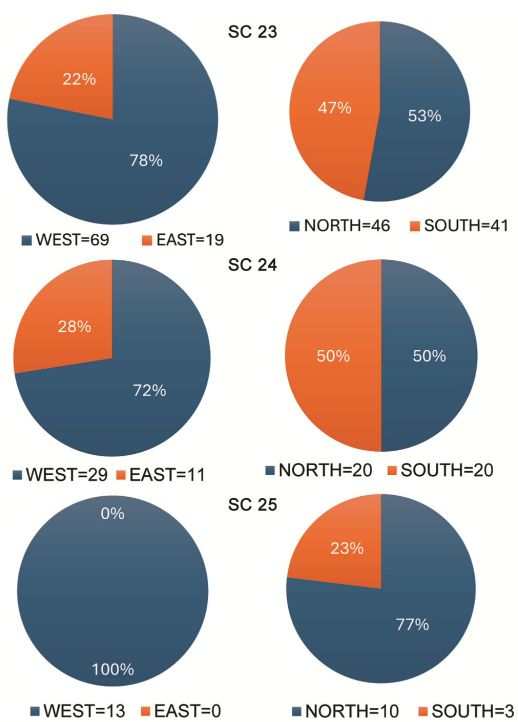

Fig 4 — SEP events distribution with solar flare location

occur when CME-driven shocks accelerate the charge particles. Due to the extreme energy, GLEs appear as outliers in SEP data. Studies show that GLE events require specific conditions like high CME speed, strong shock formation, and favourable magnetic connectivity between the Sun and Earth. For the given data set, some high-flux SEP events may occurs correspond to GLE-like conditions.

Around 16 GLE events are detected during solar cycle 23, all these linked with fast CMEs (around 2000 km/s) and X-class solar flares. The weakest GLE from this cycle was M7.1 with a CME velocity of 1200 km/s. While there was only one actual GLE event in cycle 24 (Sep 2017), numerous flares did not result in a GLE, thus indicating that unique circumstances are needed for the generation of GLEs. The first GLE in cycle 25 (GLE 74 on May 11, 2024) was produced from an X5.8 solar flare produced from active region 13664, and the CME was 1614 km/s; the rigidity was ~2.4 GV, and type II/III/IV radio bursts were present and identified as having been created from the strong shock wave of a fast-moving CME[18]

