Coronal Mass Ejections Associated with Solar Energetic Particle Events Observed in the Low Corona by the Mauna Loa Solar Observatory

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Abstract

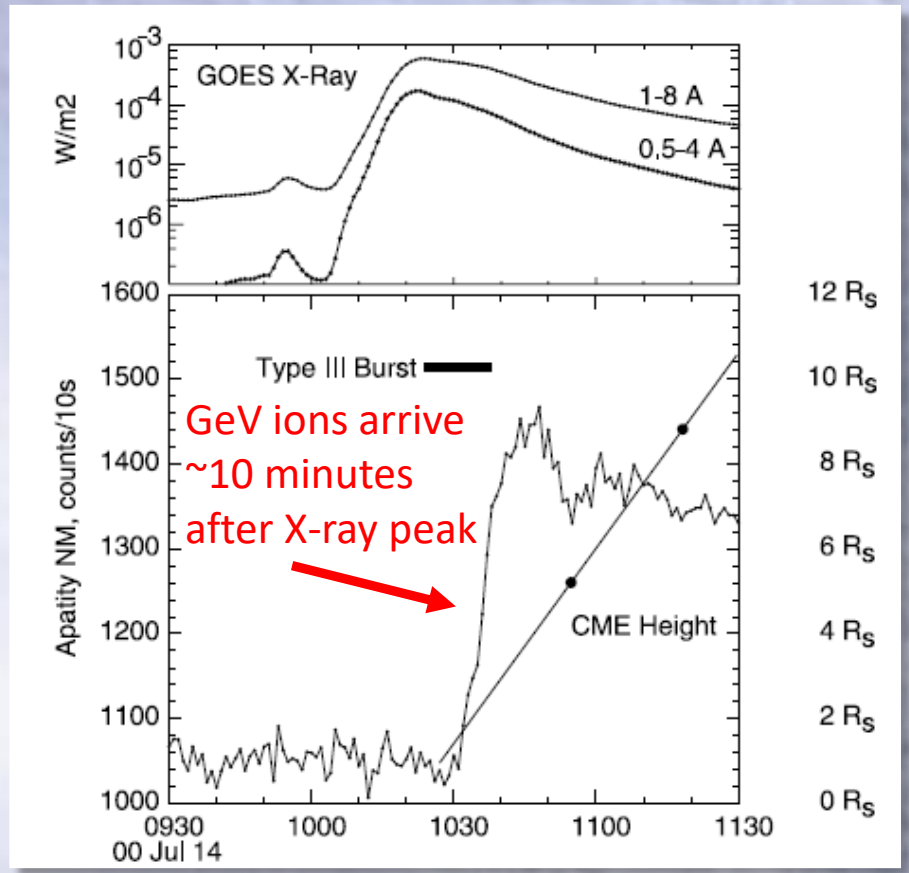
The prediction of solar energetic particle (SEP) events is an important element of space weather forecasting, and several SEP prediction models are currently triggered by *spacecraft* coronagraph observations of coronal mass ejections (CMEs) in the mid-corona (above ~2 R_s). However, these observations may not be available without significant telemetry and analysis delays. **Since 1980, the Mauna Loa Solar Observatory (MLSO) in Hawaii has routinely observed the low corona (~1.05-3 R_s) in white light with a series of improved instruments.**

The real time detection of CMEs by MLSO as they transit the low corona has the potential to provide earlier warnings of impending SEP events. **We have therefore made the first comprehensive survey of the SEP (~25 MeV proton) event-associated CMEs observed by MLSO up to the interruption of operations by the eruption of the volcano in late 2022.** Eighty four SEP-associated CMEs observed by the earlier Mk3/4 coronameters in 1980-2013 have been identified (*Richardson et al*., 2023), along with twenty seven observed by the current K-Cor coronagraph in 2013-2022. When operating, an automated CME detection scheme for K-Cor issues real time CME alerts typically before the CME enters the field of view of spacecraft coronagraphs.

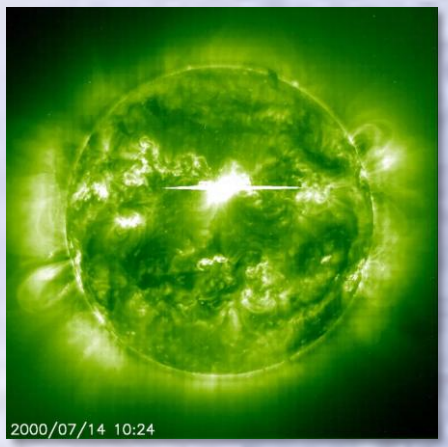
Several challenges exist in determining the relationship between CME parameters in the low corona and the properties of the associated SEP events. These include: 1) determining the CME parameters reliably from the MLSO images (in particular for Mk3/4); 2) the large CME accelerations or decelerations in the MLSO field of view, in contrast to the mid corona where the CMEs approach terminal speeds which tend to be correlated with the SEP intensity; and 3) the relatively small number of events identified does not encompass the wide variability of SEP events and their related solar phenomena. However, an interesting finding is that MLSO CMEs that include a hot flux rope (HFR) observed by SDO AIA have a strong (~80%) association with SEP events, while CMEs without HFRs have only a 10% association, suggesting that an HFR may be useful as a low coronal signature of a potentially SEP-associated CME.

Solar energetic particle (SEP) events are temporary (hours to days duration) increases in the interplanetary energetic particle population

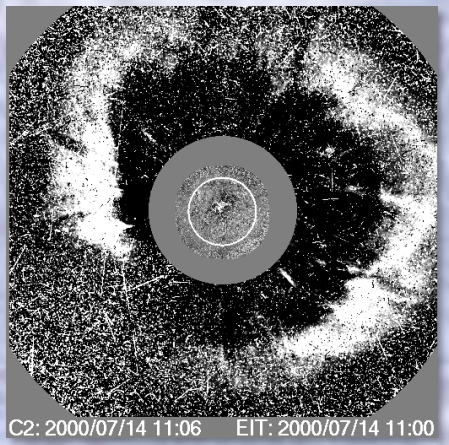
- SEPs are accelerated by solar flares and shocks driven by coronal mass ejections (CMEs);
- Consist of electrons, protons and heavy ions with energies from ~10s of keVs to GeVs;
- A significant hazard to space-based assets (spacecraft, human exploration), in particular outside the shield of Earth's magnetosphere;
- **Challenging to predict**: Occur ~randomly and with little warning – the fastest particles can arrive at Earth's orbit within minutes of the solar event.



"Bastille Day event", 2000 (Richardson et al., 2003)

