



Mauna Loa Solar Observatory K-Cor Coronagraph Observations of Coronal Mass Ejections Associated with Solar Energetic Particles

O.C. St. Cyr^{1,2} · I.G. Richardson^{1,3} · J.T. Burkepile^{4,5} · M. Galloy⁴ · T. Nieves-Chinchilla¹ · B.J. Thompson¹

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Abstract

We report on 27 coronal mass ejections (CMEs) observed in the inner corona (roughly ≤ 2 solar radii (R_s)) at the Mauna Loa Solar Observatory (MLSO) with the K-Coronagraph (K-Cor) from late 2013 until November 2022, when MLSO operations were suspended due to a volcanic eruption. All these CMEs were associated with solar energetic particle (SEP) events including ~ 25 MeV protons observed by spacecraft at different locations in the inner heliosphere (≤ 1 astronomical unit (au)). We analyzed the characteristics of these CMEs and compared them to a sample of CMEs observed by K-Cor during the same period with no known SEPs. We found that both samples of SEP and non-SEP CMEs expanded in width between the inner and middle corona ($> 2 R_s$), where they were observed by spacebased coronagraphs. However, the average and the median widths for the drivers of SEP CMEs were a factor of two larger than for the non-SEP CME drivers in both the inner and middle corona. Similarly, we found that the average speed of the SEP CMEs in the inner corona was more than a factor of two faster than the average for non-SEP CMEs, and almost a factor of two faster in the middle corona. Most of the CMEs ($> 80\%$) were accelerating in the inner corona for both SEP and non-SEP samples, though the average acceleration in the inner corona for the SEP CMEs was almost a factor three larger than for the non-SEP sample. The mass estimates provided in the Coordinated Data Analysis Workshops (CDAW) catalogue for the two samples also shows that the average for SEP CMEs was almost a factor three larger than for the non-SEP sample. The event of 2021-11-01 is presented as an example of an SEP CME included in this study. One of the 27 SEPs registered S1 on the National Oceanic and Atmospheric Administration (NOAA) solar radiation storm scale (S-scale) in the near-Earth environment, and several others were detected by the NOAA Geostationary Operational Environmental Satellites (GOES) spacecraft at lower levels. Additionally, three of the SEP events detected by the Solar Terrestrial Relations Observatory (STEREO-A) when far from Earth would have exceeded the S1 storm level. When observing, MLSO K-Cor provides near-real-time monitoring and alerts of CMEs appearing in the inner corona, hence it can provide an earlier warning than most spacebased coronagraphs of a potentially SEP-associated CME to robotic and human explorers who are concerned about the abrupt appearance of SEPs.

Extended author information available on the last page of the article

1. Background

Solar energetic particle events are temporary increases in the interplanetary energetic particle (electron, proton, and heavy ion) population. They closely follow solar eruptions and are believed to include particles accelerated by reconnection in solar flares and at shocks formed ahead of coronal mass ejections (CMEs) (e.g. Reames 1999; Desai and Giacalone 2016). The most intense SEP events can be hazardous to spacebased robotic and human exploration, and their prediction is of major current interest in support of missions to the Moon and Mars (e.g. Whitman et al. 2023). Many studies (e.g. Kahler, Hildner, and Van Hollebeke 1978; Kahler et al. 1984; Reames 1999; Richardson et al., 2014, 2026) have shown positive correlations between the speeds of CMEs in the field of view (FoV) of spacebased coronagraphs and the peak intensity of the associated SEP events. Hence, such CME observations are frequently used in SEP prediction models (e.g. Richardson, Mays, and Thompson 2018; and see Table 10 in Whitman et al. 2023).

Externally-occulted spacebased coronagraphs typically have FoVs that start at > 2 solar radii measured from the center of the Sun (e.g., $\approx 2.3 R_s$ is the inner FoV for the workhorse Solar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph (LASCO) C2, Brueckner et al. 1995). However, the fastest arriving SEPs can arrive at 1 AU in 10's of minutes – before the associated CME even enters the FoV of such a coronagraph. Internally-occulted coronagraphs, such as those deployed in space or at ground observatories, can have FoVs that commence below $2 R_s$ and hence are able to image CMEs earlier than most externally-occulted coronagraphs. Examples of internally-occulted coronagraphs include the STEREO A and B Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) COR1 coronagraphs that have FoVs starting at $1.4 R_s$ (Howard et al. 2008) and the groundbased Mauna Loa Solar Observatory K-Cor coronagraph to be discussed below.

This limitation on the inner FoV can also be overcome in a spacebased coronagraph with an occulter on an extended boom, but this accommodation is not typically practical. Another possibility is to deploy a two-spacecraft mission with one platform providing external occultation at a distance from the other platform such as the successful Proba-3 Association of Spacecraft for Polarimetric and Imaging Investigation (ASPIICS) coronagraph. That mission has an occulter spacecraft flying in formation with an imaging spacecraft at a distance of 150 meters (e.g. Lamy et al. 2010; Zhukov et al. 2025) to produce an effect similar to that provided by the Moon during a total solar eclipse.

In principle, any coronagraph can provide routine warnings of CMEs that might be associated with SEP events. However, image cadence and data latency from a spacebased instrument to the final user are typically the most significant limitations because telemetry downlink schedules for spacecraft with primarily scientific payloads can result in delays of many hours in the receipt and processing of CME observations. By this time, the SEP event is likely to be well underway at 1 AU.

From 1980 to 2013 the first two generations of groundbased coronameters (Mark-3 [Mk3; FoV 1.12 to $2.44 R_s$], and Mark-4 [Mk4; FoV 1.12 to $2.86 R_s$]) installed at MLSO were able to observe lower in the corona than most spacebased instruments (Fisher et al. 1981; Elmore et al. 2003), thus providing observations of the formation and detection of fast-moving CMEs before they entered the FoV of a spacebased instrument. Richardson et al. (2023, hereafter Paper 1) described the characteristics of 84 SEP-associated CMEs detected by those two instruments.

In late 2013, the next-generation coronagraph, K-Cor, was installed at MLSO (de Wijn et al. 2012). This instrument provided significant improvements in temporal cadence (15 s compared to 3 min) and an increased field of view ($1.05 - 3.0 R_s$) over the previous two

telescopes. The first archived coronal observations by K-Cor were on September 30, 2013 (<https://www2.hao.ucar.edu/mlso>). Similar to the earlier MLSO telescopes, K-Cor records the polarization Brightness (pB) formed by Thomson scattering of photospheric light off free electrons in the inner corona in a near-infrared (720 to 750 nm) passband. As a result, the recorded image is most sensitive to density structures near the plane-of-the-sky, with a significant fall-off in sensitivity of coronal structures located away from the solar limb (e.g. Hundhausen 1993). After the suspension of K-Cor observations due to the November 2022 eruption of Mauna Loa, limited routine observations resumed on March 31, 2026, following the completion of repairs to the access road to the observatory at an altitude of 3440 meters.

Another technical enhancement of K-Cor over the previous telescopes is that it includes a fully- automated data processing pipeline that greatly reduces the data latency compared to the previous MLSO telescopes (i.e., 2.5 minutes versus 24 hours). The pipeline was modified to include a near-real-time CME detection algorithm that scans the fully-processed K-Cor images as part of the automated data processing pipeline and sends email alerts to interested parties (Thompson et al. 2017). These alerts contain basic CME properties such as detection time, height, position angle, and speed. From 2014 until the eruption in 2022, K-Cor acquired, on average, 264 days of observations a year; while in January 2022 it began to provide unique near-real-time CME observations to the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Community Coordinated Modeling Center (CCMC) SEP Scoreboard (<https://ccmc.gsfc.nasa.gov/scoreboards/sep/>). The MLSO observer on duty can also issue their own separate alerts when they see a CME. These alerts include the width of the CME and a confidence level (low, medium, high) that relates to the visibility of the CME. In addition, a “heartbeat” signal serves as an “all clear” to indicate the observatory is currently taking data but no CMEs have been detected.

The concept of using groundbased observations to provide an early warning of a CME was discussed in St. Cyr, Burkepile, and Posner (2017) for a single SEP-associated CME observed by K-Cor at MLSO. Here, we identify an expanded sample of such SEP-associated MLSO CMEs and report on the results of our analysis of these events. This report is the second comprehensive study of the association between CMEs observed at MLSO and SEP events, here defined as those that include ~ 25 MeV protons that were detected by near-Earth spacecraft and/or the STEREO A and B spacecraft at ≈ 1 AU, as discussed by Richardson et al. (2014, 2026). When available, additional SEP observations by spacecraft in the inner heliosphere, such as Parker Solar Probe (launched in August 2018; Fox et al. 2016), Solar Orbiter (launched in February 2020; Müller et al. 2020), and Bepi-Colombo (launched in October 2018; Benkhoff et al. 2021) have been considered. Here, we document the 27 K-Cor SEP-associated CMEs identified when the observatory was operating between 2013 and 2022 and compare these events to a sample of over 50 CMEs observed by K-Cor during the same period with no known SEP associations. The following sections detail the data selection, analyze the distributions of the CME and SEP characteristics, and discuss and summarize the results. An example of a K-Cor SEP CME is in Appendix A.

2. Observations

2.1. SEP Events Associated with MLSO K-Cor CMEs

To identify SEP events associated with CMEs observed by the MLSO K-Cor coronagraph, we followed a similar procedure to that described in Paper 1. However, we have primarily

used an updated and expanded compilation of SEP events including ~ 25 MeV protons observed at ≈ 1 AU by the High Energy Telescopes (HETs) on board the Solar Terrestrial Relations Observatory (STEREO) A/B spacecraft (von Rosenvinge et al. 2008) and/or instruments on near Earth spacecraft (e.g. Electron Proton Helium Instrument (EPHIN) (Müller-Mellin et al. 1995) and Energetic and Relativistic Nuclei and Electron (ERNE) (Torsti et al. 1995) on SOHO) (see <https://doi.org/10.7910/DVN/GQPCXZ>). These observations were discussed in Richardson et al. (2026), where it was also demonstrated that these instruments are well inter-calibrated for protons, allowing us to compare proton intensities without any correction.

At the start of K-Cor operations in late 2013, near the maximum of Solar Cycle 24, the STEREO-A and B spacecraft were on the far side of the Sun from Earth, and in particular, STEREO-B (at 143° East of Earth on November 01, 2013) was magnetically well-connected to the Sun's eastern limb (relative to Earth). Energetic particles from the Sun's eastern hemisphere, including near and over the East limb, are generally more difficult to detect from near-Earth spacecraft because of the spiral configuration of the interplanetary magnetic field, but the STEREO-B spacecraft was then ideally-located to detect any SEPs associated with CMEs from this hemisphere. Contact with STEREO-B was lost in October 2014 and has not been restored. After passing behind the Sun in 2014, STEREO-A moved towards Earth above the East limb of the Sun and was well placed to detect SEPs associated with CMEs from the eastern hemisphere. In addition, spacecraft at Earth were well positioned to detect SEPs from CMEs above the West limb. Hence, the combination of SEP observations from the STEREO and near-Earth spacecraft in the Richardson et al. (2026) catalog is well-suited for identifying SEP events associated with MLSO CMEs above either solar limb, or for assessing whether no SEPs were present.

Between October 2013 and November 25, 2022, there were 215 individual SEP events catalogued, some detected at multiple locations. We selected the subset of SEP events associated with solar eruptions during the nominal K-Cor observing window, which starts ~ 17 UT each day and continues for several hours, as long as sky conditions permit. Typically, the K-Cor observations average ≈ 5.5 hours per day, but on rare occasions when sky conditions cooperate, these observations can continue until as late as ~ 05 UT the following calendar day.

Examples of SEP-associated CMEs observed by K-Cor have appeared previously (e.g., the event of January 01, 2016, in St. Cyr, Burkepile, and Posner (2017); the event of June 13, 2022, in Richardson et al. 2023; the event of May 7, 2021, in Stepanyuk and Kozarev 2024), and preliminary compilations have been presented at several workshops (e.g. Burkepile et al. 2025). In Appendix A we present a representative K-Cor CME with SEPs observed at multiple locations in the heliosphere on January 11, 2021. This event is provided as an illustration of the data analysis techniques used throughout this manuscript. A comparison of the height-time measurements between K-Cor and SOHO/LASCO for this event also reinforces the utility of imaging the inner corona as an early-warning alert system of a fast CME capable of producing an SEP event.

Based on the times of the solar events associated with the STEREO/near Earth ~ 25 MeV proton events catalogued by Richardson et al. (2026), there were 114 days when K-Cor might have detected an SEP-associated CME during its nominal observing window. However, with the limited viewing window from the groundbased observatory, and other factors such as cloudy skies and instrument maintenance, most of these SEP events (82) occurred during MLSO data gaps. For another five SEP events, K-Cor observations were available, but no CME was detected. However, four-of-five of these eruptions occurred far from the plane of the sky where the inherent sensitivity of a pB telescope like K-Cor falls more rapidly with limb distance than total intensity. Four occurred early in K-Cor operations when the

telescope performance was not optimal. These points will be addressed further in the Discussion. Thus, we have identified 27 SEP CMEs detected by K-Cor, as listed in Table 1.

We have supplemented the STEREO/Earth SEP observations by examining the inner heliosphere observations from the Integrated Science Investigation of the Sun (IS $\odot$ IS) on PSP (e.g. Mitchell et al. 2023) and the Energetic Particle Detector (EPD, Rodriguez-Pacheco et al. 2020) on Solar Orbiter to check whether they also detected SEP protons in a similar energy range associated with CMEs in the observing window or might have observed SEPs that were not evident at STEREO-A or near-Earth spacecraft. We have also referred to the “Solar Cycle 25 SEP Events Catalog” produced by the Solar Energetic Particle Analysis Platform of the Inner Heliosphere (SERPENTINE) project (<https://data.serpentine-h2020.eu/catalogs/sep-sc25/>; Dresing et al. 2024) which focuses on SEP events that include protons above 25 MeV observed at least at two spacecraft. This catalog includes observations from the Solar Intensity X-Ray and Particles Spectrometer (SIXS-P) instrument on Bepi-Colombo (Huovelin et al. 2020) in addition to those instruments noted above.

