Working Group 6, WG6:
‘Solar Energetic Particles (SEPs)’

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SCIENTIFIC ISSUES REPORTED HERE!

- **CME kinematics and SEP Spectra: 2017 Sept 23 event**
- **The Long-lasting Injection during the Widespread Dec 26 2013 SEP event**
- **ENLIL and 3-D Test Particle Model (modeling)**
- **Solar Energetic Particle events Forecasting**
  - **With Flare X-ray Peak Ratios**
  - **ESPERTA-based forecast**
  - **Sept 10, 2017 HESPERIA REleASE Forecast (Shine Campaign Event)**
- **Small-scale magnetic islands in the solar wind and their role in particle acceleration (Follow up)**

CME Kinematics & SEP Spectra: 2017 September 10 Event

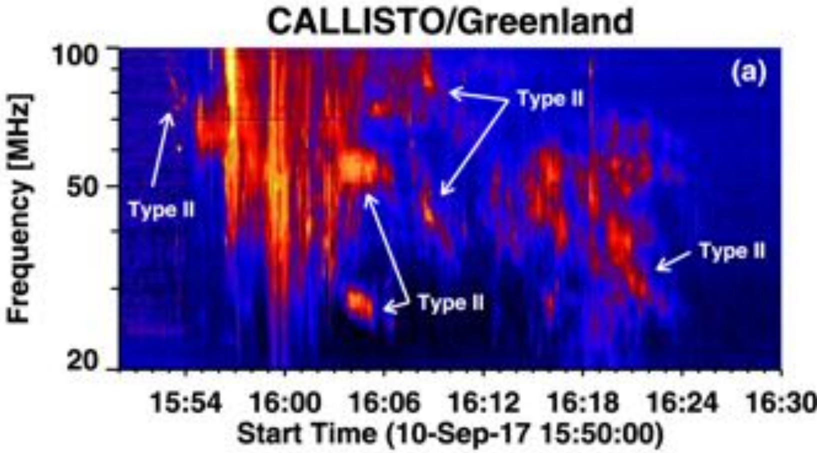
• Sep 10 eruption occurred in NOAA AR 12673 **~S09W92**: ultra-fast CME (~3200 km/s) and X8.3 SXR flare
Starting: 1525 UT, peaking: 16:06 UT, Ending: 16:31 UT

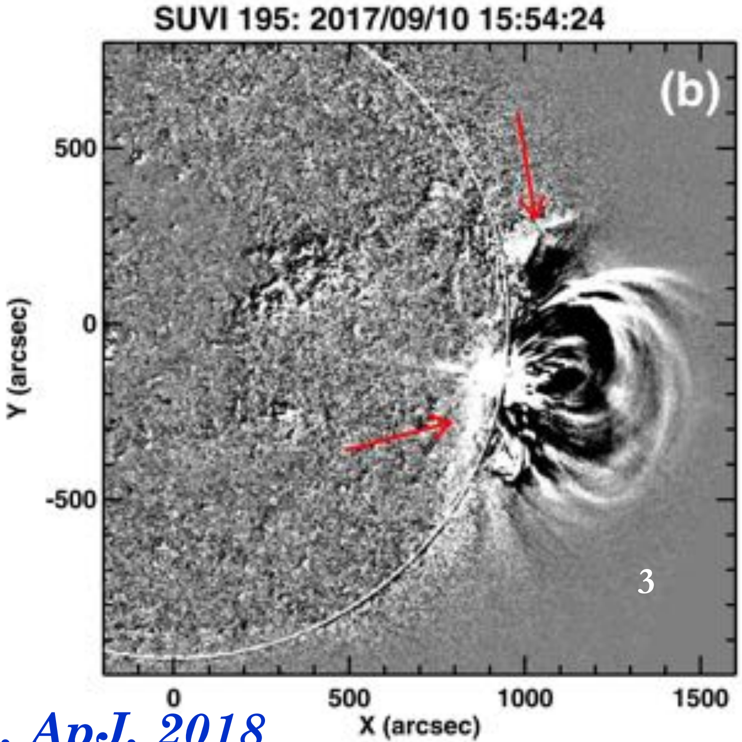
• CME and leading shock observed by SECHHI's EUV, COR1 and COR2 onboard STEREO A and by SOHO/LASCO in its C2 and C3 telescopes

• First shock signature: metric type II radio burst @15:53 UT (CALLISTO/Greenland)

• Continued metric tII episodes at f > 25 MHz until 16:24 indicates the radio emission originated from the shock front

• NOAA's SUVI: shows shock flanks to the north and east of the CME

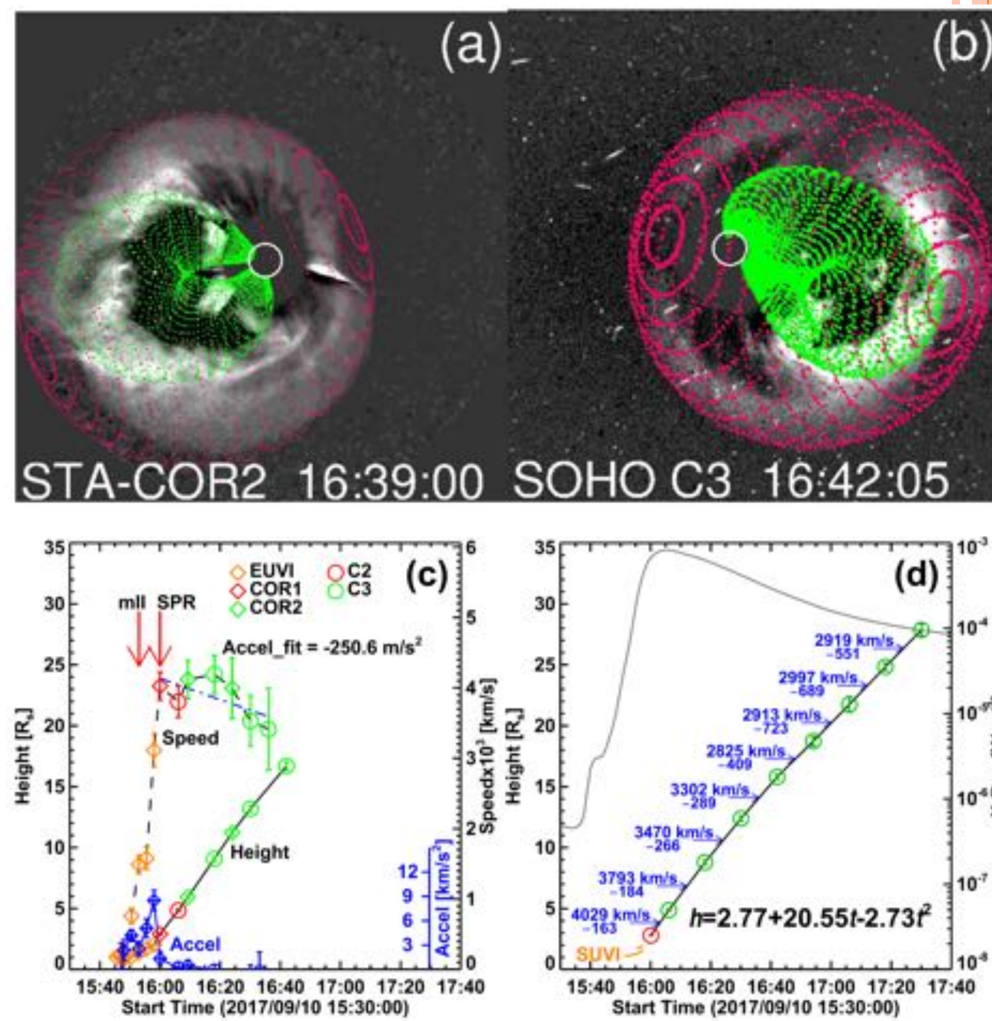




Gopalswamy, Yashiro, Makela, Xie, Akiyama, ApJ, 2018

• The coronal images by STA and SOHO view combined to fit a flux rope to the CME and a spheroid to the shock

• Figure (a) and (b): Reconstruction with the fitted **shock (red)** and **flux rope (green)** **(GCS model)** superposed on ST and SOHO images



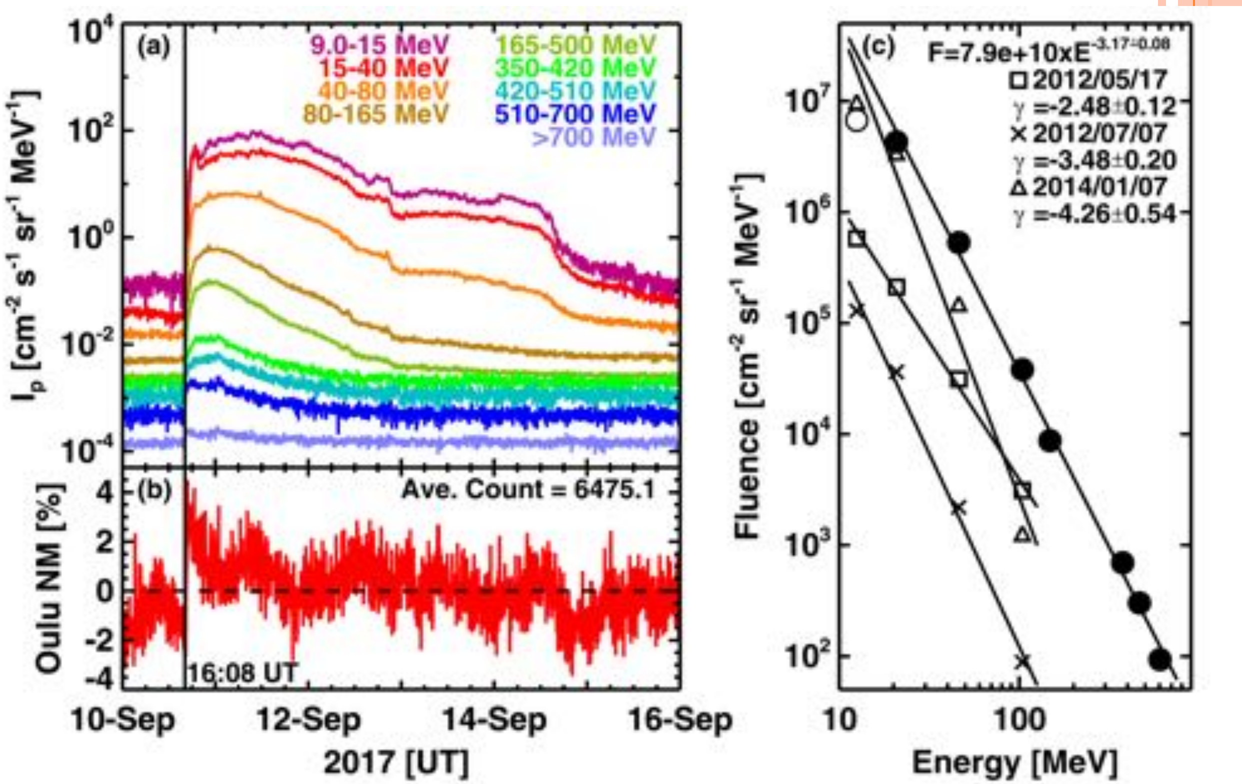
• Height, speed and acceleration of the shock from the GCS fit to SOHO and ST images

• 3 speeds describe CME kinematics:
(i) initial speed **4029** ± 163 km s^{-1}
(ii) maximum speed **4191** ± 272 km s^{-1}
(iii) average speed within the LASCO FOV **3430** ± 25 km s^{-1}

• The acceleration attained a peak value of ~9.1 km s^{-2}

Gopalswamy, Yashiro, Makela, Xie, Akiyama, ApJ, 2018

- Eruption associated with a large SEP with GLE
- SEP intensities shown in GOES-13 channels, including the >700 MeV channel and GLE intensity from the **Oulu NM** recording a **4.4% increase** above background
- Guo et al. (2018) estimated the onset at 16:15 UT
- Assuming a Parker spiral of 1.2 AU, travel time of 1 GeV protons is ~11.3 min so **the SPR time is 16:05 UT**



The Sept 10 event spectrum is **softer than the 2012 May 17 GLE** but **harder than the two non-GLE events**

- Fluence spectrum shown: $\mathbf{F=AE^{-\gamma}}$

F : Fluence (cm^{-1} sr^{-1} MeV^{-1})

A : a constant (7.9 x 10^{10})

E : particle energy

γ : spectral index (3.17 ± 0.08)

September 10 (**filled circles ●**)

