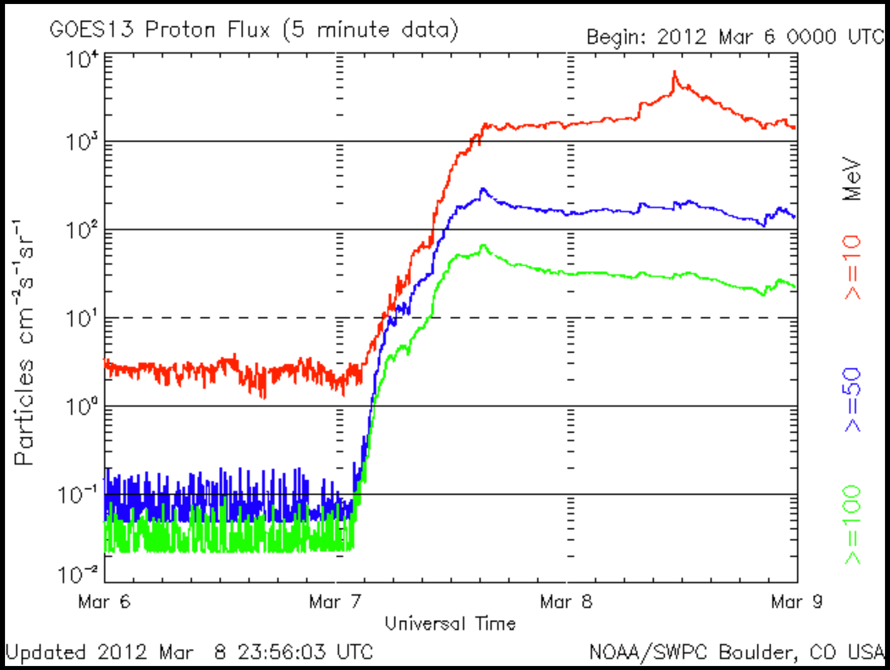
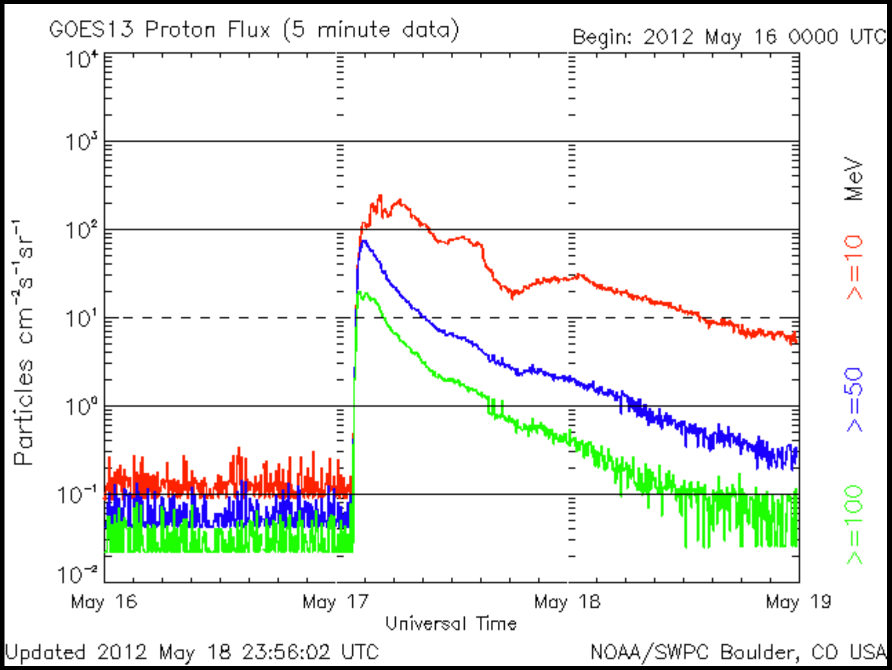
The Solar Origin of High-Energy Solar Energetic Particle Events





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What determines the SEP initial time variations?

Eruptions in the western longitudes tend to produce SEP events with quicker onsets than those elsewhere (Cane et al. 1988), but there are exceptions.

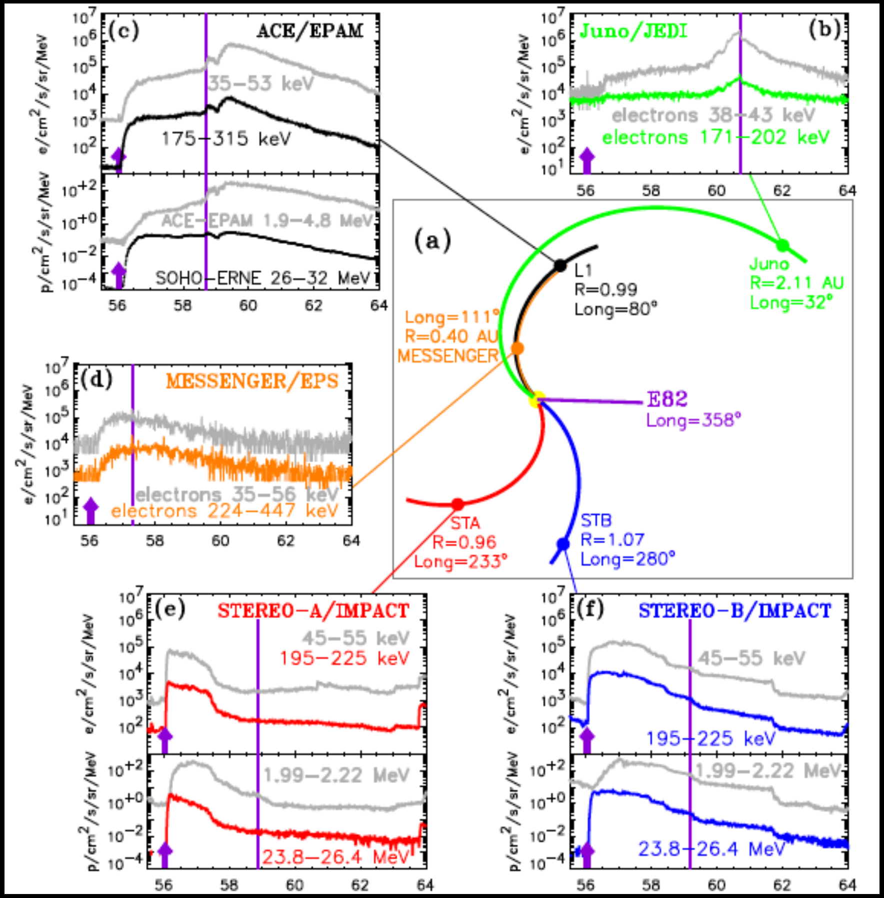
Particle release in a SEP event starts when the moving acceleration region (e.g. CME-driven shock wave in the corona) intersects field lines connecting to the observer.

First-arriving particles are probably scatter-free and not experiencing cross-field transport.

Localizing the acceleration region is important for predicting how the SEP event intensifies and how hard a spectrum it will have.

Multi-spacecraft (wide-longitude) SEP events

With STEREO and other planetary missions, the same SEP events are observed at multiple longitudes relative to the source region. Does the SEP release time coincide with the time when the CME-driven shock intersects the observer's field lines?

