DOI: 10.31401/WS.2025.proc.19

Proceedings of
the Seventeenth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere"
Primorsko, Bulgaria, June, 2025

Catalog of Solar Energetic Particles Events Registered by Liulin-MO Dosimeter at Martian Orbit during the Current Solar Cycle

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Abstract

During the ascending and maximum phases of the current 25th solar cycle the Liulin-MO dosimeter aboard Trace Gas Orbiter registered a considerable number of solar energetic particle events. The catalog presented here lists the 27 events observed till June 2025 summarising the main characteristic of each event – its dosimetric parameters, the relation of the event with a coronal mass ejection and a flare in the sun, Erath's effect.

Keywords: Solar energetic particles, dose rate and flux, Mars.

1. Introduction

Solar energetic particles (SEP) are injected into the heliosphere following energetic solar eruptions. While the galactic cosmic rays (GCR) represent an unceasing flux through the heliosphere, though with low intensity but with energies up to 10^{20} eV/nucleon, SEP are randomly distributed events. Two different acceleration mechanisms are believed to be most responsible for accelerating SEPs: magnetic reconnection during solar flares and shock acceleration at coronal mass ejection (CME)-driven shocks [Reames 1999; Kallenrode, 2003]. The flares themselves release impulsive events while the CME shocks produce gradual events [Cliver and Cane, 2002]. High fluxes of charged particles (mostly protons, some helium and heavier ions) with energies up to several GeV and intensity up to 10^4 $cm^{-2}s^{-1}sr^{-1}$ are emitted. The time profile of a typical SEP event starts with a rapid increase in flux, reaching a peak in minutes to hours. Although SEPs are more likely to occur around solar maximum, such events are at present unpredictable with regard to their times of occurrence and it cannot be assumed that SEPs will not occur under solar minimum.

The Liulin-MO dosimeter [Semkova et al., 2018] is a module of the Fine Resolution Epithermal Neutron Detector (FREND) instrument [Mitrofanov et al., 2018] aboard Trace Gas Orbiter (TGO). TGO was launched in March 2016; reached Mars in late September 2016 and till March 2017 orbited the planet at high elliptic orbits. After a year of aerobraking TGO was inserted into a Mars circular orbit with 400 km altitude (varying within ±25 km in every orbital pass), 74^0 inclination, ~ 2 hours orbit period.

Liulin-MO has provided and is providing in-situ measurements of the radiation environment during the TGO interplanetary travel and at Martian orbit. During the declining phase and the minimum of the 24th solar cycle, from 2016 till June 2021 only GCR were registered. With the increasing solar activity in the 25th solar cycle registration of SEP events at Martian orbit started. From July 2021 to the end of June 2025 twenty seven SEP events were observed. Different characteristics of the SEPs registered till October 2024 were discussed in [Semkova et al. 2022; Semkova et al., 2023; Semkova et al., 2024; Semkova et al., 2025].

The aim of the present work is to summarise in a manner suitable for easy perception the characteristics of all 27 SEP events registered till June 2025 at Mars orbit – their dosimetric parameters, the relation of each event with a coronal mass ejection and a flare in the sun, a possible effects on Earth.

2. Catalog of Solar Energetic Particles Events at Martian Orbit during the Current Solar Cycle

2.1. Complementary tools

To relate the observed SEPs at Martian orbit to solar phenomena, we use the information provided in the CME lists in the on-line catalogues: Solar Eruptive Event Detection System (SEEDS, http://spaceweather.gmu.edu/seeds/) and the CDAW catalog (https://cdaw.gsfc.nasa.gov/CME_list/), [Gopalswamy et al., 2009]. SEEDS uses images from the Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO) [Brueckner et al., 1995] C2 telescope and the outer coronagraph (COR2) of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) [Howard et al., 2002] on board the Solar Terrestrial Relations Observatory (STEREO). The CDAW catalogue uses images from SOHO/LASCO C2 and C3 telescopes.

We have used data on solar flares provided by the data center for the Spectrometer and Telescope for Imaging X-rays (STIX) on board the Solar Orbiter [Muller et al., 2020; Xiao et al,, 2023], https://datacenter.stix.i4ds.net/view/flares/list, github.com/hayesla/stix_flarelist_science.