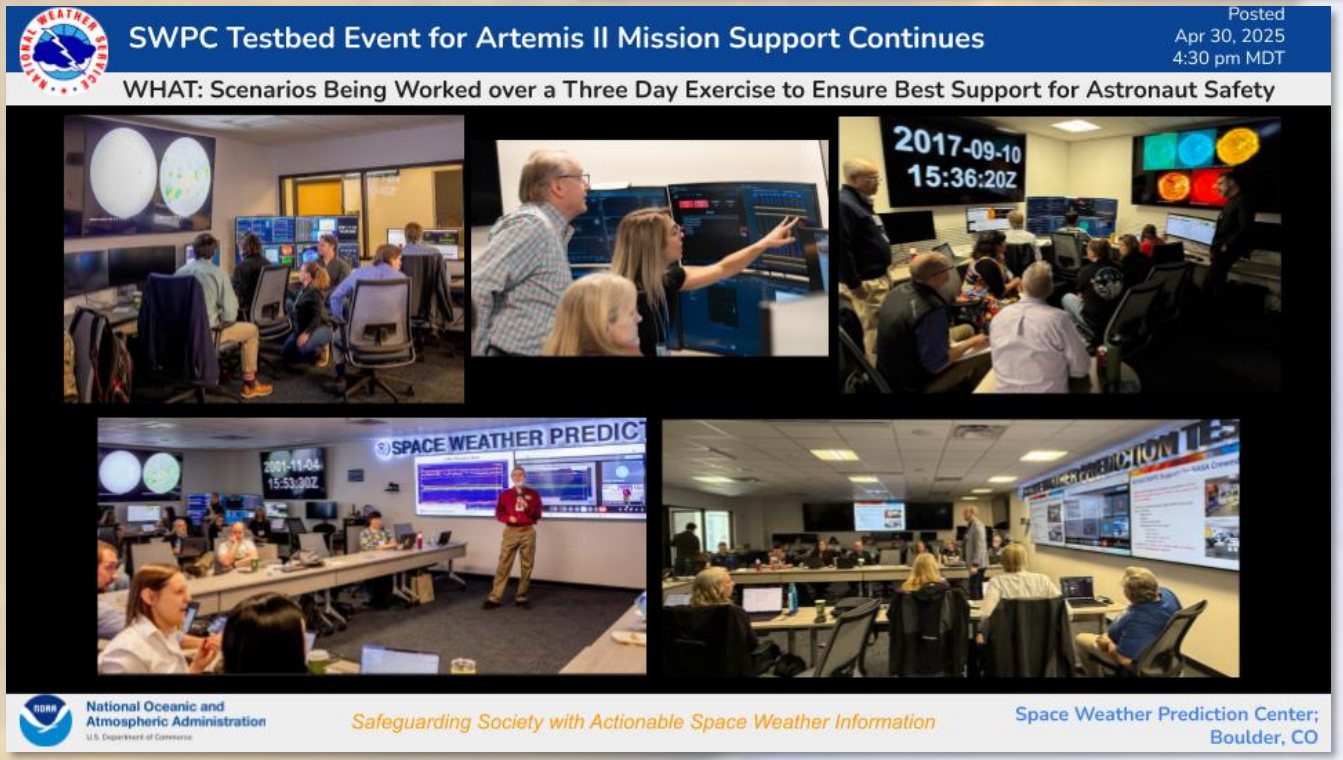


SOHO EIT



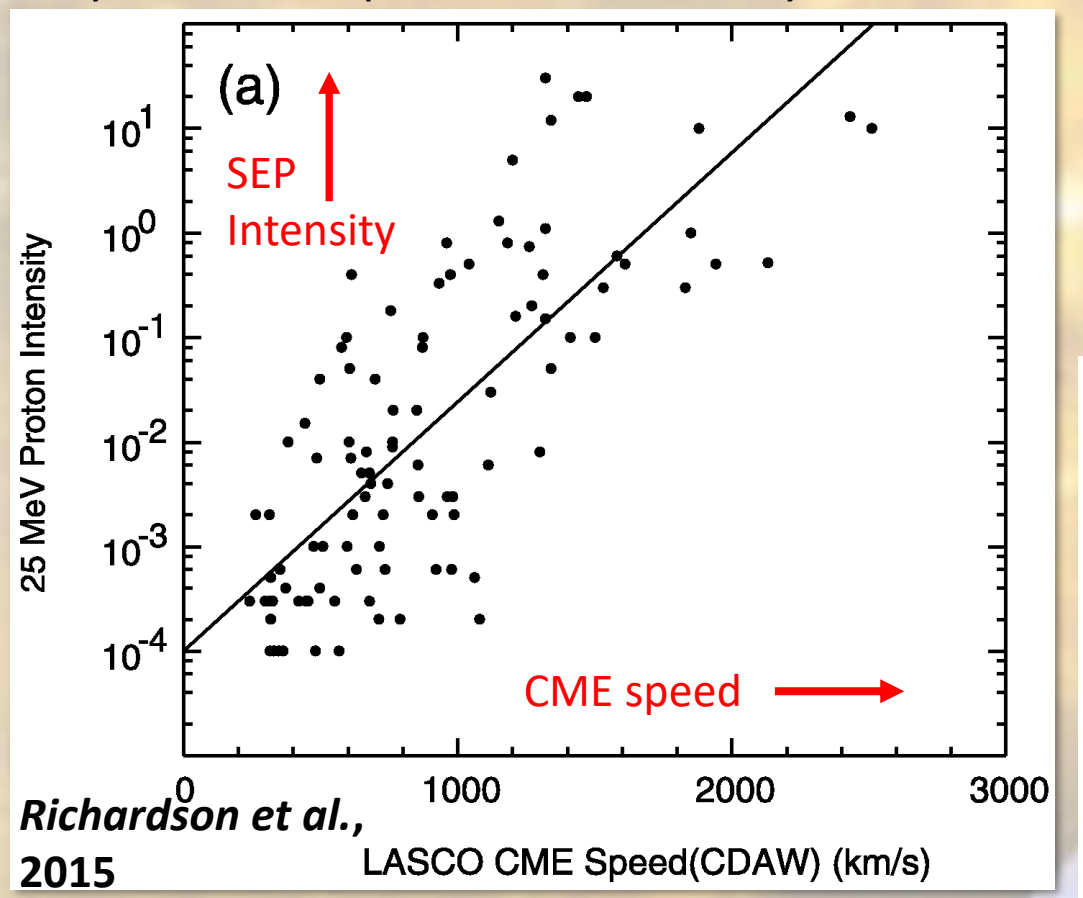
SOHO LASCO C2

The largest (?) SEP event recorded in the space era fortuitously occurred *between* the Apollo 16 and 17 Missions (image from https://youtu.be/vpNa4u997xA)



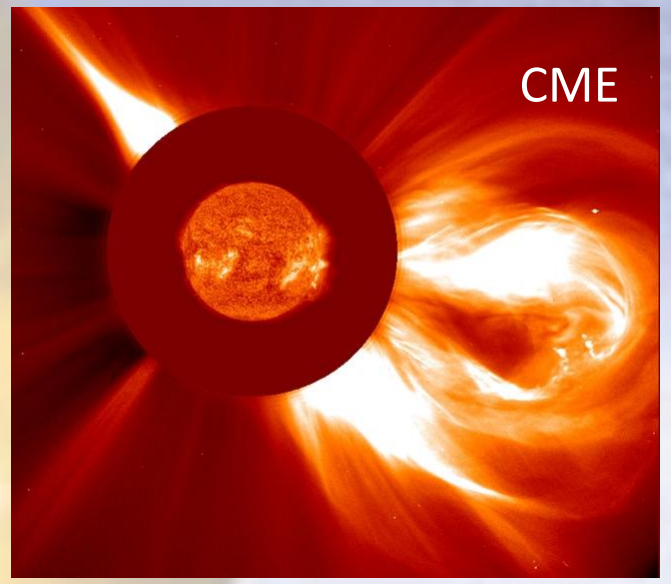
SEP prediction and warning is important for the Artemis mission. An SEP prediction "Testbed event" for Artemis II was held at the NOAA Space Weather Prediction Center (SWPC), Boulder, in April-May 2025. Attended by forecasters from SWPC, the NASA Space Radiation Analysis Group and the Goddard Moon2Mars Office, model developers, and end users.

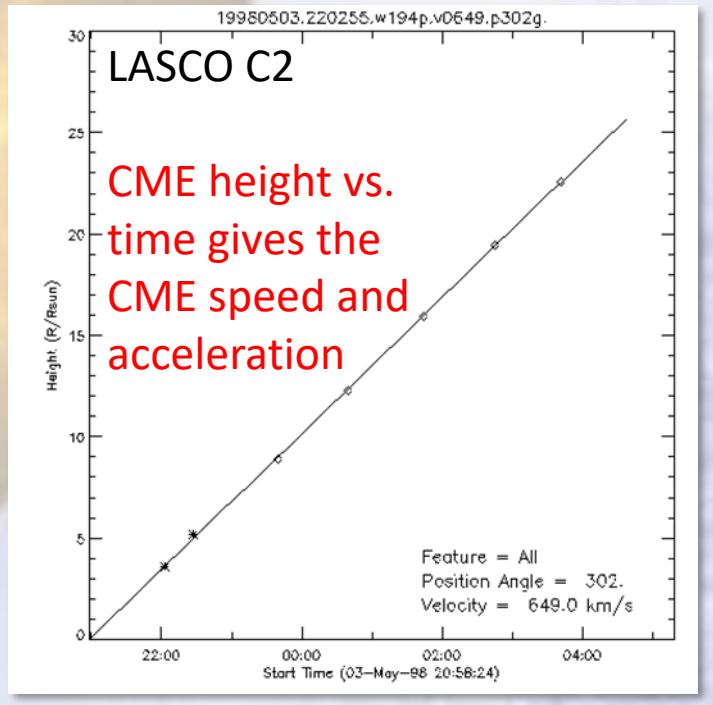
How do we predict SEP events? Some methods (see below) use CME parameters; More intense solar energetic particle (SEP) events tend to be associated with faster CMEs => CME parameters may be used to predict SEP intensity.



Richardson et al., 2015

(CME direction relative to the observer is also important!)





How do we measure CME Speeds?

A coronagraph produces an artificial solar eclipse using an occultor.

For the SOHO/LASCO C2 coronagraph, the field of view starts at 2.2 R_s (the SOHO EIT image indicates the size of the Sun).

Image cadence >~ 10 minutes

Data are downloaded only when telemetry is available => delay (may be many hours) before images are available.

(CME parameters can also be derived from multi-spacecraft coronagraph observations.)

Observations of CME parameters are frequently used in SEP intensity prediction schemes (see the table from the comprehensive summary of SEP prediction models by *Whitman et al.*, 2023). These include SEPSTER (*Richardson et al.*, 2018), SEPSTER2D (*Bruno and Richardson*, 2021).

HOWEVER: SEPs can arrive before the CME speed can be derived from observations –

- Delay until the CME reaches the coronagraph field of view (~10 minutes+)
- Data transmission delays (may be many hours for spacebased coronagraphs).
- Additional delay as the coronagraph images are analyzed by human or automated means to infer the CME speed.

Also, only a small subset of CMEs (~15%) are associated with SEP events => CME-triggered SEP prediction models produce many "false" SEP predictions (e.g. *Richardson et al.*, 2018).

Table 10
Observational measurements used as inputs into SEP models.

