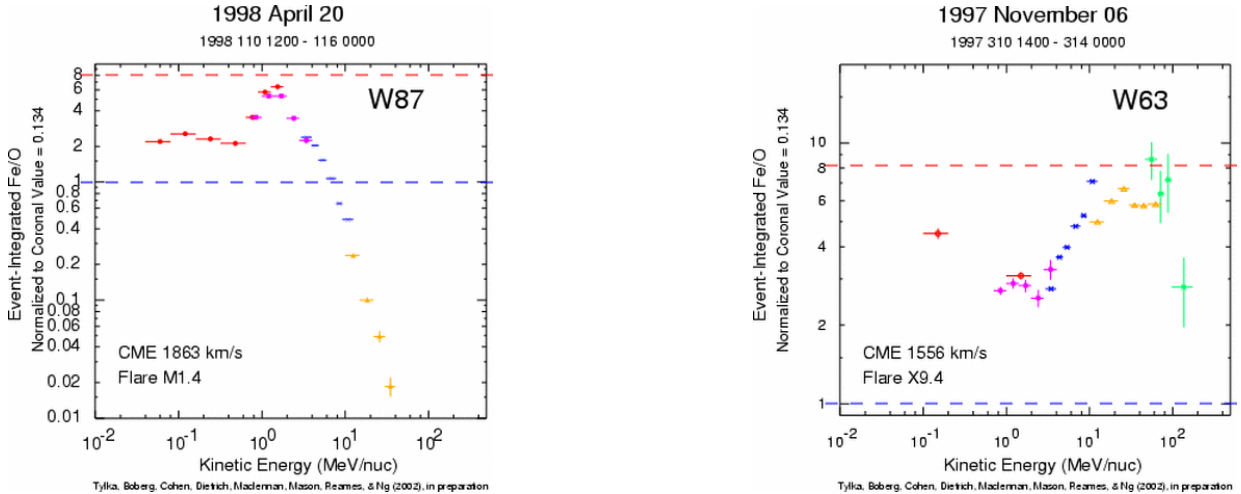
Understanding the Origin of Variable Compositions of Gradual Solar Energetic Particle Events by Combining Observations and Numerical Simulations



LWS CDAW 2002

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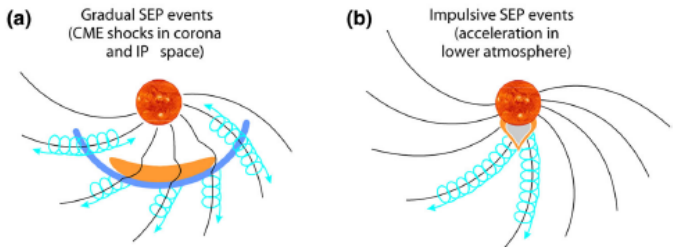
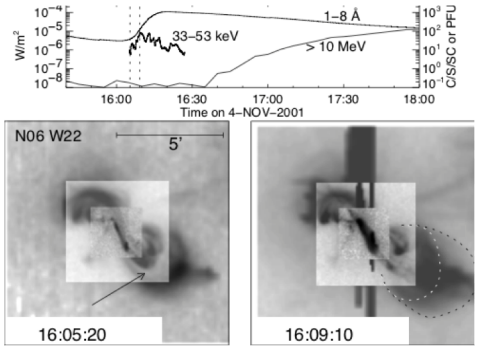
Impulsive-like Gradual (Hybrid) SEP Events

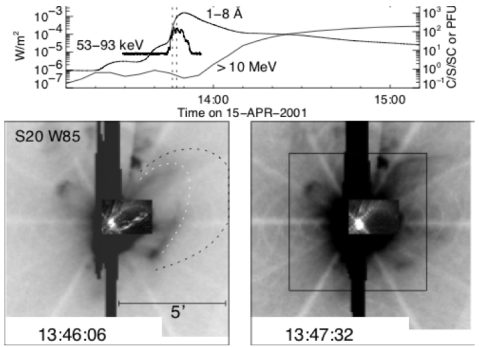


Property	Impulsive	Gradual
Electron/proton	$\sim 10^2$–10^4	~50–100
$^3He/^4He$	~1	$\sim 4 \times 10^{-4}$
Fe/O	~1	~0.1
H/He	~10	~100
Q_{Fe}	~20	~14
SEP duration	<1–20 h	<1–3 days
Longitude cone	<30°	<100°–200°
Seed particles	Heated Corona	Ambient Corona or SW
Radio type	III	II
X-ray duration	~10 min–1 h	$\gtrsim$1 h
Coronagraph	N/A	CME
Solar eind	N/A	IP shock
Events/year	~1000	~10

Desai & Giacalone 2016

For events in the early phase of solar cycle 23, Yohkoh/SXT observations hinted at possible differences of eruptions associated with Fe-rich and Fe-normal gradual SEP events.