The following data on SEP events have also been used:

- In Earth vicinity – from the NOAA Space Weather Prediction Center catalog of the Solar Proton Events Affecting the Earth Environment (https://www.ngdc.noaa.gov/stp/space-weather/interplanetary-data/solar-proton-events/SEP%20page%20code.html) and Catalogues of Solar Proton Events in the 20-25 Cycles of Solar Activity on the space weather website of the SINP MSU (https://swx.sinp.msu.ru/apps/sep_events_cat/);

To present the mutual longitudinal location of Mars and the spacecraft carrying the coronagraphs, we use the Solar-MACH on-line plotter https://solar-mach.github.io/ [Gieseler, et al., 2022]. The plots are in the Stonyhurst System of heliographic coordinates and they present the projections in the Sun equatorial plane during the discussed events. Since the propagation of high-energy charged particles in interplanetary space is controlled by the interplanetary magnetic field, we used the field lines (FL) modeled by that tool and connecting Mars and the satellites carrying the coronagraphs SOHO, STEREO A and Solar Orbiter (SolO) spacecraft to the Sun.

The GOES-18 [Kress et al., 2020] proton fluxes data used in the paper for the comparison with the Liulin-MO fluxes is downloaded from the space weather website of the Institute of Nuclear Physics of Moscow State University (section "INSTRUMENTS") https://swx.sinp.msu.ru/tools/ida.php?gcm=1. The data on GOES proton fluxes in $cm^{-2}s^{-1}sr^{-1}$ are multiplied by 2π to compare with the Liulin-MO fluxes in $cm^{-2}s^{-1}$. In the analysis of the GOES data, the paper also uses plots from NOAA/NWS Space Weather Prediction Center at https://www.swpc.noaa.gov/products/goes-proton-flux and from Space Weather Data Portal (https://lasp.colorado.edu/space-weather-portal) of the University of Colorado Boulder and Space Weather Technology, Research, and Education Center, "SWx TREC Space Weather Data Portal", Laboratory for Atmospheric and Space Physics, 2019, https://doi.org/10.25980/NMFX-XX89.

2.2. Description of the Catalog

The catalog is presented in Table 1 below. From left to right:

- *First column*: Start time of the observed SEP event in Liulin-MO data;
- *Second column*: Approximate duration of the SEP event;

- *Third column*: Total dose from background GCR and SEP (in Si) during the event /total dose from SEP (in Si) during the event;
- *Forth column*: Maximum dose rate from GCR and SEP measured during the event;
- *Fifth column*: Maximum flux from GCR and SEP measured during the event;
- *Sixth column*: Drawing of the mutual location of Mars (TGO) and the three spacecraft carrying the coronagraphs (the location of the SOHO/LASCO spacecraft is annotated as 'Earth');
- *Seventh column*: Time profiles of Liulin-MO and GOES flux increase during the event.
- *Eighth column*: Details of CME related to the corresponding event-type, onset time, an appropriate image of LASCO C2 or STEREO A Cor2. Annotation:
  ** According to CDAW C2+C3 catalog*
  *** According to SEEDS LASCO C2 catalog*
  **** According to SEEDS SECCHI COR2 catalog*
- *Ninth column*: Details of X ray flare related to the corresponding event, observing satellite and approximate peak time of the flare and location. Annotation:
  + NOAA catalogue
  ++ SINP MSU catalogue
  +++ Solar Orbiter STIX catalog