Table 1 lists the calendar date and Universal Time (UT) when the CME was first detected, Central Position Angle (CPA), and angular size of the SEP CME driver in the K-Cor field of view. For a definition of the “CME driver” see Rouillard et al. 2011. A “DG” in column 2 (1st detection time) refers to a data gap, and these were cases when the CME was already visible in the K-Cor FoV when observations resumed. As is conventional, the location is expressed as a Central Position Angle measured counterclockwise from solar North, determined by measuring the angular size (or width) of the CME driver (excluding any obvious shock wings and deflected coronal structures) and expressing the CPA as the mid-point of the CME driver width. An asterisk (*) in these columns indicates that the feature measured may not include the leading edge or entire width of the CME. For most of these eruptions, an associated low coronal source location and classification could be determined based on images from the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) (Lemen et al. 2012) or STEREO/SECCHI Extreme Ultraviolet Imager (EUVI) (Howard et al. 2008). We also tabulate the intensity and time of the NOAA GOES soft X-ray peak intensity (i.e., the flare size) for frontside or just over the limb events, obtained from operational GOES data and reports. The asterisk in this column for Jaunuary 01, 2021, indicates that the time of the X-ray peak was on the following calendar day. Note that before December 18, 2017, the reported intensities are 43% lower than the actual intensities, due to the application of a correction factor, whereas later intensities are from GOES-R with different instrumentation that provides operational data with correctly calibrated absolute soft X-ray intensities (see the X-Ray Sensor (XRS) Users Guide, available at <https://www.ncei.noaa.gov/products/goes-r-extreme-ultraviolet-xray-irradiance>). Hence, after this date, the flare intensities listed should be multiplied by 0.7 to be consistent with those of earlier events (or alternatively, earlier event intensities should be multiplied by 1.43 to give the absolute intensities).

The next five columns pertain to the CME height-time measurements from K-Cor and include the range of altitudes (measured in R_s from Sun center) when the CME was tracked, the number of measurements, and the resulting linear and quadratic weighted-regression estimates of the constant speed and the constant acceleration, respectively. An estimate of the speed at the final measurement height based on the constant acceleration is also provided. We examined the χ^2 goodness-of-fit for the two regressions and indicate in bold which fit was judged superior (e.g. Hundhausen, Burkepile, and St. Cyr 1994). It is important to note that all the CME parameters, including kinematics, discussed in this paper are plane of the sky measurements, and no correction factor for projection effects has been applied. All of these K-Cor SEP CMEs were also detected by SOHO/LASCO (e.g., as reported in

Table 1 The 27 SEP associated CMEs detected by MLSO K-Cor. See text for complete explanation of each column.

K-Cor Date	K-Cor 1st Det	K-Cor CME Driver CPA	K-Cor CME Driver Width	K-Cor Source Location	NOAA GOES SXR Peak	NOAA GOES SXR Peak [W/m ²]	NOAA GOES SXR Peak [U.I.]	K-Cor Height-Time Range	K-Cor Height-Time Measures	K-Cor Avg Vel [km/s]	K-Cor Avg Accel [km/s ²]	K-Cor Final Vel [km/s]	SEP Peak Intensity at 1 A.U. @25 MeV [(MeV·s·cm ⁻² ·sr) ⁻¹]	SEP Detected At Earth, STEREO PSP, SO, BEPI
2013-12-09	DG at start	~62	~24	~N30E70	---	---	---	---	---	---	---	---	0.0005	STB, STA
2013-12-16	20:40	244	70	S33W110	21:33	3.10E-06	21:33	1.27-2.35	1.29	347 ± 8	0.21 ± 0.03	581 ± 74	0.0002	Earth
2014-01-04	DG at start	~133	~82	S06E39	19:46	4.00E-05	19:46	---	---	---	---	---	0.002	Earth
2014-02-11	19:10	243	90	S14W116	---	---	---	2.26-2.74	20	316 ± 40	0.19 ± 0.27	421 ± 326	0.001	Earth
2014-03-13	21:43	308	100	N10W141	---	---	---	1.12-1.80	51	492 ± 24	0.12 ± 0.18	569 ± 197	0.0005	Earth
2014-08-12	20:15	82	72	N12E131	6:00E-07	6:00E-07	20:19	1.46-2.83	9	271 ± 30	0.12 ± 0.07	501 ± 252	0.001	STB, STA
2014-09-24	20:54	351	145	N20E181	---	---	---	1.12-1.75	8	915 ± 78	0.06 ± 0.12	930 ± 563	6	STB, Earth, STA
2014-10-14	18:22	107*	56*	---E100	1.10E-05	1.10E-05	18:37	1.83-2.43	68	435* ± 30	0.38* ± 0.20	644* ± 230	5	Earth, STA
2015-02-08	22:15	94	57	N05E90	---	---	---	1.59-2.60	67	664 ± 27	0.14 ± 0.16	759 ± 213	0.001	STA
2015-03-15	01:22	249	112	S22W25	9.10E-06	9.10E-06	02:13	1.48-2.25	71	461 ± 22	0.62 ± 0.17	818 ± 204	0.02	Earth
2015-05-05	22:08	61	54	N15E79	2.70E-04	2.70E-04	22:11	1.27-2.31	24	1859 ± 107	-3.22 ± 2.23	995 ± 1011	0.0004	Earth
2015-12-21	00:57	110	57	N05E81	1.42-2.36	1.42-2.36	64	1.42-2.36	64	688 ± 22	-0.20 ± 0.18	559 ± 207	0.001	STA
2016-01-01	23:00	248	64	S21W89	2.30E-05	2.30E-05	00:11*	1.56-2.66	55	510 ± 26	0.17 ± 0.14	655 ± 211	0.1	Earth
2016-02-11	DG at start	69*	41*	N11W07	8.90E-06	8.90E-06	21:03	1.90-2.20	2	860* ± 836	---	---	0.0004	Earth
2017-04-18	19:22	73*	21*	N14E77	5.50E-06	5.50E-06	20:10	1.40-1.56	9	117* ± 38	0.23* ± 0.30	218* ± 311	0.2	STA, Earth
2021-05-07	18:54	83	38	N17E78	3.95E-05	3.95E-05	19:04	1.17-2.81	11	661 ± 35	0.44 ± 0.15	1047 ± 251	0.004	SO, STA, PSP
2021-07-09	17:23	304	61	N17W90	4.70E-06	4.70E-06	17:25	1.44-2.52	57	737 ± 8	-0.27 ± 0.06	520 ± 65	0.005	Earth, PSP
2021-07-15	21:18	~120	~230	---E170	---	---	---	1.15-2.62	28	906 ± 19	0.22 ± 0.14	1129 ± 147	0.005	SO, PSP, Earth
2021-11-01	01:14	228	116	S29W45	1.50E-05	1.50E-05	01:45	1.20-2.62	20	371 ± 12	0.29 ± 0.04	751 ± 102	0.3	STA, PSP, Earth, SO
2022-01-31	23:28	238	22	S30W92	---	---	---	1.31-1.95	13	159 ± 19	0.20 ± 0.06	399 ± 160	0.001	Earth
2022-02-02	00:03	237*	21*	S35W95	---	---	---	1.31-1.75	23	62* ± 7	0.01* ± 0.01	80* ± 58	0.0002	Earth
2022-03-10	18:11	3	66	N30W12	2.80E-06	2.80E-06	20:30	1.46-2.69	13	194 ± 7	0.06 ± 0.01	330 ± 53	0.006	SO, Earth, STA
2022-03-31	18:35	272	64	N13W47	9.60E-05	9.60E-05	18:33	1.43-2.21	9	505 ± 122	-0.51 ± 0.79	203 ± 952	0.02	STA, Earth
2022-05-11	18:17	261	31	S17W90	2.70E-05	2.70E-05	18:53	2.07-2.90	16	271 ± 54	0.16 ± 0.23	444 ± 449	0.1	Bepi, Earth, STA, PSP
2022-06-13	02:38	74	88	N15E45	3.40E-05	3.40E-05	04:05	1.13-2.97	145	617 ± 8	0.35 ± 0.04	911 ± 75	0.01	Earth, STA
2022-08-30	17:51	255	36	S25W110	2.00E-05	2.00E-05	19:20	1.76-2.71	12	239 ± 60	0.71 ± 0.27	972 ± 430	0.0004	Earth, SO
2022-10-02	20:22	308	55	N17W49	1.00E-04	1.00E-04	20:25	1.13-2.25	13	1468 ± 56	3.06 ± 0.81	2311 ± 448	0.005	Earth, STA

the CDAW LASCO CME catalogue; https://cdaw.gsfc.nasa.gov/CME_list/, Yashiro et al. 2004), and we will compare their characteristics as seen in these two telescopes throughout this article.

The final two columns give details of the associated SEP event. The penultimate column indicates the highest peak intensity for the ~ 25 MeV protons observed near 1 AU by the STEREO or near-Earth spacecraft. The bold entry in the final column indicates the 1 AU location where this highest peak intensity (as noted in the previous column) was measured. In addition, for completeness, this column indicates if the SEP event was detected by one or more of the inner heliospheric spacecraft (Solar Orbiter, Parker Solar Probe, and Bepi-Columbo).

As discussed in Paper 1, we identify the SEP events using observations from science-focused instruments because these have much lower backgrounds than the GOES particle instruments that are frequently used to identify “SEP events” (e.g., the NOAA list of “Solar Proton Events Affecting the Earth Environment”, based on the GOES > 10 MeV proton flux <ftp://ftp.swpc.noaa.gov/pub/indices/SPE.txt>) and for operations (e.g. Bain et al. 2021). We also consider observations from multiple spacecraft that may detect SEP events that are not evident at Earth. Hence, we can identify many more SEP events covering a larger dynamic range of intensities than is possible using GOES data alone. An advantage for this study is that with more SEP events identified, there is a greater chance of identifying MLSO CMEs that are associated with SEP events than when just considering events observed by GOES. Furthermore, with the low instrumental backgrounds we can more confidently identify a set of control CMEs that are not associated with SEPs, as discussed below. Only nine of our 27 SEP CMEs observed by K-Cor show evidence of an increase in the GOES > 10 MeV proton flux above the high instrumental background (April 01, 2014; March 15, 2015; January 01, 2016; September 07, 2021; July 15, 2021; March 10, 2022; November 05, 2022; June 13, 2022; February 10, 2022), and one reached the operationally relevant NOAA S1-level (January 01, 2016) that is required for inclusion in the NOAA list of solar proton events that affect Earth. In addition, several other events (September 24, 2014; October 14, 2014; March 31, 2022) observed at STEREO are listed in the SEP event catalogue maintained by the STEREO IMPACT team (https://stereo-ssc.nascom.nasa.gov/data/ins_data/impact/level3/SEPs.pdf). This catalog uses observations from the STEREO High Energy Telescopes to mimic the > 10 MeV proton flux used for the NOAA solar radiation storm scale and hence categorize SEP events at the STEREO spacecraft that exceed the S1 level based on this scale.

Figure 1 summarizes how the 27 SEP (~ 25 MeV proton) events associated with K-Cor CMEs identified in this study (indicated by red circles) compare with all the SEP events (small blue circles) observed near 1 AU by STEREO A/B or near-Earth spacecraft from the Richardson et al. (2026) catalog during the K-Cor period of operation. Table 1 indicates that the K-Cor CME associated SEP events were also detected by inner heliosphere spacecraft, but we do not include these observations here due to the effect of changing spacecraft heliocentric distance on the SEP intensity. Also, note that all the SEP events were observed by at least one STEREO spacecraft and/or at Earth. There are 453 separate SEP observations (including those where no SEP was detected) in Figure 1 since each event can have up to three observations (STEREO-A, -B, and near-Earth spacecraft) located at different longitudes relative to the solar event. Of that total, 54 are the red K-Cor points. The top left panel in Figure 1 shows the observed peak ~ 25 MeV proton intensity versus the longitude of the solar event relative to the observing spacecraft. The larger red circles indicate the largest observed intensities for the SEP events associated with K-Cor CMEs, as listed in the penultimate column of Table 1. The figure illustrates that the K-Cor CME-associated SEP events are representative of the population of SEP events in terms of their distributions in intensity and longitude.

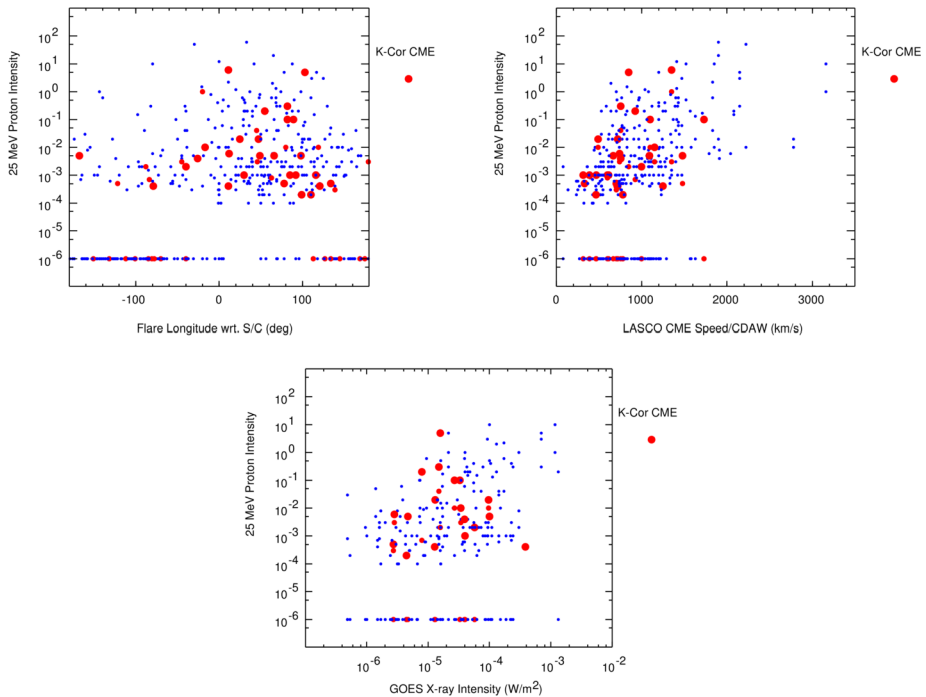


Figure 1 A graphic comparison of the K-Cor SEP CME observations with all events in the Richardson et al. (2026) STEREO/near-Earth SEP catalog during the K-Cor period of operation. The top left panel shows the distribution of SEP proton intensity (at ~ 25 MeV in $(MeV s cm^2 sr)^{-1}$) versus the longitude of the associated solar event relative to the observing spacecraft location. The red circles indicate observations of the K-Cor CME-associated SEP events and the small blue circles the other events in the SEP catalog. Cases where the SEP event was not detected at a certain spacecraft location are plotted at an intensity of 10^{-6} to indicate that the SEP was not detected at that longitude. SEP intensities from near-Earth and STEREO A/B spacecraft (as available) are included, so a given event may contribute more than one point in the figures. The largest observed peak intensity for each event, as given in the penultimate column of Table 1, is indicated by a larger red circle. The top right panel shows the observed SEP intensity (including all solar event longitudes) versus the CME linear speed in the LASCO FoV from the CDAW catalog. The bottom panel shows the proton intensity versus GOES X-ray intensity (again for all event longitudes) if a flare was observed. The flare intensities before December 18, 2017, have been multiplied by 1.43 to make them consistent with GOES-R intensities.