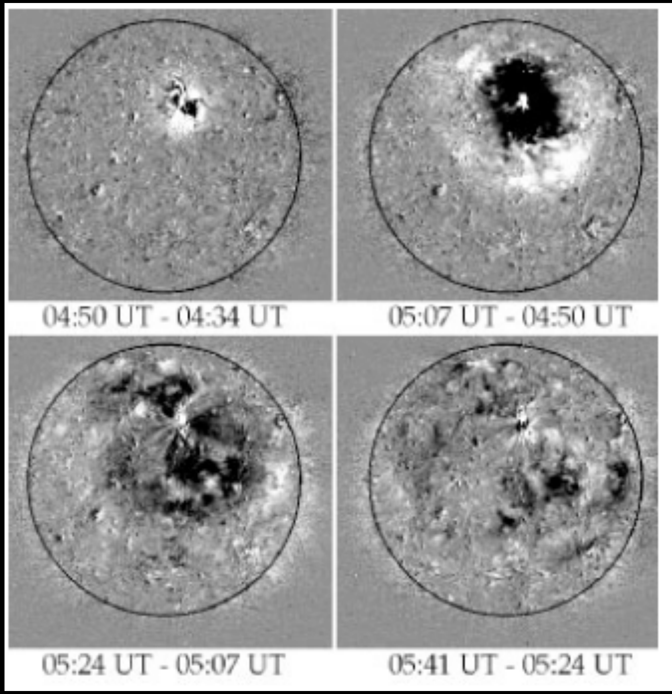


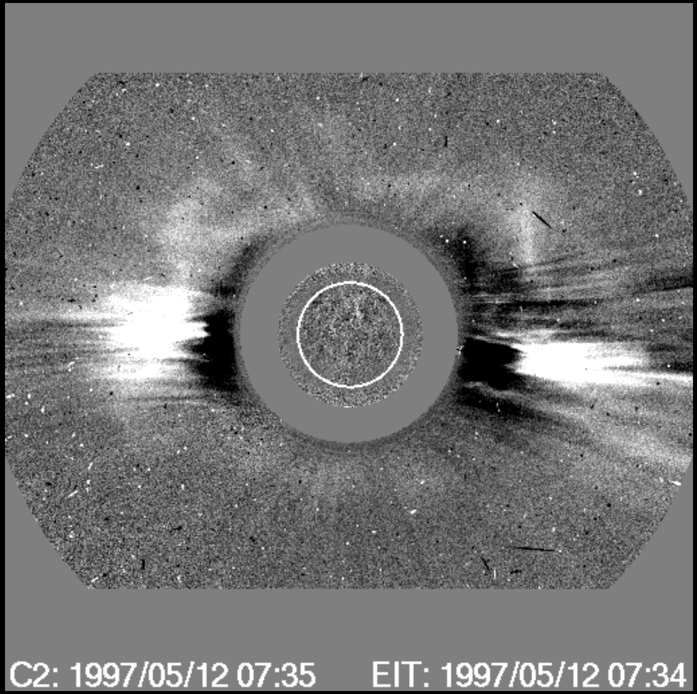
Lario et al. 2016

EIT (EUV) waves

SOHO/EIT found large-scale propagating fronts, which are interpreted as fast-mode MHD waves that can steepen to a shock if driven strongly enough.

Several authors showed that they are more intimately associated with CMEs than with flares, and some assume that they constitute the bottom part of the CME-driven shock.





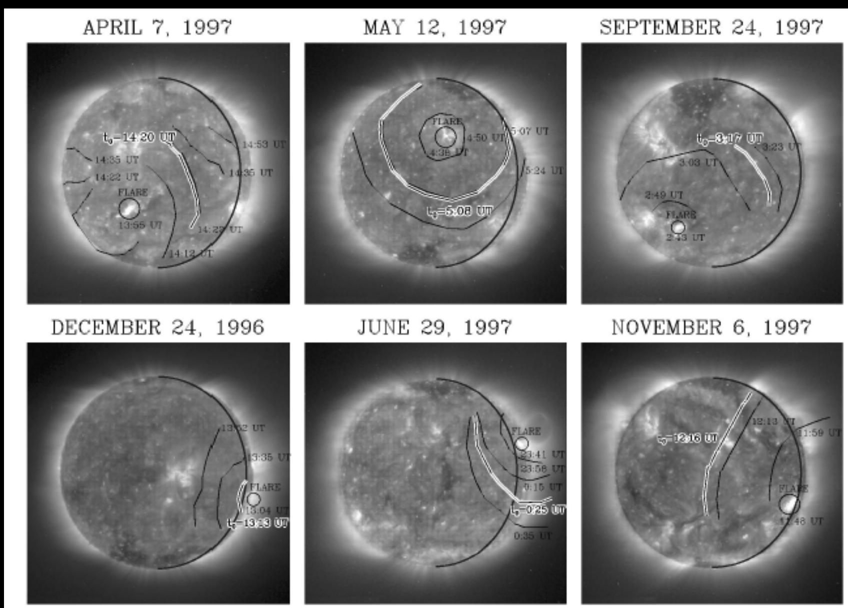
Thompson et al. 1998

EUV Waves and SEP events

Big SEP events are often associated with EIT waves.

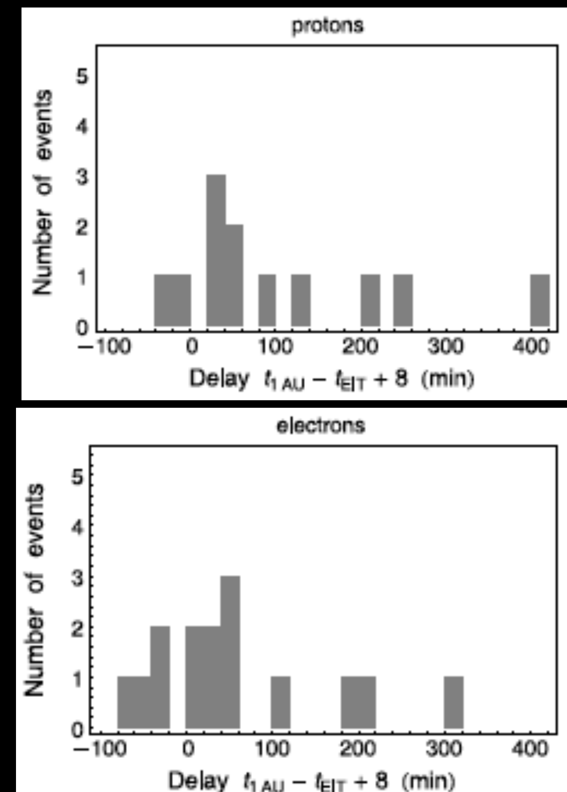
A majority of wide-longitude SEP events are accompanied by EIT waves.

Attempts to compare the SEP release times with when the EIT wave traverses the well-connected area.



Krucker et al. 1999

Electron events from ill-connected longitudes have delayed onsets, but the EIT wave is too slow to account for the delay.



Miteva et al. 2014

Similar conclusions for electrons

EUV waves and SEP events in cycle 24

If the EUV wave was too slow, EIT's compromised cadence (12–15 minutes) could have been one of the reasons. Now SDO/AIA can measure much faster EUV waves, although intrinsically slow waves do exist.