CME Input

Model	Type	Magnetograms	Optical Imaging	EUV Imaging	Soft X-ray Intensity	Ground-based Radio	Space-based Radio	Coronagraph	Solar Wind (n,T,p,v)	Suprathermal Particles	Energetic Protons	Energetic Electrons	Neutron Monitors
ADEPT	Empirical										x		
AFRL PPS	Empirical		x		x	x							
Aminalragia-Giamini model	ML			x	x								
AMPS	Physics-based	x		x				x					
Boubrahimi model	ML				x						x		
COMESEP SEPForecast	Emp. & Physics			x	x			x					x
EPREM	Physics-based	x		x				x		x			
ESPERTA	Emp. & ML			x	x		x				x		
FORSPEF	Empirical	x	x		x		x	x					
GSU	ML	x											
iPATH	Physics-based	x		x				x	x	x			
Lavasa Model	ML		x		x			x					
MAG4	Empirical	x	x		x								
MagPy	Empirical	x	x		x								
MEMPSEP	ML	x		x	x		x	x	x	x	x	x	
M-FLAMPA	Physics-based	x		x				x					
PARADISE	Physics-based	x		x				x					
PCA model	Empirical				x			x					
PHSVM	ML				x						x		
PROTONS	Empirical				x	x							
REleASE	Empirical											x	
Sadykov's Model	ML	x			x	x					x		
SAWS-ASPECS	Empirical	x	x		x			x			x	x	x
SEPCaster	Physics-based	x		x				x	x				
SEPMOD	Physics-based	x		x				x					
SEPSTER	Empirical			x				x	x				
SEPSTER2D	Empirical			x				x	x				
SMARP Model	ML	x											
SOLPENCO	Physics-based			x				x					
SOLPENCO(2)	Physics-based			x				x	x		x		
South African model	Physics-based			x	x			x					
SPARX	Physics-based			x	x								
SPREAdFAST	Physics-based	x		x				x		x	x		
SPRINTS	ML	x		x	x						x		
STAT	Physics-based	x		x				x		x			
UMASEP	Empirical				x	x					x		
Zhang model	Physics-based	x		x				x	x				
Total		19	6	21	19	4	3	21	7	5	11	3	2

Whitman et al., 2023

Mauna Loa Solar Observatory Coronagraphs

https://www2.hao.ucar.edu/mlso/mlso-home-page

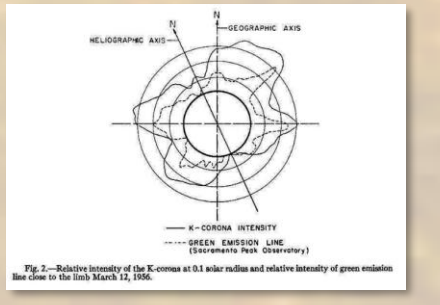
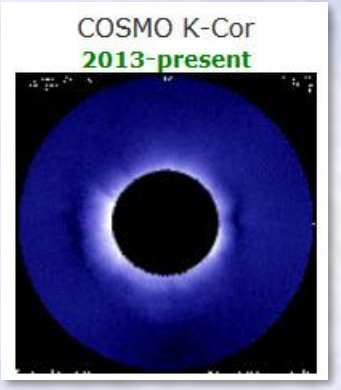


Fig. 2.—Relative intensity of the K-corona at 0.1 solar radius and relative intensity of green emission line close to the limb March 12, 1956.

Mark-I & II



Nominal Observing Window
17 U.T. – 02 U.T.

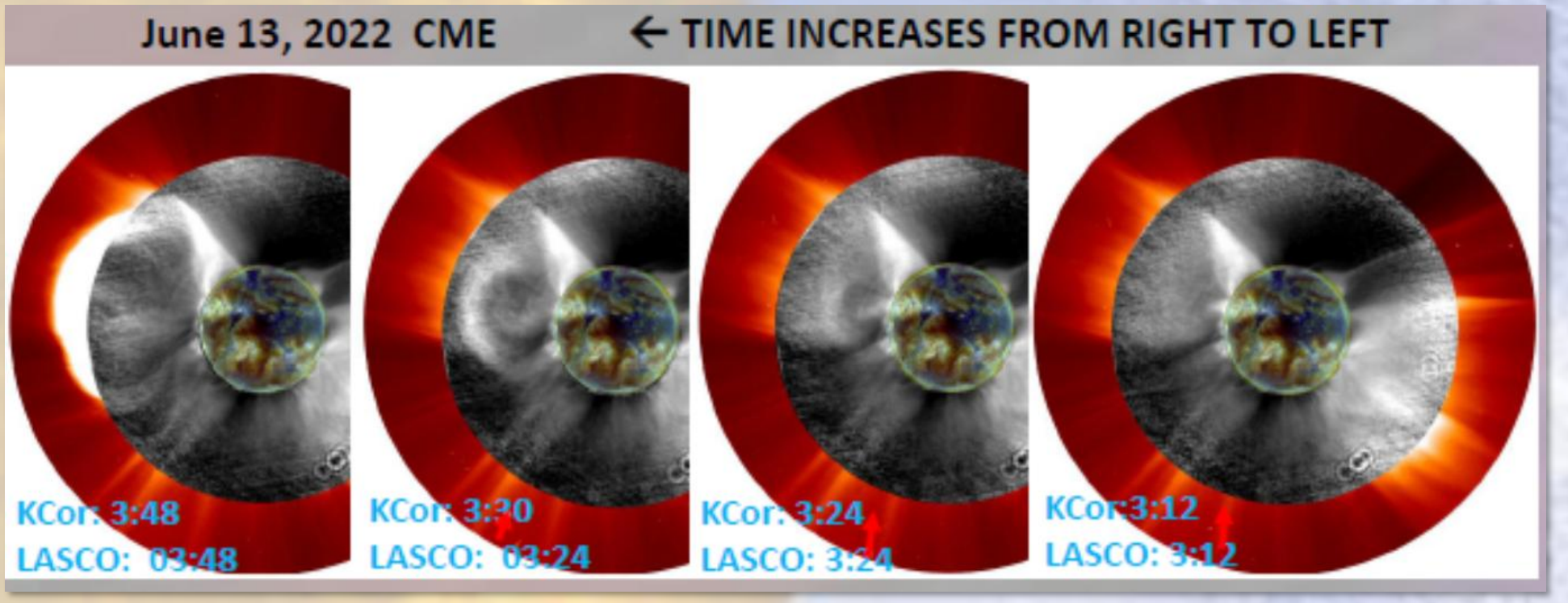
MLSO has been closed since the eruption in November 2022 cut off access and power.

- Mark-I [installed at Climax, 1957]
- Mark-II [Haleakala, Maui, then MLSO in 1963]

- Mk3: The first groundbased telescope to image the corona outside of total eclipse (Feb 1980)
- Mk4: Reworked Mk3 with upgraded detector
- K-Cor: A new design to improve spatial and temporal resolution

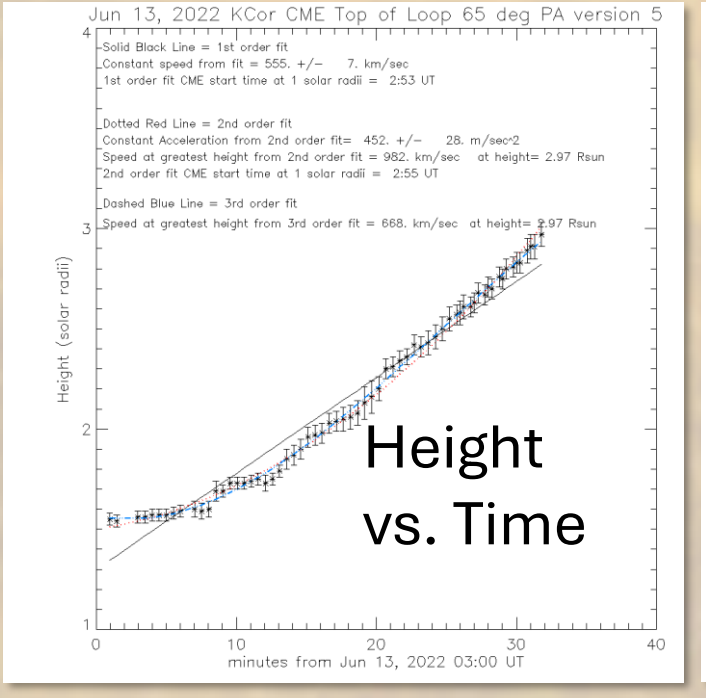
Cadence
3 min
20 sec

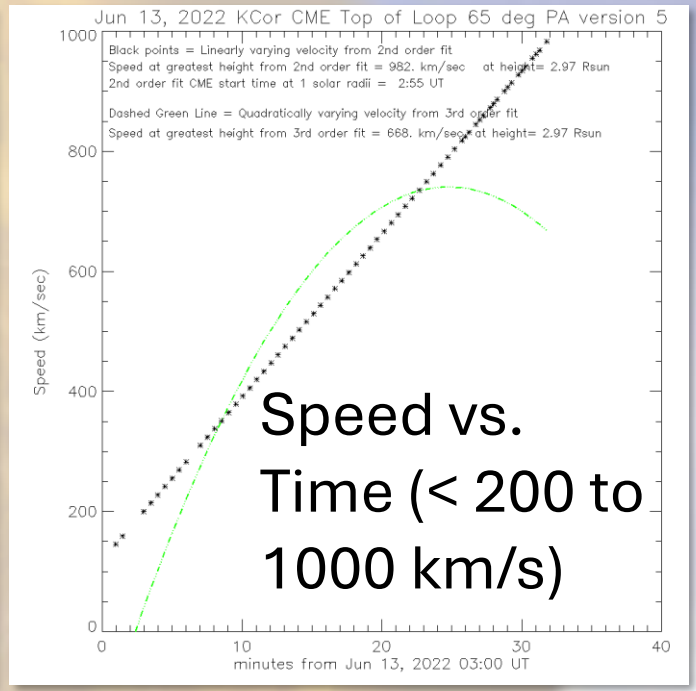
CMEs can be detected and tracked by the Mauna Loa Solar Observatory Coronagraph well before they enter the SOHO/LASCO coronagraph field of view.