2012 May 17 (squares □) **GLE**

2012 July 7 (crosses+) ***non-GLE***

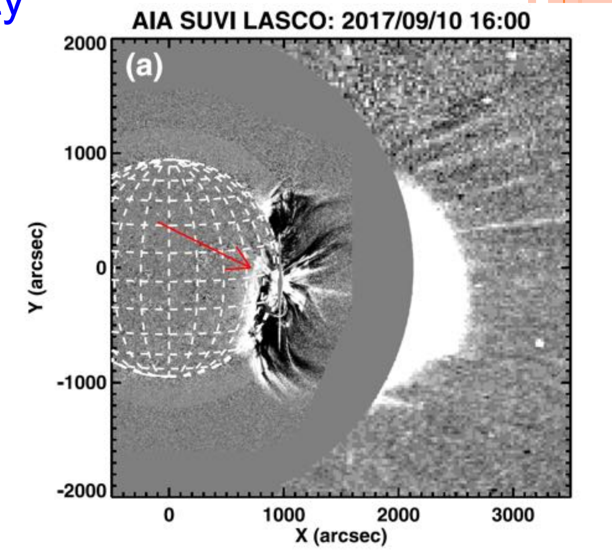
2014 January 7 (triangles Δ) ***non-GLE***

Main Results

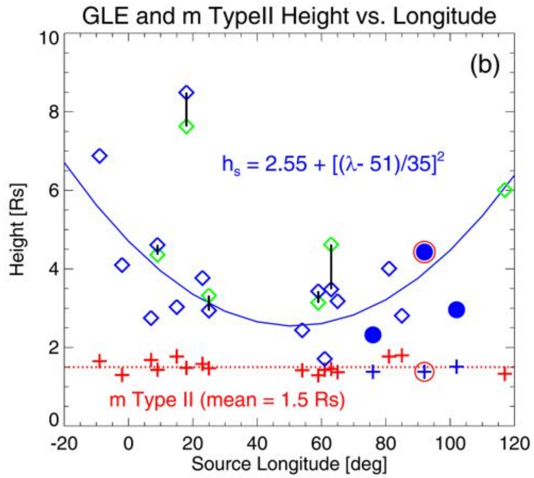
- The CME Leading Edge (LE) had an acceleration of 9.1 ± 1.6 km s^{-2} : the highest ever observed in the STEREO era & ever since the CME phenomenon discovery

- The initial speed computed using the two height-time data points was ~4029 ± 163 km s^{-1} also one of the highest in the SOHO era

- The CME LE was at a height of 1.4 R_S at the time of the TII burst onset, consistent with all GLE events of SC 23 and 24. But the CME LE at SPR (4.4 ± 0.38 R_S) was larger-than-average because of poor longitudinal connectivity



- SPR time: consistent with the crossing of the Sun-Earth field line by the eastern flank of CME-driven shock inferred from the EUV wave propagating across the disk



- The shock height at SPR: consistent with the parabolic relationship between shock heights and source longitude derived for SC23 GLE events

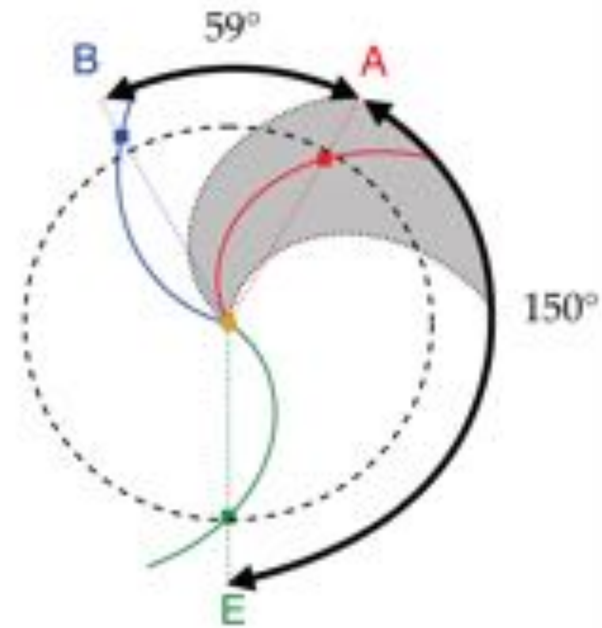
Gopalswamy, Yashiro, Makela, Xie, Akiyama, ApJ, 2018

THE LONG-LASTING INJECTION DURING THE WIDESPREAD DEC 26 2013 SEP EVENT

The long-lasting injection during the widespread Dec 26 2013 SEP event

Key points:

- Widest SEP spread ever observed (σ=55° for 55-105 keV electrons)
- Very long rise times
- Very long-lasting anisotropies
- Two distinct SEP components: the high energy component arrives 4 hours later!

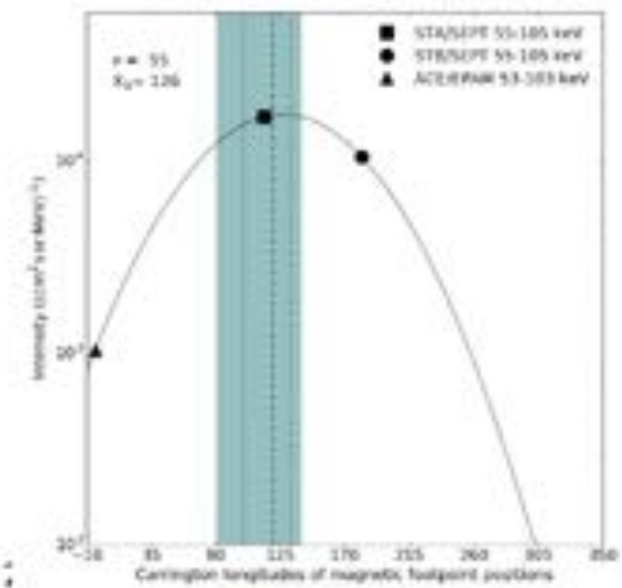


N. Dresing, Gomez-Herrero, B. Heber, A. Klassen, M. Temmer, A. Veronig, A&A, 2018

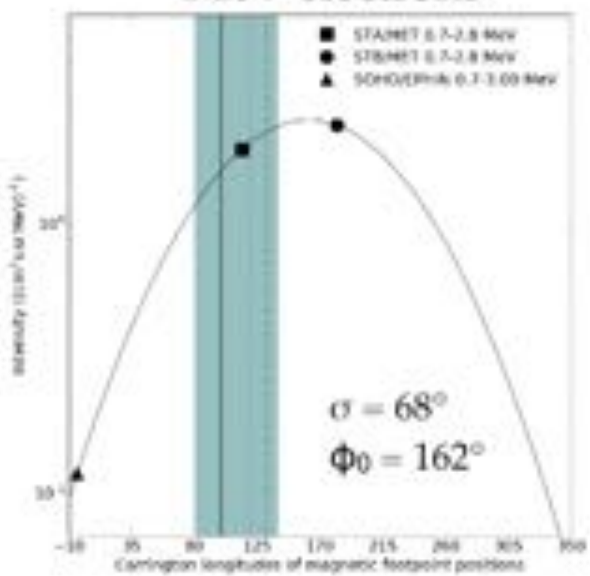
Longitudinal width of the distribution: Gaussian approximation of peak intensities

- Very wide Gaussian distributions for electrons and protons

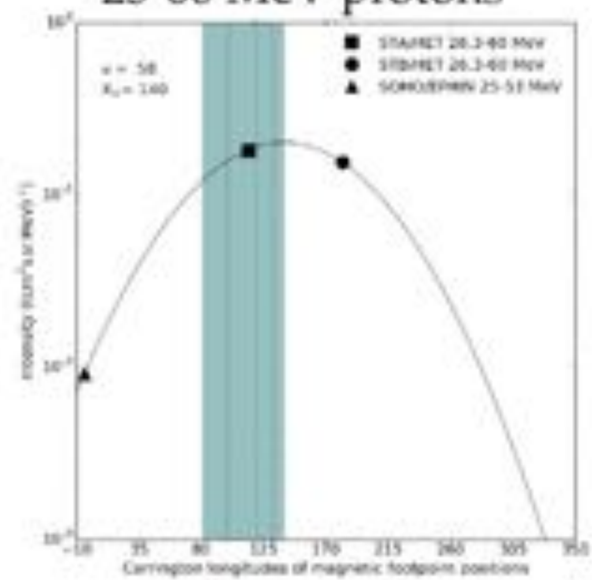
55-105 keV electrons



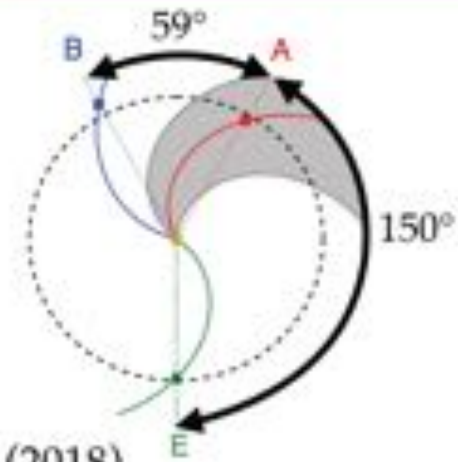
MeV electrons



25-60 MeV protons

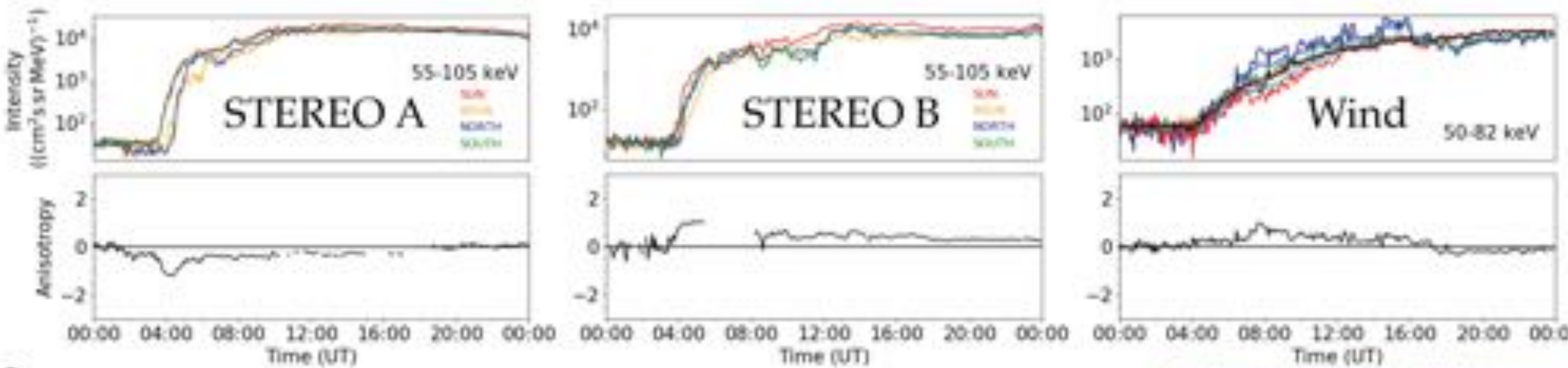


The 26 Dec 2013 widespread SEP event



- Long-lasting anisotropies (several hours up to > 1 day at STB)
  - A long-lasting SEP injection must be present

Dresing et al. (2018)



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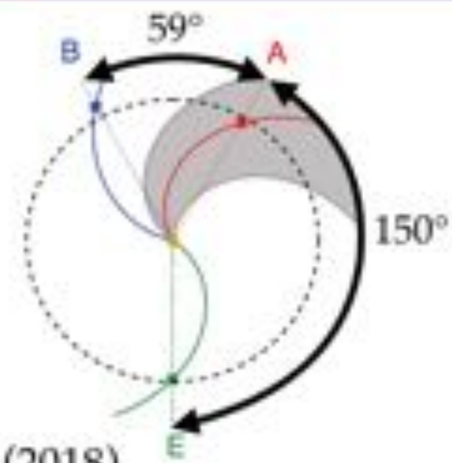
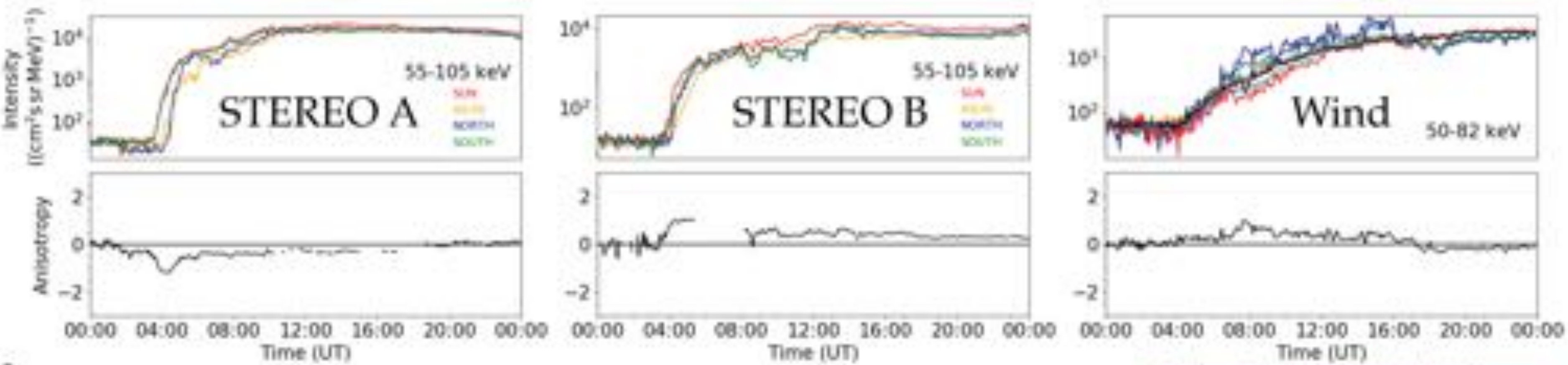
Dresing et al., University of Kiel, Germany