Again, it is evident from Figure 1 that this limited sample of events does not include any of the relatively rare most intense events, the largest K-Cor CME-associated events being around an order of magnitude smaller than the most intense events at ~ 25 MeV. The top right panel in Figure 1 shows the peak ~ 25 MeV proton intensity versus CME speed from the CDAW catalog including observations at all longitudes and demonstrates that SEP events associated with particularly fast LASCO CMEs (above 1800 km/s in the CDAW catalog) are not represented in our limited sample of K-Cor CME-associated events. In the bottom panel of Figure 1, showing the proton intensity plotted versus GOES X-ray intensity (again for observations at all longitudes), we can see that our sample of K-Cor CME associated SEP events does not include larger SEP events associated with stronger (e.g., X-class) flares observed by GOES.

2.2. The Non-SEP CMEs

A “control” set of a comparable number of MLSO CMEs without SEP events is required to assess whether or not parameters such as CME speed and/or width in the inner corona could provide a useful discriminator of SEP versus non-SEP-associated CMEs. About 600 CMEs have been detected since 2013 by MLSO K-Cor, but to identify a control set we started with a subset that has already been examined and published. Specifically, Song et al. (2023) catalogued 71 K-Cor events from 2014–2022 to investigate the evolution of the three-part structure of CMEs from the inner corona into the middle corona using K-Cor and SOHO/LASCO C2. Their selection criteria included: (1) events within 30° of the limb for front-side events, (2) “normal” CMEs (i.e., angular width $> 30^\circ$ in C2), and (3) those for which K-Cor clearly saw the early eruption. We have examined all 71 events, eliminating 11 that were SEP CMEs already listed in Table 1. An additional eight were excluded from further consideration for reasons outlined in Appendix B, which is a listing of the remaining 52 CMEs not associated with SEP (~ 25 MeV proton) events that were used as a control non-SEP sample for comparison to the 27 SEP CMEs. Similar to Table 1, Appendix B also provides CME characteristics for these 52 CMEs.

The top panel of Figure 2 shows the annual occurrence of the SEP and non-SEP CMEs discussed in this study. To help visualize distinctions between the two populations throughout this article, we highlight the **SEP CMEs in red**, and the **non-SEP CMEs in black**. The bottom panel illustrates the yearly variation in the numbers of larger populations of CMEs from the CDAW and MLSO catalogs, ~ 25 MeV proton events from Richardson et al. (2026), and NOAA > 10 MeV proton events, over this same time period, which encompasses the peak of Solar Cycle 24, the descending phase into minimum, and the ascending phase of Cycle 25. The samples of SEP and non-SEP CMEs selected for this study both are similarly distributed in time and follow the general solar cycle variations in the number of CMEs and SEP events. Moreover, these occurred during the same periods of longitudinal coverage by STEREO. We therefore assess that the lack of SEPs detected for the non-SEP CMEs is more likely due to a genuine lack of SEPs and not due to a difference in longitudinal coverage.

We note, however, that there appears to be a smaller number of CMEs detected by K-Cor in the first years of observation relative to LASCO in the bottom panel of Figure 2. When observations with K-Cor began in late 2013 the instrumental stray light was initially higher, making it more difficult to detect fainter CMEs. However, multiple improvements over time reduced the stray light, which in turn accounts for the improved agreement between K-Cor and LASCO in the later years of Figure 2. We will expand on this topic further in Section 5.

3. Properties of SEP-Associated and Non-SEP K-Cor CMEs

In this section, we examine the macro properties of the K-Cor CMEs, comparing the SEP-associated events to those without SEPs. We first consider the locations in the corona where these events appeared. As is described above, the CPA is measured counterclockwise from solar North, determined as the midpoint of the angular size (or width) of the CME driver. A tally of the CME driver CPAs by (plane of sky) hemisphere as viewed from Earth is shown in Table 2, where it is clear that they happen to be nearly identically distributed North versus South, and East versus West, for both the SEP and non-SEP samples. Although there is no reason to expect these should be equal since SEP events are rather rare and often occur in clusters associated with large active regions, and our sample sizes are relatively small,

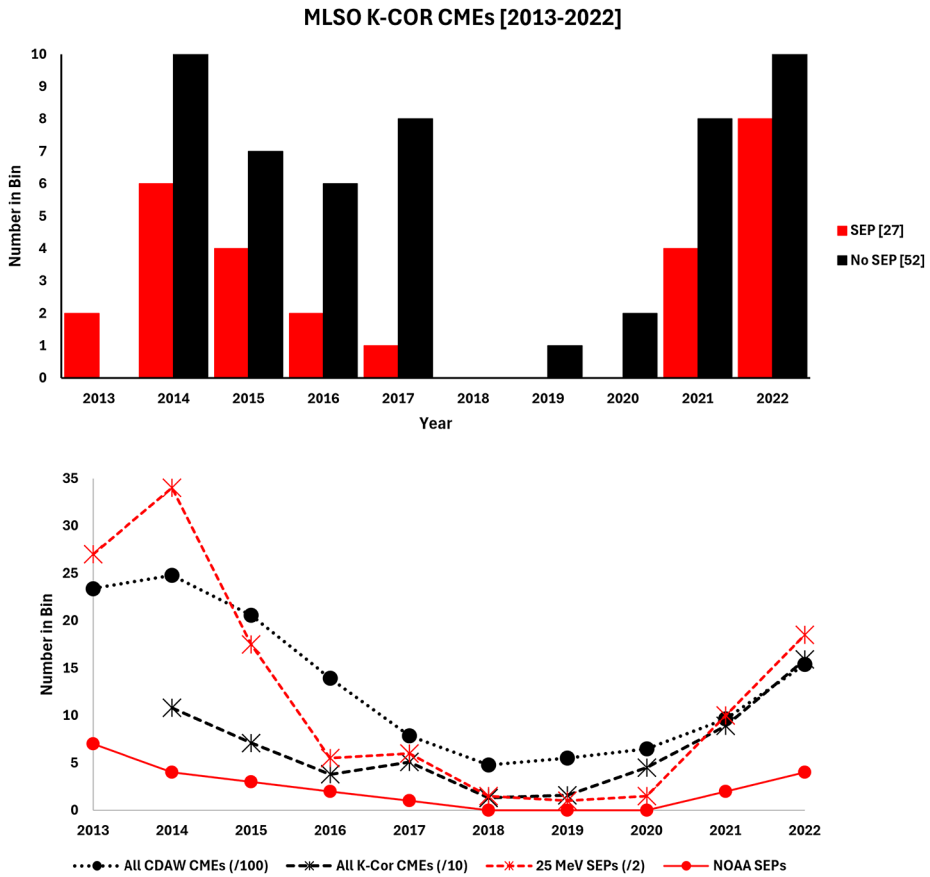


Figure 2 The top panel shows the annual counts for the SEP and non-SEP K-Cor CMEs considered in this article. The bottom panel shows the annual counts for: all CMEs listed in the CDAW compilation (scaled by a factor of 100), all CMEs detected by MLSO K-Cor (scaled by a factor of 10), all of the individual ~ 25 MeV SEP events listed in Richardson et al. (2026, scaled by a factor of 2; note also that the number of SEP events is influenced by the changing locations of the STEREO spacecraft relative to Earth), and all GOES > 10 MeV proton events that registered on the NOAA S-level scale.

Table 2 The distributions of the central position angles of the two samples of K-Cor CMEs. They appear to be equally divided between North and South hemispheres, as well as East and West limbs, for both sets of events.

CME	K-Cor	K-Cor
LOCATION	Non-SEP	SEP
Total	52	27
EAST CPA	25 [48%]	13 [48%]
WEST CPA	27 [52%]	14 [52%]
NORTH CPA	27 [52%]	13 [48%]
SOUTH CPA	25 [48%]	14 [52%]

it is likely there would have been fewer eastern SEP-associated CMEs had the STEREO spacecraft observations not been included.

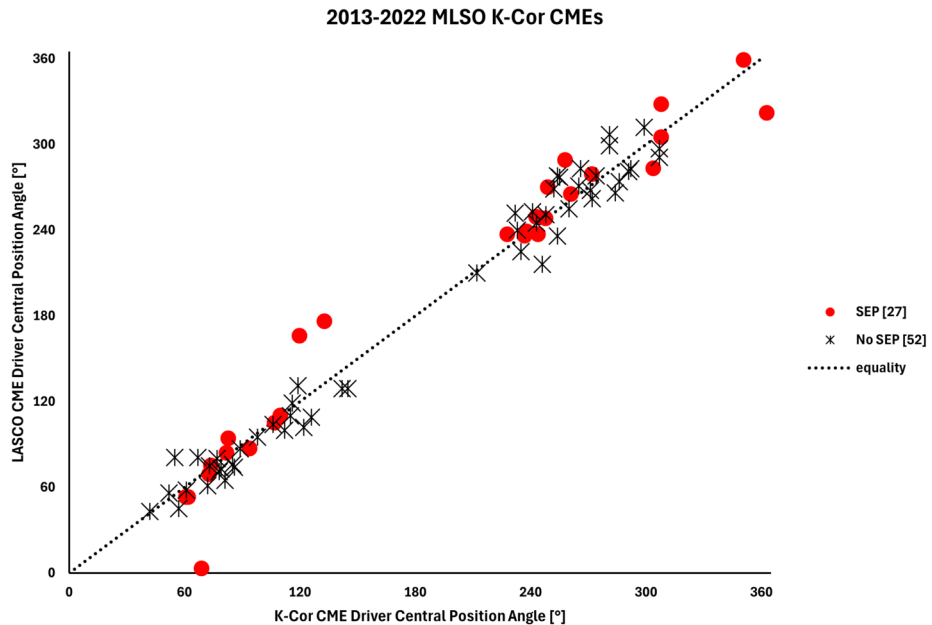


Figure 3 Scatterplot of the CPAs in MLSO and LASCO for both CME populations. Some of the scatter may be due to deflections as the CMEs traveled from the inner to the middle corona.

This is also apparent in the scatterplot in Figure 3, where CMEs in both samples have similar CPAs in the inner corona (K-Cor) and in the middle corona (LASCO C2) – the dotted line indicates equal CPAs in K-Cor and C2. The two groupings in the figure correspond to CMEs above the East or West limbs and indicate the general absence of events at high latitudes, though there are two SEP-associated CMEs with apparently high northern CPAs near 360° in K-Cor, and one maintains this direction in LASCO. The noticeable outlier at K-Cor CPA $\approx 65^\circ$ occurred on February 11, 2016, which was a day with poor data quality for K-Cor. This resulted in a portion of the CME not being visible in the angular width measurement, hence the K-Cor CPA is offset from that measured in LASCO C2. There appears to be little difference between the two populations of SEP and non-SEP CMEs based on the location of their appearance.

The angular size (width) of the CME driver is the next characteristic to examine, and in Figure 4 we see clear distinctions between the SEP and non-SEP populations. As discussed below and in Appendix A, the size of the driver CME is measured as low in the FoV of K-Cor or LASCO C2 as possible after the event has formed fully, and it excludes any obvious deflected structures or shock wings. The top panel of Figure 4 shows the distribution of widths in the inner corona (typically $< 1.5 R_s$) as measured in K-Cor, and the bottom panel shows the same parameter measured in LASCO C2 (typically $\sim 2.5 R_s$). Although the sample size is smaller for the SEP CMEs so the distribution is less clear, their widths tend to be larger in the low and middle corona than for the non-SEP CMEs and include several particularly wide examples that are not found for the non-SEP CMEs. The averages in each region of the corona are shown, and they indicate expansion between the inner and middle corona for both samples of SEP and non-SEP CMEs; however, the average and the median widths for the SEP CMEs are a factor of $\sim$ two larger than the non-SEP in both the inner and middle corona.

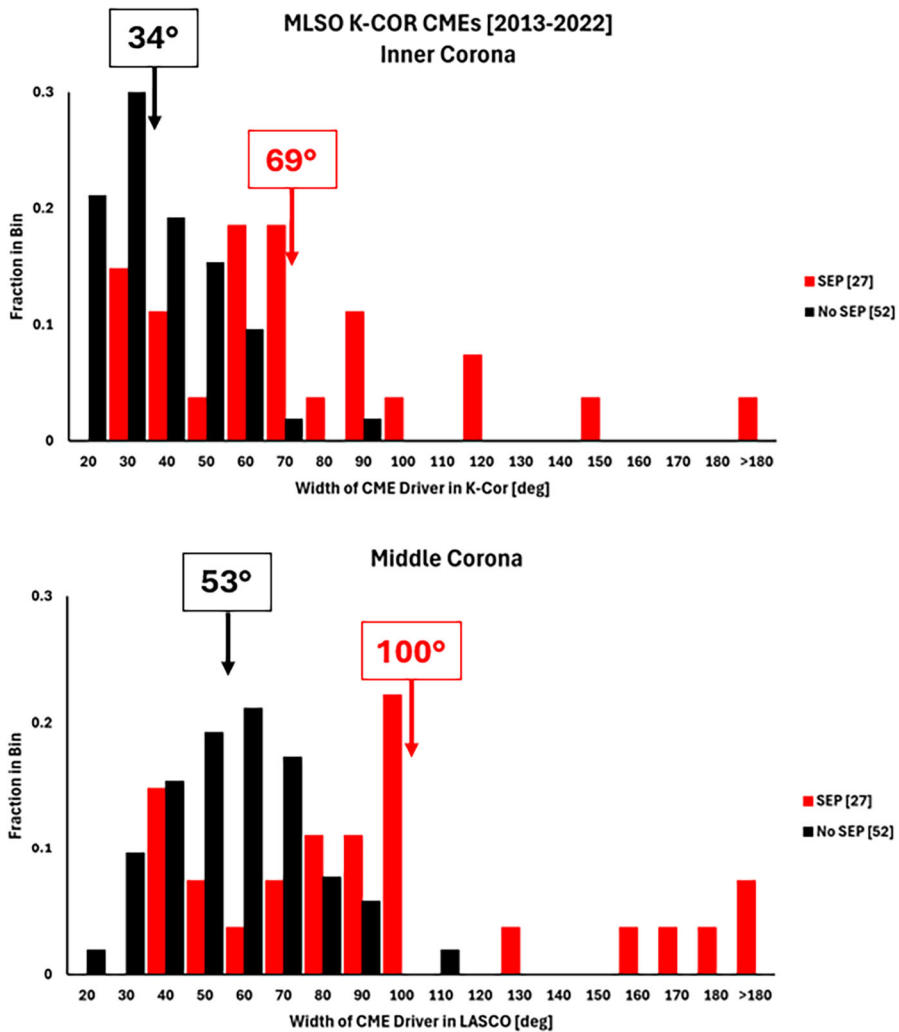


Figure 4 Histograms of the angular size of the CME driver for both SEP and non-SEP samples. The fraction in each 10° bin is plotted. The top panel shows the distributions as measured in the inner corona in K-Cor, and the bottom panel shows the CME driver sizes in the middle corona, as measured in SOHO/LASCO C2. The average size is indicated for each sample in each panel. The median CME driver size in K-Cor was 30° (61°) for non-SEP (SEP), and the median CME driver size in LASCO C2 was 53° (85°) for non-SEP (SEP).