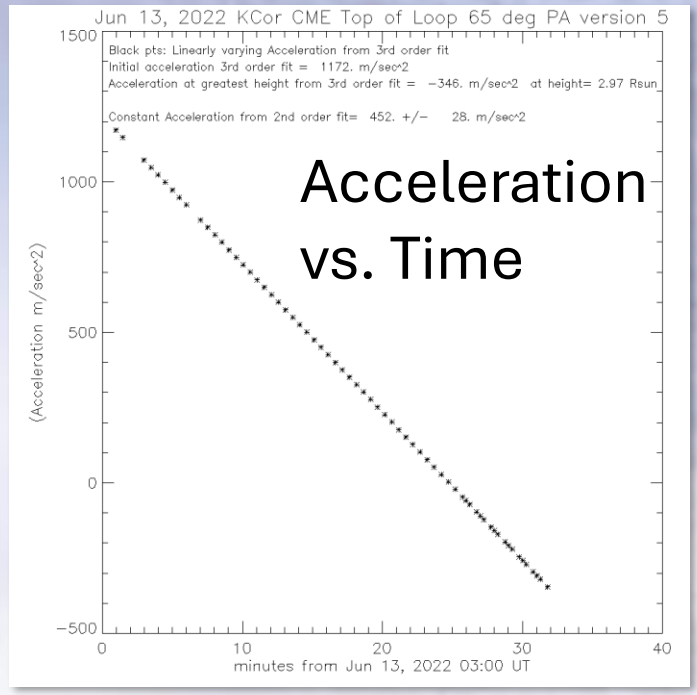


CME on June 13, 2022 observed by the MLSO-K-Cor (grey) and SOHO/LASCO (orange) coronagraphs.

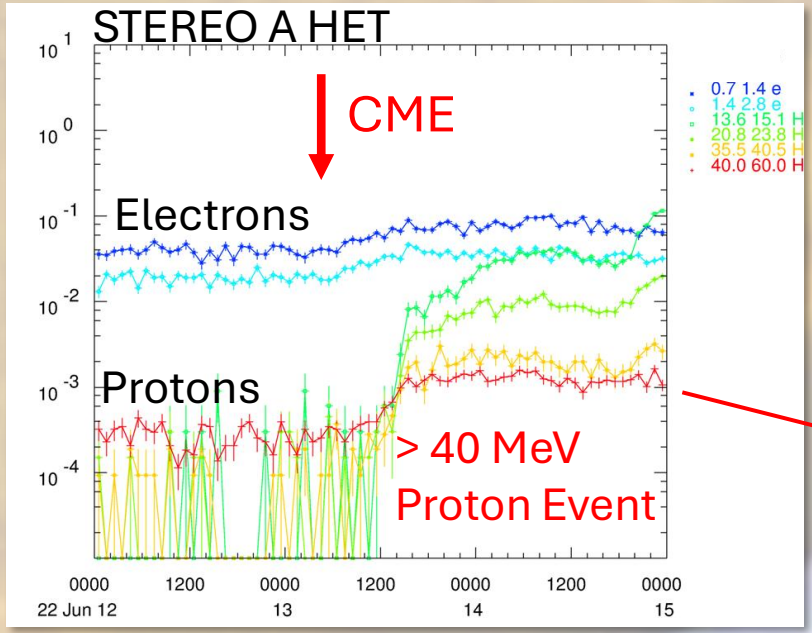
- MLSO field of view: 1.05-3 R_s (LASCO field of view starts at 2.2 R_s.)
- 20 s cadence
- Automated CME detection scheme (W. Thompson, GSFC) provides CME alerts and parameters
- CME alerts can be disbursed within a couple of minutes of observations
- **BUT** limited duty cycle (Sun above horizon, weather, maintenance, staffing etc)

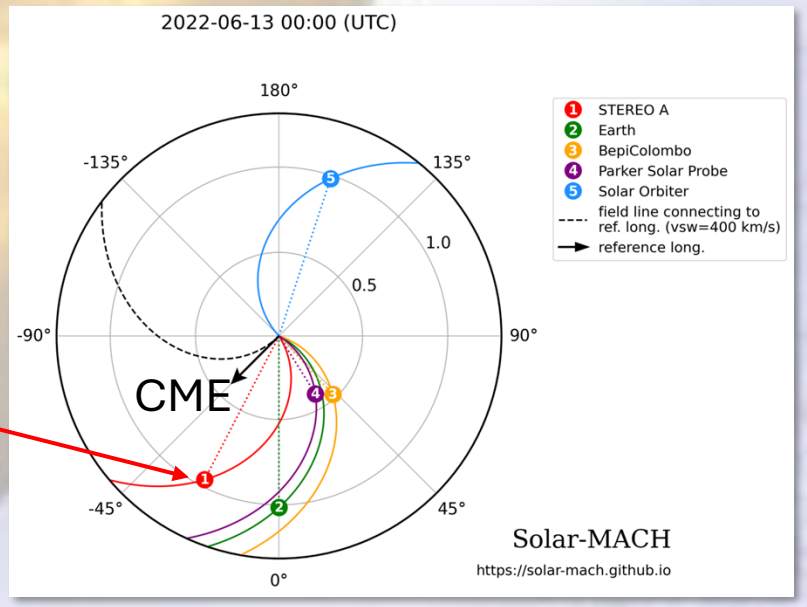






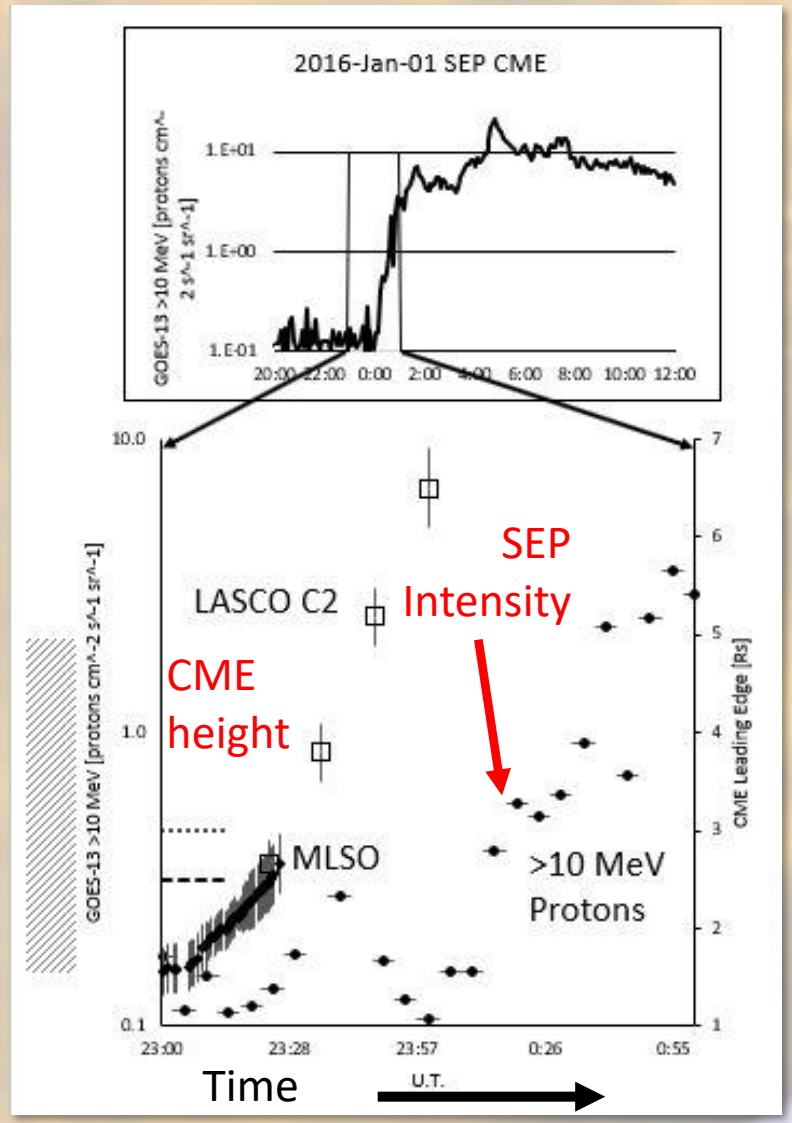
K-Cor height, speed and acceleration vs. time for the 2022-06-13 CME. *This CME strongly accelerated in the MLSO field of view.*





The 2022-06-13 CME was accompanied by a Solar Energetic Particle event detected by the STEREO A spacecraft:

A motivation for this study: *St. Cyr et al.* (2017) demonstrated that MLSO observes CMEs in the low corona and can provide a first warning of a CME, and potentially of a solar energetic particle event.



=> NASA Living With a Star grant (*St. Cyr, Richardson, Thompson, Fry*): First ever comprehensive study of the association between SEP events and MLSO-observed CMEs in 1980-present.

Science questions include:

- What can MLSO observations tell us about particle acceleration by CMEs?
- What CME characteristics in MLSO observations are indicative that an SEP event is likely?
- Could a network of real-time Earth-based coronagraphs be routinely used for SEP warnings?