The 26 Dec 2013 widespread SEP event



- Long-lasting anisotropies (several hours up to > 1 day at STB)
  - A long-lasting SEP injection must be present
  - **looks like a shock!** **True?**

Dresing et al. (2018)



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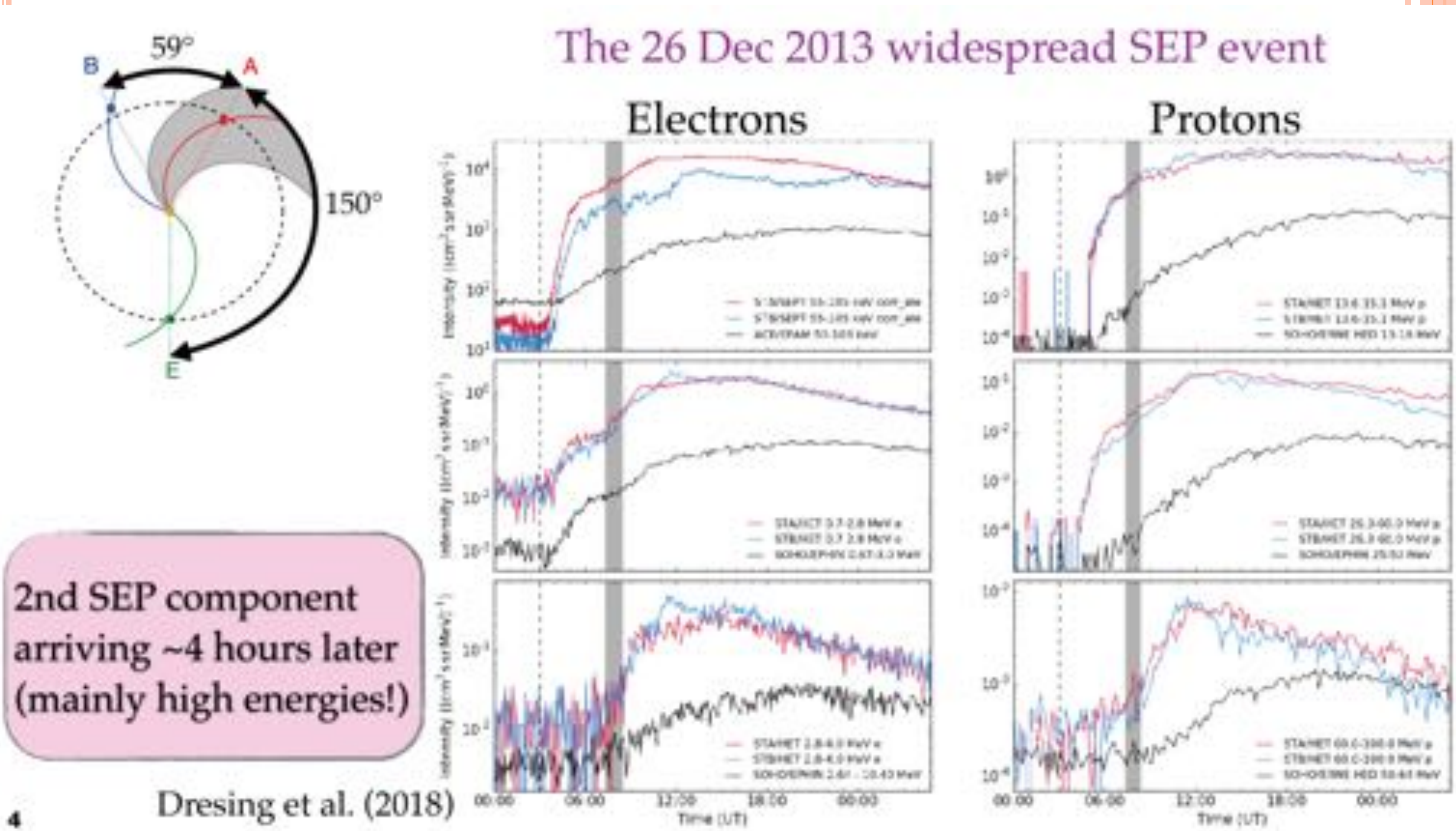
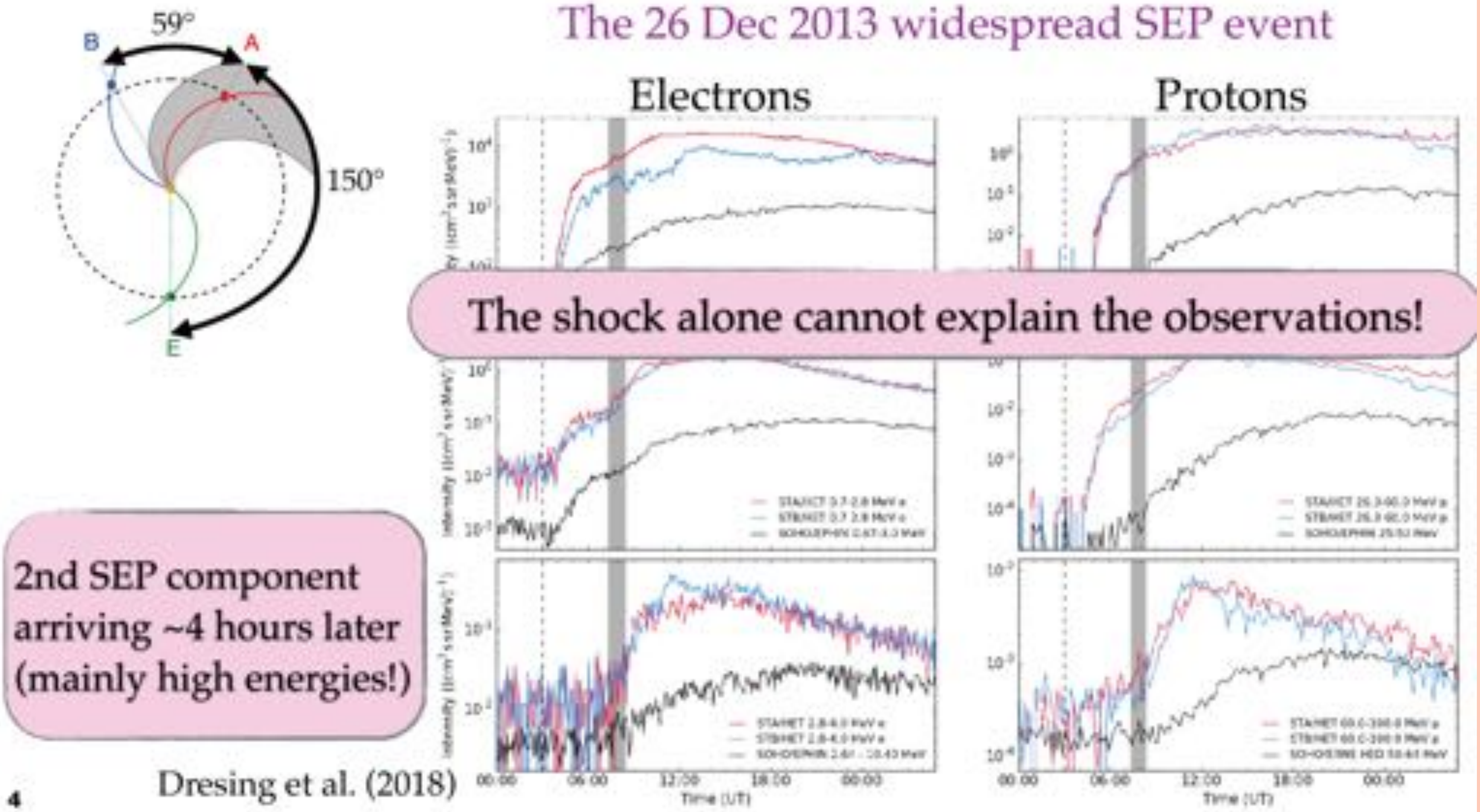
Dresing et al., University of Kiel, Germany



The 26 Dec 2013 widespread SEP event
59°
B
A
150°
E
Electrons
Protons
2nd SEP component arriving ~4 hours later (mainly high energies!)
Dresing et al. (2018)
4
00:00
06:00
12:00
18:00
00:00
Time (UT)

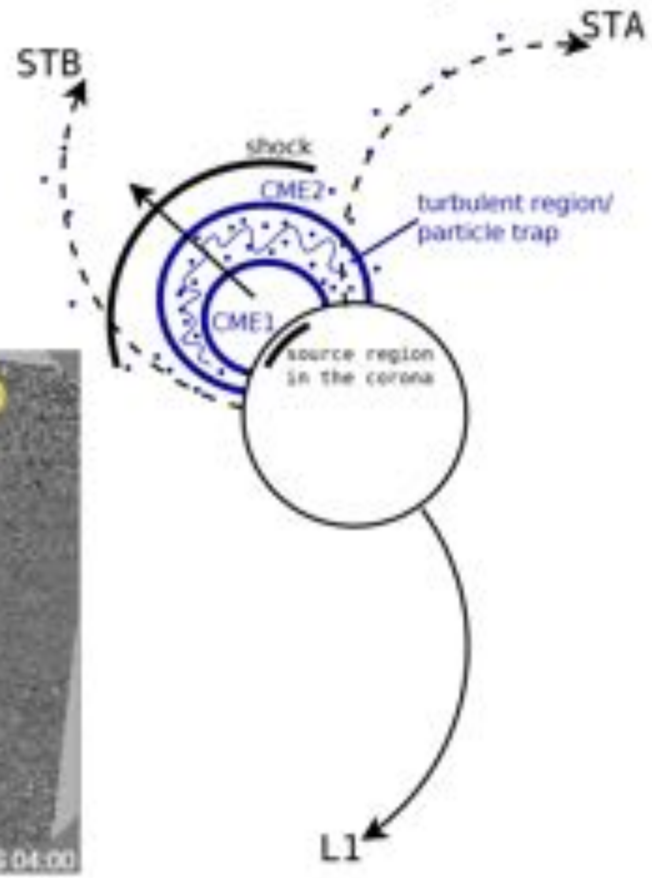
The 26 Dec 2013 widespread SEP event

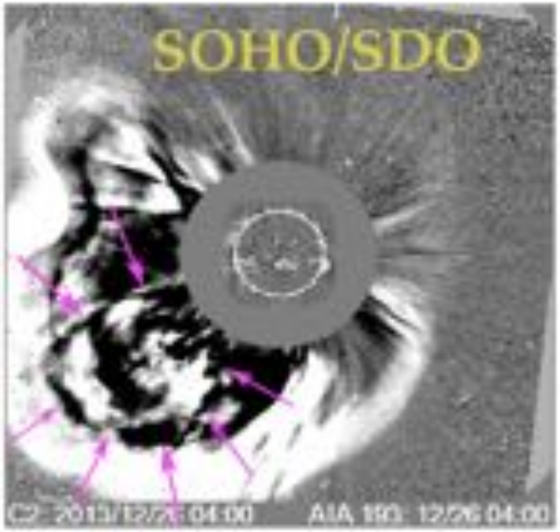


The Dec 26 2013 event: A complex scenario

Interaction of 2 CMEs early in the event. This may form a particle trap where SEPs are accelerated further. When the trap opens ~4 hours later, the high energy component is released.