Moreover, the above two papers used the Parker spiral down to the solar surface. This limited the footpoint to the ecliptic, which is unrealistic. We also need to localize the connection point rather than assuming that all the latitudes in the well-connected longitudes are connected to the observer.

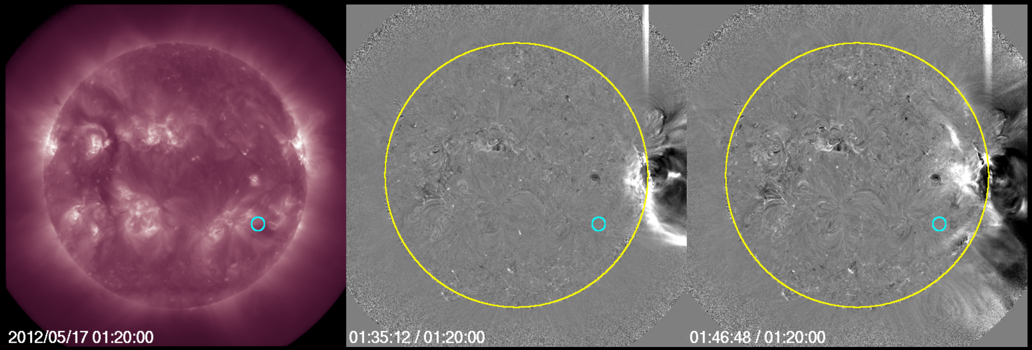
Some recent papers gave an impression that the SEP release time matches (within the uncertainties of determining the particle onsets and tracing the EUV waves) the time when the EUV wave hits the connection point. But they did not always trace the waves; instead they extrapolated the locations of the front to the connection point often with a simplified shape of the front.

Note that the trajectories of EUV waves may be complex, including deflection at magnetic obstacles such as coronal holes and active regions.

EUV waves and SEP events in cycle 24

According to Lario et al. (2014, 2016, 2017), the EUV wave never reached the connection points at least for some locations (STB, L1 or STA) in three events.

Out of the 50 near-relativistic events studied by Nitta et al. (2018), the EUV wave reached or traversed the connection point more than 10 minutes too early in 29 events, about the right time (within ±10 minutes) in 3 events, and more than 10 minutes too late in 2 events. In the remaining 16 events, the EUV wave did not reach the connecting point.



The source region is at N11 W76. The connection point is far into the southern hemisphere. The diffuse front almost contacted it, but not quite.

The EUV wave may often be a red herring when talking about SEPs?

EUV waves and CMEs

Despite the frequent association with SEP events, especially wide-longitude events, EUV waves in loose definition seem to be not relevant for SEP acceleration/transport in many cases (cf. progressively hardening hard X-ray spectra in solar flares.)

Although they often accompany CMEs, EUV waves may not be either necessary or sufficient conditions of CMEs. Nothing, even including coronal dimming, may not replace coronagraph data.

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Observing coronal mass ejections without coronagraphs

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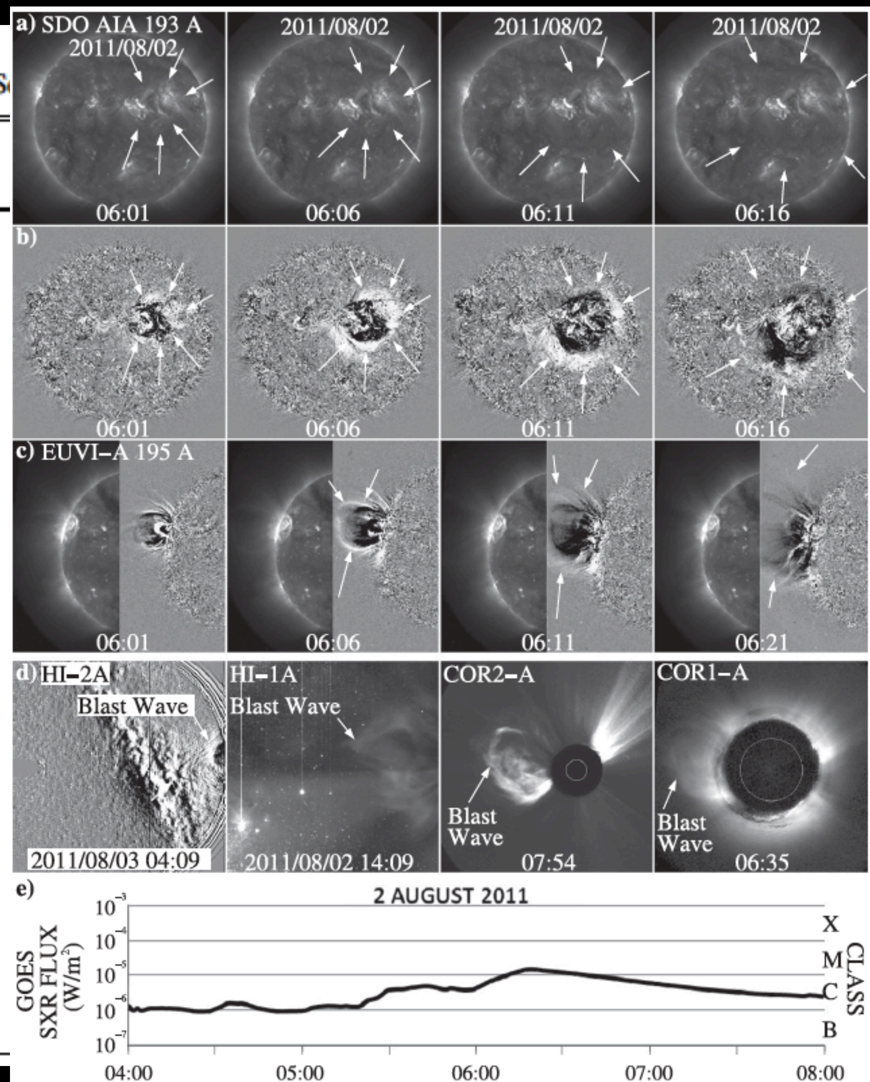
EUV waves = driverless?

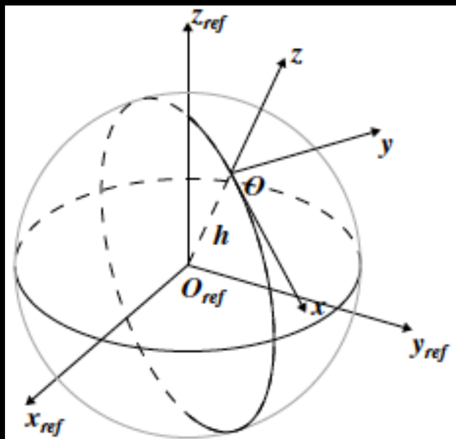
"Blast wave" hypothesis (Howard and Pizzo 2016)

Our S... ...l. list.