3. References

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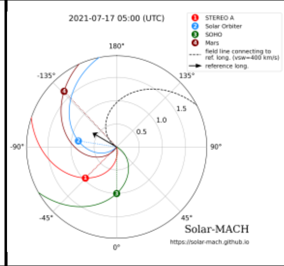
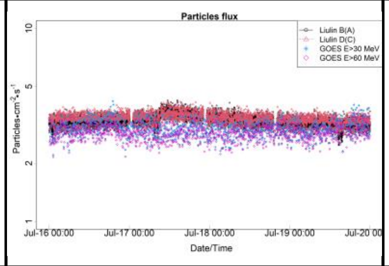
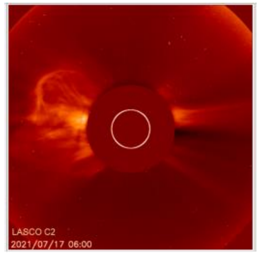
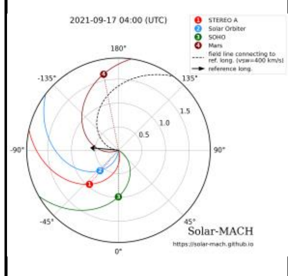
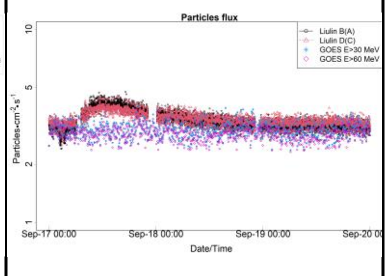
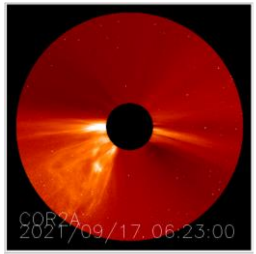
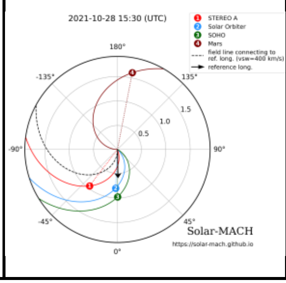
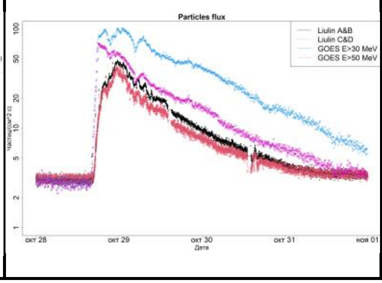
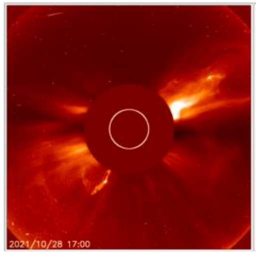
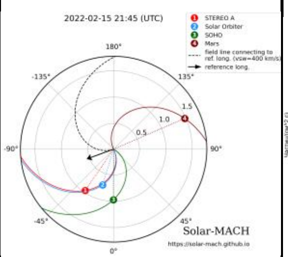
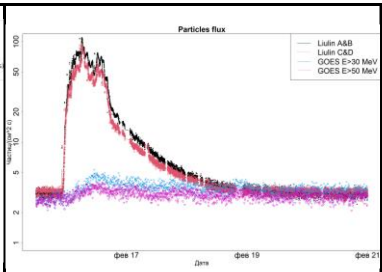
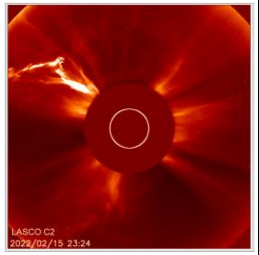
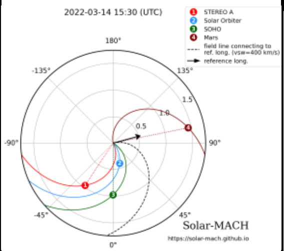
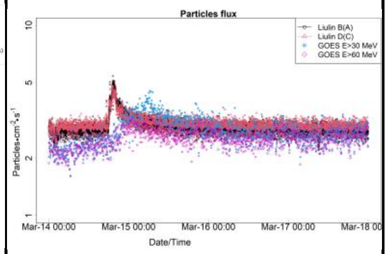
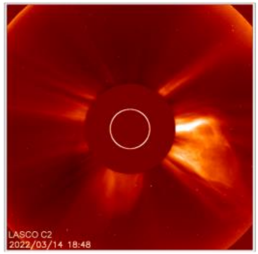
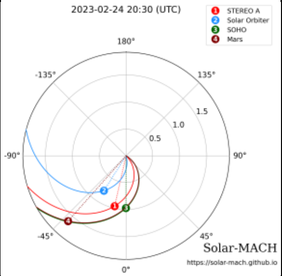
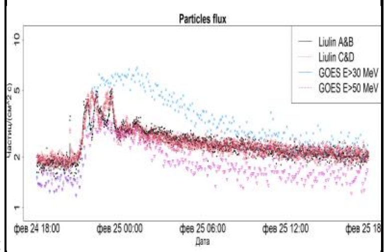
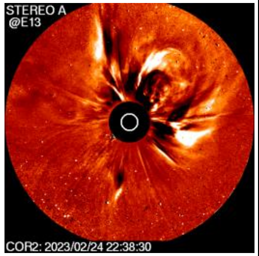