Dresing et al. (2018)





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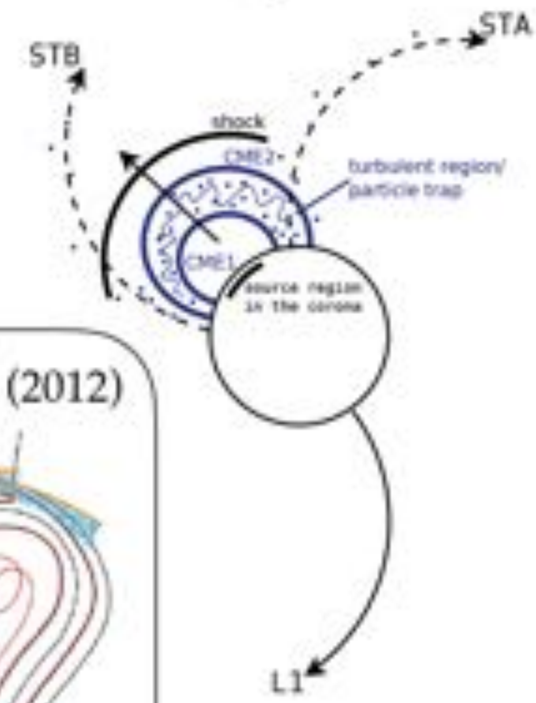
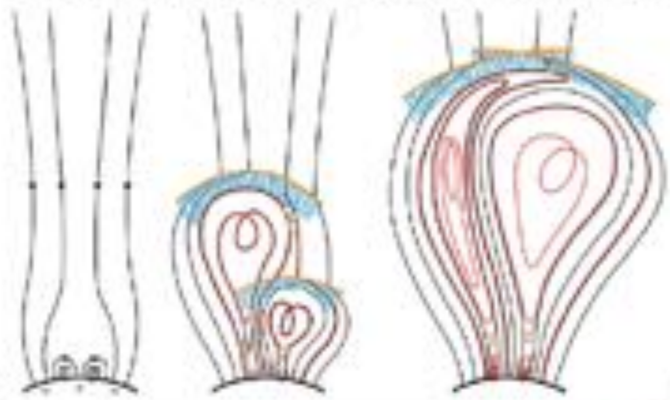
The Dec 26 2013 event: A complex scenario

Dresing et al. (2018)



CMEs from the same active regions erupting in a sequence seem to enhance SEP acceleration [Gopalswamy et al. (2004), Li et al. 2012]

Twin-CME scenario, Li et al. (2012)



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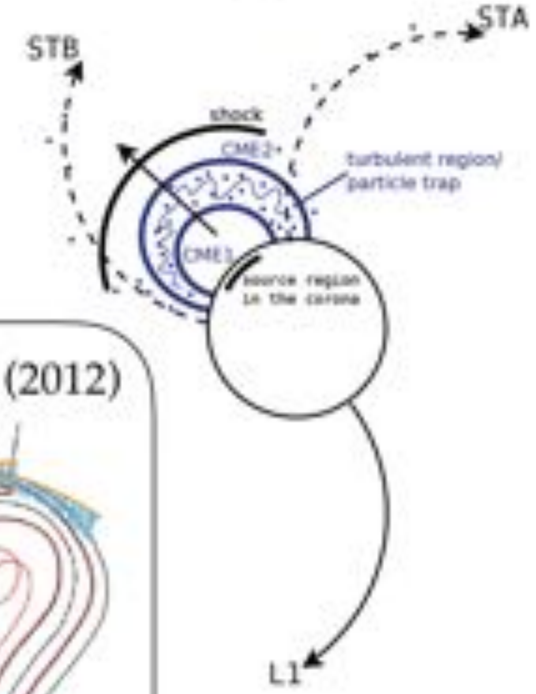
Dresing et al., University of Kiel, Germany

The Dec 26 2013 event: A complex scenario

The unusually long-lasting anisotropies together with the high energy SEP component injected ~4 hours later require a more complex scenario

Dresing et al. (2018)



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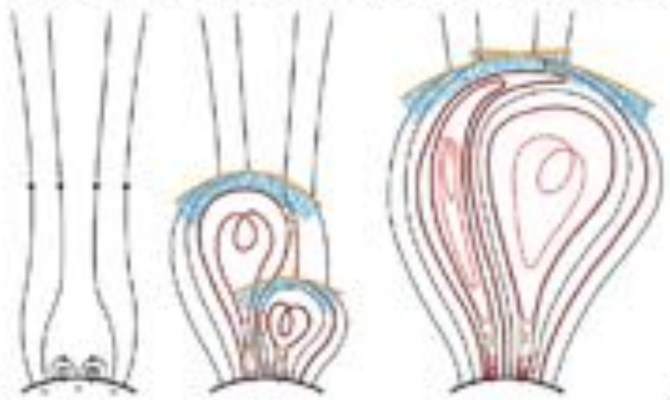
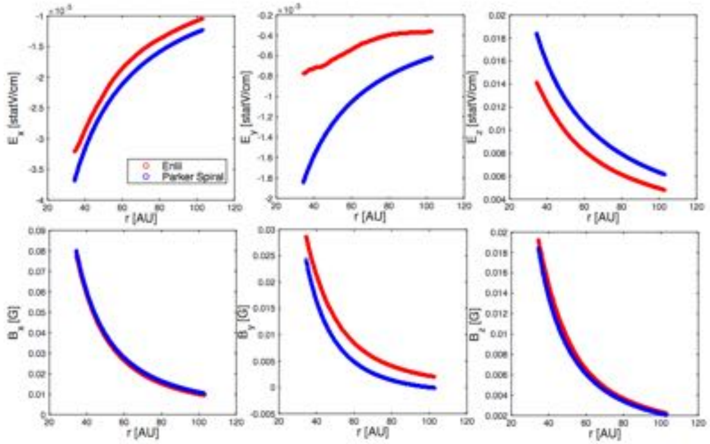
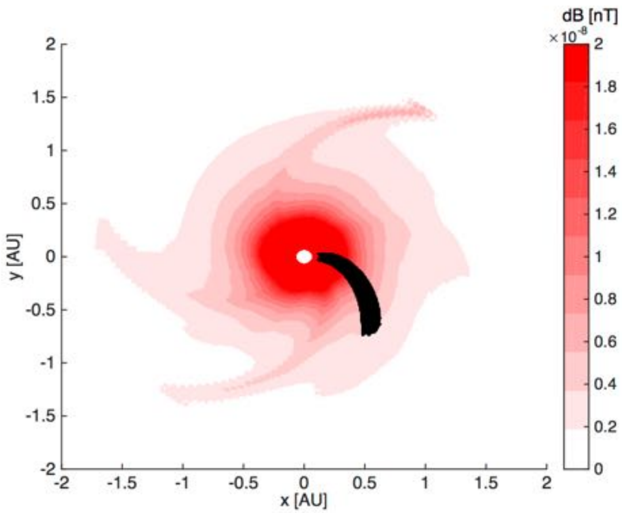


ENLIL AND 3D TEST PARTICLE MODEL

- 3-D test particle model, includes pitch-angle scattering, drifts and deceleration (Marsh et al 2013)
- SPARX forecasting tool based on this model
- interpolate ENLIL fields to obtain ***B*** and ***E*** for the location of test particle in the simulation; currently use linear interpolation
- a population of particles is injected into these fields and trajectories integrated

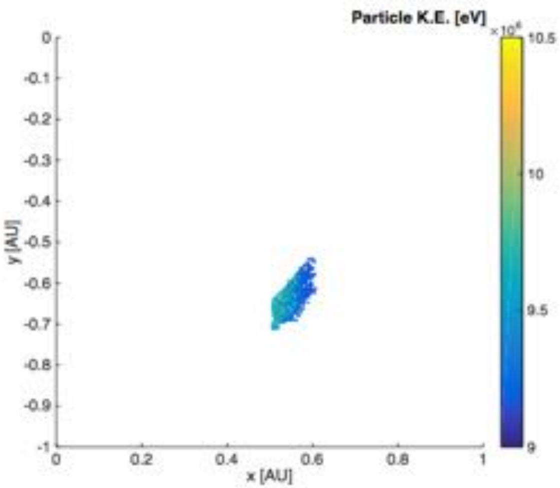




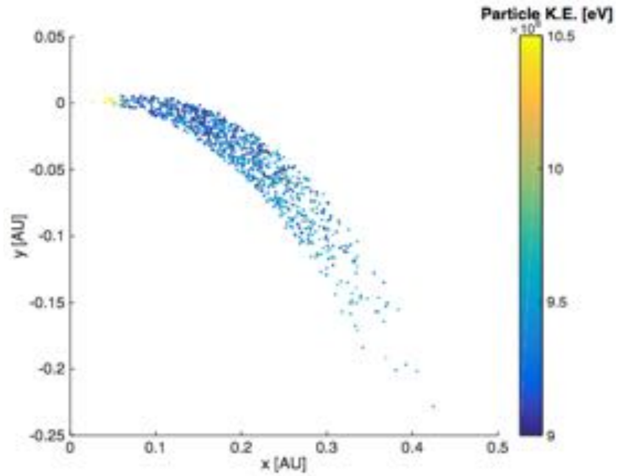
S.R. Thomas, S. Dalla, T. Laitinen, M. Battarbee, M. Marsh

uclan University of Central Lancashire

RESULTS AND DISCUSSION



No Scattering

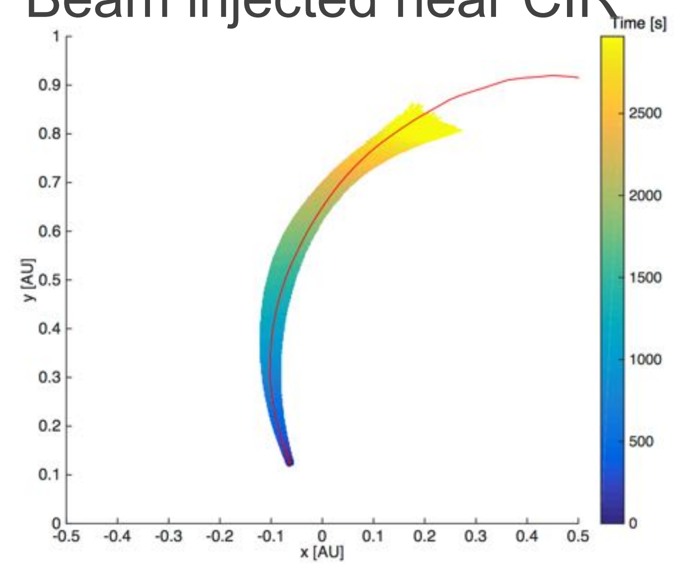


Scattering mfp = 0.1AU

- Characterise differences between ENLIL and Parker spiral runs
- Analyse behaviour with energy, mean free path

- particle runs with scattering require ENLIL fields to distances beyond 1.5 AU – outer boundary must be further out – loss of resolution
- aim to model SEP events from shock waves using time-dependent injections from CMEs

Beam injected near CIR



Thomas et al, in prep (2018)

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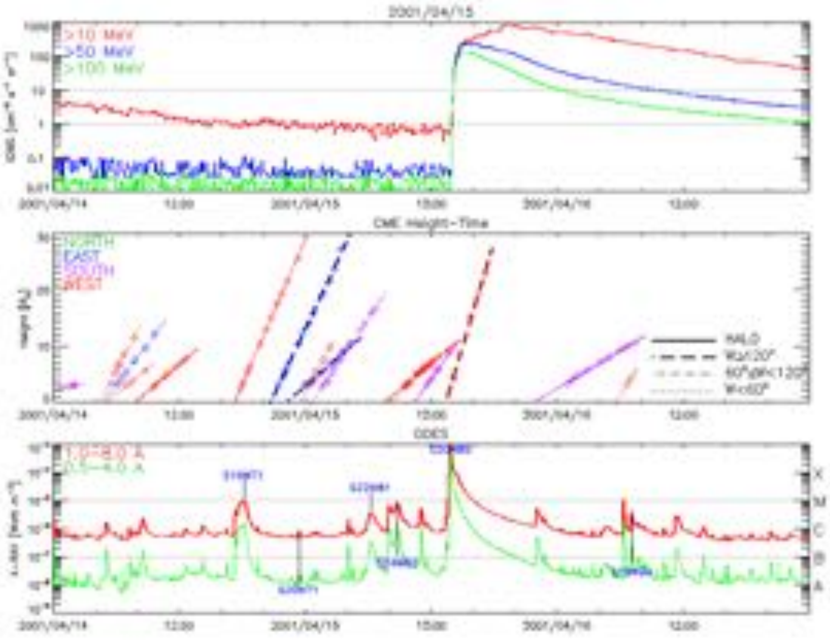
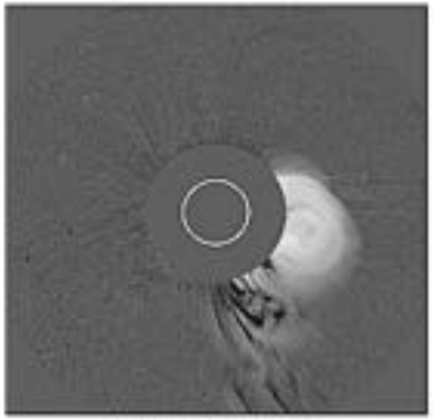
SEP events Forecasting
1) With Flare X-ray Peak ratios

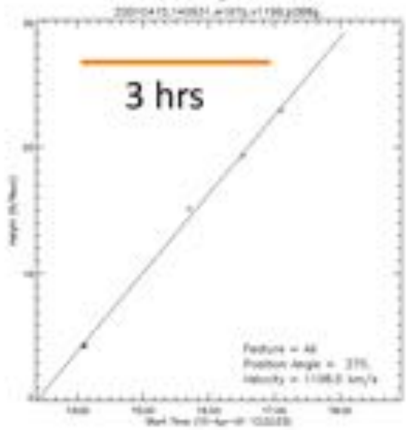
CMES AND SEP EVENTS

CME speeds and widths are well correlated with SEP peak intensities, but flaring X-rays provide an earlier signal and also correlate with SEP peaks.