The scatterplot in Figure 5 shows how each individual CME driver expanded from K-Cor to LASCO C2. The separation between the SEP CMEs and the non-SEP samples is again apparent, as the SEP CME drivers are generally wider in both regions. Most points lie above the line of equality, indicating the well-established fact that most CMEs are expanding between the inner and the middle corona [e.g. Cremades, Iglesias, and Merenda 2020].

We also quantified the kinematic behavior of these two samples of CMEs. As described in Section 2.1 and illustrated in Appendix A, we determined two fits for each set of height-time measurements in the inner corona, where the uncertainty of each measured point is consid-

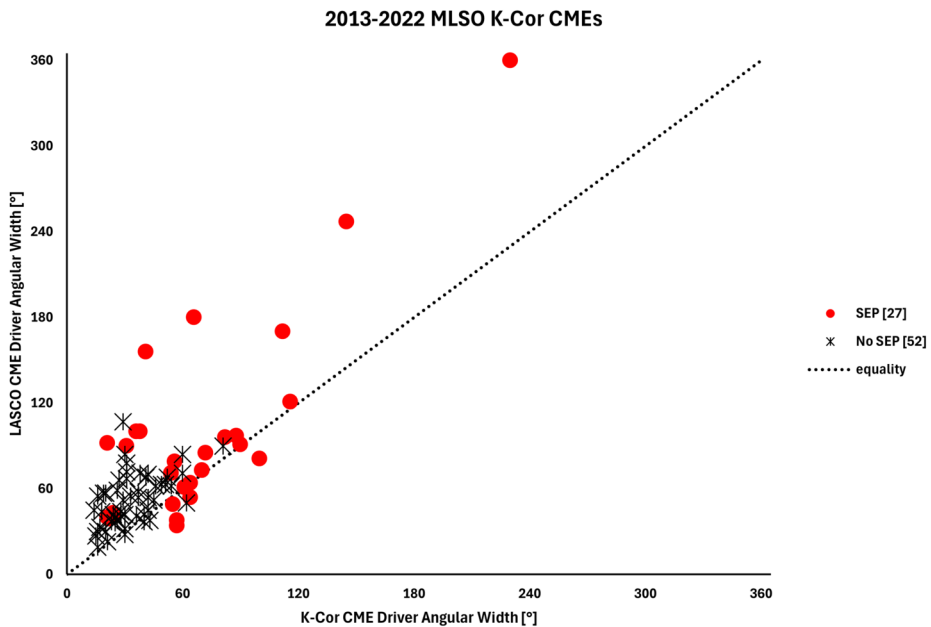


Figure 5 Scatterplot of the CME driver size in both the inner and middle corona, for both samples. Most CME drivers were wider in the middle corona, lying above the line of equality.

ered through its weighting in the regression analysis. Although in most cases one would expect the quadratic regression to provide a better fit, we computed the χ^2 goodness-of-fit as a primary criterion in determining which fit was superior. Other criteria included the distribution of the measurements (to avoid clustering of points made at similar times/heights), and how well the linear regression passed through the error estimates of all the data points.

The most meaningful kinematic measure of a CME is the speed of its leading edge (LE), so we concentrate on those measurements here. There were 21 SEP K-Cor CMEs where we were able to determine a speed for the leading edge (i.e., excluding 2 SEP CMEs where no speed could be determined, and another 4 SEP CMEs where speed measurements were only available for a trailing feature). The non-SEP sample contained 43 K-Cor CMEs with measurements of the leading edge speed. The distributions of leading edge speeds for both samples are shown in the inner and middle corona (taken as the linear speed in LASCO from the CDAW catalog) in Figure 6, where it is apparent that the SEP CME average speed in the inner corona (773 km/s) is more than a factor of two faster than the non-SEP average (344 km/s). Nevertheless, there are several non-SEP CMEs with relatively high speeds above 1000 km/s in the inner corona.

Figure 7 shows a scatterplot of the individual CME speeds in the inner and middle corona; a nominal 10% uncertainty in the speed is shown as an error bar. It is important to note that several of the SEP events have significantly higher speeds in the K-Cor FoV compared to the speed measured in LASCO. These events have undergone large initial accelerations in the inner corona but are decelerating to lower speeds in the middle corona as seen in LASCO. This reinforces the point that it is important to include low corona observations of CMEs when comparing CME kinematic properties to characterize the associated SEP events.

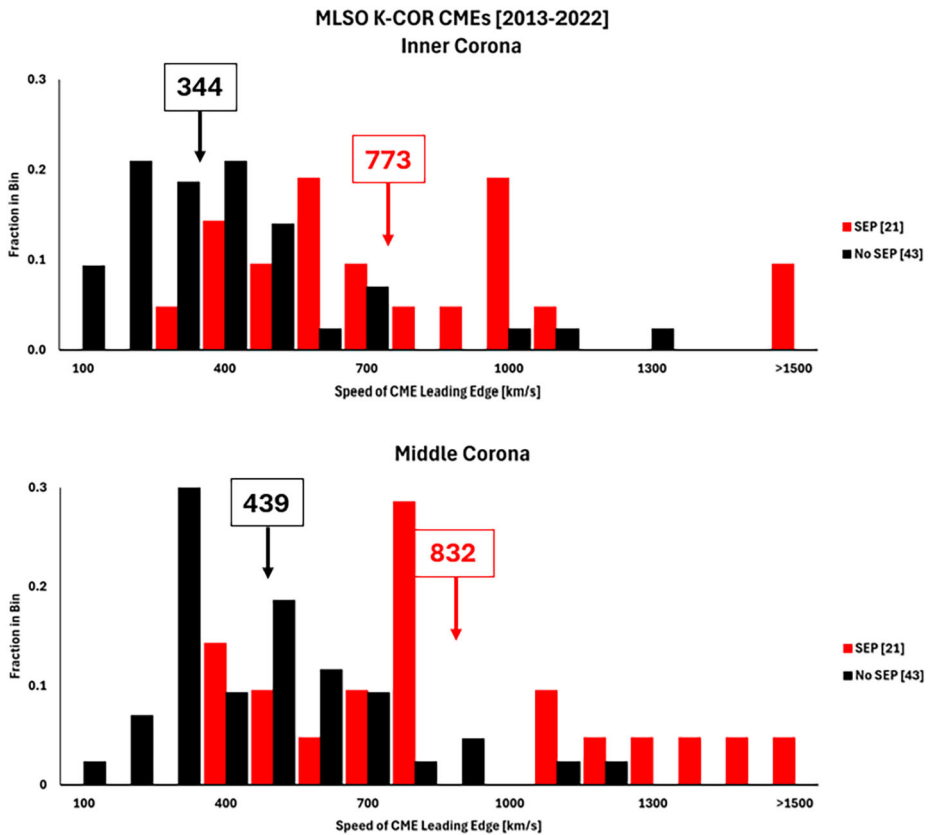


Figure 6 Histograms of the speeds of leading edges for SEP and non-SEP CMEs. The fraction in each 100 km/s bin is plotted. The top panel shows the distributions as measured in the inner corona in K-Cor; and the bottom panel shows the CME speeds in the middle corona, taken from the CDAW catalog and measured in SOHO/LASCO C2. The average speed is indicated for each sample in each panel. The median speed for the non-SEP sample in the inner [middle] corona was 303 km/s [428 km/s]. For the SEP sample the median speed in the inner (middle) corona was 664 km/s (742 km/s).

Because of the high temporal cadence in K-Cor, we were able to determine a reliable acceleration for most CMEs while they were in the inner corona. For those cases where the χ^2 test indicated that the quadratic fit was superior to the linear fit for the CME speed, we compared the accelerations measured in K-Cor with those listed in CDAW, which were determined from measurements made in the middle corona. Almost all of the accelerations/decelerations based on LASCO measurements in the middle corona are best fit by a linear regression and fail the χ^2 comparison with the quadratic fit, and the LASCO average accelerations are about 20 times smaller than the averages in K-Cor. As expected, we found that most of the CMEs (> 80%) are accelerating in the inner corona for both SEP and non-SEP CME samples. This is shown in Table 3, where both the average deceleration and acceleration are larger for the SEP CME sample, though we caution that the deceleration averages may not be significant since the number of decelerating CMEs is small. We see that the average acceleration in the inner corona for the SEP CMEs is almost a factor 3 larger than for the non-SEP sample.

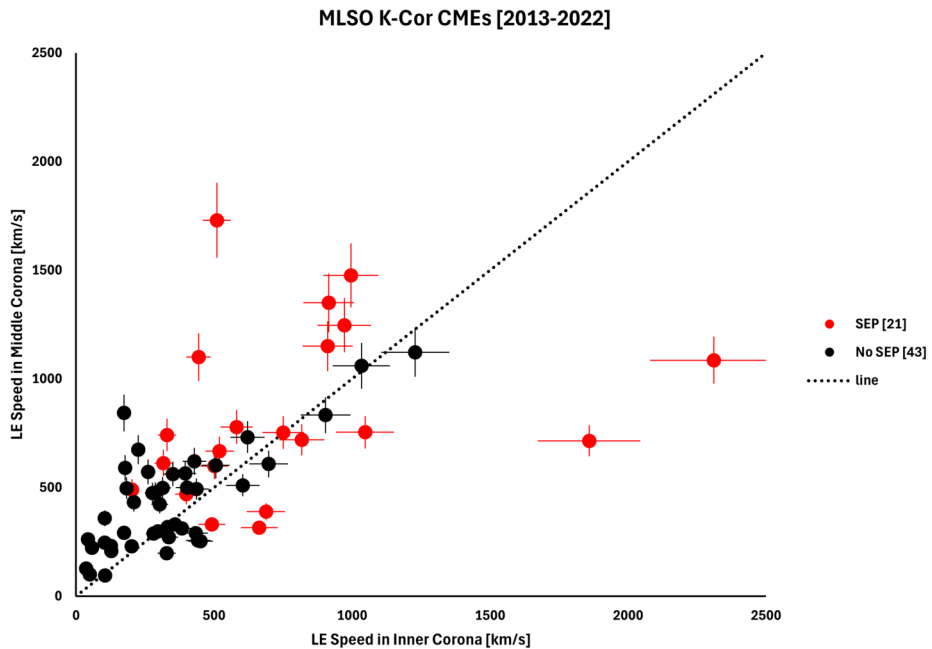


Figure 7 Scatterplot of the CME leading edge speeds in the inner and middle corona, for both SEP and non-SEP populations. The middle corona speeds are taken from the CDAW catalog.

Table 3 In the two columns labeled “K-Cor” are the numbers of events and average decelerations and accelerations in the inner corona for events where the χ^2 indicated the quadratic fit to the inner corona height-time measurements was superior to the linear fit. The values in the rightmost two columns are taken from the CDAW catalog of LASCO CMEs in the middle corona for each sample of CMEs.

	K-Cor	K-Cor	LASCO	LASCO
	NO SEP	SEP	NO SEP	SEP
Total	43	21	52	27
Quadratic Superior	19 [44%]	13 [62%]		
Number Decelerating	3 [16%]	2 [15%]	20 [38%]	15 [55%]
Average Deceleration [km/s ²]	-0.22	-0.39	-0.012	-0.016
Number Accelerating	16 [84%]	11 [85%]	32 [62%]	12 [44%]
Average Acceleration [km/s ²]	+0.18	+0.53	+0.007	+0.014

Figure 8 shows the distributions of the acceleration and deceleration for the two CME samples in the low and middle corona. The semi-logarithmic plot shows rather dramatically that most of the acceleration (and deceleration) for CMEs takes place in the inner corona. The middle corona accelerations/decelerations (taken from the CDAW catalog) are around an order of magnitude or more smaller than in the inner corona, which is in agreement with the similar result found in Paper 1 using the lower (3 minute) cadence MLSO Mk3/4 observations. The distributions are also similar for both the SEP and non-SEP CMEs.

We have also examined the estimated masses (derived from CME brightness) for the CME SEP and non-SEP samples. A comprehensive study of the evolution of mass in the

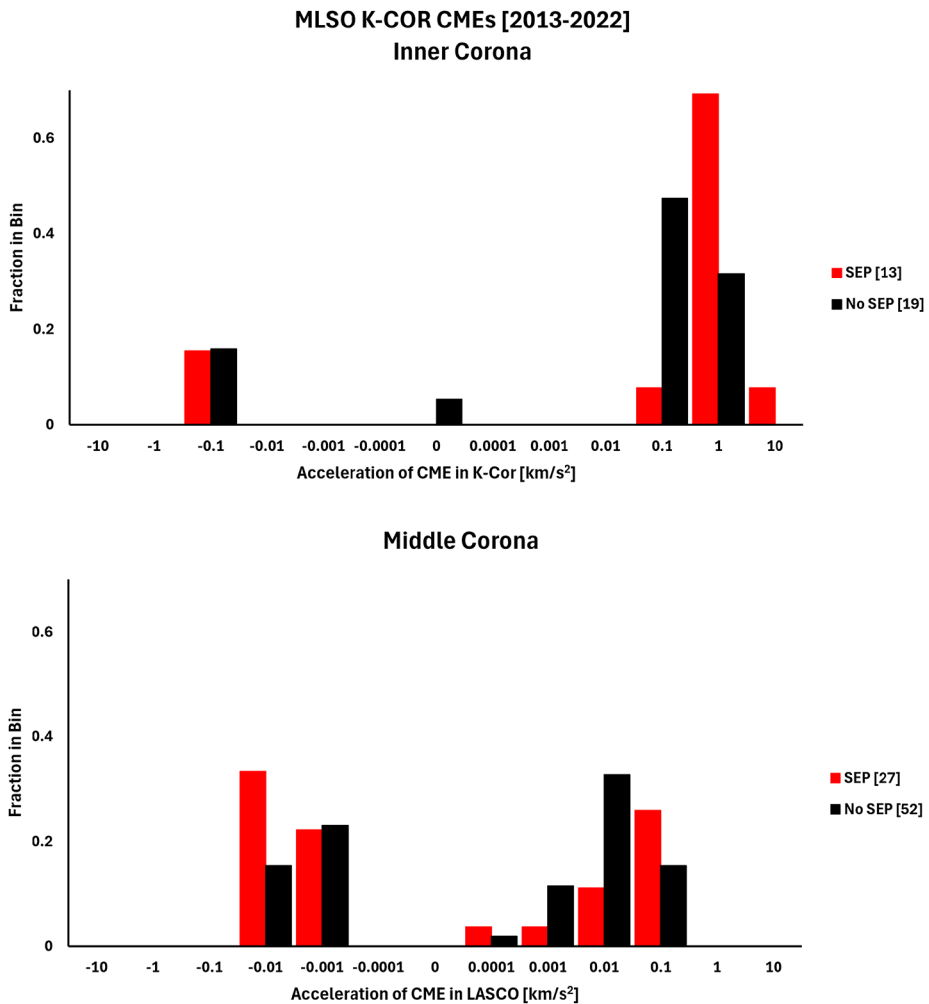


Figure 8 Histograms of the CME acceleration, both positive and negative for SEP and non-SEP CMEs. The fraction in each logarithmic bin is plotted. The top panel shows the accelerations of CMEs in the inner corona measured by K-Cor for those cases where the quadratic regression fit to the height-time measurements was considered superior to the linear fit. The bottom panel shows the histogram of accelerations in the LASCO FoV from the CDAW catalog for all CMEs in both SEP and non-SEP samples. The accelerations/decelerations are evidently larger in the inner corona than in the middle corona but have similar distributions for the SEP and non-SEP CMEs. Also, the average acceleration in the inner corona for SEP CMEs is almost a factor of 3 larger than for the non-SEP sample.