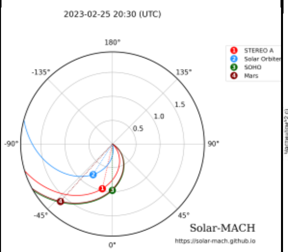
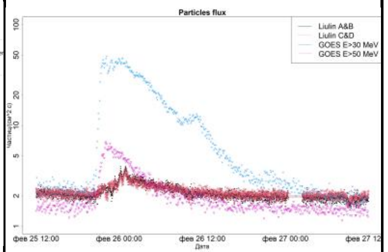
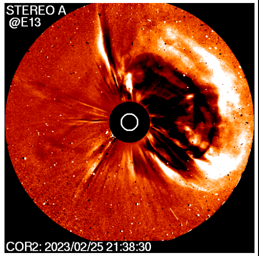
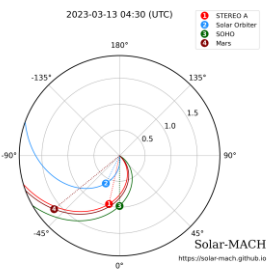
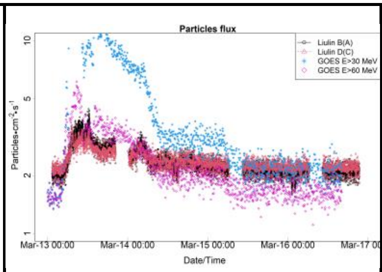
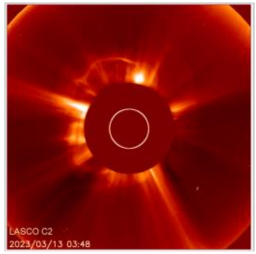
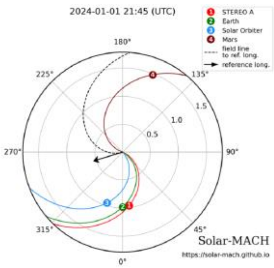
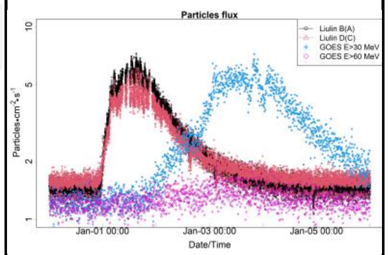
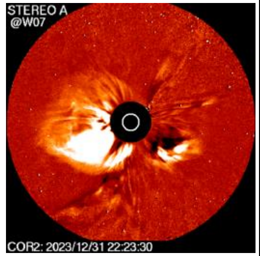
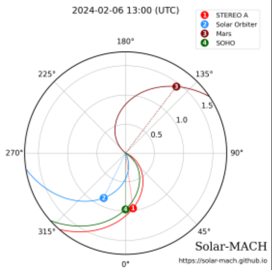
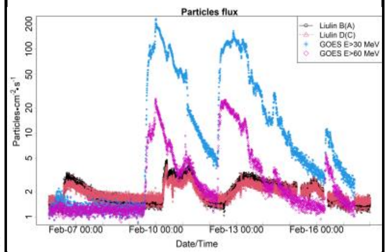
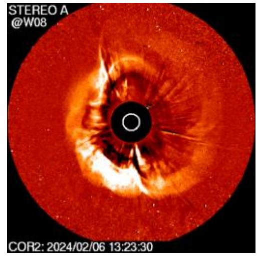
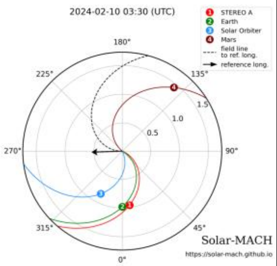
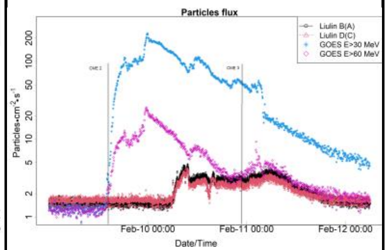
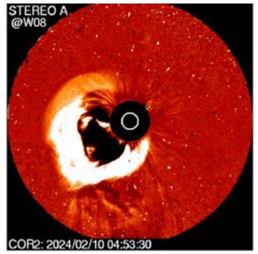
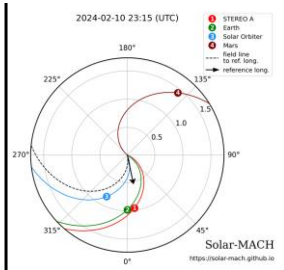
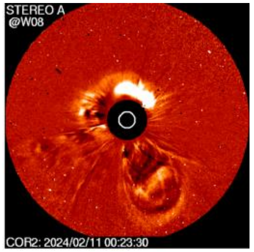
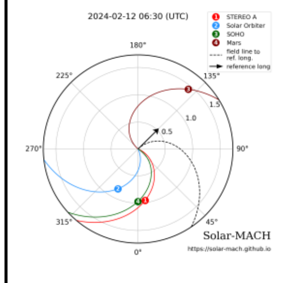
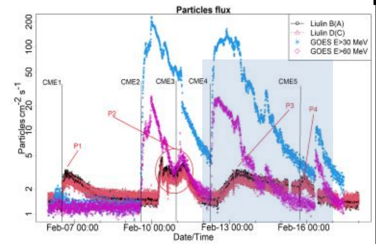
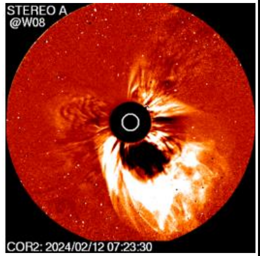