Solar Physics (2023) 298:105
https://doi.org/10.1007/s11207-023-02192-9

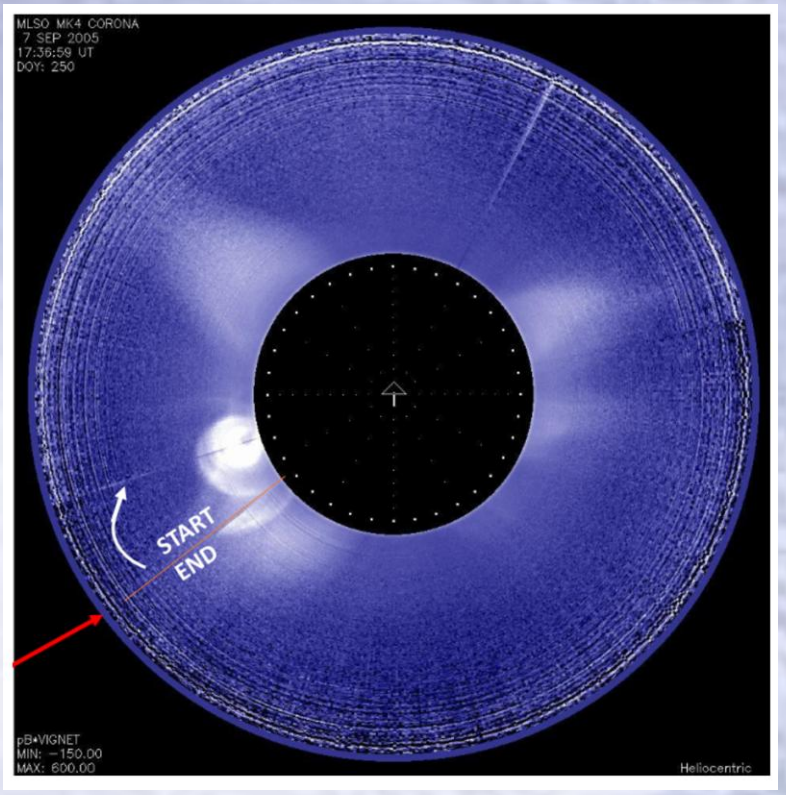
RESEARCH

Check for updates

Solar Energetic-Particle-Associated Coronal Mass Ejections Observed by the Mauna Loa Solar Observatory Mk3 and Mk4 Coronameters

I.G. Richardson[1,2] · O.C. St. Cyr[1,3] · J.T. Burkepile[4] · H. Xie[1,5] · B.J. Thompson[1]

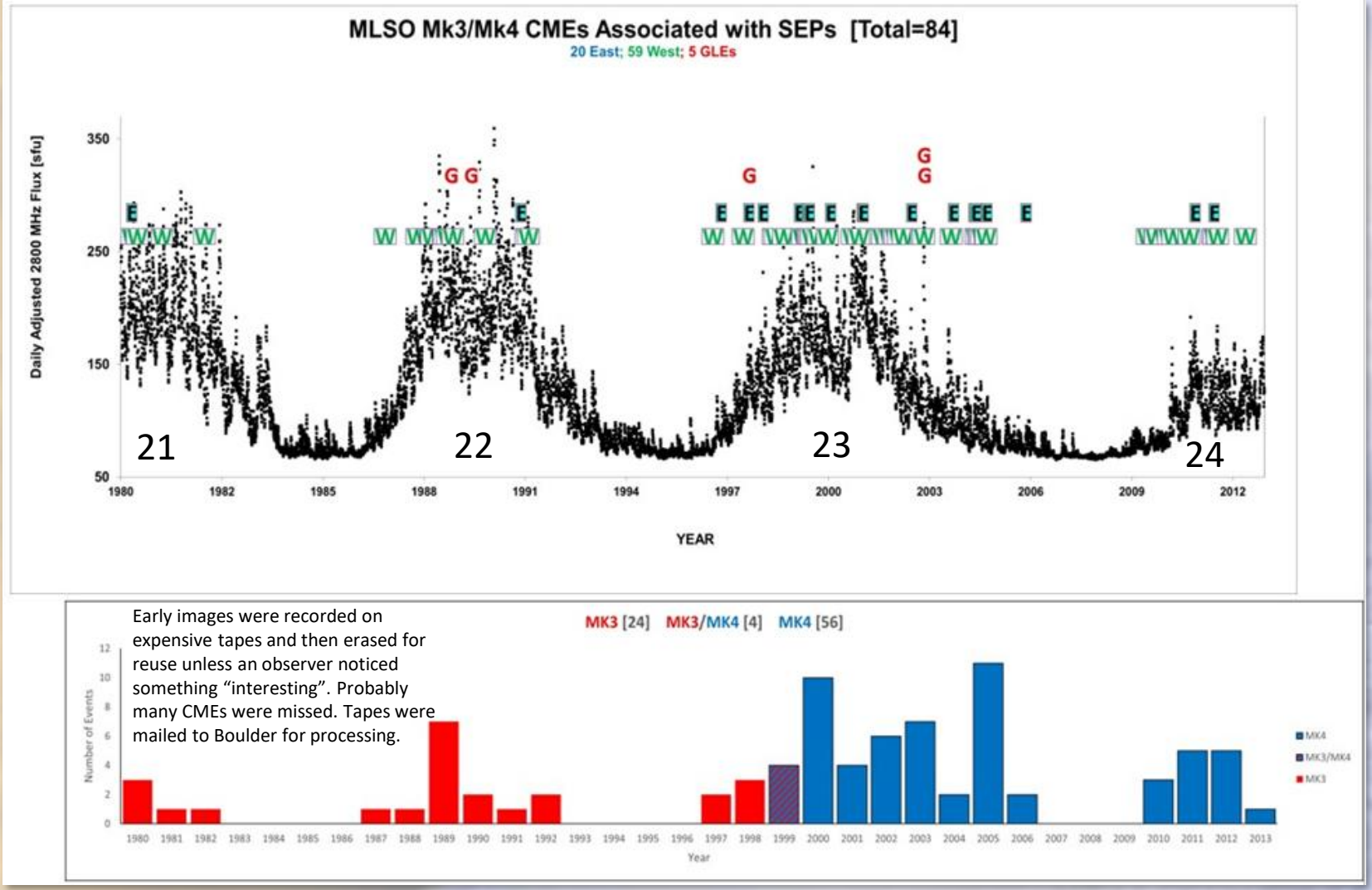
- Used SEP observations from multiple spacecraft (ISEE-3, SOHO, ACE, IMP7/8, Helios 1/2, Ulysses, STEREO A/B) to identify ~25 MeV proton events above the instrumental backgrounds in 1980-2013 during the MLSO observation window (~17-02 UT).
- Examined the MLSO Mk3/4 coronameter observations in1980-2013 to identify SEP-associated CMEs; 84 events identified.
- Derived the CME kinematics from manual measurements of the height-time profiles, where possible, for these CMEs
- Incorporated CME observations from spacecraft coronagraphs (Solwind, Solar Maximum Mission, SOHO LASCO) to track the CMEs into the mid corona.
- **It is difficult to infer unambiguously the CME kinematics from ~3 minute cadence Mk3/4 observations built up from a scanning linear diode**.



A discontinuous *scanning* image of a fast CME on September 7, 2005, that happened to be closely aligned with the start/end of the Mk4 coronameter linear diode scan (3 minutes clockwise then 3 minutes anticlockwise). The lower part of the CME was imaged ~3 minutes later than the upper part. The CME had left the field of view by the end of the anti-clockwise return scan. (*Richardson et al.*, 2023)

Times of 84 CMEs in 1980-2013 observed by MLSO Mk3/4 associated with SEP events including ~25 MeV protons (*Richardson et al.*, 2023)

***When making observations*, Mk3/4 detected at least 92% of the SEP-associated CMEs observed by SOHO/LASCO in 1996-2013.** Most of the missed events were after 2011 when a lightning strike degraded the detector electronics.

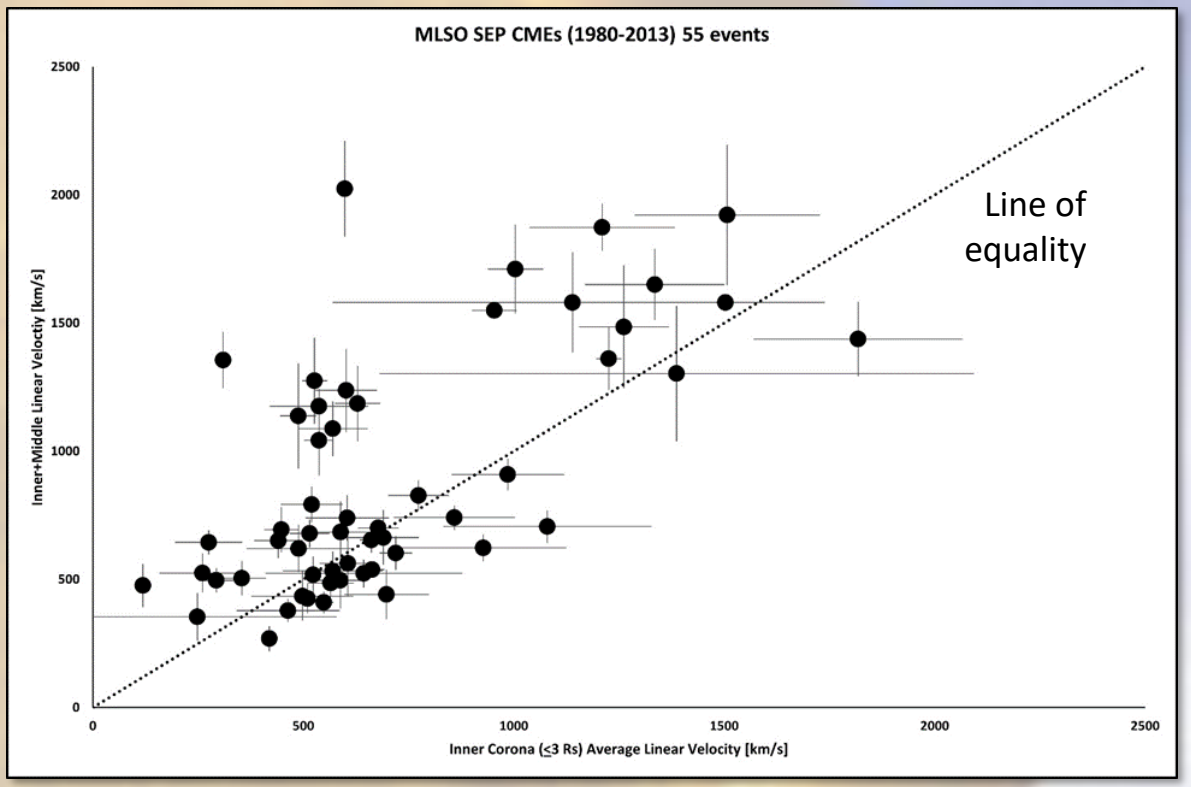


Penticton 10.7 cm radio flux shows Solar Cycles 21-24

W=western hemisphere event
E=eastern hemisphere event
G=ground level enhancement detected by neutron monitors

Annual number of SEP-associated CMEs detected by Mk3 (red) or Mk4 (blue).