inner corona for CMEs detected by K-Cor has not been performed, but an initial characterization of the electron densities and excess mass in CMEs is underway (F. Lopez, personal communication, 2025). In the interim, we can compare the mass estimations from LASCO observations of the middle corona provided in the CDAW catalog for each CME in the two samples (e.g. Vourlidis et al. 2011). While the absolute values of the CME masses are generally considered uncertain, they are useful to compare across large samples. One source of uncertainty in the CDAW mass estimates is that the entire angular width (i.e., includ-

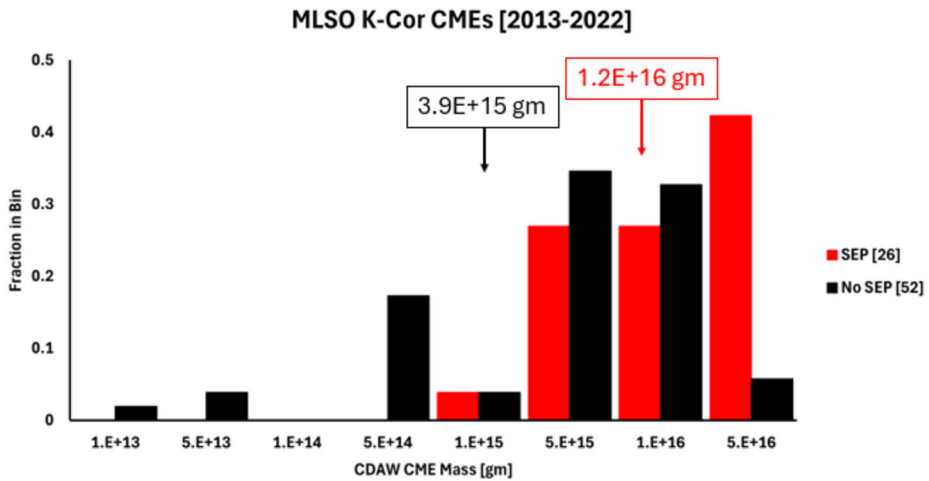


Figure 9 Histograms of the mass estimates for SEP and non-SEP CME samples from the CDAW catalog and measured in SOHO/LASCO C2. The SEP CME of January 4, 2014, did not have a mass estimate in CDAW because it was a “LASCO C3 only” detection. The average mass is indicated for each sample. The median mass for non-SEP (SEP) CMEs was 2.1×10^{15} g (8.7×10^{15} g).

ing deflections and shock wings) is used in the brightness-to-mass calculation, though these features are considered to make a small contribution to the total mass (S. Yashiro, personal communication, 2025).

In Figure 9 we show the distribution of CDAW mass estimates for the SEP and non-SEP CMEs. Both the average and the median masses for the SEP CME sample are ~ 3 times larger than those for the non-SEP CMEs, with the main differences in the distributions being the tail of low mass non-SEP CMEs and the preponderance of SEP CMEs in the largest mass bin. Of course, the increased mass is not solely due to the larger average width, but also likely due to higher density.

4. Solar Activity Associated with the MLSO K-Cor CMEs

4.1. GOES X-ray Signatures

We have examined the SEP and non-SEP CME samples with respect to the peak intensity of the GOES soft X-ray flares that accompanied the events. Figure 10 shows the histogram of the peak X-ray flux distribution for the two samples (corrected as in Figure 1). The average peak X-ray intensity for SEP CMEs is a factor of ten higher than the average for non-SEP; the SEP CMEs are most likely to be associated with mid-M class flares, compared to mid-C class for non-SEP CMEs. However, as discussed above, our SEP CME sample does not include major SEP events associated with intense X-class flares during the study period since the few significant events during this era occurred when MLSO was not making observations.

Using the K-Cor observations in this study we were able to determine the height of the CME at the time of peak X-ray flux, which can be directly determined with the combination of MLSO and LASCO observations without the need for extrapolations; this distribution is shown in Figure 11. The average height is similar for both CME samples, with over 70%

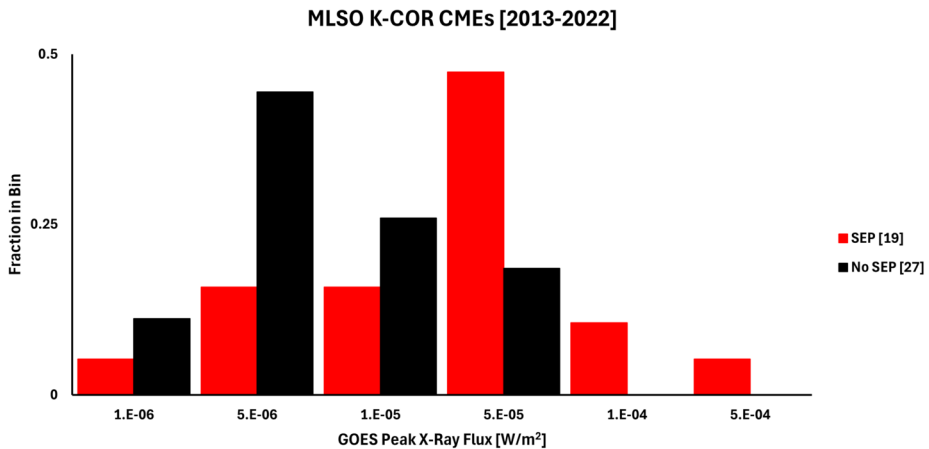


Figure 10 Histograms of the GOES peak soft X-ray flux for the two CME samples. The values prior to December 18, 2017, have been multiplied by 1.43. The average peak flux is indicated for each sample, and the median values for SEP (non-SEP) were $2.0\text{E-}5$ ($4.7\text{E-}06$) W/m^2 .

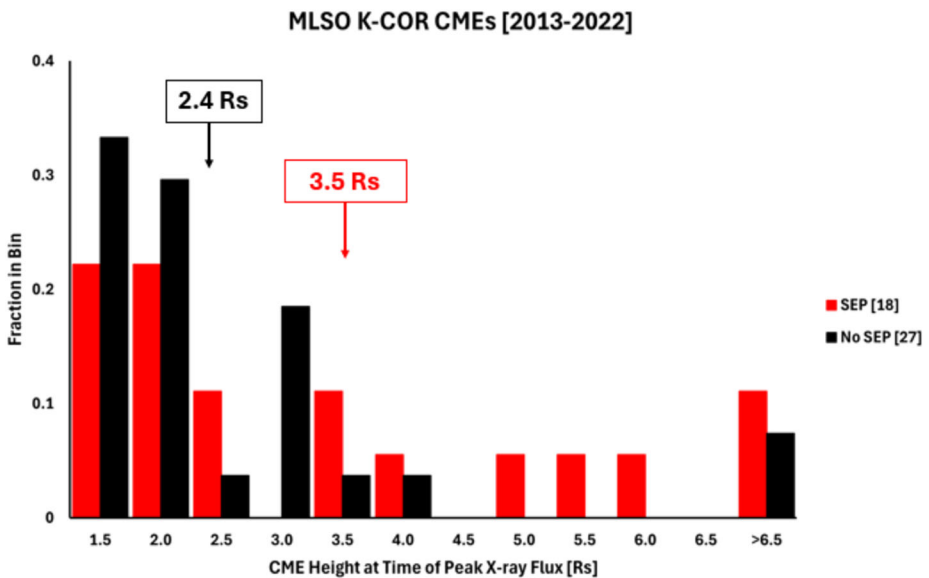


Figure 11 Histograms of the height of the CME at the time of peak X-ray flux. Over 70% for both samples are $< 4 R_s$ at the time of peak X-ray flux.

of the CMEs being $< 4 R_s$ at the time of peak X-ray flux in both samples. We have further examined the 10 events (7 SEP and 3 non-SEP, or about 13% of the total events) where the CME height was $> 5 R_s$ at the time of peak X-ray flux. Not surprisingly, the average terminal speed of these events is higher than the average for those whose height is $< 5 R_s$. Conversely, there are other events in both samples with very high terminal speeds yet the CME was very low in the corona when the X-rays peaked, so speed is not the only factor determining this height. In particular, in 7/10 cases with heights $> 5 R_s$, the rise time of the

Table 4 The tabulation of the eruption type for the SEP and non-SEP samples as determined from SDO AIA images. See text for explanation of different categories.

		AIA	Prominence	Coronal	Very Hot
	TOTAL	Data Gaps	Eruptions	Temperature	Trailing
				Loop/Bubble	Flux Rope
SEP	15	0	11	15	7
No SEP	49	3	36	36	2

X-rays appeared to be slow and/or extended; and in half the cases, the associated activity was slightly behind the solar limb.

4.2. SDO/AIA Signatures

For each of the SEP and non-SEP CMEs, we have examined the properties of the low corona eruption observed by SDO/AIA and have identified a feature in these observations that may help to distinguish which eruptions are likely to be associated with SEPs. We considered only those CMEs that were close to the limb, thereby ensuring that the morphology of the erupting feature might be better viewed by AIA. With a few exceptions, we were able to use most of the Song et al. (2023) sample of 52 non-SEP CMEs since they were originally chosen to be near-limb events. Based on the location of the associated activity for the K-Cor SEP CMEs (Table 1), we identified 15/27 SEP events as being within 30° of the limb.

As briefly described in Appendix A, we used a simplified classification scheme for the eruption based on Nindos et al. (2015). There were three morphological features we attempted to identify for each CME in the study:

- Was an erupting flux rope (EFR) visible in the coronal channels? This may appear as a loop/bubble in the AIA 171 Å, 193 Å, 211 Å, 335 Å channels, and is likely in the 1–2 MK temperature range.
- Was structured prominence material visible in emission in the AIA 304 Å channel and/or in absorption in the coronal temperature channels?
- Was a very hot trailing flux rope visible in the AIA 94 Å or 131 Å channels? Hot trailing flux ropes are mostly detected in association with > M-flares, but they do not appear in the cooler coronal channels. Frequently these very hot flux ropes trail the coronal loop/bubble by $\sim 0.1 R_s$.

These are not exclusive categories – a prominence may or may not be an erupting flux rope, or there might not be an EFR, or all three features might be present. Table 4 shows the associations for the samples of near-limb SEP and non-SEP CMEs. Most interestingly in terms of an association with SEPs, there were 9 CMEs with very hot flux ropes in the 64 events for which an AIA classification could be made, and most (7/9 or 78%) were associated with SEP events. Hence, based on these results, the observation of a very hot flux rope associated with a CME appears to be a strong indicator of a potential SEP event. On the other hand, we also note that there are SEP CMEs (8/15) that lack hot flux ropes (such as the November 01, 2011, event discussed in Appendix A), so that this is not a necessary signature of an impending SEP event.

5. Discussion

This study has demonstrated that MLSO K-Cor can detect CMEs associated with SEP events over a range of intensities and locations, and it suggests that SEP associated CMEs have

Table 5 Date and time listed in CDAW catalog for the five CMEs that occurred during MLSO K-Cor observations that were associated with SEP events, but were not evident in K-Cor. The source location (determined from SDO/AIA and/or STEREO/EUVI images, e.g., Richardson et al. 2026) and the CDAW estimated mass are in columns 3 and 4.

Date	CDAW 1st Appearance [U.T.]	Source Location	CDAW Mass [gm]
2014-01-21	18:48	30° behind West limb	2.5×10^{15}
2014-01-21	21:17	69° behind East limb	9.3×10^{14}
2017-09-04	20:36	Near disk center	7.6×10^{15}
2018-02-12	1:25	Near disk center	6.2×10^{15}
2021-07-13	19:00	88° behind West limb	5.2×10^{15}

average properties that differ from those that are not associated with SEPs. However, our sample of SEP-associated events is rather limited due to MLSO operational constraints and an overall paucity of extreme eruptions during 2013–2022. Here we discuss further several considerations relevant to the analyses presented in this study.

5.1. SEP CME Detection Rate and Brightness

There were five SEP-associated CMEs that were reported in the CDAW catalog when K-Cor was observing but were not detected, and they are shown in Table 5. We can conclude that out of a possible 32 SEP CMEs that occurred when K-Cor was observing, 27 (84%) were detected and characterized, which is a slightly smaller percentage than, but commensurate with, the 92% detection rate estimate reported in Paper 1 for the 1980–2013 period using the MLSO Mk3/4 coronameters.

Is there a reason why these five SEP-associated CMEs were not detected despite there being reasonable K-Cor observations during their passage? Historically, Webb and Howard (1994) were able to define a “visibility function” correction to compare CME rates between various coronagraphs; this was expanded by Vourlidis et al. (2020) to different spacebased telescopes during the K-Cor era. As described in detail in St. Cyr et al. (2000), the contrast of a CME in a coronagraph depends on the change in brightness in the imaged scene compared to the background comprised of the F- and K-coronae, as well as any instrumental stray light. For a spaceborne instrument in constant daylight like SOHO/LASCO at the Lagrangian L1 point, there is a rather slowly varying background that can be modeled and subtracted, as well as a mostly unchanging stray light pattern, resulting in a large dynamic range of detectable changes. For a groundbased coronagraph measuring changes in pB, an inherently lower signal than the total intensity observed by spacebased instruments is detected against a larger fluctuating background of changing sky conditions. Additional variations in the background include changes in the sky from terrestrial weather, dust, insects, and pollutants; changes in the cleanliness of the optical train in the telescope due to dust intrusion; and changes in the polarization as the Sun moves across the sky. These factors have not all been accounted for in K-Cor, so that, for example, the mass estimates for K-Cor CMEs in the inner corona are ongoing work. The K-Cor processing pipeline corrects for variation in sky brightness and sky polarization over the observing day. However, the quality of the observations is significantly degraded by increases in aerosols, as noted above, and when sky brightness becomes large enough that the signal-to-noise ratio approaches or falls below one (1).