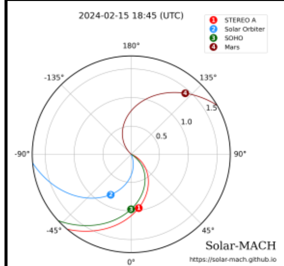
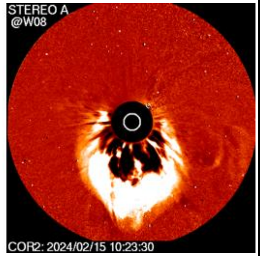
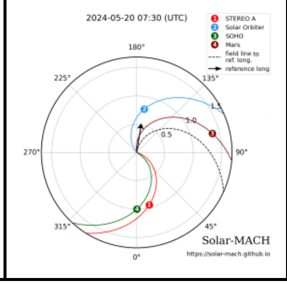
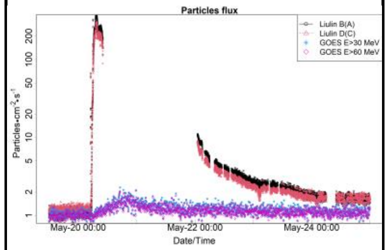
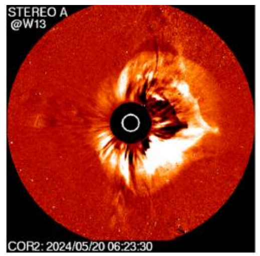
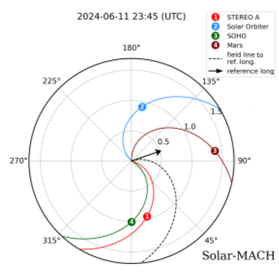
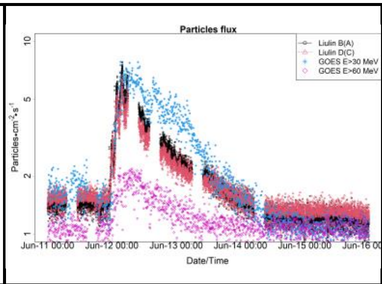
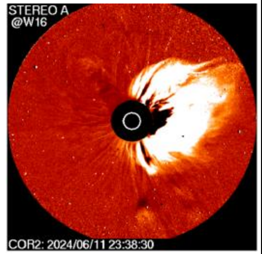
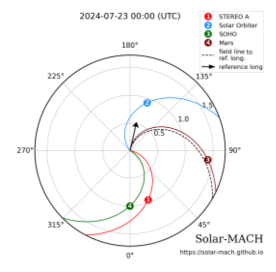
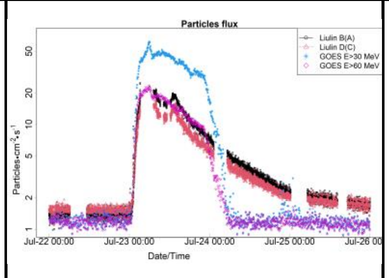
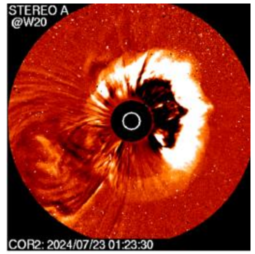
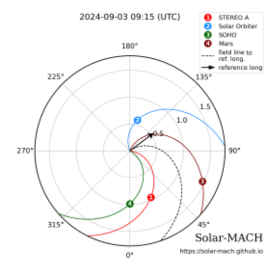
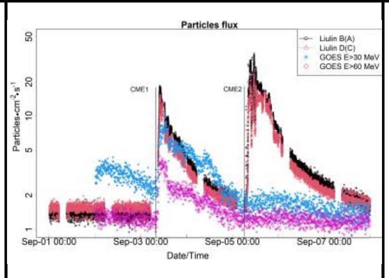
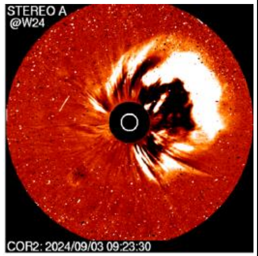
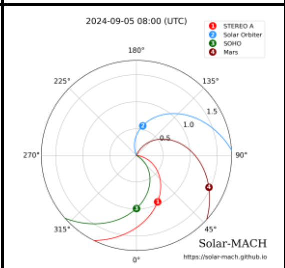
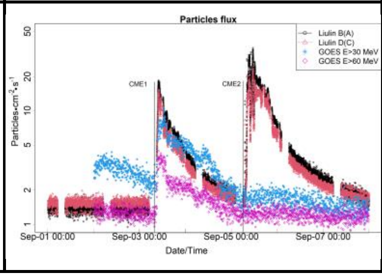
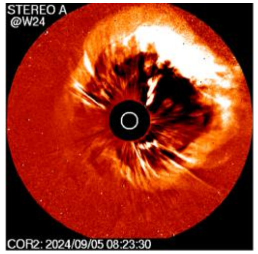
Table 1: Catalog of Solar Energetic Particles Events registered by Liulin-MO at Martian Orbit during the Current Solar Cycle