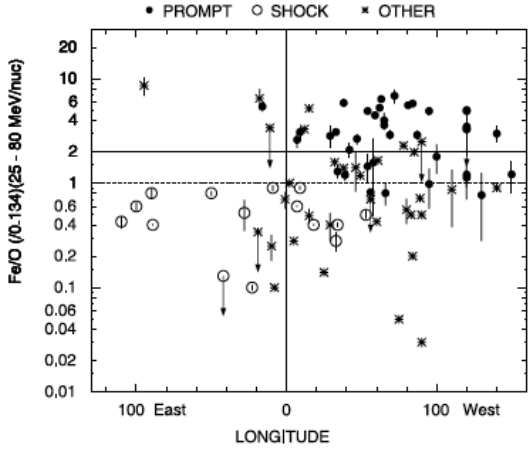


Fe-normal: AR-scale eruption preceded by gradual rising motions. Fe-rich: Eruption starting localy and explosively. This distinction may have to do with two types of CMEs with different morphologies and kinematic behaviors.

Nitta, Cliver, & Tylka 2003

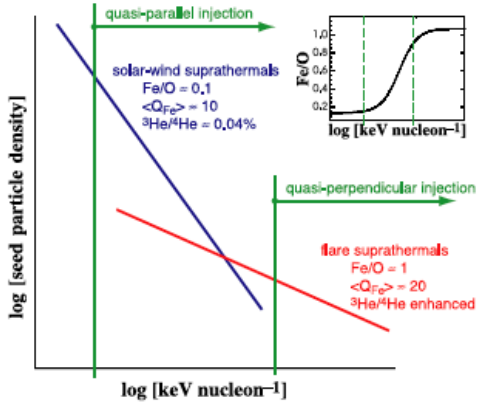
Two Hypotheses for Fe-rich Gradual SEP Events

- Direct flare contributions (Cane et al. 2003, 2006, 2010, 2017 (SHINE plenary talk)).
- Fe-rich events tend to have a prompt onset and to come from the western hemisphere that is statistically well-connected.
- Not shown how flare-accelerated particles can get out of the closed structure of the CME.



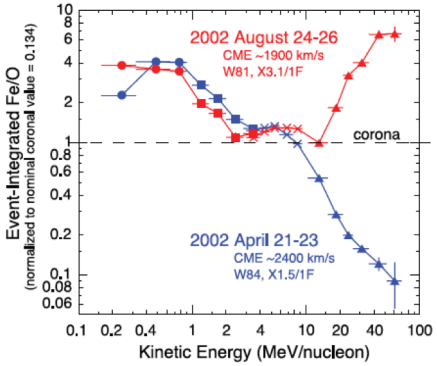
Cane et al. 2006

- Acceleration of suprathermal particles that may be remnants of previous flares or impulsive SEP events, the high-energy tail of which abounds in Fe.
- These high-energy suprathermals can be preferentially accelerated at quasi-perpendicular ($\Theta_{BN} \gtrapprox 45°$) shocks that have higher injection energies.



Tylka et al. 2005

Two Contrasting Events in 2002



Tylka 2006

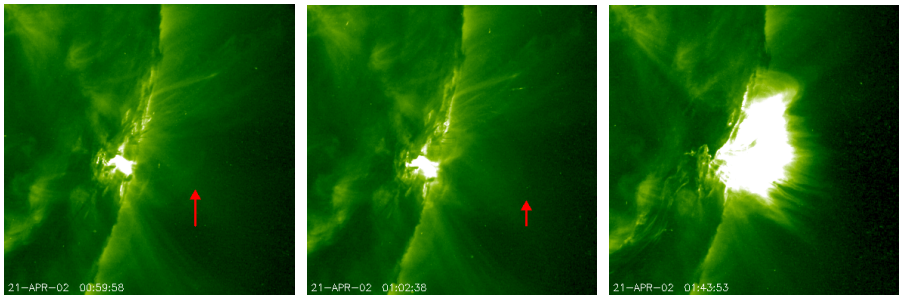
Two events in similar western longitudes had markedly different behaviors in Fe/O above 10 MeV/n.