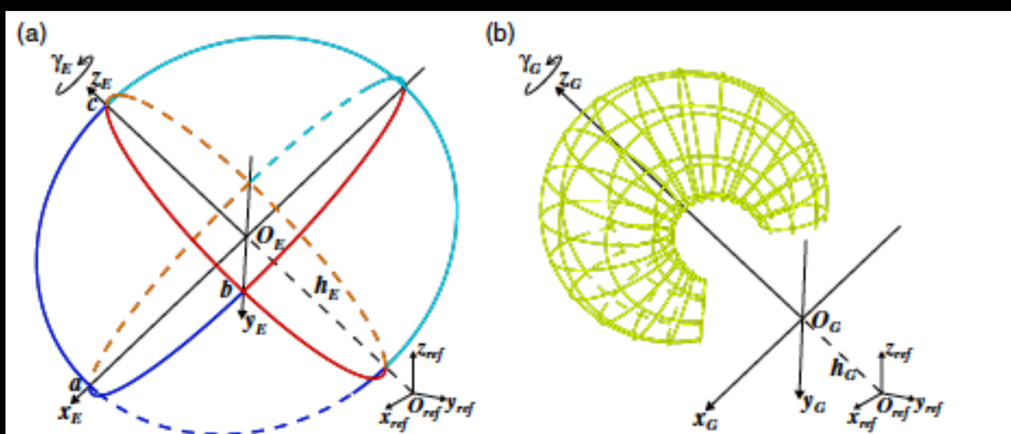
#	Date	...itu ...ture	Variety
1	2010 Jan 17		Combination
2	2010 Apr 08		Combination
3	2010 May 04	ata gap?)	Flux rope
4	2010 Jul 16		Blast wave
5	**2010 Aug 01**	**-MC**	**Combination**
6	2010 Aug 07	18:30UT	Blast wave
7	2010 Nov 13		Blast wave
8	2011 Feb 13		Blast wave
9	2011 Feb 15	00UT	Blast wave
10	2011 Mar 07		Combination
11	2011 Mar 27		Blast wave
12	**2011 Jul 11**		**Flux rope**
13	**2011 Aug 02**	**30UT**	**Blast wave**
14	2011 Sep 06	R.shock+MC	Combination
15	2011 Sep 06	R.shock+MC	Combination
16	2011 Sep 07		Blast wave
17	2011 Oct 01		Combination
18	2011 Oct 02		Combination
19	2011 Oct 02		Blast wave
20	2012 Mar 09	00UT	Combination
21	2012 Mar 14		Blast wave
22	2012 Mar 17		Blast wave



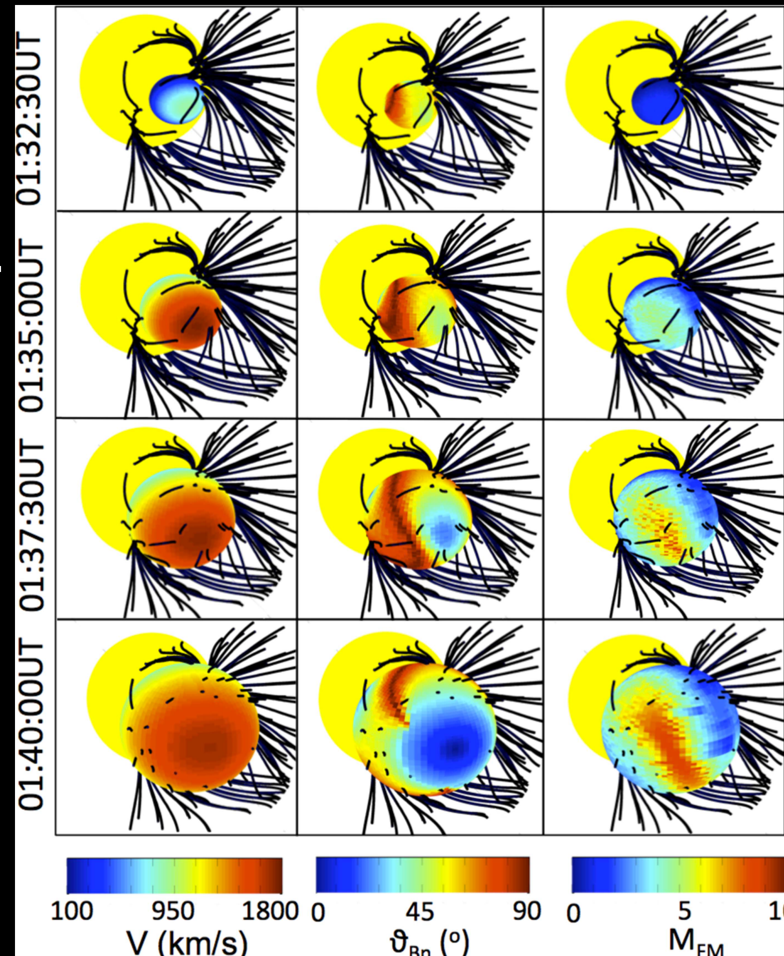
CME-driven shock based on geometrical models



Forward-fitting geometrical (GCS+ellipsoid) models by Kwon et al. (2014), Rouillard et al. (2016) and Xie et al. (2017)



Kwon et al. (2014)



Rouillard et al. (2016)

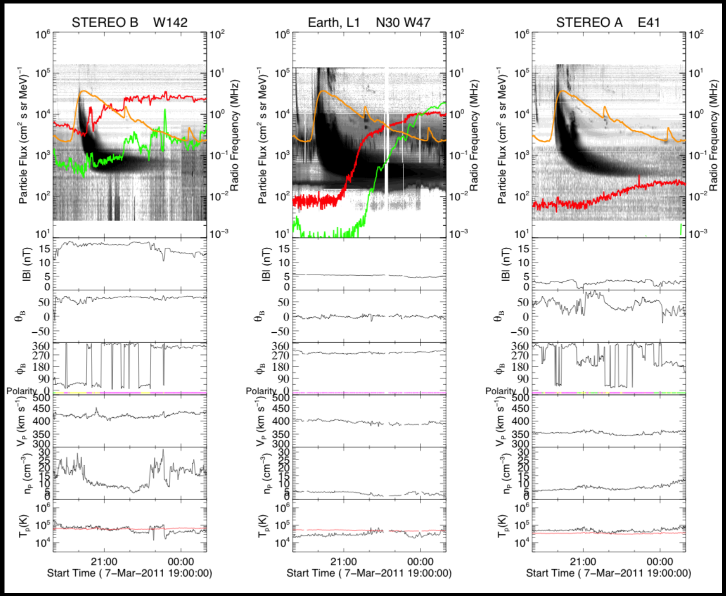
Use static model for magnetic field traversed by the shock

Alfven Wave Solar Model (AWSoM)

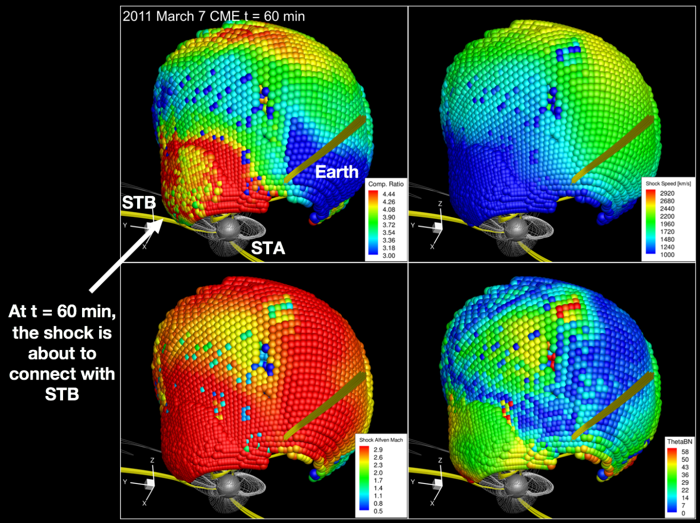
Numerical simulations to capture dynamically evolving CME and ambient field = complementary to geometric models

Part of the U Michigan Space Weather Modeling Framework (SWMF) based on BATS-R-US. It includes most of the physical processes related to solar wind (van der Holst et al. 2014), so AWSoM is awesome.