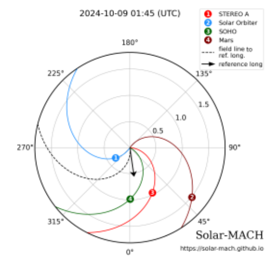
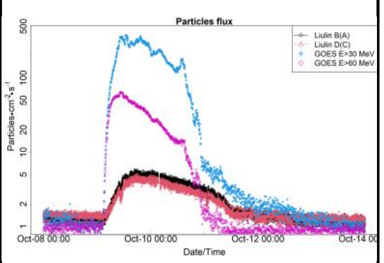
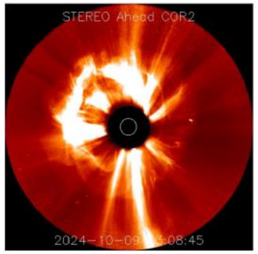
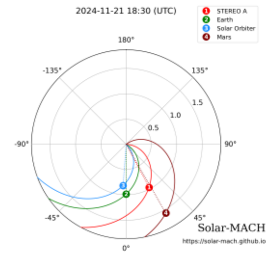
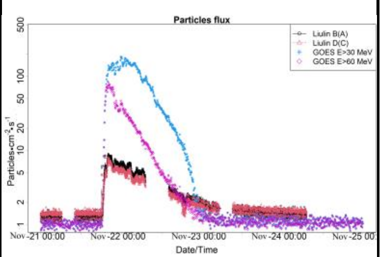
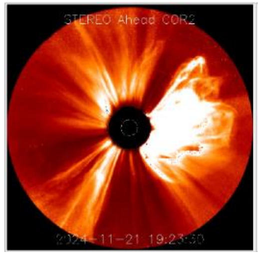
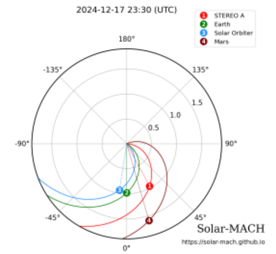
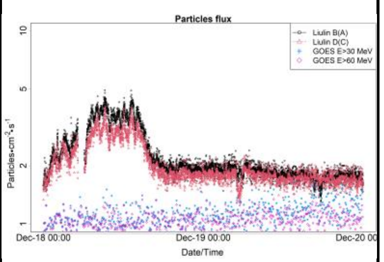
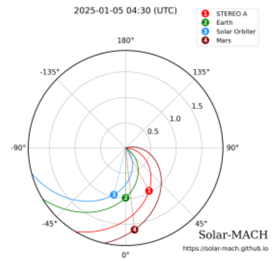
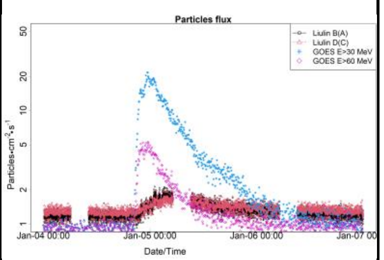
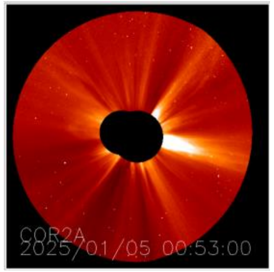
Start time of SEP event [UT]	**Duration [h]**	**Total dose/ total dose from SEPs (in Si) [µGy]**	**Maximum dose rate [µGy/h]**	**Maximum flux [cm^{-2} s^{-1}]**	**Location**	**Time profiles of Liulin-MO and GOES-18 flux rates**	**CME Type onset UT**	**X ray flare class *(GOES scale)* flare list location**
17 July 2021, 09:06	23	444.9±44.5/ 96.2±9.6	20.3±2	4.25±0.2			*Behind the E limb halo CME 04:55:05 - 05:04:45, 17 July 2021 	Behind limb event
17 September 2021, 07:12	37	757±76/ 185±19	25.6±2.6	4.5±0.2			*East limb partial halo CME 04:05:17 – 04:17:47, 17 September 2021 	Backside event
28 October 2021, 16:55	79	7700±770/ 6500±650	402±40.2	48.5±2.43			*Halo CME, 15:25:32 - 15:32:36, 28 October 2021 	++X1.0 28 October 2021, 15:17 S26W05