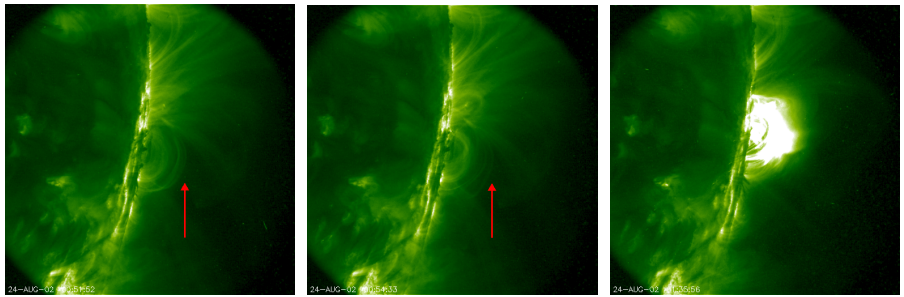
- Both were associated with a fast halo CME.

- Bad for direct flare contribution hypothesis.

- But the shock angle hypothesis is not supported either until Θ_{BN} is measured close to the Sun.

21 April 2002 TRACE 195 A images 24 August 2002





Eruption in more “open” environment? Then the outgoing shock may be more quasi-parallel.

Eruption in more “closed” environment? Then the outgoing shock may be more quasi-perpendicular.

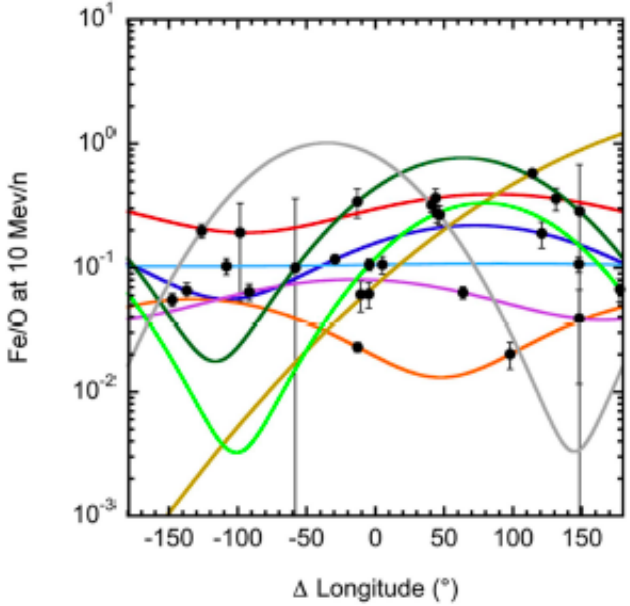
What to Expect on Multi-spacecraft Observations

Thanks to STEREO, the same SEP events in solar cycle 24 have been observed at different longitudes relative to their origins.

The direct flare hypothesis predicts Fe/O to be higher if the SEP event is observed at well-connected longitudes.

The shock angle hypothesis predicts Fe/O to be independent of the relative longitudes.

Observations of a limited number of events do not seem to be conclusive.