As mentioned in Section 2.2 (with regard to Figure 2), improvements in the instrumental stray light rejection in K-Cor took place during the initial years of observations. These

included more frequent cleaning of the objective lens, as well as improved cleaning techniques. More importantly, the introduction of new, black, absorptive material in the telescope light dump and occulter assembly in 2019 significantly improved the stray light rejection. We note that four of the five SEP CMEs not detected by MLSO occurred before 2019, and we attribute this in part due to the higher instrumental stray light. There are two additional relevant factors that support this reasoning, and they are listed in Table 5. First, based on the location of the associated activity in the low corona, four of these five CMEs were not near the plane-of-the-sky, which means the scattering function for pB radiation was significantly reduced. In fact, of the 27 K-Cor SEP CMEs in Table 1, 15 (55%) were within 30° of the Sun's limb. The second factor in these five non-detections is evident in the CDAW mass estimates for those CMEs (as noted above, we do not yet have mass estimates based on MLSO). The average was 4.5×10^{15} g, meaning these were faint events for any coronagraph attempting to image them. Although there are a few non-SEP events with similar low mass estimates in Figure 9, recall that all of the non-SEP events were selected by Song et al. (2023), to be near the limb, whereas these five non-detections were both faint and well out of the sky plane.

We note that the results of CME mass analyses have appeared before in the literature for SEP versus non-SEP events. Kahler and Vourlidas (2005) concluded that SEP-rich CMEs have a higher mass density (as expressed in [grams/degree]) than SEP-poor CMEs, which is complementary to Figure 9 of this article. In addition, we note that the 11 “fast and wide” CMEs during the STEREO era that were not SEP-productive reported by Lario et al. (2020) had (using the CDAW compiled mass estimates) an average mass of 4.7×10^{15} g, which is similar to the average in Figure 9 for the non-SEP sample in this study.

5.2. SEP CMEs and Associated Activity

Most CME compilations have been based on observations by externally-occulted space-based coronagraphs; hence it has been necessary to extrapolate from middle corona measurements back to the inner corona. This introduces uncertainty in determining such properties as the sequence of associated activity, the initial acceleration of the CME, or the CME location at any given time (e.g. MacQueen 1985). Many researchers have reported on the initial acceleration of CMEs near the Sun and the relationship with GOES X-rays light curves. Zhang et al. (2001) and Zhang and Dere (2006) argued that the impulsive acceleration of the CME often coincided with the rise of the X-ray flux to its peak value, after which a much smaller residual acceleration resulted in a constant speed. This connection between the flare rise timing and the CME acceleration was strengthened by Bein et al. (2012) who examined a sample of 95 CMEs detected by the STEREO/SECCHI suite of instruments. For 70 of those events, the associated GOES X-ray emission could be identified, and they found that for 60% of these cases, the time difference between the peak CME acceleration and maximum X-ray flux derivative was smaller than ± 5 minutes. More recently, Majumdar et al. (2020) examined 59 CMEs observed by STEREO and found that in most cases, the impulsive acceleration as well as width expansion occurs in the $2-3 R_S$ altitude range.

We believe Figure 11 demonstrates for the first time the relationship between direct measurement of the height of our samples of SEP and non-SEP CMEs and the timing of peak X-ray flux. Improved understanding of this relationship may have potential utility for SEP prediction – as Whitman et al. (2023) note, many SEP models use CME parameters as input, as well as the flare peak time typically defined by the GOES/XRS full-disk soft X-ray flux.

5.3. The Importance of Inner Coronal Observations for CME Warning Time

St. Cyr, Burkepile, and Posner (2017) discussed how near-real-time alerts of the formation of a fast CME could provide a useful warning for the possible onset of a SEP event, and they provided a single example demonstrating this concept (the K-Cor event of January 01, 2016). In Paper 1, we examined the timing of the SEP near-relativistic electron onset (typically the earliest arriving particles) versus the first CME detection for a sample of 50 MLSO Mk3 and Mk4 CMEs, and we assessed the improvement in the detection time over that of a spacebased coronagraph. This assessment can be expanded with the samples of SEP and non-SEP CMEs used in this article.

The top panel of Figure 12 shows graphically the 1st detection height for all 64 K-Cor CMEs (21 SEP CMEs and 43 non-SEP CMEs) for which we could estimate the speed of the leading edge (circles; the vertical lines from each circle indicate the range of heights for the K-Cor observations). We found that the average 1st detection height in K-Cor for the 21 SEP CMEs (43 non-SEP CMEs) where the leading edge could be measured was $1.4 R_s$ ($1.4 R_s$), and those measurements were made over an average span of $1.0 R_s$ ($0.9 R_s$). This can be compared with the average 1st detection height in LASCO C2 of $3.2 R_s$ for SEP events and $2.7 R_s$ for non-SEP events (asterisks in the top panel of Figure 12 indicate this height for individual CMEs). In analyzing the events in this study, we noted that most of the SOHO/LASCO C2 images were acquired with a cadence of about 12 minutes, similar to the value reported by Wang and Colaninno (2014) who found that the LASCO image cadence averaged 13.8 minutes after 2010. This is important because, for a given FoV, the image cadence convolved with the CME speed determines how quickly one can acquire the images needed to generate a CME detection, speed, and ultimately an alert (neglecting any other effects such as latency) compared to any SEP arrival time.

An alternative way to assess the value of MLSO K-Cor in providing an earlier warning of a CME than a spacebased externally-occulted coronagraph is in terms of the interval between the 1st CME detections in the two telescopes, as shown in the bottom panel of Figure 12 versus the CDAW LASCO CME speed. This is demonstrated in Appendix A of this manuscript for the November 01, 2011, example. The average time difference between the K-Cor and LASCO C2 first detection of each SEP (non-SEP) CME was 28 minutes (56 minutes). If we disregard the three slow non-SEP CMEs with very long delays between their detection by K-Cor and appearance in the LASCO C2 FoV that are beyond the range of the plot (indicated by upward arrows), the average drops to 40 minutes for non-SEP CMEs. Of course, these times do not include data latency, which for K-Cor is 2.5 minutes, and for LASCO can be many hours. The figure also shows a general trend towards shorter time differences between first detection for faster CMEs, as might be expected. While this does suggest that the earlier warning provided by a groundbased observatory is less significant for the fastest CMEs (that are of particular interest to their potential for SEP productivity), we reiterate that this assessment does not take into account the additional latency for spacebased observations resulting from lower image cadence and telemetry downlink limitations.

5.4. The Future

How do K-Cor and groundbased coronagraphs in general fit into current and future plans for CME monitoring? Considering the spacebased observations, SOHO was launched 30 years ago, and although many of the instruments continue to produce scientific quality measurements (including LASCO), that mission will be decommissioned by both ESA and NASA

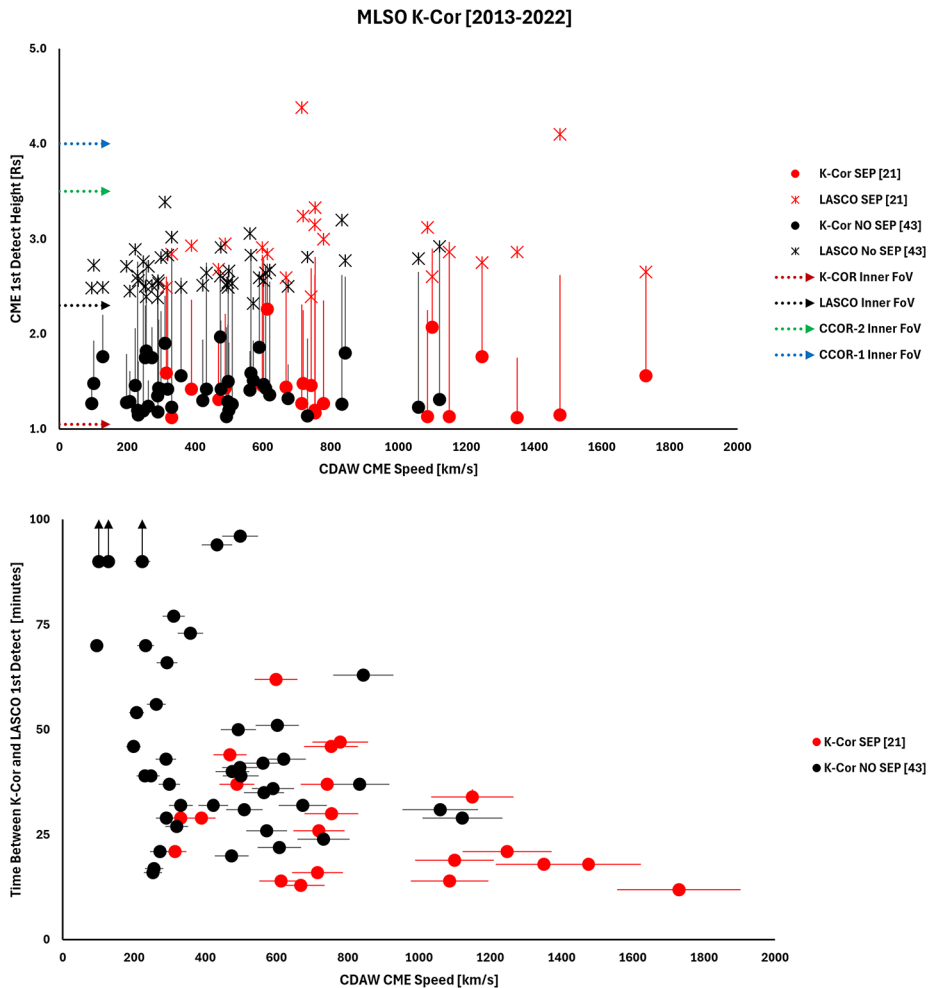


Figure 12 The top panel is a scatterplot showing the 1st detection heights of SEP and non-SEP CMEs in the inner corona from K-Cor (circles) and the middle corona from LASCO C2 (asterisks) versus the speed in LASCO from the CDAW catalog. Horizontal arrows along the vertical axis show the inner fields of view for relevant coronagraphs. The spans of measurement heights from K-Cor are shown as vertical lines. In the bottom panel, the vertical axis is the time [in minutes] between K-Cor and LASCO C2 first detecting each CME. The horizontal axis is again the CDAW CME Speed (with nominal 10% error bars on these speeds). See text for discussion of average values.

at some point in the foreseeable future (D. Muller, personal communication). The decommissioning will follow an extended period of overlap to accomplish calibration and validation activities between SOHO/LASCO and the two new NOAA CCOR (Compact CORonagraphs, Thernisien et al. 2025) that are now in space. CCOR-1 was launched in June 2024 on GOES-19 into a geostationary orbit, and CCOR-2 was launched in September 2025 on board Space Weather Follow-On at Lagrange Point 1 (SWFO-L1) (recently renamed as Space weather Observations at L1 to Advance Readiness - 1 (SOLAR-1)) that has arrived at the Lagrangian L1 point. These two coronagraphs have similar optical design characteristics, with CCOR-1 (CCOR-2) having a FoV extending from 4–22 R_s [3.5–26 R_s] and a

spatial resolution of 39 arcsec (65 arcsec). The image cadence for each CCOR is 15 minutes, and the plan for both spacecraft is to have a latency of 30 minutes or less between image capture in space and when the image is available to a forecaster.

The primary goal of the NOAA CCOR telescopes is to monitor and track CMEs as the drivers of significant geomagnetic storms. Additionally, these telescopes will certainly be useful for archival studies of the terminal speed for CMEs associated with SEP events, but can they be utilized to monitor and provide alerts for SEP events? To determine the potential warning time for a fast CME, we examine the timing. Recall from Figure 6 that the average speed of SEP CMEs in this study was just over 800 km/s, and the average time between K-Cor 1st detection and LASCO C2 1st detection was 28 minutes. Given the inner FoV for CCOR-2 at 3.5 R_s , a CME traveling 800 km/s would add at least an additional 17 minutes detection delay compared to LASCO C2, assuming it was imaged as it emerged from behind the C2 occulter at the 2.3 R_s inner FoV. Depending on when it appeared relative to the CCOR-2 15 minute image cadence, this delay could increase to 32 minutes. Another 15 minutes would be necessary to obtain a second CCOR-2 image in order to determine the CME speed. Since a 25 MeV proton travels ~ 0.23 c and traverses the nominal 1.2 AU Parker spiral path in about 43 minutes (assuming no scattering), the SEP event would be in progress at 1 AU by the time the CME speed determination was available, assuming minimal telemetry latency and ground processing. The situation is even more critical for the higher energy particles that are of major concern for space and aviation operations because they will arrive even earlier. Although such high energy events are likely to be associated with CMEs that are much faster than the average speed considered here, the appearance of the CME relative to the 15 minute observing cadence, and the need to obtain and transmit a second image, will still be critically important factors.

As of this writing, STEREO A carrying the SECCHI COR1 and COR2 coronagraphs continues to operate nominally, and since August 2023 it has been in its second orbit around the Sun at ≈ 1 AU, drifting in longitude by 22° /year. Although it was designed to meet a two-year operational requirement, it has now been operating for almost 19 years. It continues to downlink a near-real-time broadcast of highly compressed solar images and in situ measurements that have proven useful to space environment situational awareness (Biesecker, Webb, and St. Cyr 2008); its continued health so long beyond its engineering design has been a boon to forecasters and researchers. Over the past few years Solar Orbiter, in a highly eccentric orbit through the heliosphere, has been downlinking daily snapshots of images and in situ conditions through a low-latency channel (e.g. Rouillard et al. 2020). In the future, a relevant quasi-operational platform off the Sun-Earth line may be the European Space Agency's Vigil mission to the Lagrange L5 point (e.g. ESA-S2P-LGR-MO-0002 2022) that will include a coronagraph based on the CCOR instruments discussed above.

We conclude that MLSO K-Cor could provide an early warning of SEP CMEs to complement spacebased observations in the future. The results discussed here do show differences in the average properties of SEP and non-SEP CMEs in the inner corona, though there is overlap in their properties. An additional issue is that the sample of SEP-associated K-Cor CMEs that we have identified (27 events) from 2013 to the interruption in MLSO operations in November 2022 is rather limited and is insufficient to represent the rich variety of SEP events (e.g. Desai and Giacalone 2016) in terms of their time profiles, intensities, and source properties (e.g., CME and flare characteristics, connection to the observing location). In particular, the largest SEP events associated with particularly fast CMEs are not represented. This does not appear to be due to a K-Cor selection bias against CMEs that are fast in the LASCO FoV but is simply due to the fact that none of these CMEs happened to occur during a window when MLSO observations are available. For example, the exceptionally

Table 6 From the CDAW catalog, a comparison of the number of fast (> 1800 km/s) CMEs based on the calendar days available for K-Cor observations (3343 days) to other relevant periods. NOAA S-level > 10 MeV proton events are listed for each period in the right-hand column. The Mk3/Mk4 period has not been corrected to account for the 5 month “vacation” that SOHO endured in 1998, so the number of CMEs and fast CMEs is a lower limit. Also note that in the less than three years to June 30, 2025, after K-Cor entered its hiatus in 2022, the Sun has produced 80% more fast CMEs, and almost as many S-level proton events, compared to the numbers during the 9 years of K-Cor observations.