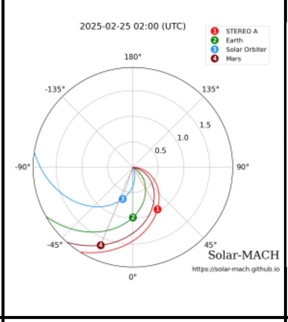
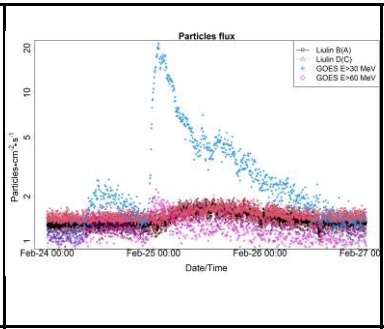
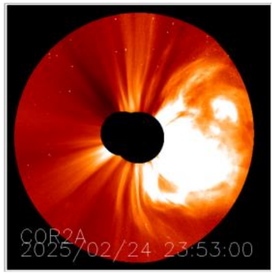
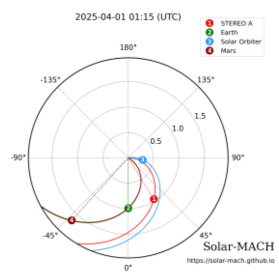
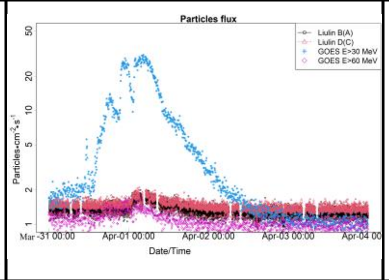
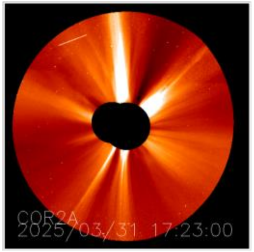
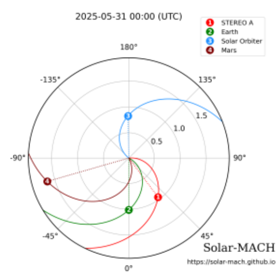
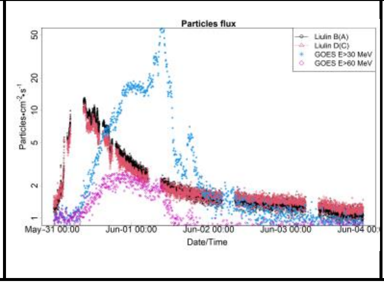
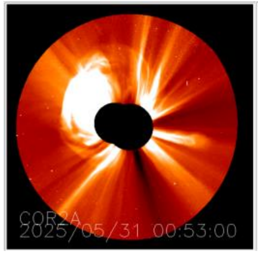
15 February 2022, 23:00	76	15000±1500/ 13800±1380	1009±101	109.7±5.5			Behind the east limb halo CME # 21:25, 15 February 2022 *from STEREO A EUV images* 	++M1.3 15 February, 18:15
14 March 2022, 17:55	17	328.1±33/ 95.2±9.5	31.2±3.1	5.13±0.26			*Behind the W limb partial halo CME, 17:02:17 - 17:16:28, 14 March 2022 	Behind limb event
24 February 2023, 21:07	24	413.4±41.3/ 194/55±19.45	58.83±5.9	5.1±0.25			*Halo CME, 20:09:46 - 20:13:22 24 February 2023 	++M3.7 24 February, 20:03 N29W24
25 February 2023, 21:20	21	354.36±35.44/ 162.87±16.3	33.87±3.4	3.9±0.2			*Halo CME, 19:10:47 - 19:08:05 25 February 2023 	++M6.4 25 February 2023, 18:40 N24W45