7 March 2011 Event



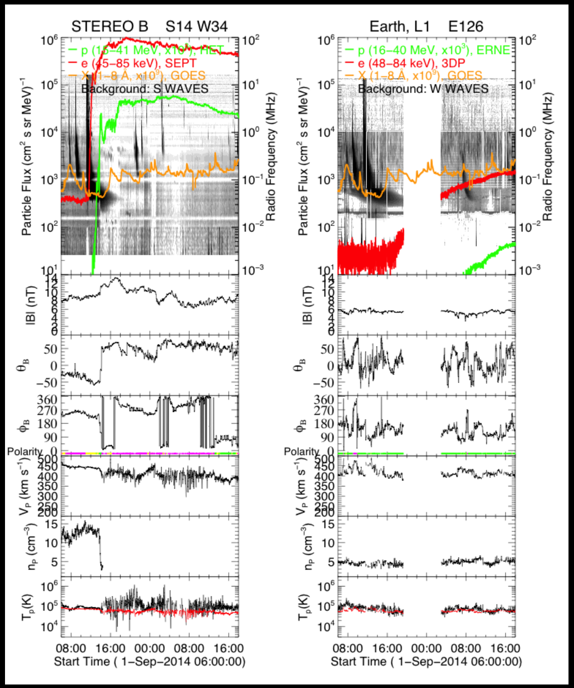
t = 60 min

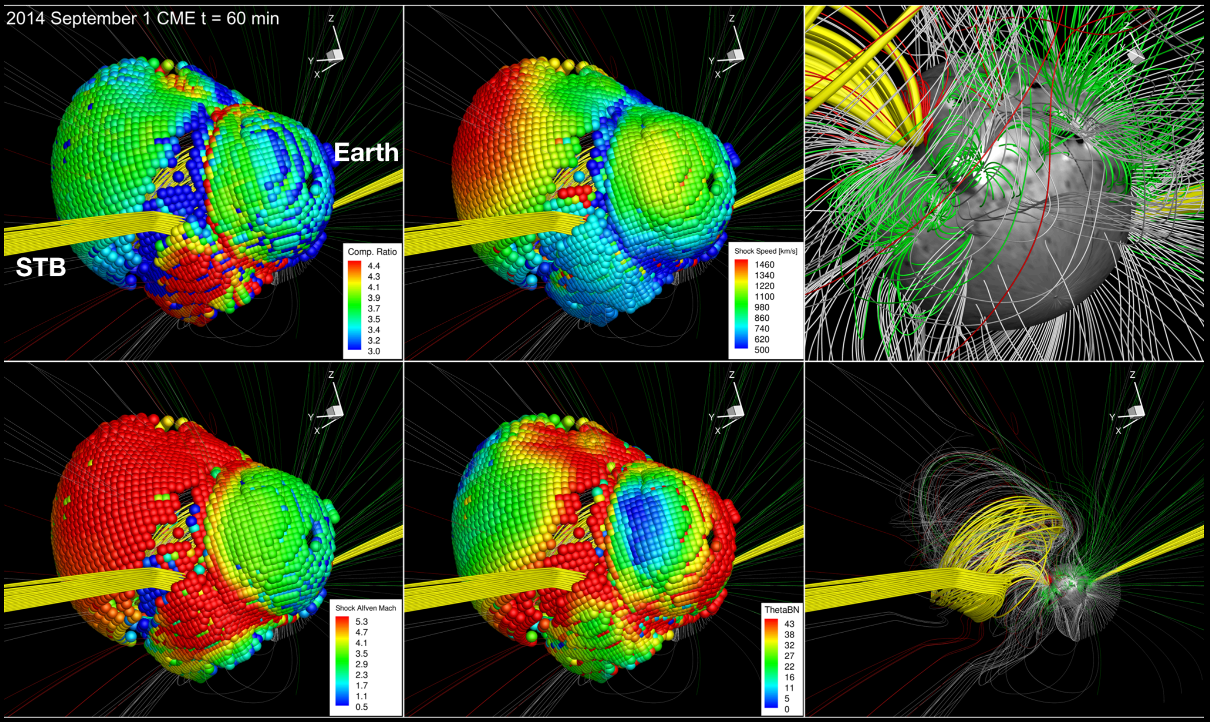


Earth was connected to the shock from the beginning, then STB, but not STA within 60 minutes.