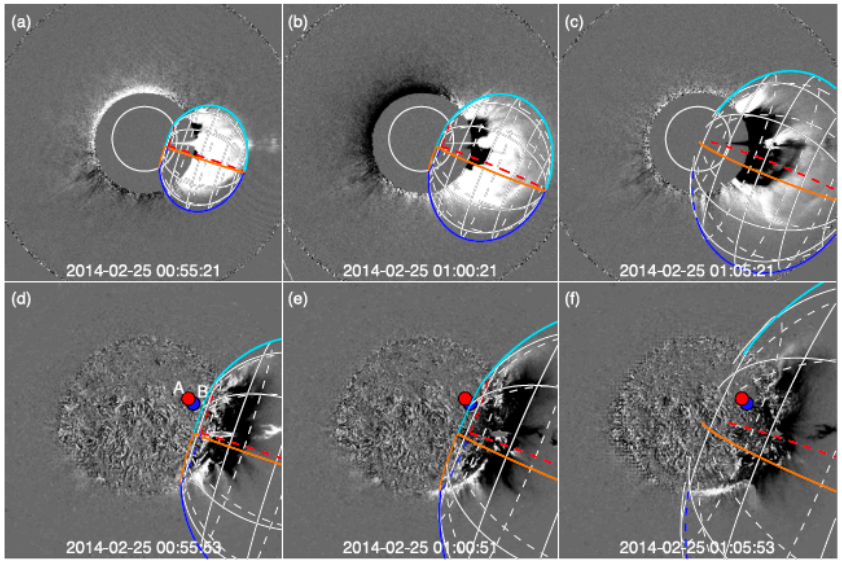
Cohen et al. 2017

Note that the frequency of Fe-rich events is much smaller in cycle 24 than in cycle 23.

Shock Angle Θ_{BN}

STEREO data have allowed us to study the 3D geometry and trajectory of CMEs, using cone models, graduated cylindrical shell (GCS) models, etc.

The CME-driven shock has been added on top of the flux rope, by fitting an ellipsoid to the CME leading edge (Kwon et al. 2014, Rouillard et al. 2016).



Lario et al. 2016

Then Θ_{BN} is derived at the intersection of the shock surface and the field line that traverses the observer at each of the three locations. The technique has also yielded other shock parameters, in combination with numerical models of the ambient solar wind (Rouillard et al. 2016, Lario et al. 2017).

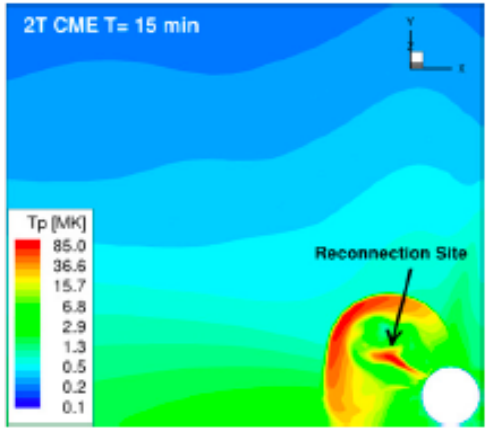
Simulations of CMEs Responsible for SEPs

Several CMEs have been simulated whose associated SEP events show widely different ratios of Fe/O. We use the Alfven wave Solar Model (AWSoM; van der Holst et al. 2014, Sokolov et al. 2013) that is part of the Space Weather Modeling Framework (SWMF; Tóth et al. 2005, 2012).

MHD model with a domain extending from the upper chromosphere to the corona and heliosphere

- Alfvén waves are driven at the inner boundary with a Poynting flux that scales with the surface magnetic field observations
- Electron heat conduction (both collisional and collisionless) and radiative cooling are included to self-consistently create the transition region
- Electron and Proton temperatures are treated separately
- The model involves physically consistent treatment of wave reflection, dissipation, and heat partitioning between the electrons and protons

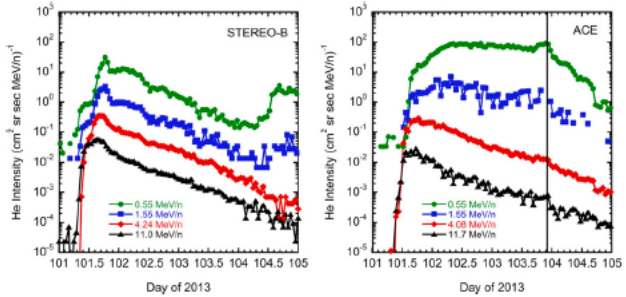
Proton temperature gradient is used to locate the shock.