2001 April 15



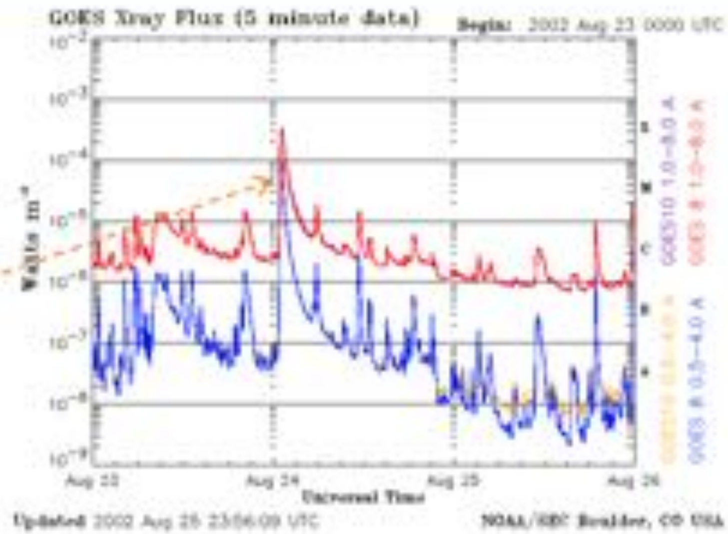
Unclassified: Cleared for public release

AFRL

Kahler, S.W., Ling, A.G., J. Space Weather & Space Climate, accepted, 2018

GRADUAL SEP EVENTS AND SOLAR FLARES

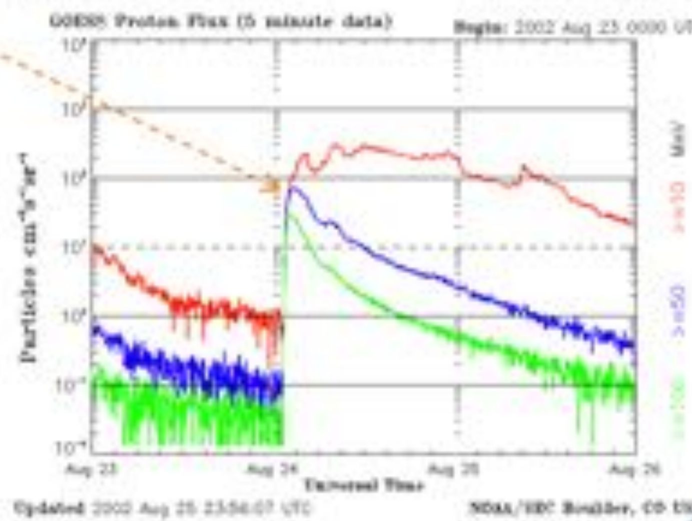
GOES X-Rays



A big solar flare almost always precedes by minutes to a few hours the onset of a large SEP event.

X-ray flares are an obvious component of any SEP forecasting tool.

GOES SEPS



SEP EVENT FORECASTING WITH SOLAR X-RAYS

Forecasting SEPs with GOES X-ray flares

The following SEP event prediction tools use the 0.1 – 0.08 nm flare peak or fluence (flux integrated over event duration)

- Proton Prediction System (PPS) [Kahler et al., 2017]
- PROTONS [Balch, 2008]
- IZMIRAN prognostic practice [Belov, 2009]
- ESPERTA [Alberti et al., 2017]
- SPARX [Marsh et al., 2015]

There are 2 X-ray bands on the GOES full-Sun X-ray sensors (XRS)

- 0.1 – 0.8 nm
- 0.05 – 0.4 nm
- The ratio of the two bands provides an effective flare temperature.

The 0.05 – 0.4 nm band is available, but not used.

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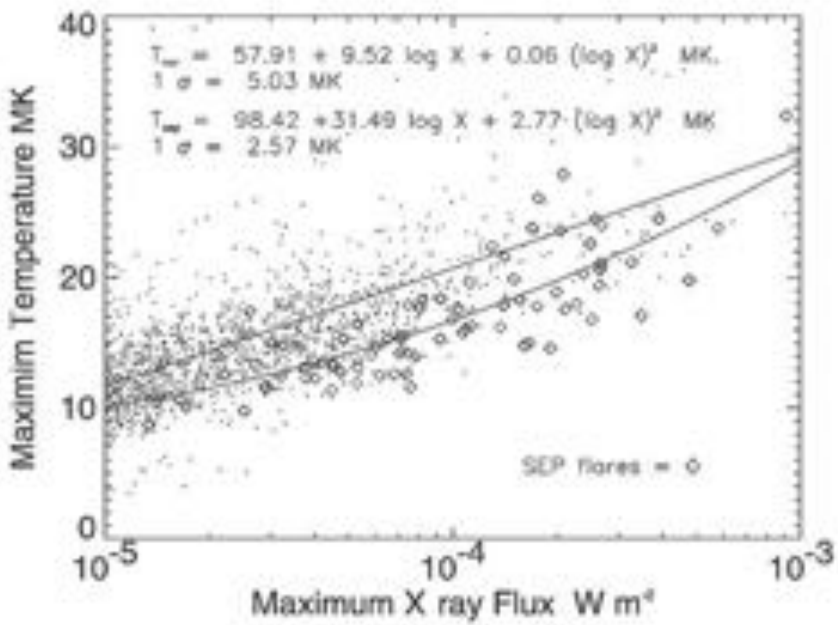
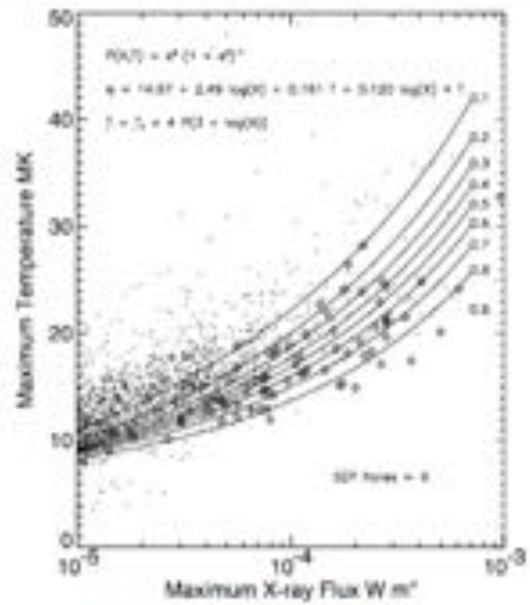
SEP EVENTS AND X-RAY TEMPERATURES

Howard Garcia [2004] compared GOES X-ray flare ratios (temperatures) with peak 0.1-0.8 nm fluxes and selected those flares with associated SEP events.



0.1-0.8 nm flux



0.1-0.8 nm flux

Same plot as SEP event probability curves

X-ray events 1988 to 2002

The basic point is that Garcia used the additional information of the 0.04-0.5 nm X-ray band in his SEP event forecast system.

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RATIOS OF X-RAY PEAKS AND SEP EVENTS

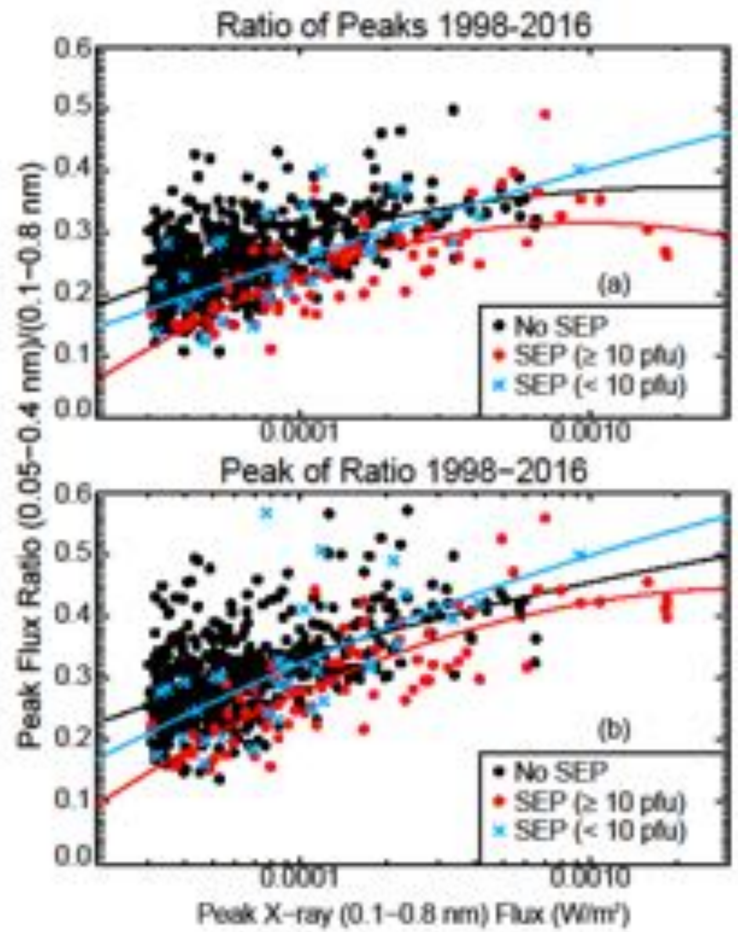
We revisit the Garcia temperature-based SEP event associations.

Select all > M3 flares with known flare locations from 1998 to 2016.
Consider three groups of E > 10 MeV SEP events:

- No SEP event association
- NOAA list (> 10 pfu) SEP events
- Small (1.2 to 10 pfu) SEP events
- Large (> 300 pfu) SEP events

The ratios of the two peaks (top) and the peak values of the running ratios (bottom) give similar results and confirm Garcia's results using X-ray temperatures.

- SEP events (red, blue) are statistically associated with cooler X-ray flares.



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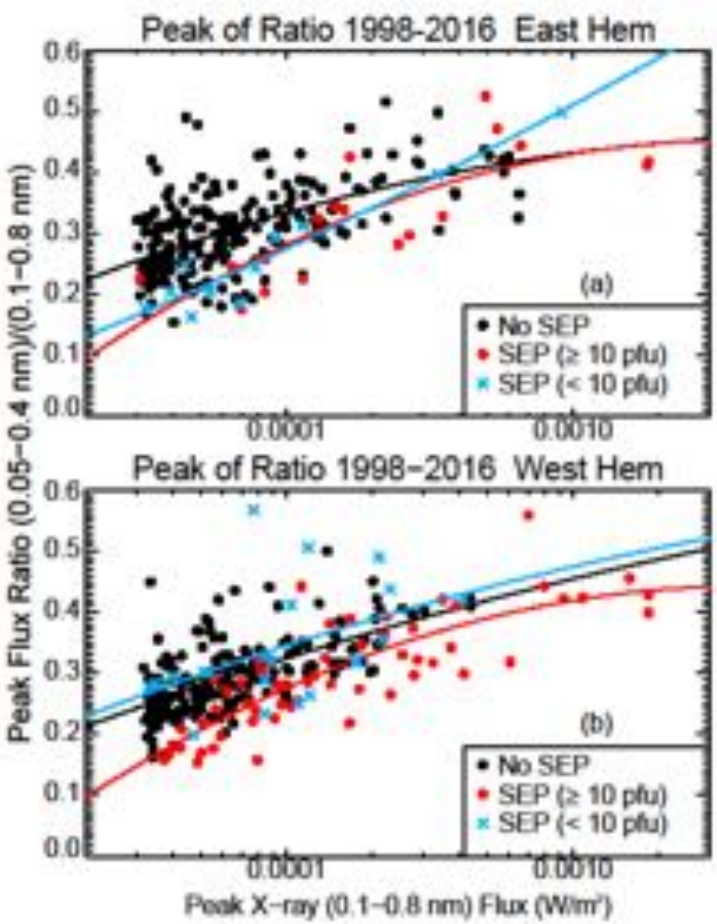
SMALL SEP EVENTS BY HEMISPHERE

We divide the data set into east and west hemispheres and three SEP event classes.