MLSO Coronagraph	Date Range	[N ⁰ Days]	[N ⁰ CDAW CMEs]	[N ⁰ CDAW CMEs] w/speed > 1800 km/s	N ⁰ NOAA Proton Events
Mk3/Mk4	1996-01-11 to 2004-08-03	3127	12,072	39	80
Mk4	2004-08-04 to 2013-09-29	3343	12,707	37	40
K-Cor	2013-09-30 to 2022-11-25	3343	11,364	10	17
None	2022-11-26 to 2025-06-30	947	5292	18	14

fast (3163 km/s) CME on September 10, 2017, that entered the LASCO C2 FoV at 16:00 UT was well beyond the K-Cor FoV when observations started at 17:11 UT on that day, although K-Cor observed a bright, thin current sheet (e.g. Webb et al. 2003; Cheng et al. 2018) in the wake of the CME.

We do note that fast CMEs associated with intense SEP events were detected in Cycles 21–23 by the much less sensitive MLSO coronagraphs Mk3/4 (Richardson et al. 2023), including ground level enhancements. However, as Table 6 shows, the K-Cor observation era has been unusual in the low number of fast CMEs produced – there were only a fraction (10 events) of the very fast (> 1800 km/s) CMEs in the CDAW catalog during the 11 years of K-Cor operations as compared to the 37 in a period with the same number of days during the Mk4 era. In fact, there were 76 of these fast CMEs reported during the 17 years of Mk3/4 operations described in Paper 1 when LASCO was also making observations. Similarly, there were only $17 \geq S1$ proton events in the NOAA event catalog during the period of K-Cor operations, compared with 40 during the period with the same number of days preceding K-Cor, and a total of 120 during overlapping LASCO and Mk3/4 operations. K-Cor observations have taken place during the descending phase of Solar Cycle 24 and the ascending phase of Cycle 25, and both cycles were much less active than the previous cycles, especially in terms of very energetic events. Therefore, we anticipate that, with the restoration of MLSO operations, there will be opportunities in the future to characterize CMEs associated with such major SEP events during their passage through the inner corona.

Our sample of SEP CMEs highlights the limitations of using a single groundbased observatory for CME monitoring, in particular due to the restrictions on observation time due to geographic location, weather, maintenance, staffing, and, in the case of MLSO, an extended shutdown due to the Mauna Loa eruption. Nevertheless, there is keen interest in both the near-real-time alerts of CME detections and characterization, and the “all clear” signal that K-Cor produces when observing. Moreover, it is clear from the above discussion that the transition from LASCO C2 to coronagraphs using the CCOR design in the upcoming years will result in a reduction in opportunities to use those spacebased coronagraphs for the early detection of SEP associated CMEs. MLSO, now back in operation, will help to provide this early CME detection.

6. Summary of Findings

We have identified 27 CMEs observed by the MLSO K-Cor coronagraph that were accompanied by SEP events, specifically including ~ 25 MeV protons, detected by STEREO A/B and/or near-Earth spacecraft and by spacecraft in the inner heliosphere, from the installation of K-Cor in late 2013 to the eruption of Mauna Loa in November 2022 which closed the observatory (now reopened as of late March 2026). We have compared the properties of these CMEs with those of a control set of 52 CMEs that were not associated with detected SEP events, selected from a set of near-limb K-Cor CMEs discussed by Song et al. (2023). The associated SEP events cover a range of intensities and related solar phenomena that are typical of events during this period of reduced solar activity, but they include only a single large (S-level) event at Earth that would be of particular interest for NOAA operations; however, three events were detected at STEREO-A that appear to be S-level. The small sample of SEP CMEs largely results from the restricted observing time of MLSO due to geography, weather and operational factors, and the relatively low levels of activity in the weak Solar Cycles 24 and 25. The results suggest, at least on average, that the properties (e.g., speed, width, acceleration and mass) of SEP and non-SEP CMEs differ in the inner corona, with SEP CMEs having significantly larger average values for these parameters. We also conclude that real time monitoring of CMEs using groundbased coronagraphs will complement operational spacebased coronagraphs due to the smaller inner FoV and near real time CME identification and analysis with low latency that will allow earlier CME alerts to be issued.

Appendix A: K-Cor SEP CME of November 01, 2021

This is not intended to be a detailed description of all aspects of the solar eruption and subsequent SEP event (such as the events discussed by, e.g., Rouillard et al. 2012 and Kollhoff et al. 2021), but it does provide the reader with a flavor of the types of imaging and in situ data that are available to perform such case studies. It also illustrates types of data and some of the analysis techniques used throughout this article.

Figure 13 includes 1 minute averaged 0.7–1.4 MeV electron and proton (13.6–60 MeV) observations from the HET on STEREO-A and shows a clear SEP onset early on November 01, 2021, superposed on the decay of a previous SEP event that commenced on October 28. Relevant times of first detections by K-Cor and LASCO C2 are also indicated. As is typical (e.g. Posner 2007), the near-relativistic electrons, with onset at $\approx 02:01$ UT, arrived ahead of the tens of MeV protons which showed the energy dispersion typical of an SEP event onset. For example, Figure 14 shows that the SEP onset on November 01, 2021, was observed by the Energetic Particle Detector (Rodríguez-Pacheco et al. 2020) on Solar Orbiter and extended to at least 50 MeV protons above the elevated background from the previous event. The SEP event was associated with a solar event in NOAA Active Region 12887 located at S29W45 (the flare longitude is indicated by the black arrow in Figure 15) that included a NOAA GOES M1.5 soft X-ray flare that peaked at 01:45 UT. The CDAW catalog reports a LASCO CME at 02:00 UT (i.e., this CME was first observed by LASCO nearly simultaneously with the SEP electron onset at STEREO-A) with a linear speed of 753 km/s and width of 274° at a central position angle of 201° . From Figure 15 we see that several spacecraft were ideally located to observe the SEP event, including Solar Orbiter, Parker Solar Probe, near-Earth spacecraft, and STEREO-A located 37° East of Earth. All these spacecraft detected the event (e.g., see event C25-0016 in the SERPENTINE Cycle 25 SEP event

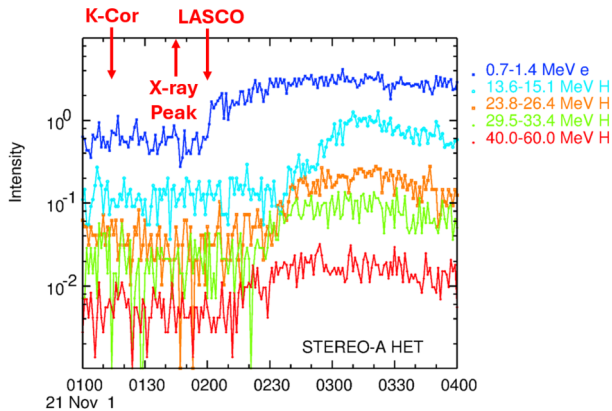


Figure 13 1 minute averaged STEREO-A HET electron and proton intensity observations (in $(\text{MeV s cm}^2 \text{sr})^{-1}$) on November 01, 2021, showing a clear SEP event onset commencing at $\approx 02:01$ UT in $0.7 - 1.4$ MeV electrons and a subsequent dispersive onset in $13.6 - 60$ MeV protons. As noted by Richardson et al. 2014, the HET electron intensity may be a factor of ~ 14 too low. The times of first CME detection in K-Cor and LASCO C2 based on archival images are indicated, as is the time of peak GOES X-ray flux.

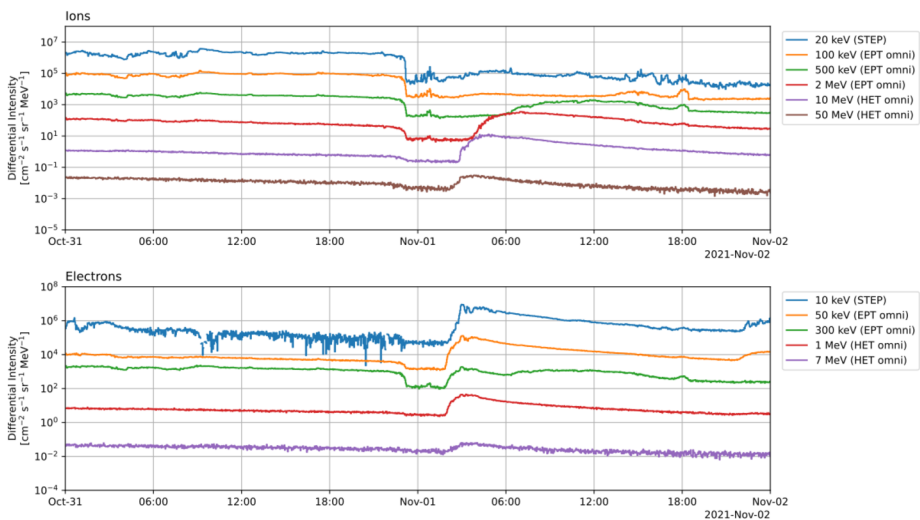


Figure 14 Solar Orbiter EPD quick look proton (top) and electron (bottom) observations showing the SEP onset early on November 01, 2021 (from <https://espada.uah.es/epd/data/plots/quicklook>).

catalog). Figure 16 shows that this SEP event was accompanied by complex type III radio emissions detected by multiple spacecraft as well as type II emission reported in the CDAW type II radio event list (https://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html) that lasted ≈ 21 minutes (01:45 to 02:06 UT) with an ending frequency of 6.7 MHz.

The low corona eruption associated with this SEP event was visible in all of the SDO/AIA coronal channels, with the erupting coronal loop being particularly noticeable in $171 \text{ \AA}$, $193 \text{ \AA}$, $211 \text{ \AA}$, and weaker but visible in $94 \text{ \AA}$ and $131 \text{ \AA}$. Thus, this was not a “very hot flux rope”, confined to the shortest wavelength SDO/AIA observations, as described in Zhang,

Figure 15 Locations of various spacecraft on November 01, 2021, with the longitude of the active region associated with the MLSO SEP CME indicated by the black arrow. Parker spiral field lines assume a solar wind speed of 400 km/s. Figure generated by Solar-MACH (Gieseler et al. 2022).

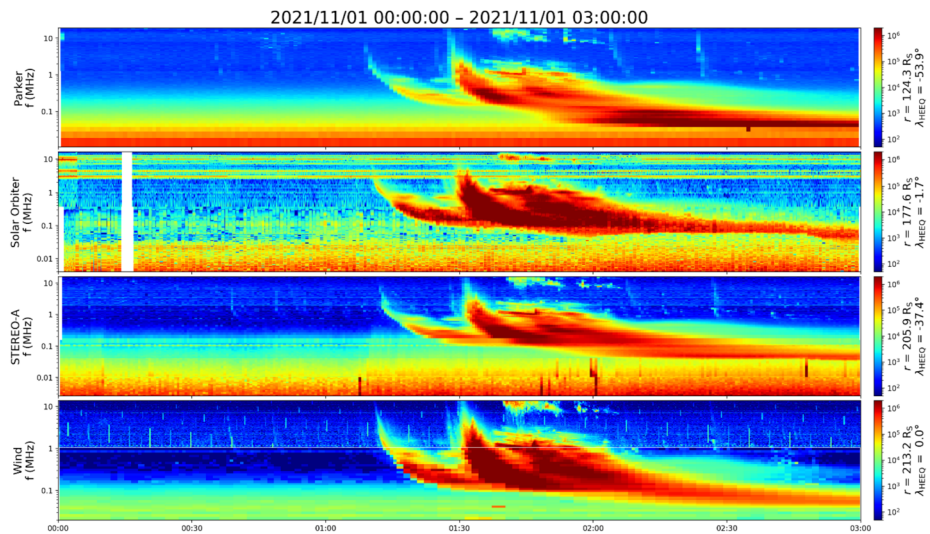
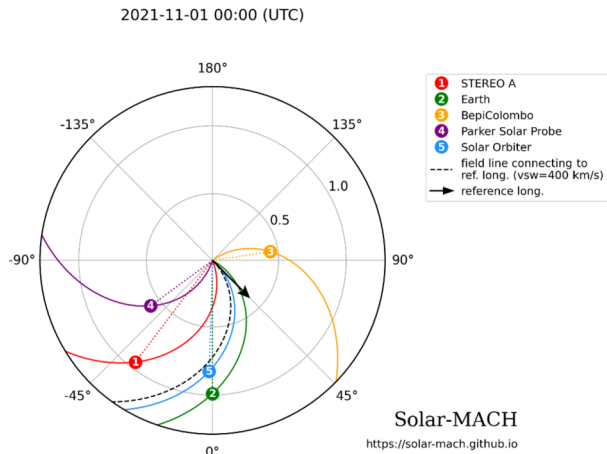


Figure 16 Radio emissions detected by inner heliosphere and 1 AU spacecraft at 0–3 UT on November 01, 2021, showing the complex type III emissions associated with the MLSO SEP CME on this day, with the onset of the strongest emission at $\sim 01:30$ UT. The CDAW type II list (https://cdaw.gsfc.nasa.gov/CME_list/radio/waves_type2.html) indicates type II emission from 01:45 to 02:06 UT falling from 14 MHz to 6.7 MHz. Figure from the “Coordinated Radiodiagnostics Of CMEs and Solar flares” (CROCS), <https://parker.gsfc.nasa.gov/crocs.html>.

Cheng, and Ding (2012) and Nindos et al. (2015) and discussed further in Section 4.2, but appeared to be a coronal temperature loop. In 193 Å and 211 Å, a strong “EUV wave” (e.g. Thompson et al. 1998; Nitta et al. 2013) was present sweeping mostly to the North but with a component moving eastward. A transient coronal hole appeared at the site of the eruption in several AIA coronal channels. Figure 17 shows representative images of the eruption from SDO/AIA, K-Cor, and SOHO LASCO C2.