1 September 2014 event

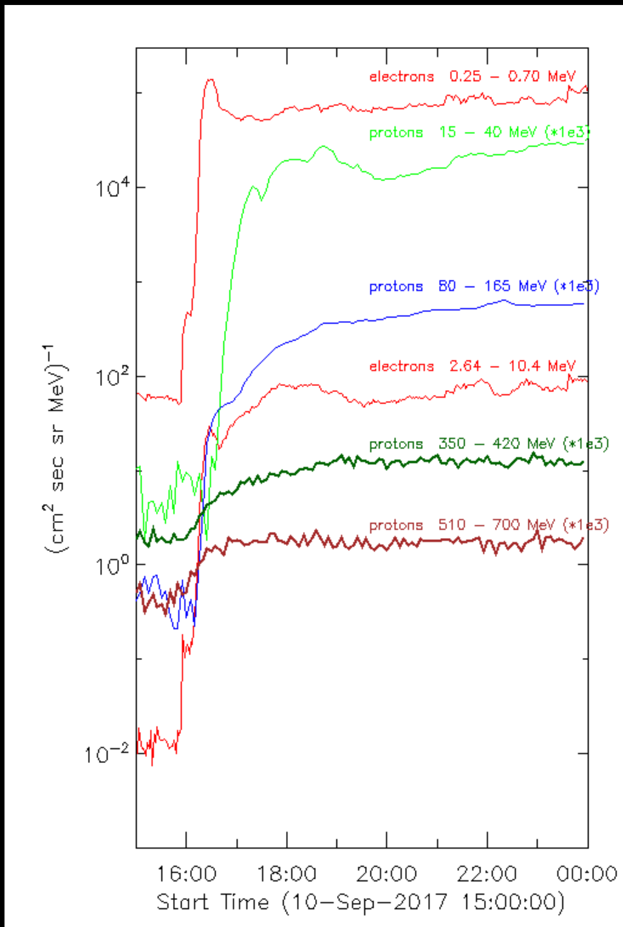
t = 60 min

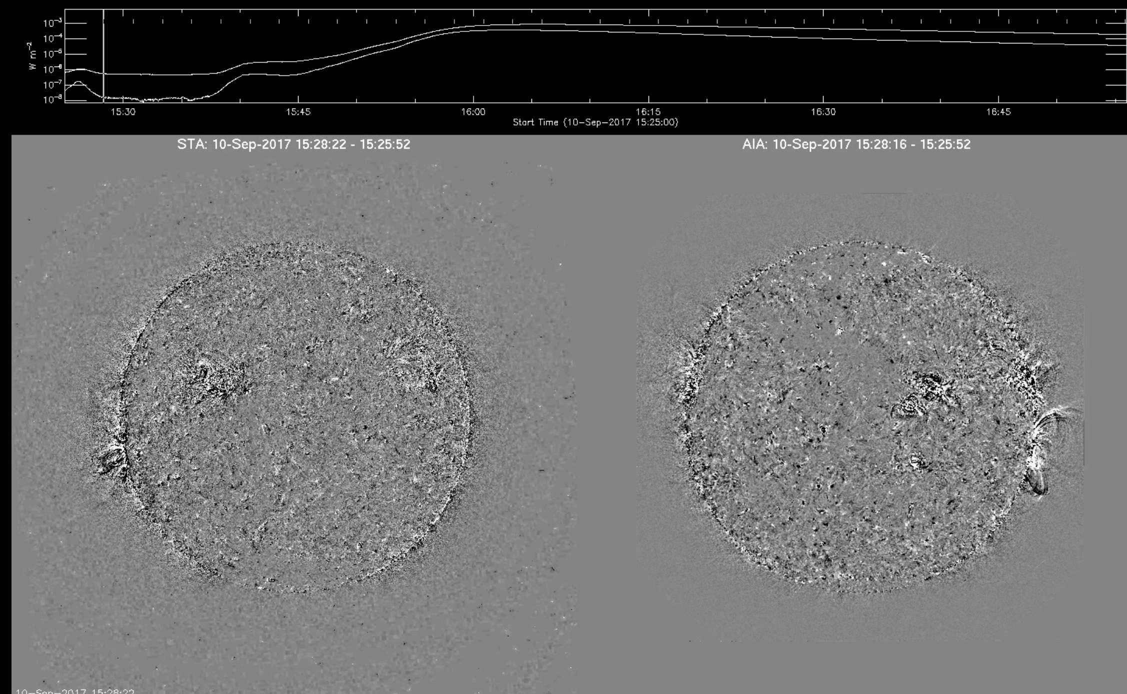




STB always connected to the shock, initially quasi-parallel then then to quasi-perpendicular. Earth was not connected to the shock.

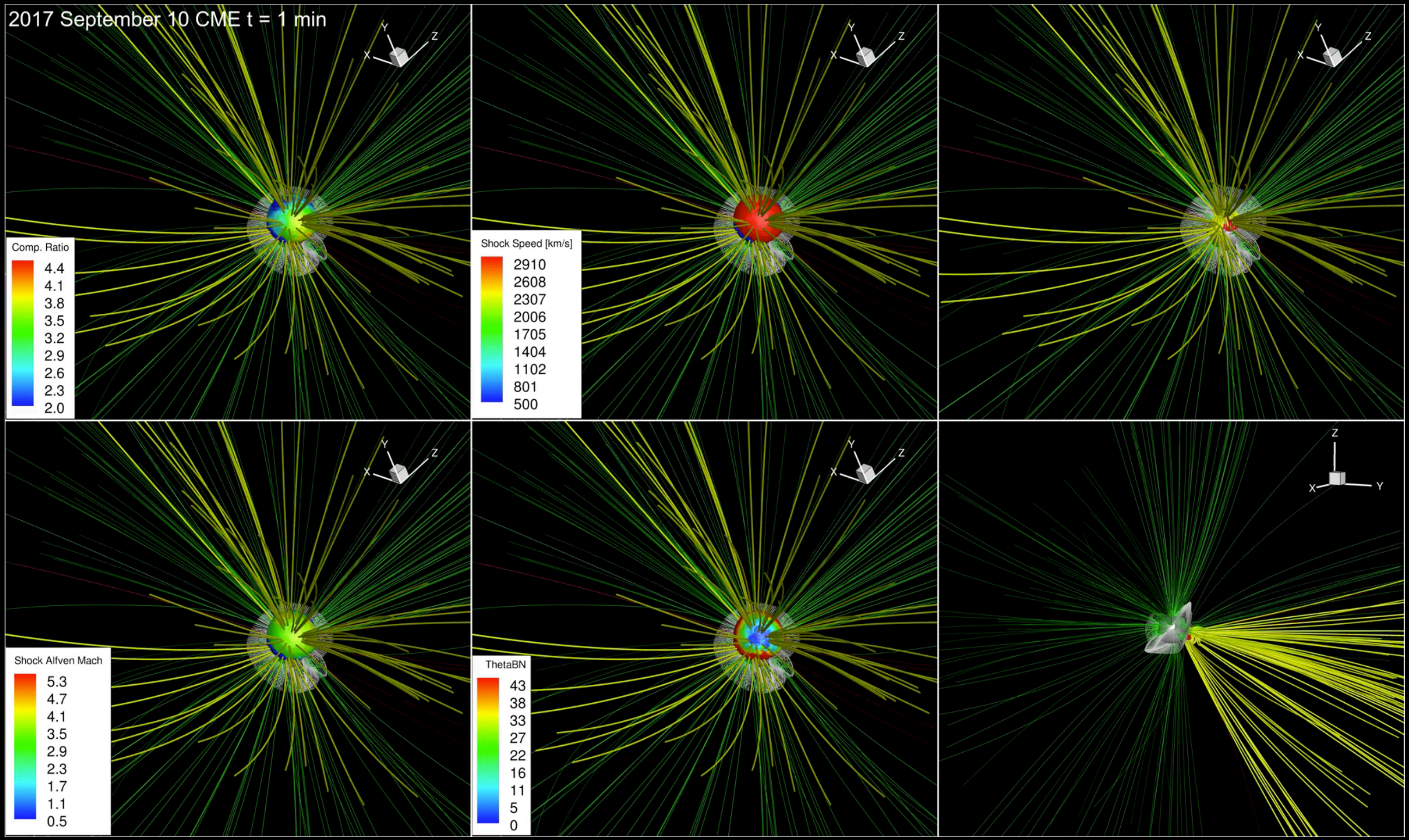
10 September 2017 event





At STEREO-A (~128 degs behind the east limb), the SEP event was just a small gradual increase.