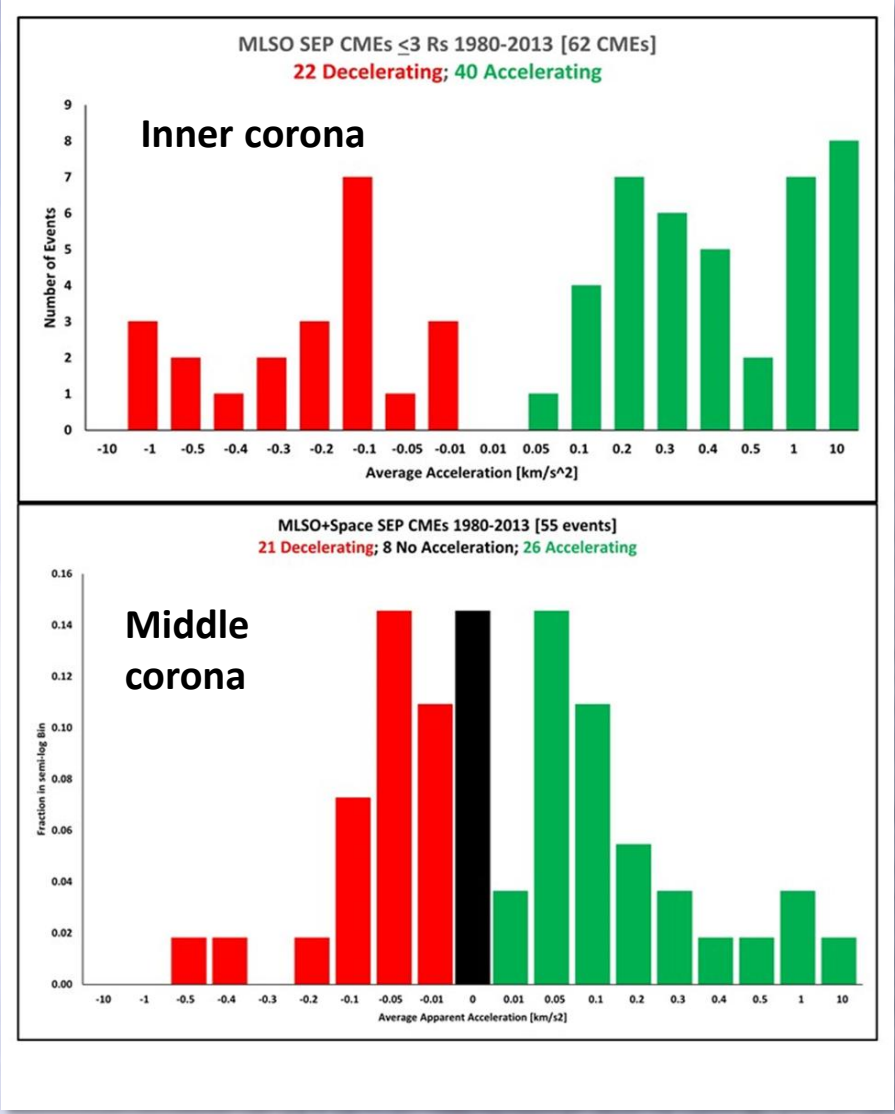
CME Speed in the Middle Corona



CME Speed in Inner Corona (MLSO)

Comparison of the Linear Speed of the MLSO SEP CMEs in the inner versus middle corona. While the fastest CMEs in the inner corona tend to be fast in the middle corona, the converse is not always the case.

See *Richardson et al.*, 2023 for more results.



SEP-associated CMEs typically have ~orders of magnitude higher average accelerations or decelerations in the inner corona than in the middle corona (note the log. scale).

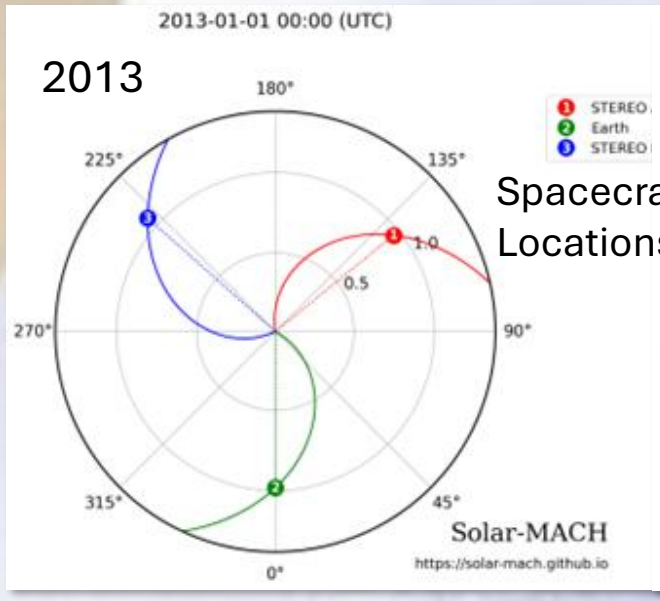
We are now focused on SEP-associated CMEs observed by K-Cor in 2013-2022

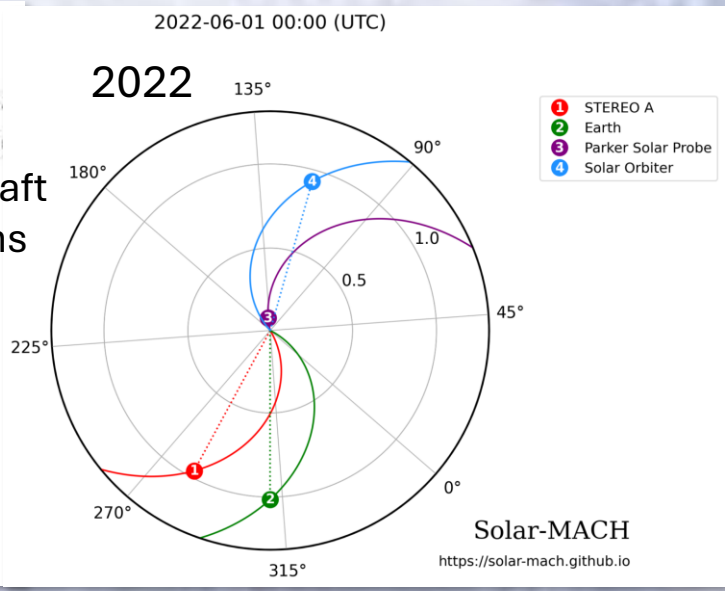
Use SEP observations from STEREO, SOHO and missions in the inner heliosphere (Parker Solar Probe, Solar Orbiter). Require >20 MeV protons. 27 SEP-associated MLSO CMEs have been identified, with a range of SEP peak intensities.

<= K-Cor provided *automated* alerts for SEP-associated CMEs on average 15 minutes before the CME was first detected by SOHO/LASCO, and ~ 1 hour before LASCO data were received on the ground.