More than 2200 K-Cor images were obtained during the observing run that commenced on October 31, 2021, at 17:26 UT and continued for 10 hours until 03:26 UT the following

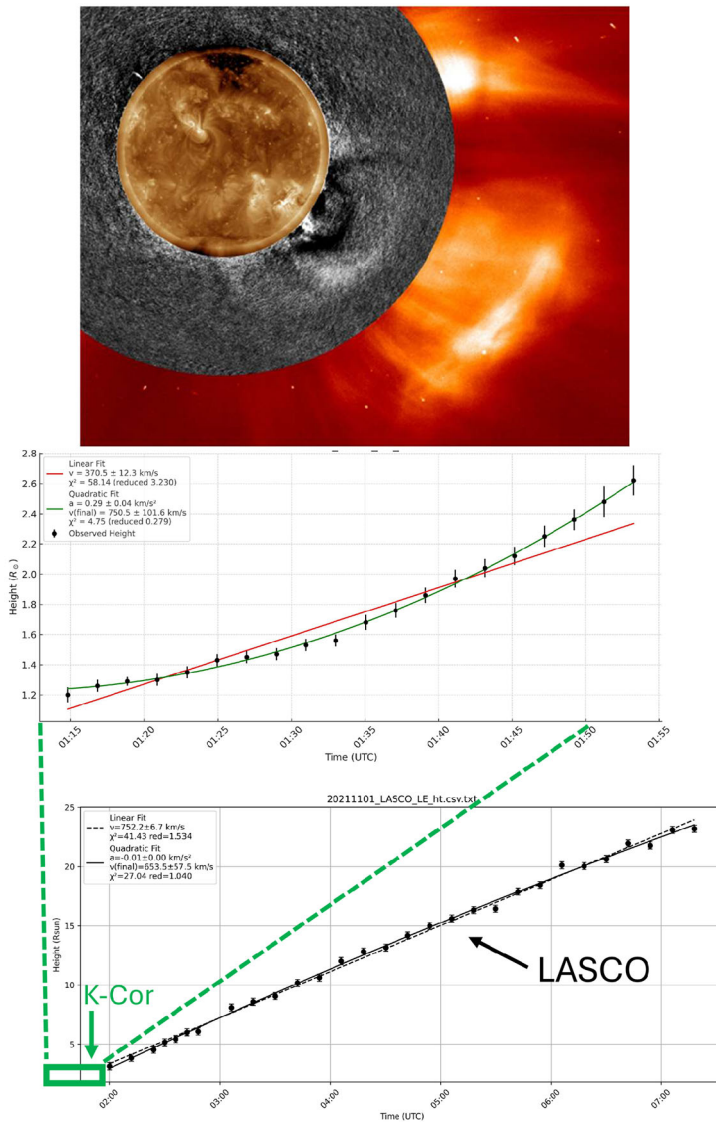


Figure 17 At the top is a composite image from November 01, 2021, showing an SDO/AIA 193 Å pre-event image (01:37 UT), a portion of a K-Cor base difference image (01:44 UT) when the CME leading edge was $\approx 2.0 R_s$, and a portion of a SOHO/LASCO C2 image (02:24 UT) with the CME leading edge at $\approx 5 R_s$. The “leading edge” of a CME is typically the furthest point from disk center, and it is frequently near the CPA. The middle panel shows the linear (red) and quadratic (green) fits to the height-time measurements made through the K-Cor field of view. The χ^2 indicates the quadratic fit (green) is superior to the linear fit (red); the speed of the CME as it left the K-Cor field of view was 750 km/s, which is equivalent to the terminal speed listed on the CDAW website for this CME. The bottom panel is the height-time diagram for this event as measured in SOHO/LASCO C2 and C3 (from $3.2 R_s$ to $23.2 R_s$) and recorded by CDAW. A small green box shows the time and height coverage of the CME by K-Cor (i.e., the middle panel); it is clear that it is earlier than any LASCO measurement, along with the CME trajectory as seen in K-Cor (upper plot) and LASCO (lower plot).

day. Using the near-real-time CME detection software, a CME that is clearly consistent with the SEP event electron onset at ~ 02 UT and the associated X-ray flare peak at 01:45 UT was first detected in K-Cor at 01:22 UT; the automated CME-alert detection sent out the email notification a few minutes later. Thus, the alert from MLSO was 34 minutes before the CME was first imaged by LASCO C2 at 02:00 UT when the leading edge (LE) was at a height of $3.2 R_s$. Note that this interval does not account for the inherent latency to get the LASCO data telemetered to the ground and processed, which can take several hours. One other point to note, as is evident in Table 1 for this event, is that from visual examination of the archival data, we could detect this CME in K-Cor even earlier, beginning at 01:14 UT when the LE was at a height of $1.2 R_s$.

We measured the plane of the sky location and size of the CME for this (and all the events in Table 1) at two different times when the CME was fully-formed – in the inner (middle) corona with K-Cor (LASCO C2). For these measurements, we have concentrated on determining the size of the CME driver as close to the occulting disk as possible, excluding any deflections of pre-existing nearby features or any accompanying coronal shock wings. Hence, there is frequently a difference when comparing our CME driver angular width with the width listed in the CDAW (Yashiro et al. 2004) compilation of CMEs detected in SOHO/LASCO which may include such features.

For the event of November 01, 2021, we found that the CPA in the inner (middle) corona was 228° (237°) and the angular size of the CME driver was 116° (121°). Thus, for this CME there was little-or-no deflection, nor was there significant expansion in width, during its transit through the near-Sun corona, at least within the measurement uncertainties (typically only a few degrees). We note that the CDAW catalog lists a much larger angular width (274°) for this event which also accounts for the offset in the CDAW CPA (201°) compared to our measurement. The average linear velocity through the K-Cor FoV (Figure 17) was 371 km/s, but the quadratic regression was judged superior to the linear fit. The acceleration of $+0.29 \text{ km/s}^2$ led to a speed at the final measurement height ($2.6 R_s$) of 751 km/s, which matches closely the linear speed listed in the CDAW catalog through the LASCO field of view (753 km/s).

Appendix B: K-Cor Non-SEP CMEs

Song et al. (2023) catalogued 71 K-Cor events (Table 7) from 2014–2022 to investigate the evolution of the three-part structure of CMEs from the inner corona into the middle corona using K-Cor and SOHO/LASCO C2. Their selection criteria included: (1) events within 30° of the limb for front-side events, (2) “normal” CMEs (i.e., angular width $> 30^\circ$ in C2). and (3) those for which K-Cor clearly saw the early eruption.

We have examined all 71 events, eliminating 11 that were SEP CMEs already listed in Table 1 of this article. Those 11 were: Nos. 1, 10, 15, 18, 25, 45, 49, 56, 57, 62, and 67 in Table 1 of Song et al. (2023). An additional eight were excluded from further consideration for the following reasons: Nos. 13, 14, 64, and 70 were separate CMEs in K-Cor but merged with other CMEs in the LASCO FoV; No. 19 contained a data gap in K-Cor and we judged that it did not see the initiation; No. 27 was a complicated, slowly rising prominence in K-Cor and LASCO C2, but the 3-part structure appeared later; No. 44 was too far behind the East limb; and No. 50 had a LASCO CME in progress before K-Cor detected it. The remaining 52 K-Cor CMEs not associated with SEP ($\sim 25 \text{ MeV}$ proton) events were used as a control “non-SEP” sample for comparison to the 27 SEP CMEs. Though the absence of SEPs is primarily based on the STEREO and SOHO observations, where available, we also

Table 7 The 52 non-SEP associated CMEs detected by MLSO K-Cor from Song et al. (2023). See text for complete explanation of each column.

Song et al. (2023)	K-Cor CME	K-Cor Driver CPA	K-Cor Driver Width	K-Cor 1st Measure	K-Cor 1st Ht	K-Cor Ht Span	K-Cor Number H-T	Constant Linear Speed	Constant Accel	Speed @Final Ht	GOES X-ray Peak	GOES X-ray Peak
Event No.	Date	[deg]	[deg]	[U.T.]	[Rs]	[Rs]	[No.]	[km/s]	[km/s ²]	[km/s]	[U.T.]	[W/m ²]
2	2014-02-20	266	16	22:26	1.28	0.51	10	328	-0.15	331	22:34	1.6E-06
3	2014-04-29	235	28	19:47	1.15	0.56	6	126	-0.03	79	---	---
4	2014-05-24	72	46	20:27	1.75	0.32	4	336	---	---	20:25	1.5E-06
5	2014-05-28	281	20	---	---	---	---	---	---	---	---	---
6	2014-06-14	106	51	19:24	1.14	0.81	9	621	0.13	692	19:29	1.5E-05
7	2014-06-26	57	49	21:08	1.29	0.81	13	183	-0.05	97	1:14	1.6E-06
8	2014-06-30	241	42	17:40	1.24	0.27	6	139	-0.12	43	---	---
9	2014-09-23	79	42	23:31	1.90	0.50	5	384	0.48	613	---	---
11	2014-11-05	78	52	19:26	1.43	1.17	11	485	0.24	698	19:44	2.9E-05
12	2014-12-10	254	31	Missed LE	---	---	---	---	---	---	19:22	5.9E-06
16	2015-04-25	281	37	17:58	1.13	0.94	8	335	0.09	437	18:49	2.0E-06
17	2015-05-01	252	38	21:56	1.75	0.55	6	451	0.28	563	---	---
20	2015-05-25	85	37	21:35*	1.21	1.13	15	---	---	---	---	---
21	2015-07-02	42	60	17:43*	2.00	0.62	5	---	---	---	---	---
22	2015-08-01	52	30	17:06*	1.62	0.58	7	---	---	---	17:51	8.0E-07
23	2015-09-23	116	30	18:01	1.59	1.29	14	198	0.08	395	18:57	3.3E-06
24	2015-12-17	61	19	Missed LE	---	---	---	---	---	---	---	---
26	2016-01-15	254	16	19:30	1.43	0.72	16	95	0.03	174	20:16	9.0E-07
28	2016-02-09	86	23	18:10	1.56	1.03	11	104	0.01	131	---	---
29	2016-06-11	81	16	22:14	1.27	0.21	9	105	-0.07	66	---	---
30	2016-08-08	284	18	20:16	1.32	0.36	10	143	0.09	225	20:18	2.0E-06
31	2016-08-08	299	14	23:16	1.76	0.44	5	36	0.00	---	---	---
32	2016-09-29	248	29	Missed LE	---	---	---	---	---	---	---	---
33	2017-01-28	274	26	21:06	1.41	0.41	8	351	-0.07	320	21:09	2.8E-06
34	2017-03-27	98	25	17:33	1.20	1.56	21	202	0.00	193	18:20	5.1E-06
35	2017-04-02	291	26	18:45	1.20	0.71	10	402	0.24	553	18:38	2.1E-05
36	2017-07-13	272	45	20:07	1.18	1.32	15	434	-0.13	231	20:08	6.0E-06
37	2017-07-20	265	31	17:36	1.86	0.68	9	178	-0.01	167	---	---
38	2017-08-20	89	21	19:30	1.29	0.32	7	128	-0.01	122	19:39	9.4E-06
39	2017-09-13	255	30	18:32	1.42	0.72	10	153	0.07	287	---	---
40	2017-10-20	112	41	23:28	1.23	1.67	26	359	-0.03	299	23:28	1.1E-05
41	2019-04-22	286	40	2:52	1.30	0.64	9	463	-0.29	303	---	---
42	2020-11-01	260	30	19:05	1.35	1.25	58	281	-0.05	190	19:16	1.6E-06
43	2020-11-26	55	62	20:46	1.51	0.42	10	261	-0.09	204	21:23	2.6E-06
46	2021-06-10	67	81	17:47	1.26	1.36	15	387	0.40	904	---	---
47	2021-06-25	243	15	20:57	1.48	0.45	12	49	0.00	57	---	---
48	2021-06-26	271	29	22:41	1.46	0.60	15	42	0.00	58	---	---
51	2021-08-29	233	25	19:53	1.23	1.42	36	413	0.59	1034	20:22	8.6E-07
52	2021-10-09	292	33	21:02	1.42	1.33	19	114	0.02	209	---	---
53	2021-10-10	307	24	22:47	1.42	0.82	15	297	0.04	336	23:02	2.3E-06
54	2021-11-02	156	40	22:04	1.97	0.66	10	277	0.09	358	---	---
55	2021-11-03	212	60	21:05	1.26	1.42	20	373	0.16	604	21:17	5.2E-06
58	2022-04-19	246	36	20:45	1.19	1.46	14	504	-0.24	104	20:49	3.7E-05
59	2022-04-25	122	43	17:33	1.42	1.13	10	332	0.03	370	17:35	7.0E-06
60	2022-04-25	115	42	18:48	1.50	1.19	17	115	0.06	313	21:00	5.0E-06
61	2022-05-08	119	31	21:33	1.47	1.32	12	216	0.14	506	22:40	2.0E-06
63	2022-05-14	145	17	17:21	1.80	0.80	8	77	0.03	174	---	---
65	2022-07-10	212	28	Missed LE	---	---	---	---	---	---	---	---
66	2022-07-31	77	20	22:43	1.31	1.59	13	502	0.71	1229	23:09	9.3E-06
68	2022-09-24	142	20	Missed LE	---	---	---	---	---	---	---	---
69	2022-09-28	73	27	17:19	1.82	0.94	10	442	-0.10	335	---	---
71	2022-11-25	307	54	21:41	1.36	1.19	17	255	0.10	429	---	---

checked observations from inner heliosphere spacecraft to verify that no SEPs were detected at these locations.

The columns in Table 7 list the original event number from Table 1 in Song et al. (2023) and the calendar date of the CME, followed by parameters derived from K-Cor observations: the CME driver CPA, the CME driver width, the time that height-time measurements of the CME leading edge began in K-Cor (UT), the 1st height recorded in those measurements, the height span of the measurements, the number of measurements, the constant linear speed derived from the weighted fit to those measurements, the constant acceleration, and the derived speed at the final height measurement using that acceleration. As in Table 1 for the K-Cor SEP CMEs, the preferred regression solution based on a χ^2 determination is indicated in **bold**. The final two columns give the GOES X-ray peak time and intensity for the associated flare.

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Author Contributions Author Contributions: OCS and JTB compiled the SEP CME list and performed analysis on these events. IGR provided the SEP event catalog, SEP analysis and figures, and contributed to the solar event identifications. MG is manager of the K-Cor data pipeline. OCS, IGR, and JTB wrote the manuscript. All authors read and reviewed the manuscript.

Data Availability All data supporting the findings of this study are publicly available.

Declarations

Competing Interests The authors declare no competing interests.

Note Added in Proof Recently a Data Release Note (DRN) was added to the CDAW SOHO LASCO CME compilation (https://cdaw.gsfc.nasa.gov/CME_list/SOHO_LASCO_CME_Data_Release_Note_20260331.pdf). We note that the incorrect CDAW position angle measurements and CME angular widths discussed in the DRN do not affect the study presented here. The measurements used in this study were independently made with the JHelioviewer software application rather than files affected by the error in the LASCO pipeline processing. However, the CME mass estimates cited in Figure 9 and Table 5 may be slightly affected (estimated to be <10%, A. Vourlidas, personal communication, 2026).

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Authors and Affiliations

O.C. St. Cyr^{1,2} · I.G. Richardson^{1,3} · J.T. Burkepile^{4,5} · M. Galloy⁴ · T. Nieves-Chinchilla¹ · B.J. Thompson¹

✉ O.C. St. Cyr
ocstcyr2@gmail.com

¹ Heliophysics Science Division, NASA-GSFC, Greenbelt, MD 20771, USA

² Retired, Rancho Palos Verdes, CA 90275, USA

³ Department of Astronomy, University of Maryland, College Park, MD 20742, USA

⁴ High Altitude Observatory, NCAR, Boulder, CO, USA

⁵ Retired, Boulder, CO, USA