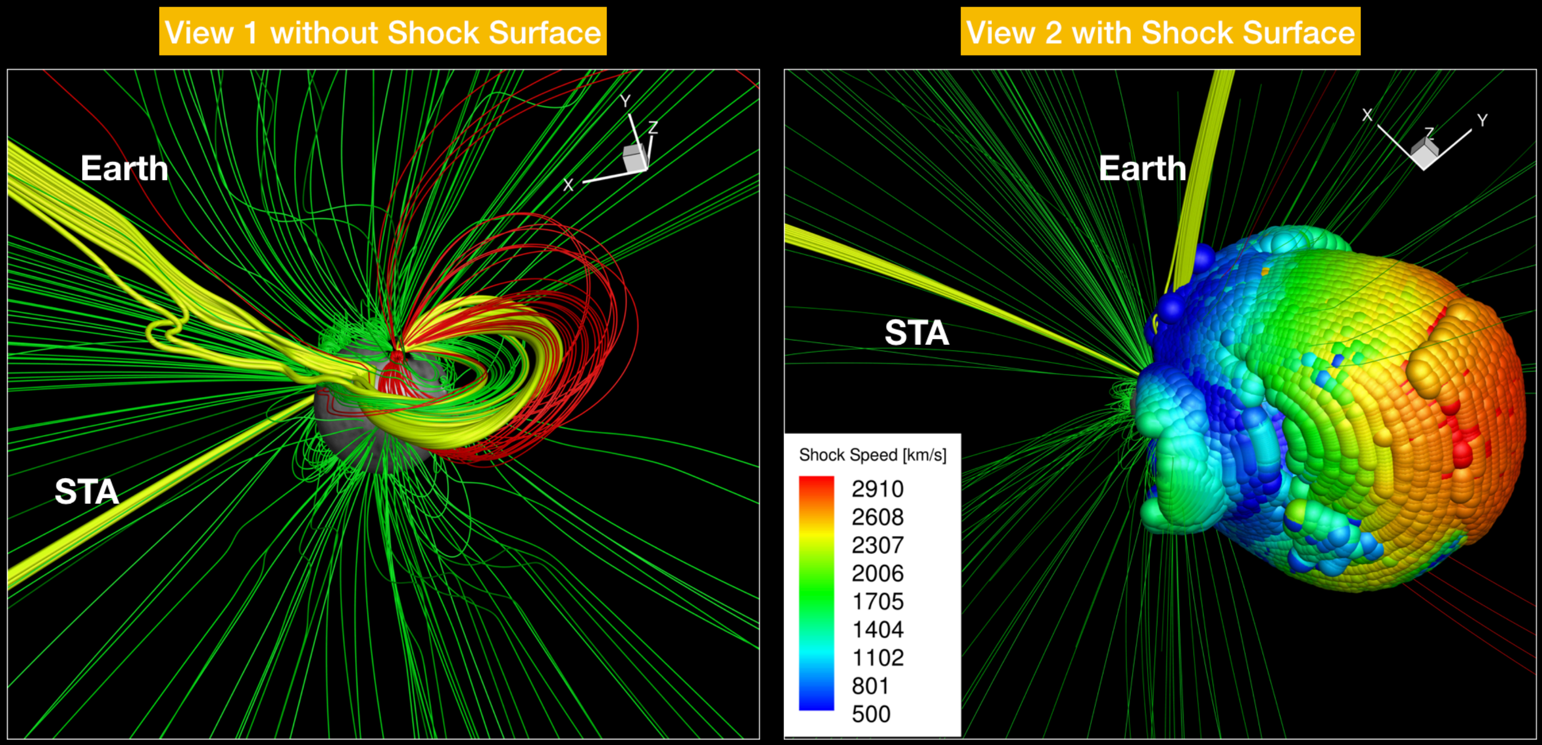
10 September 2017 event



Shock view (the source region S09 W88 from Earth)

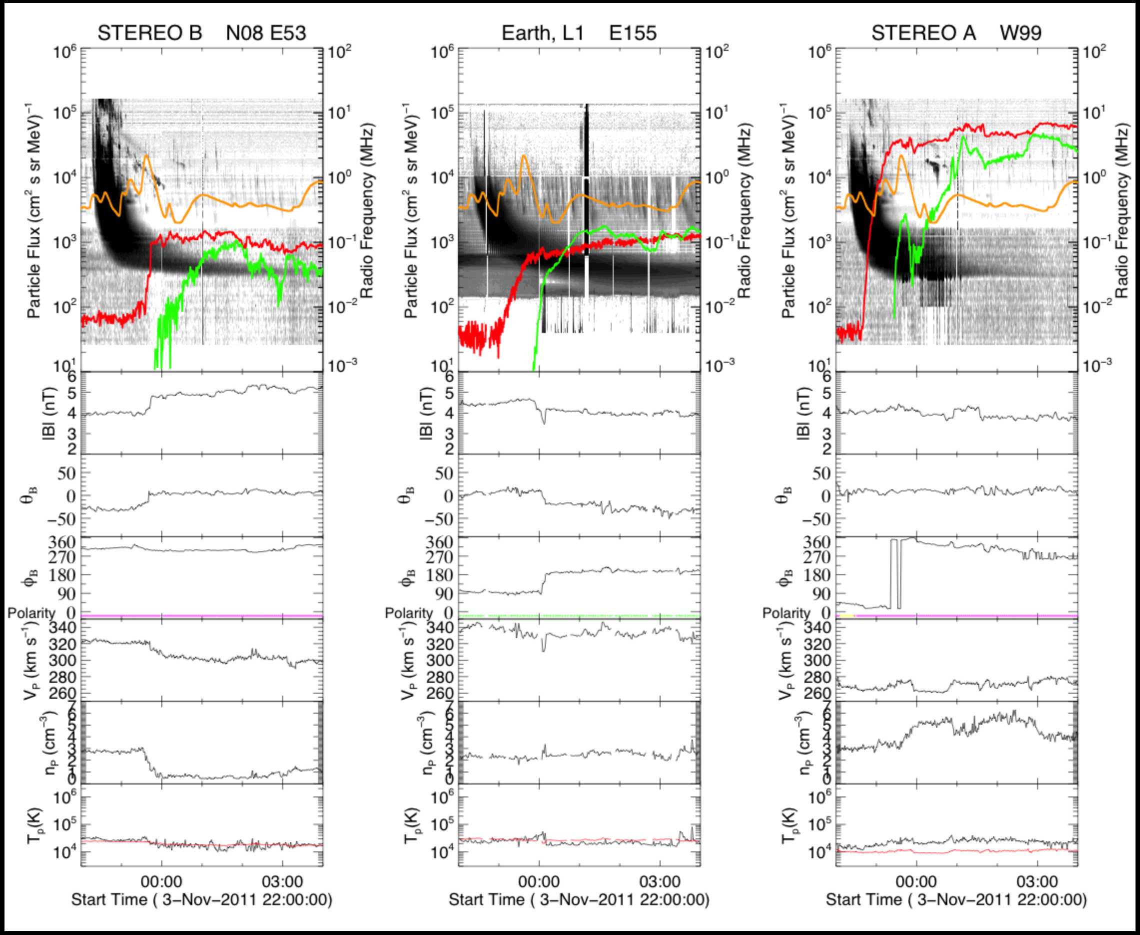
10 September 2017 event

t = 30 min



- **The field lines connecting to L1 can trace back to the source region of the CME. The connectivity changes from the beginning are due to magnetic reconnection.**
- **These field lines also develop connection to the edge of the shock after ~30 min in the simulation.**
- **It seems that STA does not develop any connection to the shock, at least the major part of the shock during the evolution.**

Circumsolar event on 3 November



The most challenging problem is to let particles arrive at L1 ~40 minutes after the eruption.