TABLE 1: SEP EVENTS Detected DURING K-Cor Observations

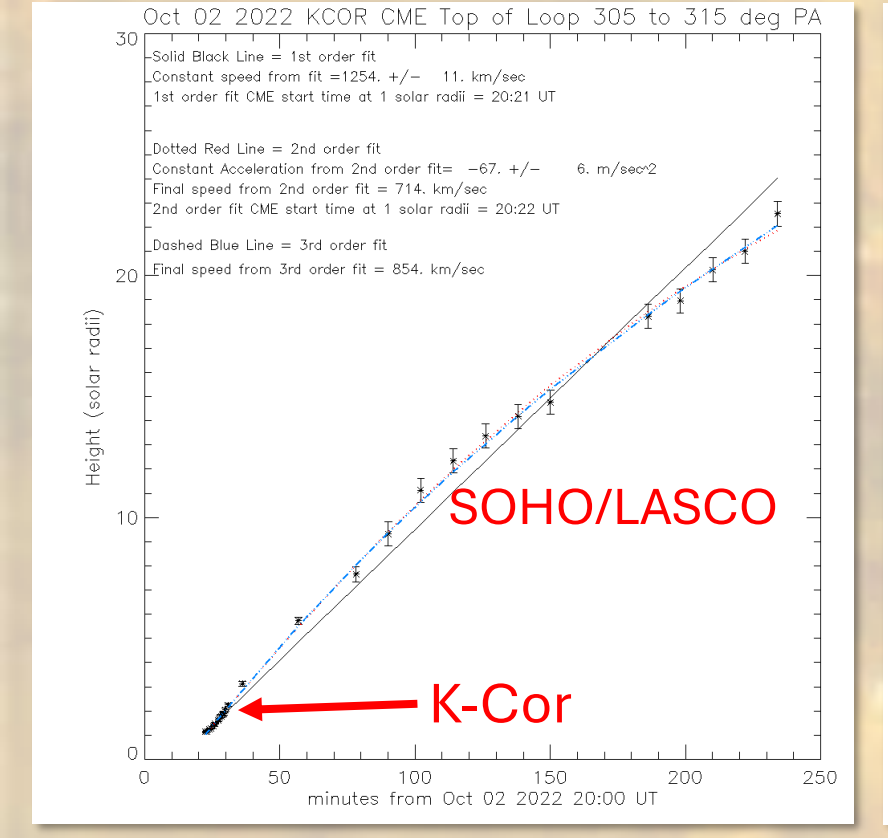
DATE OF SEP-associated CME	Time CME Alert issued Includes K-Cor latency	Time of LASCO first CME image	Time between LASCO and CME alert RED: detection after CME in LASCO BLACK: detection before CME in LASCO	Time between LASCO and alert INCLUDES 40-min LASCO latency
12/9/2013	19:36:57	19:36:05	> 0 min 52 sec	< 39 min 8 sec
12/16/2013	20:49:09	21:39:14	< 50 m 05 sec	< 90 m 05 sec
2/11/2014	19:00:39	19:24:05	< 23 m 26 sec	< 63 m 26 sec
9/24/2014	21:04:20	21:30:06	< 25m 46 sec	< 65m 46 sec
10/14/2014	18:50:24	18:48:06	> 2 min 18 sec	< 37 min 42 sec
2/8/2015	22:30:10	22:36:06	< 5 min 54 sec	< 45 min 54 sec
3/15/2015	01:29:58	01:48:05	< 18 min 7 sec	< 58 min 7 sec
1/1/2016	23:11:55	23:24:04	< 12 min 9 sec	< 52 min 9 sec
4/18/2017	19:31:23	19:48:05	< 16 min 42 sec	< 56 min 42 sec
5/7/2021	19:07:06	19:24:05	< 16 min 59 sec	< 56 min 59 sec
7/9/2021	17:37:43	17:48:05	< 8 min 22 sec	< 48 min 22 sec
7/15/2021	21:31:18	21:36:05	< 4 min 47 sec	< 44 min 47 sec
11/1/2021	01:25:14	02:00:06	< 34 min 52 sec	< 74 min 52 sec
1/31/2022	23:48:21	00:12:05	< 23 min 44 sec	< 63 min 44 sec
2/2/2022	00:22:15	01:25:48	< 63 min 33 sec	< 103 min 33 sec
3/10/2022	19:25:59	18:48:05	> 37 min 54 sec	< 2 min 6 sec
3/31/2022	18:45:57	19:12:05	< 26 min 8 sec	< 66 min 8 sec
5/11/2022	18:35:33	18:36:05	< 0 min 32 sec	< 40 min 32 sec
6/13/2022	03:03:37	03:12:11	< 8 min 34 sec	< 48 min 34 sec
10/2/2022	20:38:27	20:36:05	> 2 min 22 sec	< 37 min 38 sec
AVG time between CME Alert and LASCO 1st image			**14 min 49 sec *before* LASCO**	**54 min 49 sec *before* LASCO**

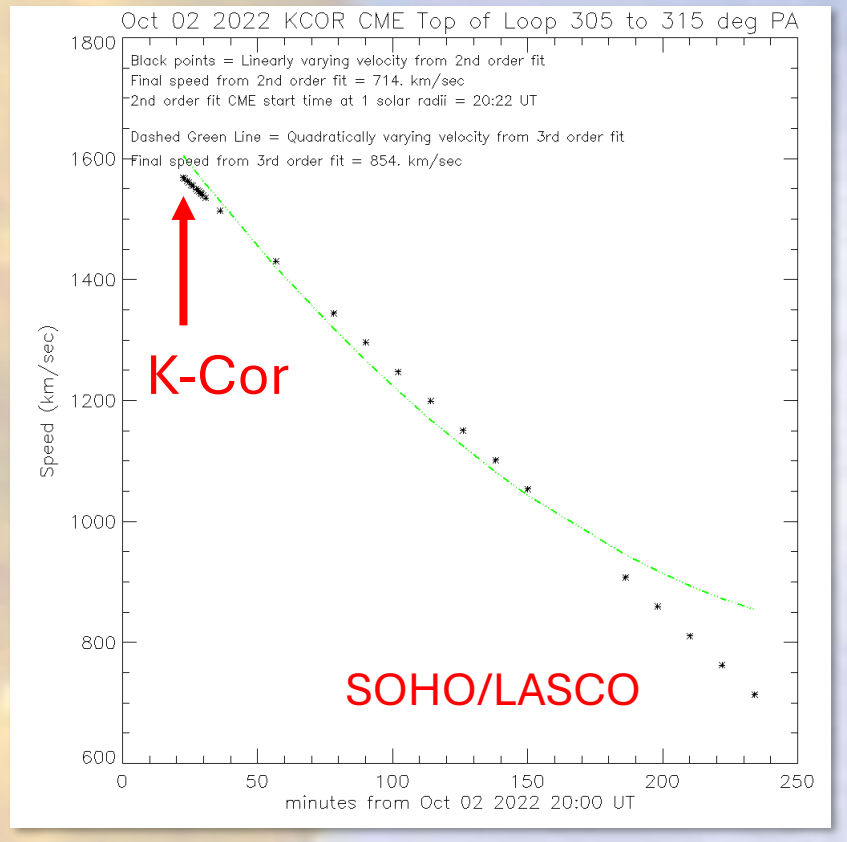


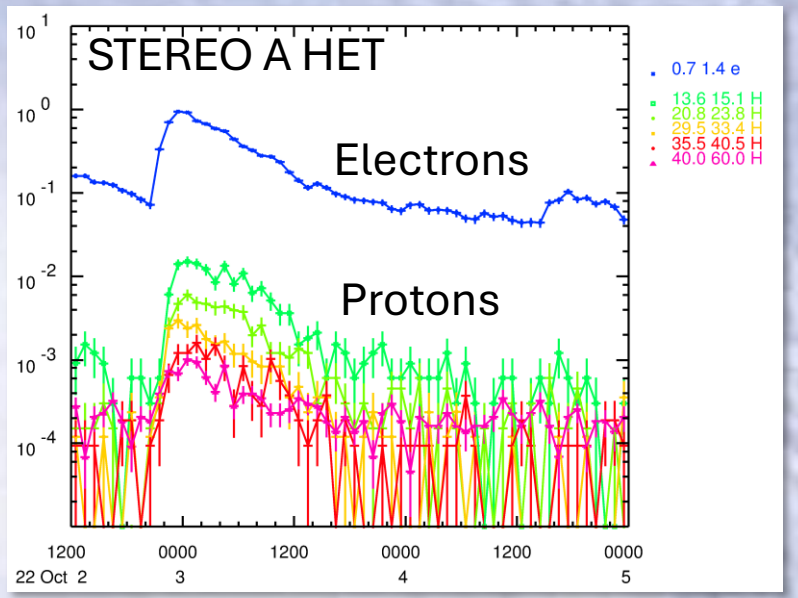


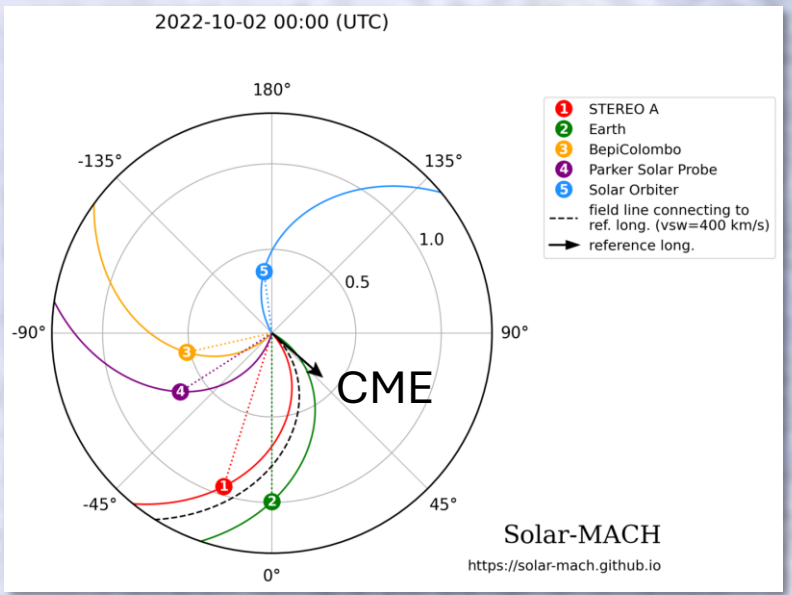
Burkepile et al., Space Weather Week, 2025

Combined K-Cor and LASCO Height and Speed vs. Time Plots for the October 2, 2022 CME, the fastest seen by K-Cor. The initial CME speed in K-Cor at ~1 R_s was ~1600 km/s, but rapidly ***decelerating*** to ~700 km/s at ~20 Rs.