13 March 2023, 05:24	39	668.9±66.9/ 270.9±27.1	41.7±4.2	4.4±0.22			*Halo CME 03:18:20 - 03:24:29 13 March 2023		Behind limb event
01 January 2024, 00:08	81	2220±222/ 1670±167	70.5±7	7.3±0.37			*Halo CME 21:42:57 - 21:45:45, 31 December 2023		++X5.0 31 December 2023, 21:52 N04E73
06 February 2024, 13:10	40	630±63/ 350±35	24.8±2.5	3.2±0.16			*Backside halo CME 11:23:26 - 11:28:14, 06 February 2024		no data
10 February 2024, 06:30 merged events	39	944±94/ 647±65	36.3±3.6	4.6±0.23			*East Limb halo CME (CME2) 03:28:41- 03:29:37, 10 February 2024		+++M3.4, 10 February 2024, 03:48 S14E88

							*Halo CME (CME3) 23:10:53- 23:11:13, 10 February 2024		+++M9.0 10 February 2024, 23:07 S10W12
12 February 2024, 12:10 merged events	107	1945±195/ 1280±128	24.6±2.5	3.3±0.17			*Halo CME behind the Limb (CME 4) 06:25:45 - 06:29:05, 12 Feb 2024		S36W135 *estimated*
							**Behind the W limb (CME 5) 18:26:14 - 18:52:59 15 February 2024		No data
20 May 2024, 05:40	64	25220±2522/2 4720±2472	2800±280	383 ± 19			*Backside halo CME 05:06:25- 05:10:26 20 May 2024		+++X12 20 May 2024 05:14:40 S18W171

11 June 2024, 23:30	52	1020±102/ 660±66	51.6±5.2	7.8±0.39			*Halo CME Behind west limb 22:27:56 , 11 June 2024		+++X3 11 June 2024 22:38:52 S16W118
23 July 2024, 01:20 Merged events	95	3200±320/ 2580±258	197±20	21.8±1.1			**Backside halo CME, 23:51:22, 22 July – 00:01:46, 23 July 2024		+++X14 22 July 2024 23:56:37 N15 behind the W limb
03 September 2024, 09:15	47	1817±182/ 1521±152	208.3±21	18.8±0.95			***Behind west limb partial halo CME1, 07:32:56 - 07:50:20 03 September 2024		+++X2.4 03 Septem-ber 2024, 07:55:36 N21W125 (estima-ted)
05 September 2024, 07:52	59	3522±352/ 3138±314	336±34	35.9±1.8			***Backside halo CME2, 05:57:25 - 06:36:17 05 September 2024		+++X2 05 Septem-ber, 06:35:16 No flare position

09 October, 2024, 06:05	52	1675±168/ 1380±138	54±5.4	5.8±0.29			***Halo CME 01:50:45 - 01:50:41 09 October 2024 	++X1.8 09 October, 01:35:23 N13W08
21 November, 2024, 18:30	40	1256±126/ 1025±103	76±7.6	8.8±0.44			*Beyond W limb halo CME 17:43:40 - 17:55:09 21 November 2024 	Beyond western limb S12
17 December 2024, 23:20	38	631±63/ 402±40	50±5	4.6±0.23			No appropriate CME found	
05 January 2025, 04:30	18	178±18/ 70±7	22±2.2	2.1±0.1			*** West limb partial halo CME 19:40:47 4 January 2025 	+C7.6 4 January, 19:55 S17W61

25 February 2025, 02:10	32	285±28/ 92±9.2	25±2.5	1.8±0.09			West limb semi-halo CME ** 20:53 – 21:30 ***22:02: 24 February 2025 	+M3.9 24 February, 23:02 around SW Lim
01 April 2025 01:10	15	147±15/ 45±4.5	17.7±1.8	2±0.1			*** Behind East limb CME, 16:43 31 March 2025 	+X1.1 28 March, 15:21 N05E85
31 May 2025 01:24	48	1872±187/ 1592±159	179±18	13±0.65			***East limb halo CME 23:03 30 May 2025 	+++M8.2 30 May 23:24