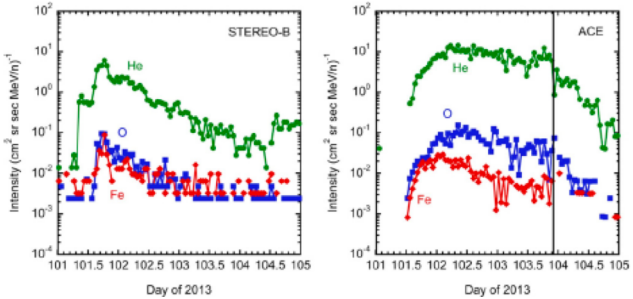
Jin et al. 2013

11 April 2013 Event

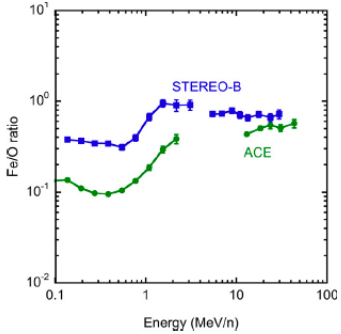
One of the rare Fe-rich SEP events in solar cycle 23, M6.5 flare at N10E15



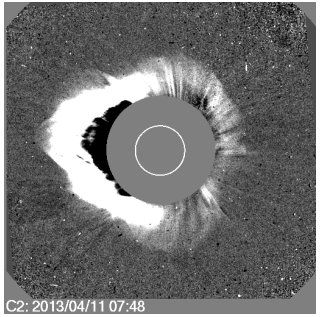
He intensity time profiles at STB and ACE



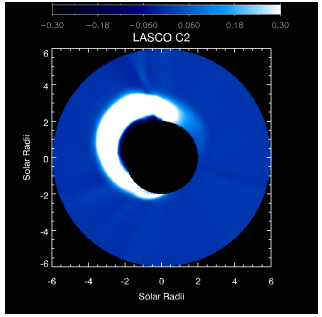
He, O, Fe (1.1 MeV/n) intensity time profiles at STB and ACE