East hemisphere (top): small (< 10 pfu) and NOAA events separate from No-SEP events.

West hemisphere (bottom): small (< 10 pfu) events blend with No-SEP events.



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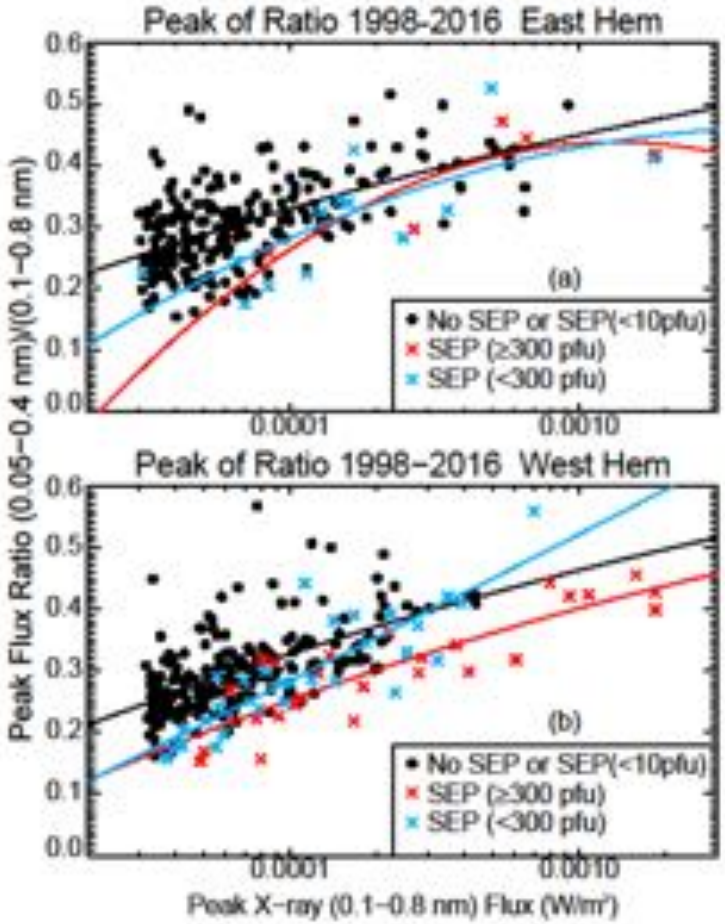
LARGE SEP EVENTS BY HEMISPHERE

We divide the data set into east and west hemispheres and three SEP event classes.

East hemisphere (top): large (> 300 pfu) SEP events blend with NOAA events.

West hemisphere (bottom): large (> 300 pfu) events separate from NOAA events.

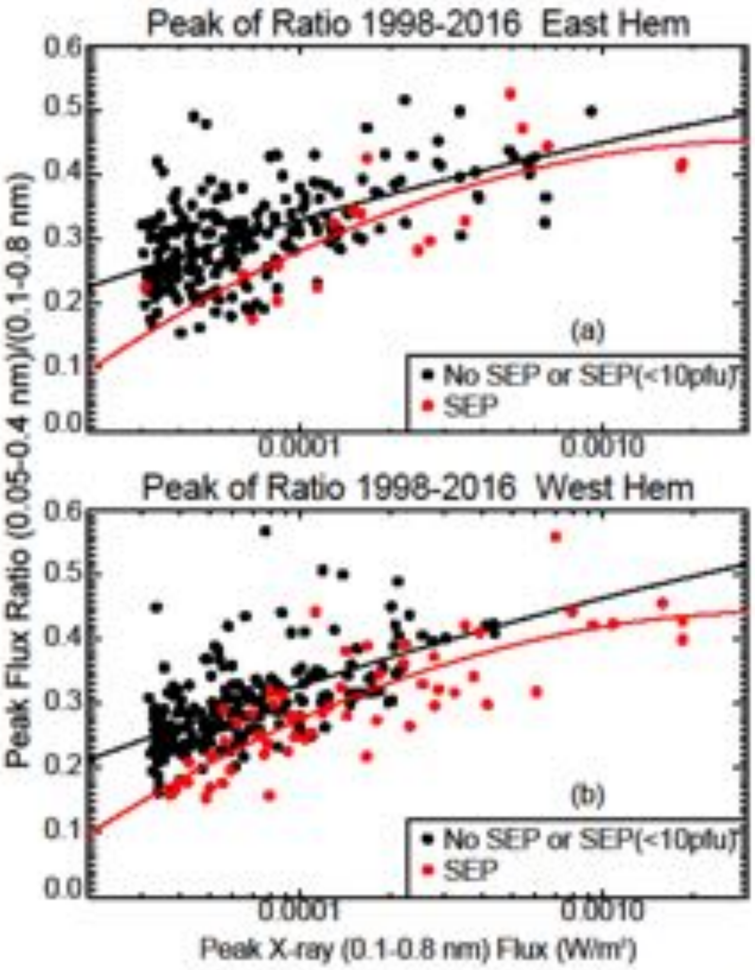


NOAA (> 10 pfu) SEP EVENTS BY HEMISPHERE

We divide the data set into east and west hemispheres to compare basic NOAA events with No-SEP events.

East hemisphere (top): NOAA events separate from No-SEP events.

West hemisphere (bottom): NOAA events separate from No-SEP events.



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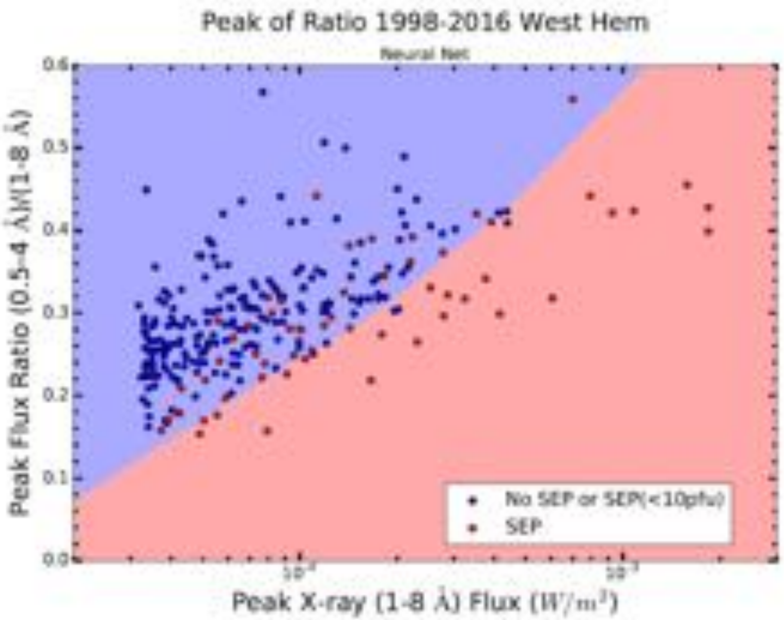
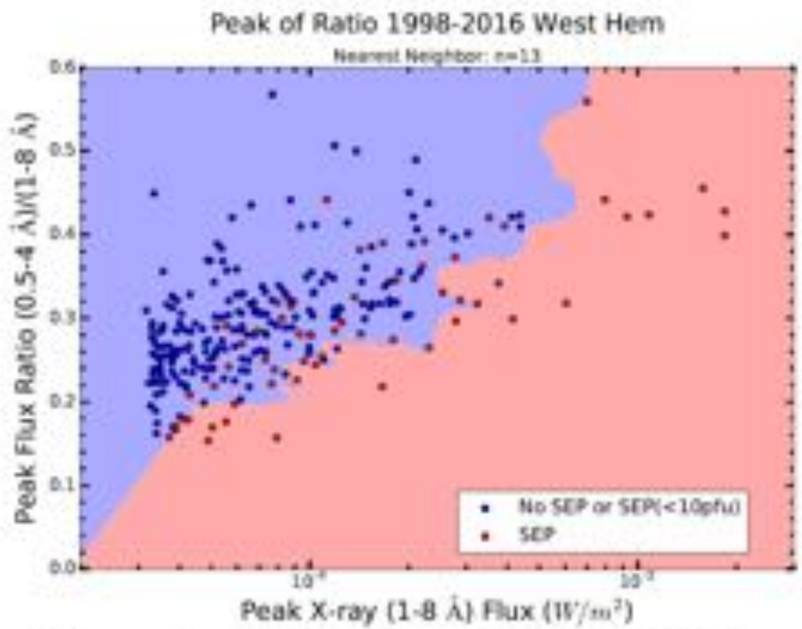
MACHINE LEARNING APPLIED TO SEP EVENTS

We use machine learning techniques to divide the flux ratio plot space of X-ray flares between probable No-SEP (blue) and NOAA (pink) events.



Neural net classification



Nearest neighbor (n = 13) classification

SUMMARY OF X-RAY FLUX RATIOS AND SEPS

Current SEP event forecast methods use GOES 0.1-0.8 nm flare peaks or fluences.

The accompanying GOES 0.04-0.5 nm flare fluxes are a valuable but untapped source of additional information for SEP event forecasting.

We validate the peak-ratio results of Garcia (2004) with new GOES X-ray and SEP data sets.

We encourage the SEP forecast community to adopt this peak-ratio tool to improve SEP event forecasts.

The physics relating low-temperature flares with SEP events (& CME-driven shocks) is not clear.

SEP events Forecasting
2) ESPERTA-based forecast
ESPERTA model

Empirical model for **S**olar **P**roton **E**vents **R**eal **T**ime **A**lert, based on observations of associated precursors phenomena on the Sun with data available in real time (Laurenza et al., 2009; Alberti et al., 2017, Laurenza et al., 2018)

- Designed to maximize warning time
- Not Physics based
- Prediction of >10 MeV proton events with peak flux ≥ 10 pfu
- Only makes predictions for ≥ M2 SXR flares

Inputs:

1) Flare location (particle propagation)
2) Integrated SXR flux (flare importance and its duration)
3) Integrated 1 MHz emission (particle escape)

Technique: Logistic regression

Warning time: 10 minutes after the SEP associated flare peak time

Output: Yes/no forecast for the occurrence of an SEP event

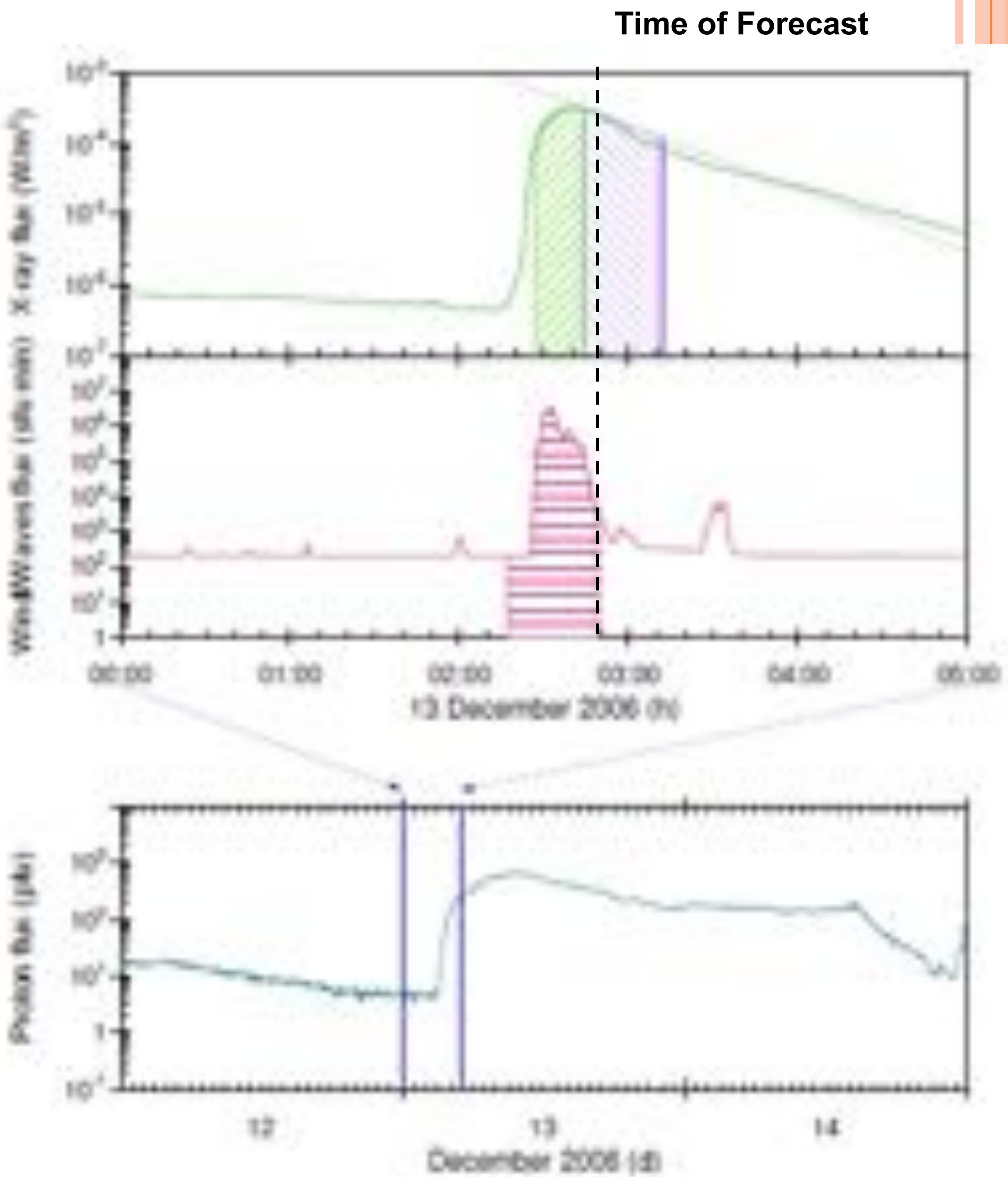
Input Parameters

The SXR time integrated flux (I) is calculated from the 1/3 power point before the peak to the 1/3 power point after.