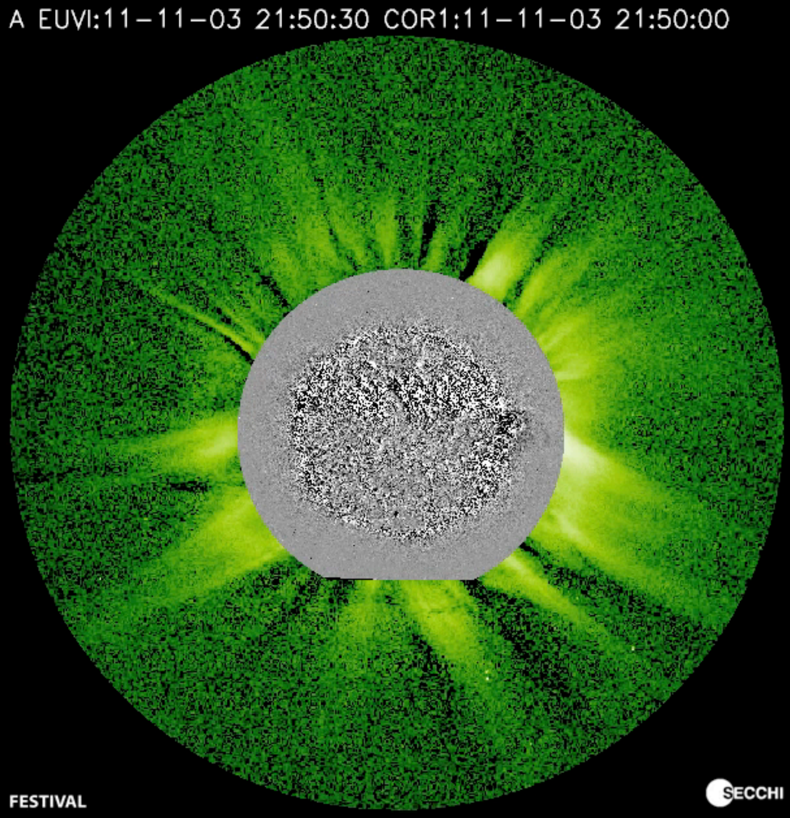
The source region was located at N08 E155. The nominal Parker spiral footpoint of L1 was N04 W67. The EUV wave was only ≦500 km s^{-1}.

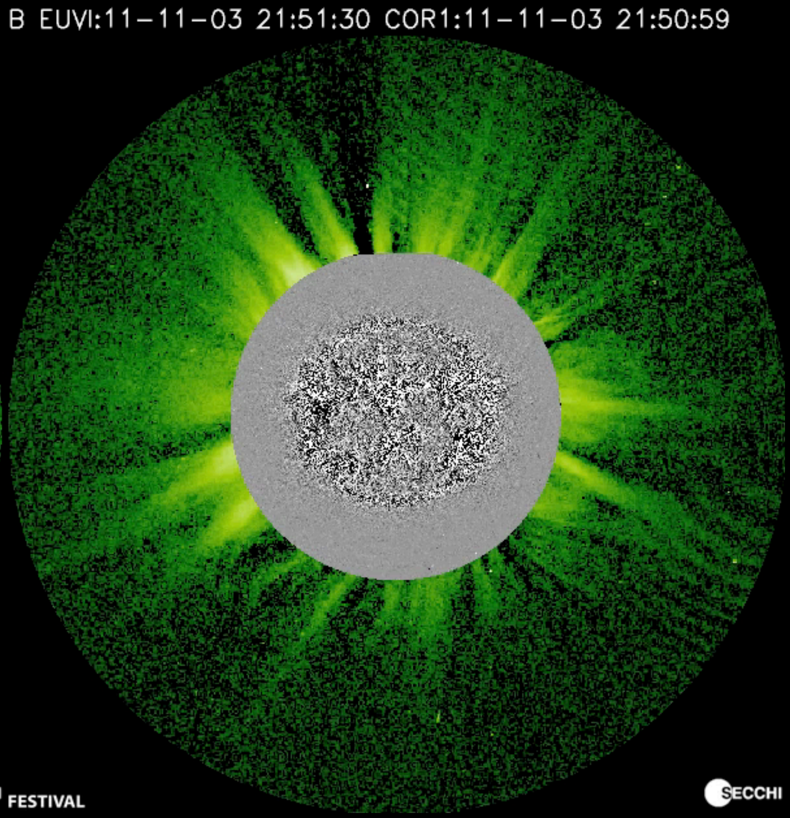
It takes a 500 km s^{-1} wave 55 minutes to travel the two points in great circle. The wave was likely much slower.

The 3D geometric model with the PFSS field line predicts the arrival of the CME shock at the footpoint of the L1 Parker spiral field line on the source surface at 23:39 (Kwon, private communication, 2016), ~40 minutes too late.

STEREO Movie for the 3 November 2011 Event

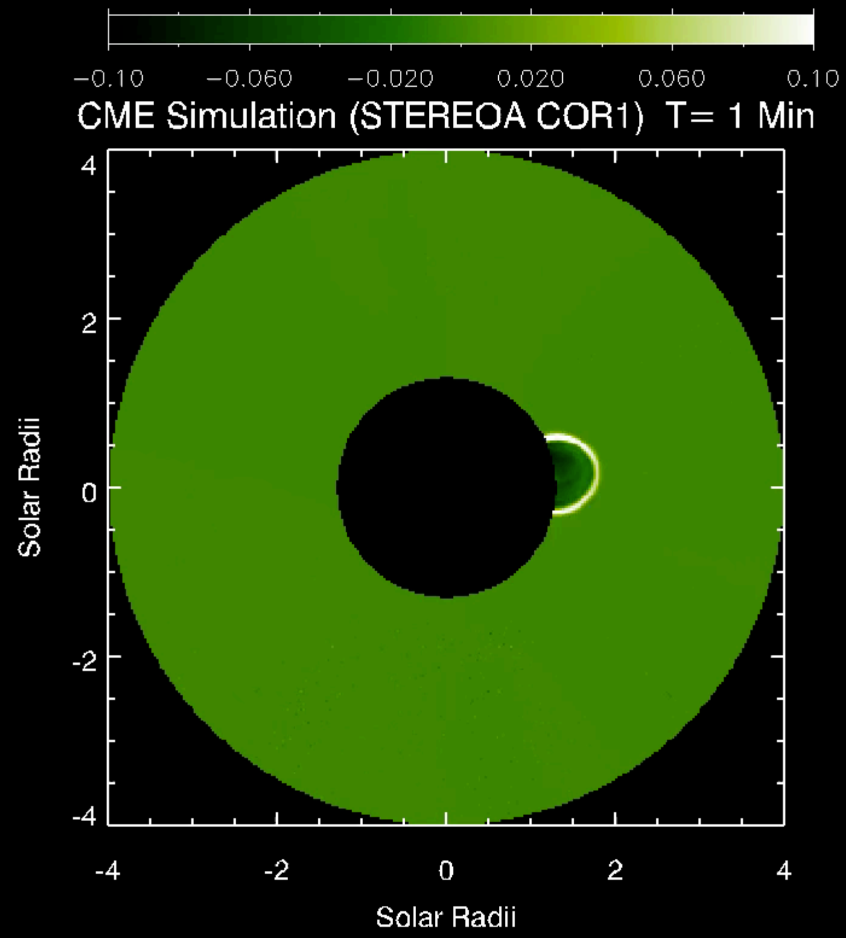
Note the disturbances that reach the south polar region around 23:00 UT.





STEREO Movie for the 3 November 2011 Event

Simulations reproduce the flank of the CME-driven wave passing the south polar region.



Summary

- The EUV waves are frequently associated with SEP events, but they are not the acceleration agent in many events.
- They may not be used as the low coronal counterpart of the CME-driven shocks.
- Promising geometric models to show the importance of the magnetic field connection of the observer to the CME-driven shocks for understanding the SEP evolution.
- In particular, the state-of-the-art numerical modeling may provide in situ measurement of the plasma and magnetic field around the shock regions.
- Questionable magnetic field connection modeling (due largely to the lack of full-surface magnetic field observations, especially polar regions). Problem to be addressed by next-generation heliophysicists.