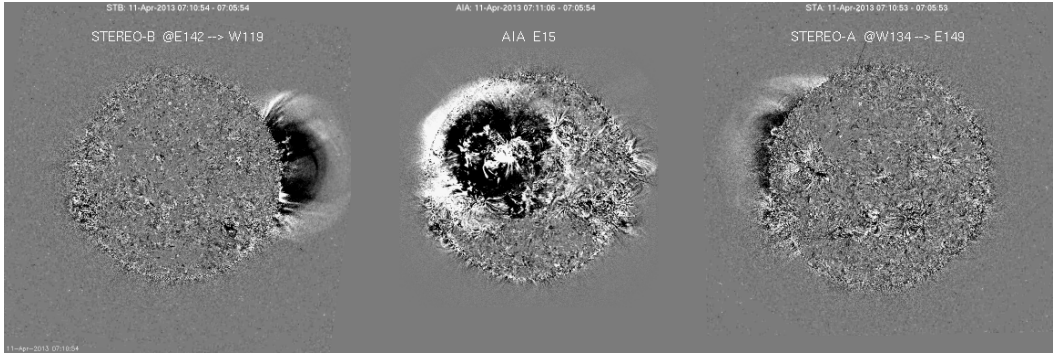
Fe/O vs Energy



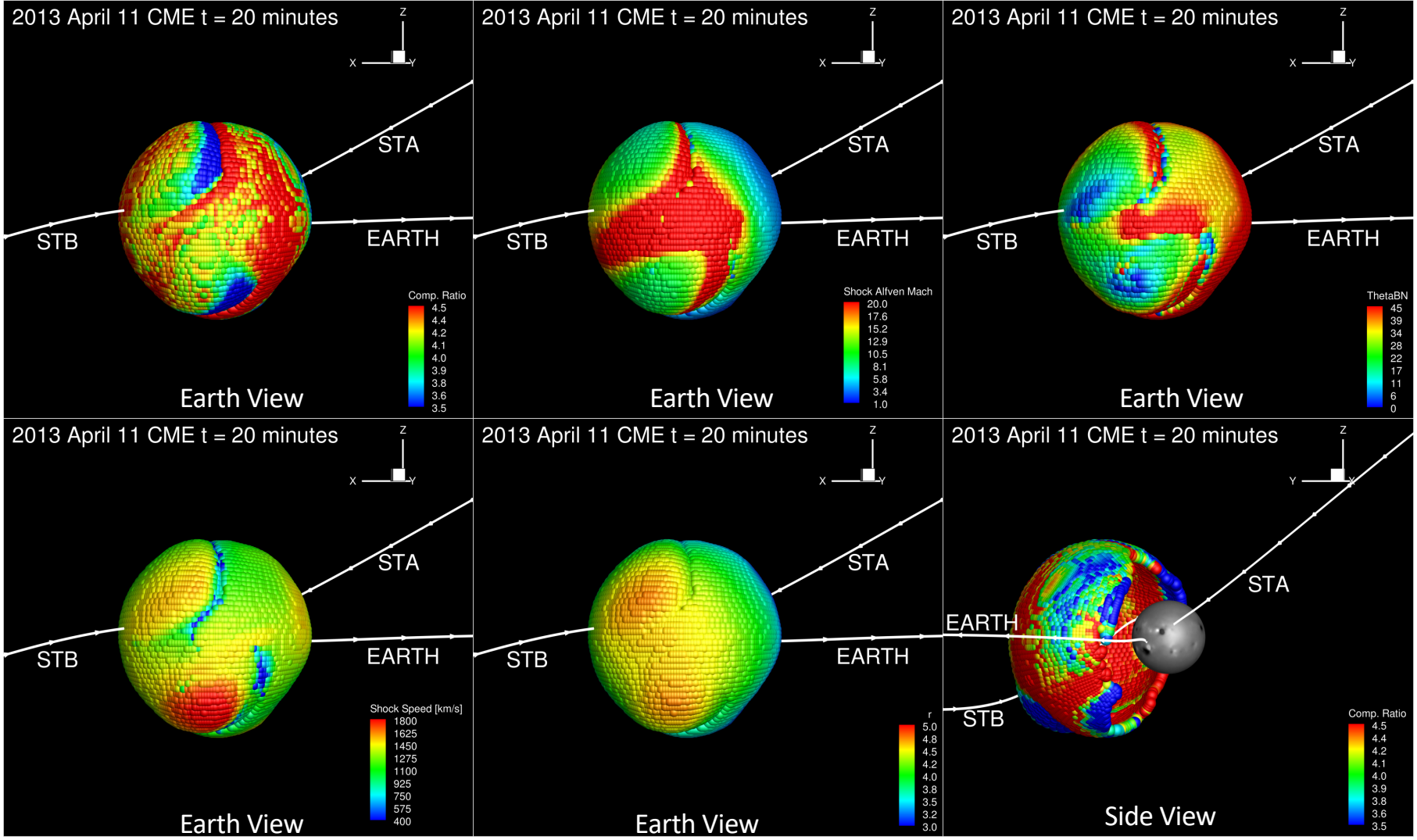
Observation



Synthesized image from simulation



EUV (195/193A) running difference images at STB, SDO, STA


2013 April 11 CME t = 20 minutes
Z
X
Y
STA
STB
EARTH
Comp. Ratio
4.5
4.4
4.2
4.1
4.0
3.9
3.8
3.6
3.5
Earth View
2013 April 11 CME t = 20 minutes
Z
X
Y
STA
STB
EARTH
Shock Alfven Mach
20.0
17.6
15.2
12.9
10.5
8.1
5.8
3.4
1.0
Earth View
2013 April 11 CME t = 20 minutes
Z
X
Y
STA
STB
EARTH
ThetaBN
45
39
34
28
22
17
11
6
0
Earth View
2013 April 11 CME t = 20 minutes
Z
X
Y
STA
STB
EARTH
Shock Speed [km/s]
1800
1625
1450
1275
1100
925
750
575
400
Earth View
2013 April 11 CME t = 20 minutes
Z
X
Y
STA
STB
EARTH
r
5.0
4.8
4.5
4.2
4.0
3.8
3.5
3.2
3.0
Earth View
2013 April 11 CME t = 20 minutes
Z
Y
X
STA
EARTH
STB
Comp. Ratio
4.5
4.4
4.2
4.1
4.0
3.9
3.8
3.6
3.5
Side View

Summary

- The SEP event on 11 April 2013 was Fe-rich at STEREO-B, and less so at Earth. Contrary to the expectations from the shock angle hypothesis, the simulations show that STEREO-B was connected to a quasi-parallel part of the shock; the shock Earth was connected to, although weak, was more quasi-perpendicular.
- Other cases also do not support the Fe-rich and quasi-perpendicular link (e.g. 10 September 2017 at Earth, which was not Fe-rich.)
- It may not be worth tweaking input parameters (and magnetogram) to somehow reproduce the above link.
- To understand the compositional variability of SEP events, we need to explore the origins of suprathermal seed particles, regardless of the shock geometry.