If the X-ray intensity drops by a factor 3 within 10 minutes of the peak, the integration stops, otherwise an exponential fit of the flare is used to extrapolate the intensity curve to the 1/3 power point.

The fit is based on the intensity values from 6 to 10 minutes after the peak and it a reasonable tool to take into account the flare profile.

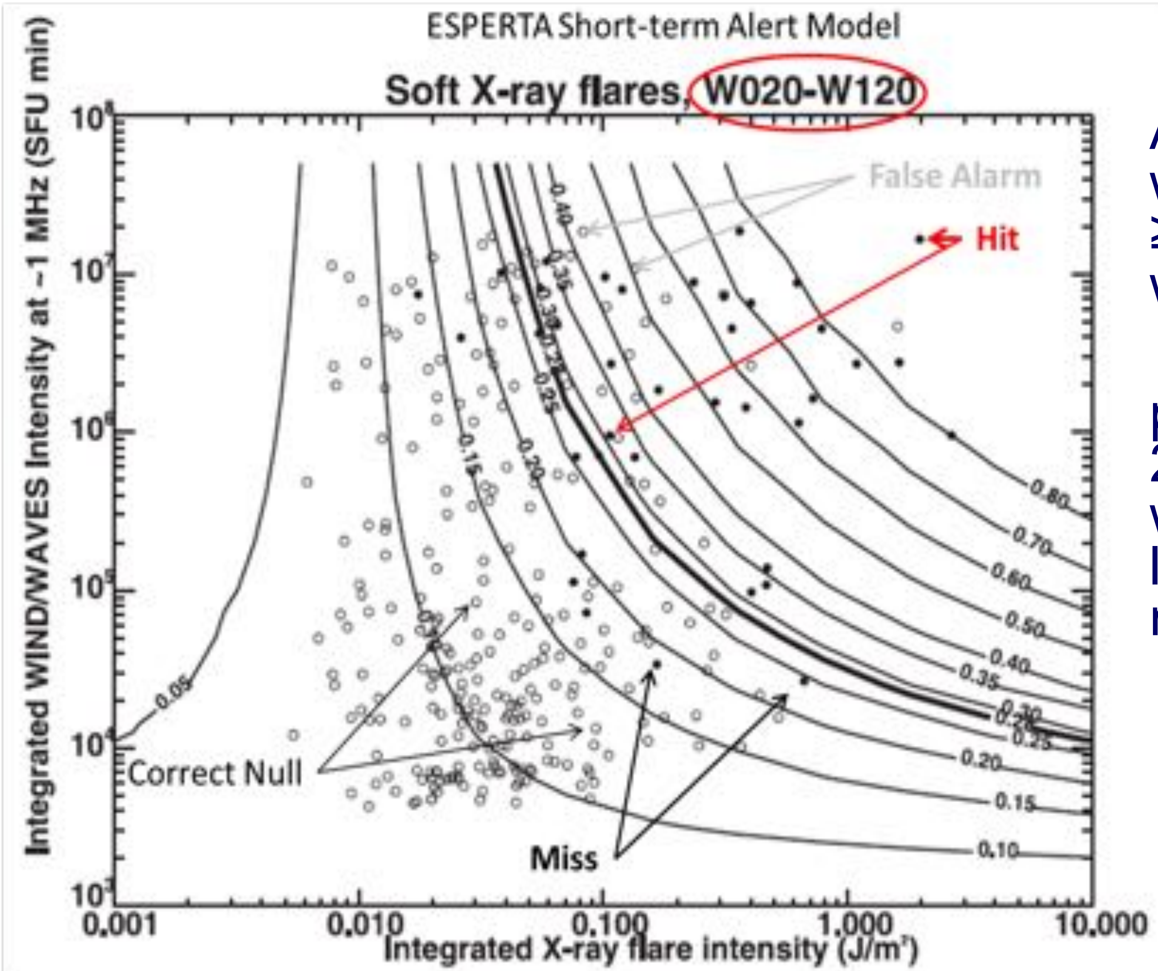
The radio time integrated flux (E) is computed by integrating the ~1MHz flux from 20 minutes before the time of the 1/3 X-ray peak until 10 minutes after the X-ray peak.



Hα flare location: S05W23

Different probability levels were computed for three heliographic longitude intervals: W20-W150, E40-W19 and E120 – E41.

Definition of a probability threshold pt for each interval.



A warning is issued whenever the forecast ≥ pt, otherwise no warning is issued.

pt values are 28%, 28% and 23% for west, central and east longitudes, respectively.

Laurenza et al., 2009

Evaluation of the model

The forecasts and observations can be analyzed in terms of the following probability of detection (POD) and false alarm rate (FAR):

POD = A / (A+C);
FAR = B/(A+B);

where:

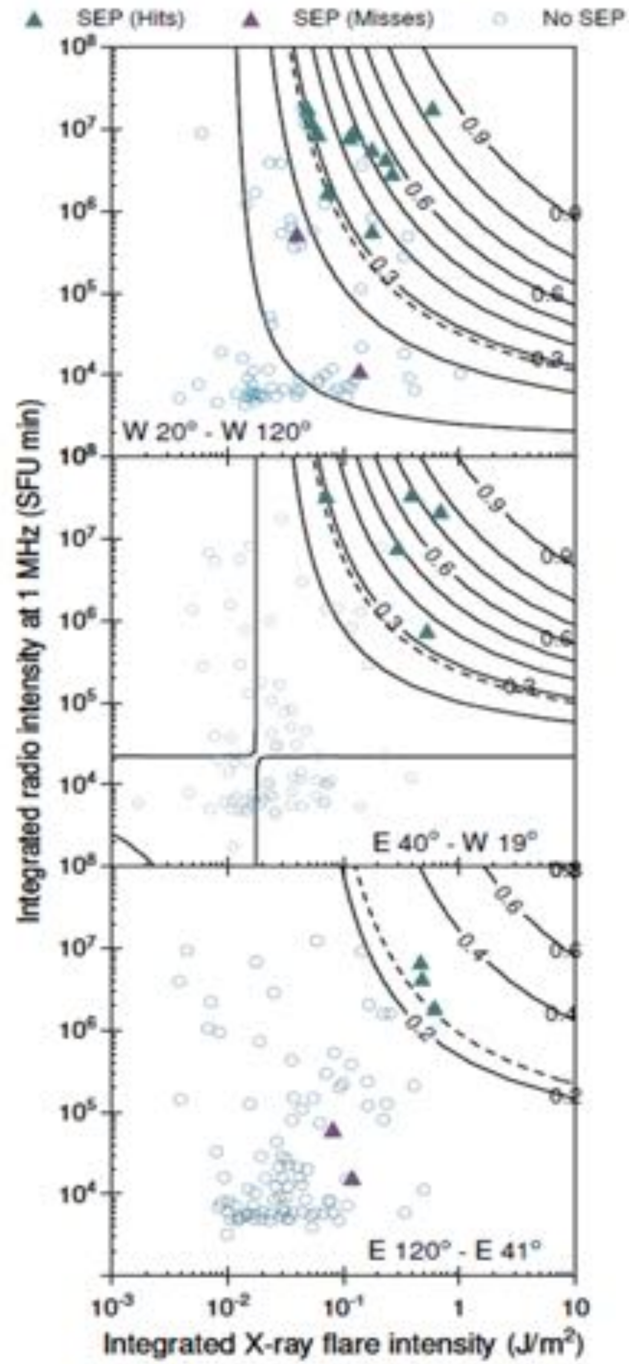
A = number of hits (a SEP event was forecast and one occurred);

B = number of false alarms (a SEP event was forecast but none occurred);

C = number of missed events (no SEP event was predicted but one occurred).

The computed median warning time is 4.8 h.

	1995 – 2005	2006 – 2014	1995 – 2014
POD	63 % (47/75)	60 % (19/32)	62 % (66/107)
FAR	42 % (34/81)	30 % (8/27)	39 % (42/109)



Alberti et al., 2017

Using ESPERTA to predict ≥S2 Events (≥100 pfu)

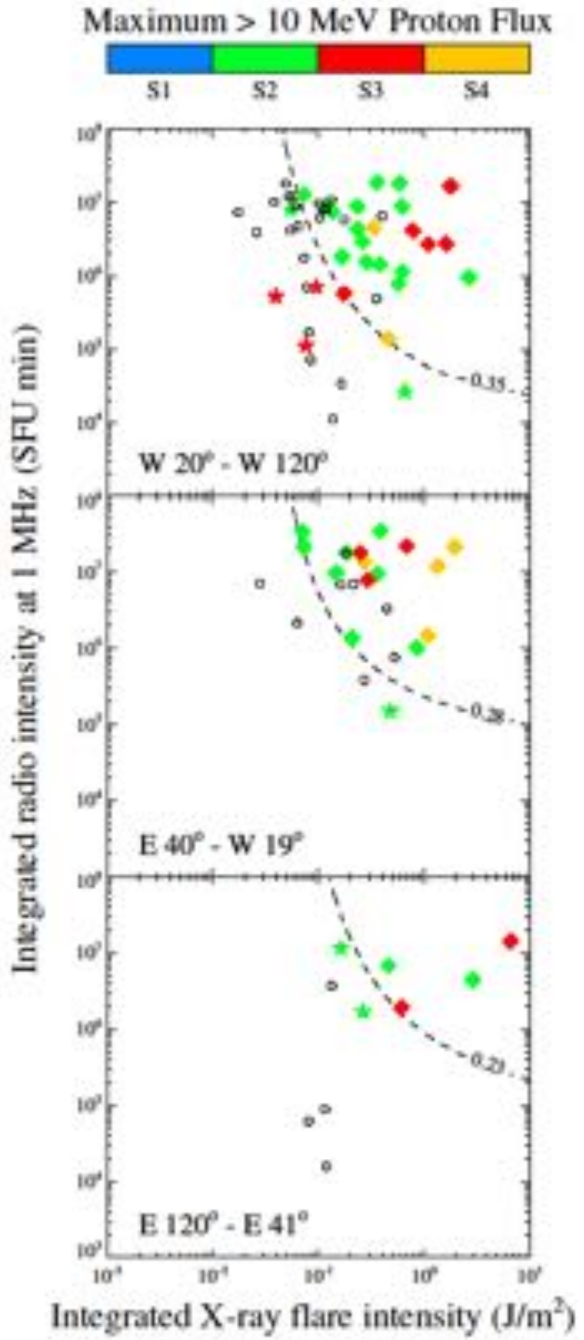
Same inputs and technique with the following changes:

- Use 0.35 contour for W20-120 longitude range
- Issue forecast when >10 MeV flux crosses 10 pfu threshold
- Inclusion of shock spike events

Two special cases:

- ≥M2 flares that occur when >10 MeV flux is > 10 pfu: issue forecast after 10 minutes from the SEP associated flare peak time
- ≥M2 flares that occur when >10 MeV flux is > 100 pfu: no prediction is made

Laurenza, M., Alberti, T., Cliver, E.W., 2018



Prediction of ≥S2 Events (≥100 pfu)

Alerts are restricted to S1 threshold crossings that followed ≥M2 SXR peaks (+10 minutes) within 6/15/30 h of west/central/eastern flares, respectively.

They correspond to the maximum S1 crossing delays for the 41 Hit events.

The warning time was computed as the difference between the time of the 100 pfu proton flux threshold overcome and the time when a warning is issued. The median warning time is 1.7 h.