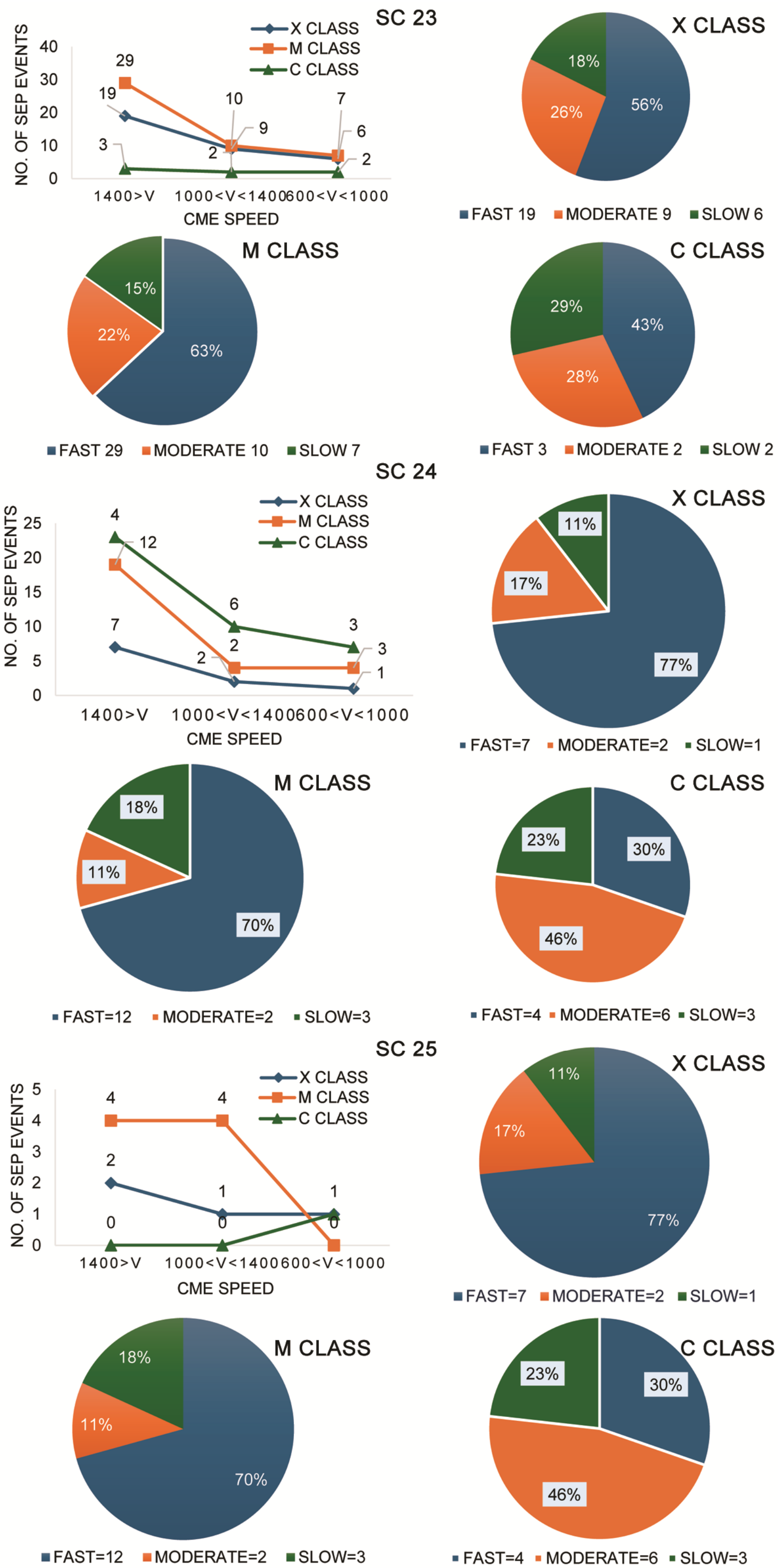

Fig. 5 — Distribution of SEP events with CME speed and solar flare class

widely considered as one of the most significant high-energy particle events. This event highlights the importance of considering additional parameters beyond CME speed for the acceleration of SEPs.

4 Conclusion

A total of 140 SEP events was identified between 1997 and 2024. Approximately 75 % of these SEP events linked to halo CMEs show a strong connection between large CME structures and the production of SEP events. Solar cycle 23 had the highest number of SEP events, i.e. 87, followed by SC 24 with 40 and SC 25 with 13. SEP events mainly occurred during solar maxima, with little activity at the start and end of each solar cycle.

The CME speed is a key factor affecting the intensity and occurrence of SEP events.SC 23 had the highest average CME speed of approximately 1350 km/s, followed by SC 24 at approximately 1000 km/s and SC 25 at approximately 850 km/s. for SC 23: 52 %, SC 24: 57 % and SC 25: 46 % SEP events linked to fast CMEs. This shows that higher CME speeds increase the likelihood of SEP occurrence. A weak positive linear correlation was observed between CME speed and SEP flux. The low R^2 values suggest that the CME speed alone accounts for less than 5 % of the variation in the SEP flux, which confirms that additional parameters such as CME width, flare energy, magnetic connectivity and particle acceleration in the inner heliosphere also play an important role in determining SEP Flux. More than 70 % of SEP events were connected to solar flares in the western hemisphere. This is mainly due to magnetic connectivity between Earth and western solar longitudes, which allows for more efficient transport of accelerated particles.

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