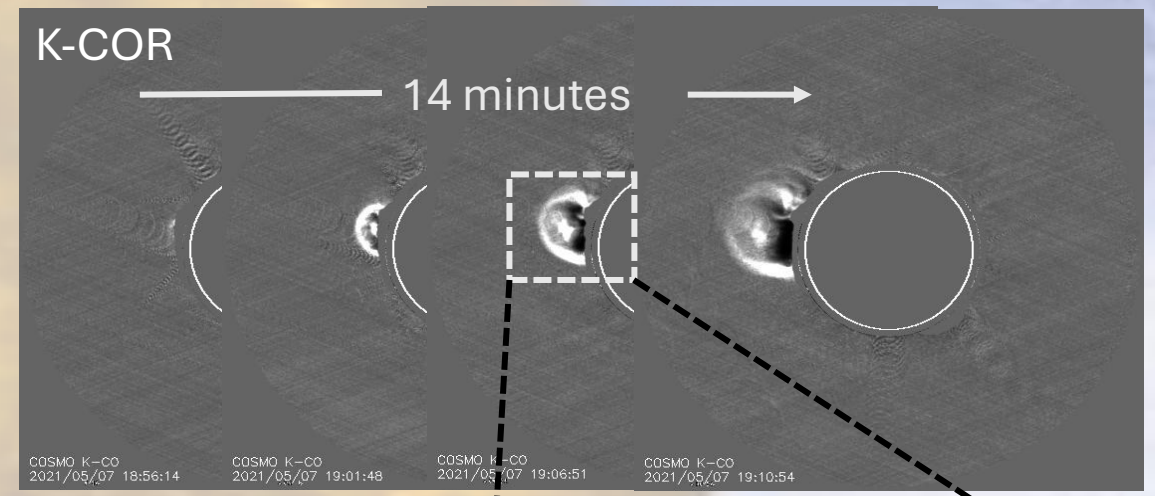




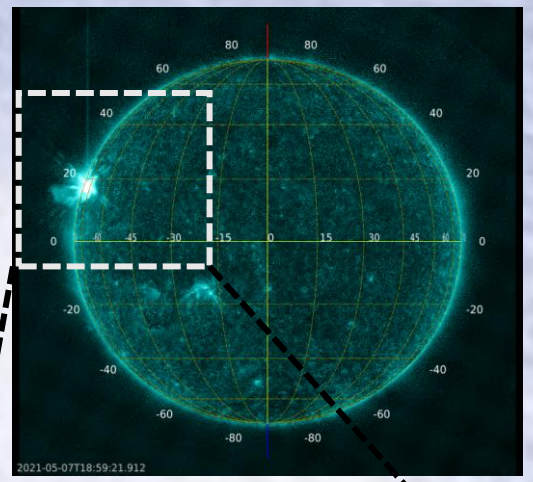
This CME was associated with a modest but energetic (>60 MeV), short duration impulsive SEP event at STEREO A and Earth. It is possible that particle acceleration was efficient in the low corona, where the CME was fast moving, but faded as the CME slowed in the middle corona, leading to the brief SEP event. **Another SEP-associated K-Cor CME that *accelerated* in the low-mid corona was shown above. These events exemplify the variety of CME dynamics in the low corona. Also using a population of non-SEP associated MSLO CMEs, we are trying to understand how these dynamics relate to SEP events beyond a generalization that "faster" CMEs (especially based on mid corona observations where accelerations are small) tend to be associated with larger SEP events.**

SEP-Associated MLSO CMEs Tend to be Associated with “Hot (>5 Mk) Flux Ropes” Observed by the Solar Dynamics Observatory

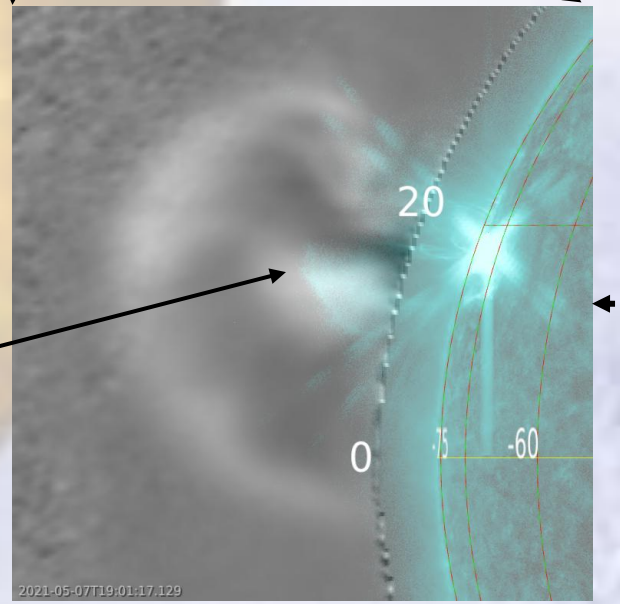
An example of an SEP-associated MLSO CME containing a hot flux rope (HFR) observed by the SDO AIA. HFRs are seen only in 94 Å and 131Å, but not in cooler coronal channels. HFRs are also most evident in AIA when close to the limb.

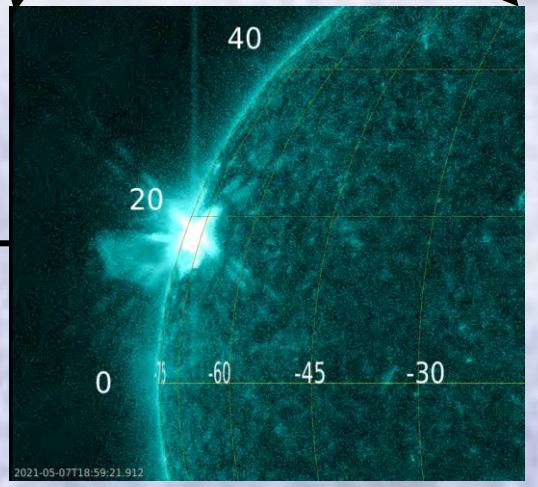


SDO/AIA 131 Å

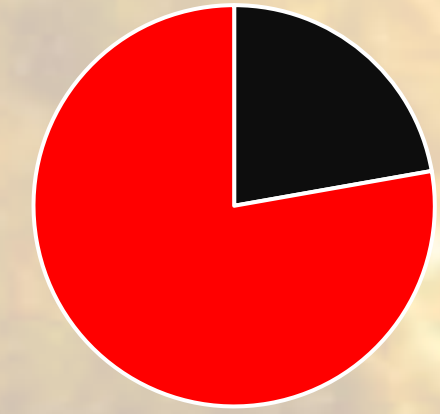


CME of 2021-05-07
In this overlay of SDO/AIA 131Å (blue) and K-Cor (gray) at 19:01 U.T., the **hot magnetic flux rope** is spatially coincident with the CME core in MLSO



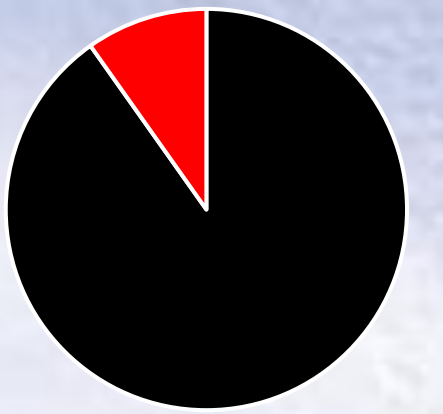


Hot Flux Rope



7/9 (78%) of CMEs
associated with SEP event

No Hot Flux Rope



5/51 (9.8%) of CMEs
associated with SEP event

We have identified a complementary population of MLSO CMEs *without* SEP events from the catalog of *Song et al*. (2023). **Only 5/51 of the CMEs (9.8%) without hot flux ropes were associated with SEP (~25 MeV proton) events compared to 7/9 (78%) of those with hot flux ropes.** We do not claim that there is a physical association between hot flux ropes and SEP events, but rather, both phenomena probably reflect more energetic solar eruptions. Nevertheless, this result suggests that the observation of a hot flux rope by SDO AIA or a similar instrument may be a useful low coronal signature that is predictive of an SEP event, at least when the eruption is close to the limb.

Summary

- We have made the first comprehensive survey of the association between CMEs in the low corona observed by MLSO since 1980 and SEP (~25 MeV proton) events. Archival SEP and space-based CME observations have been included in this survey.
- 84 SEP-associated CMEs in 1980-2013 observed by the MLSO Mk3/4 coronameters have been identified (*Richardson et al*., 2023) and the CME and SEP properties determined- A major problem is characterizing the CME dynamics reliably due to limited cadence of the observations.
- 27 SEP events in 2013-2022 have been associated with CMEs in the low corona observed by MLSO K-Cor. Analysis of the CME dynamics is largely complete. Unfortunately, the sample of events is limited due to the Mauna Loa eruption. Efforts are underway to reopen MLSO.
- We have found an interesting close association between CMEs including hot (>5Mk) flux ropes and SEP events that may lead to a way to predict potential SEP events from solar/low coronal remote sensing observations.

References:

Richardson et al. (2014) DOI: 10.1007/s11207-014-0524-8
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Richardson et al. (2018) DOI: 10.1029/2018SW002032
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St. Cyr et al. (2017) DOI: 10.1002/2016SW001545
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