Evaluation over the 1995 – 2014 period

PoD	FAR
75% (41/55)	24% (13/54)

Laurenza, M., Alberti, T., Cliver, E.W., 2018

Conclusions

The ESPERTA forecasting model yields a POD of 62% and a FAR of 39% when validated on a database covering the period 1995 - 2014. The obtained values are comparable with past estimates.

Short-term alerts should focus on ≥ S2 events.

The ESPERTA modified model is the only forecasting technique predicting the occurrence the SEP events producing radiation storm level ≥ S2. The performance of the method is high: POD = 75%; FAR=24% with a good median warning time (1.7 h).

Increased time between flare and 100 pfu threshold crossing may increase utility of physics-based forecast models

Laurenza, M., Alberti, T., Cliver, E.W., 2018

High Energy Solar Particle Events Forecasting

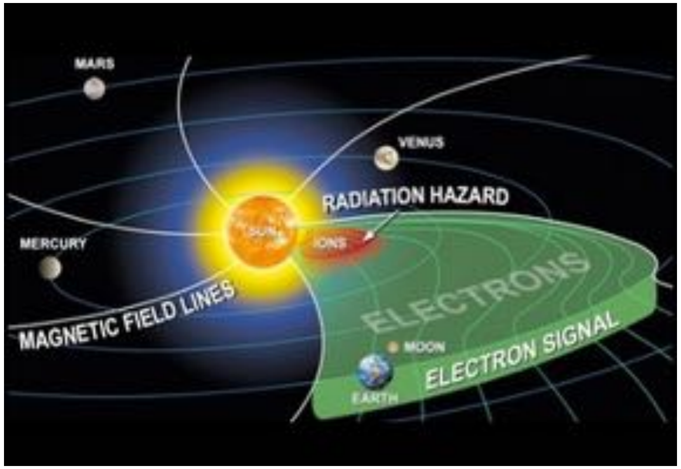
HESPERIA REleASE and HESPERIA UMASEP-500 tools

O. Malandraki, M. Nunez, B. Heber, J. Labrenz, P. Kuehl, A. Posner, M. Karavolos

Activity of the Balkan, Black Sea and Caspian Sea Regional Network on Space Weather Studies (BBC SWS)
http://www.bbc-spaceweather.org/
Chair of Steering Committee: Dr. Olga Malandraki, Greece

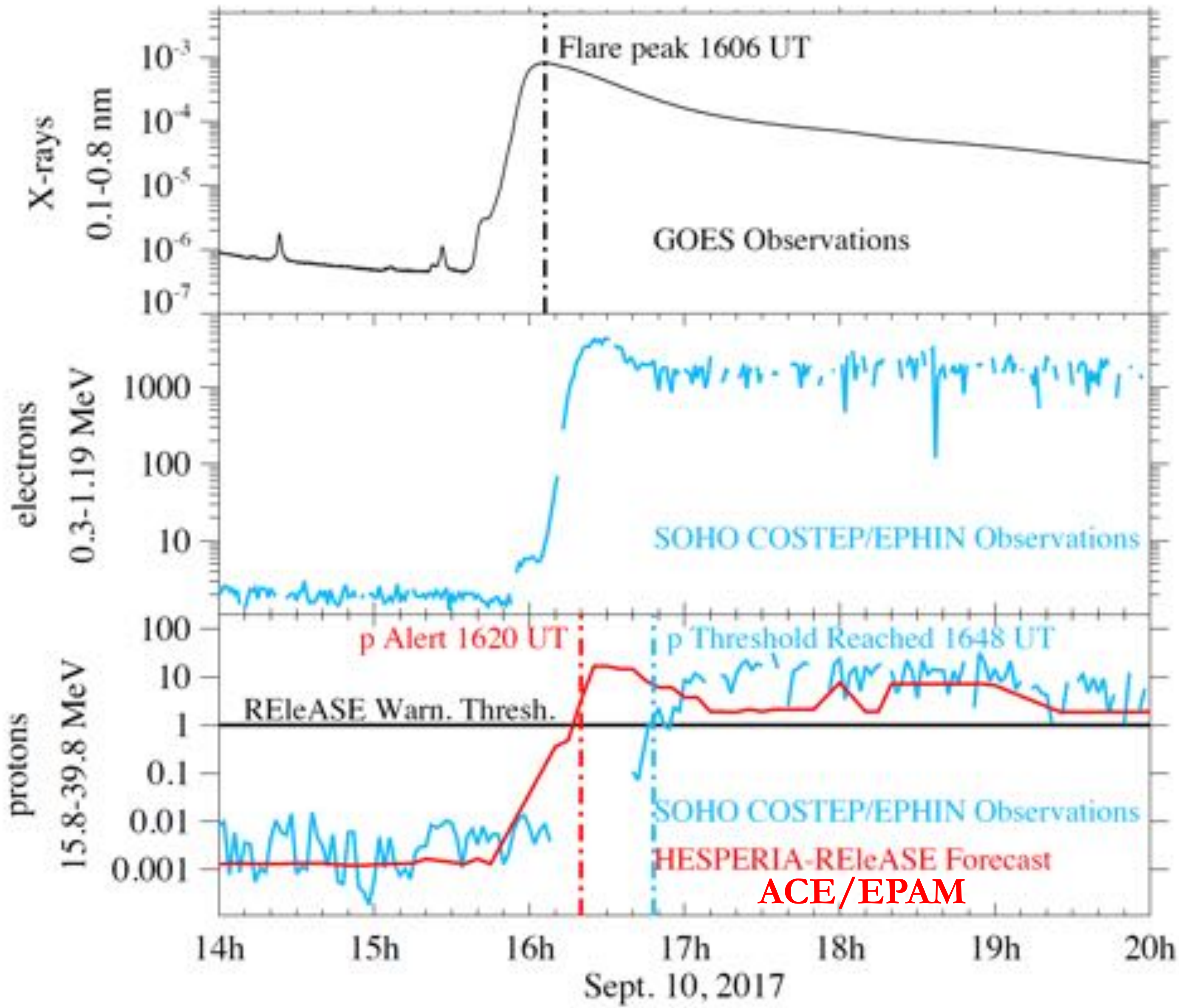
HESPERIA REleASE

Predicting 30-50 MeV SEP events by using the Relativistic Electron Alert System for Exploration (REleASE) scheme



- This tool has been implemented and evaluated a real-time SEP predictor by using the REleASE scheme (Posner, 2007)
- The implemented model infers the maximum proton intensity and onset at 30-50 MeV based on near relativistic and relativistic electron intensity time profiles measured by SOHO/EPHIN and **ACE/EPAM**
- The tool provides advanced nowcasting/forecasting methods
- Validation: POD, FAR, and average warning time.

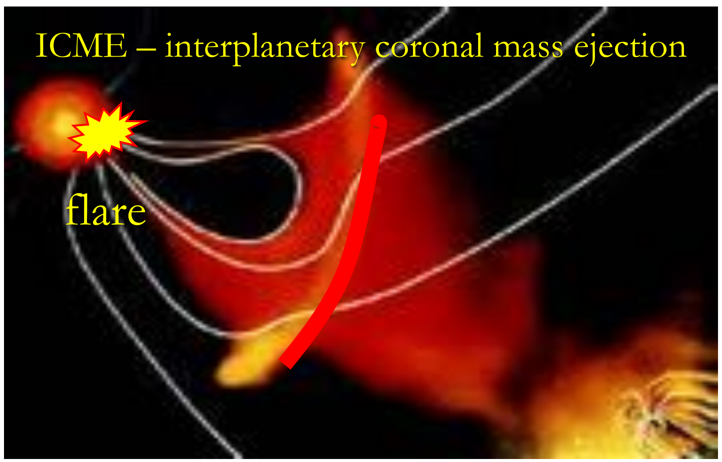
Sept 10, 2017 Shine campaign event HESPERIA REleASE Forecast

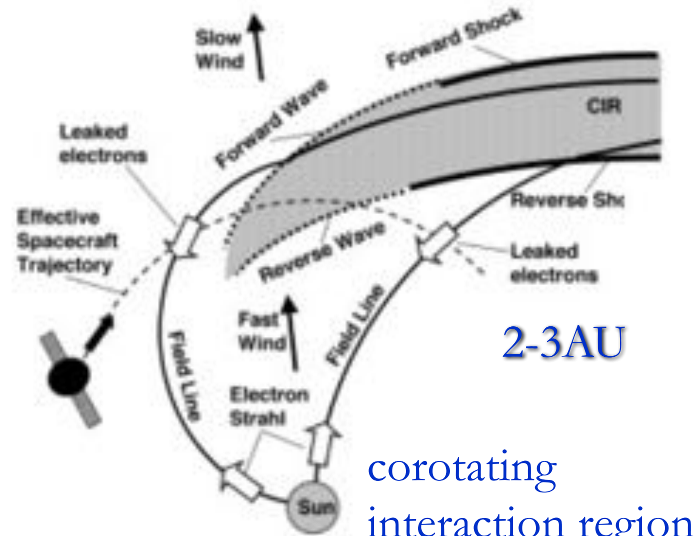


WIND & THEIR ROLE IN PARTICLE ACCELERATION (FOLLOW UP)

Is particle acceleration possible inside magnetically confined cavities?

- Some atypical energetic particle events (AEPEs) do not align with standard particle acceleration mechanisms, such as flare-related or simple diffusive shock acceleration processes related to interplanetary coronal mass ejections (ICMEs) and corotating interaction regions (CIRs).

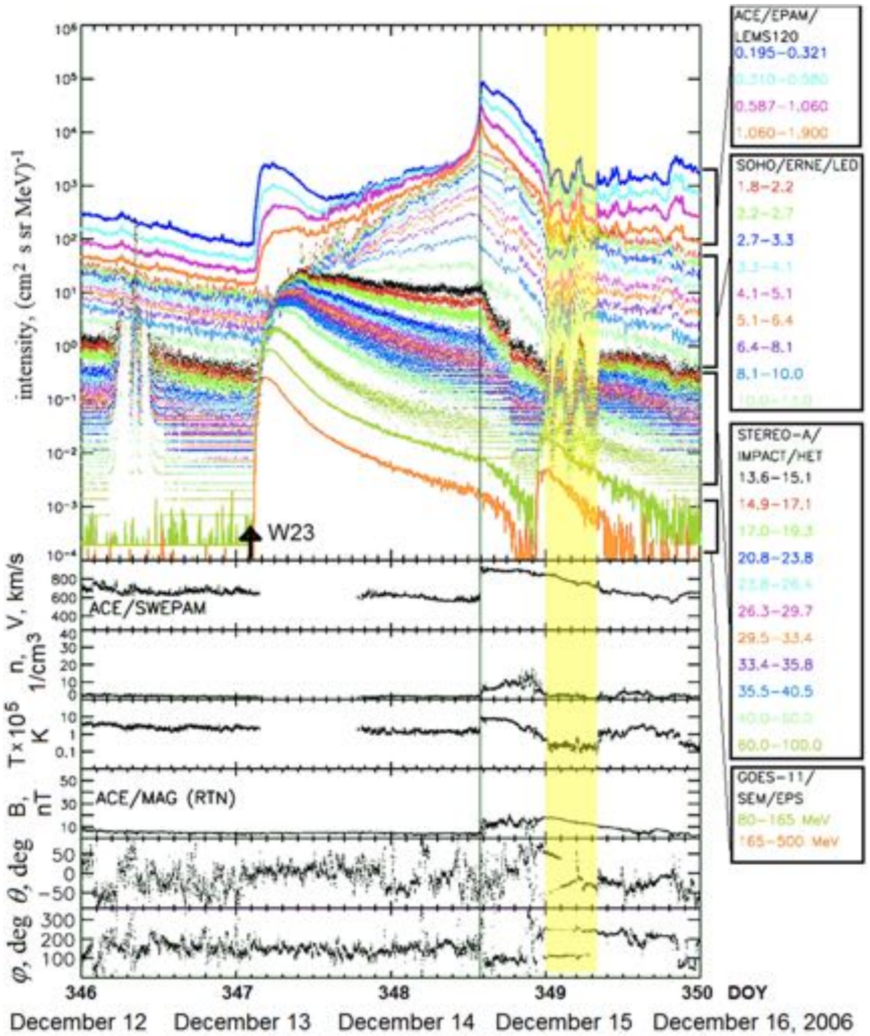




- We provide some observations that support the idea and the theory of particle energization produced by small-scale-flux-rope dynamics (Zank et al. and Le Roux et al.). If the particles are pre-accelerated to keV energies via classical mechanisms, they may be additionally accelerated up to 1–1.5 MeV inside magnetically confined cavities of various origins.

O. Khabarova, G. Zank, G. Li, O. Malandraki, J. Le Roux, G. Webb

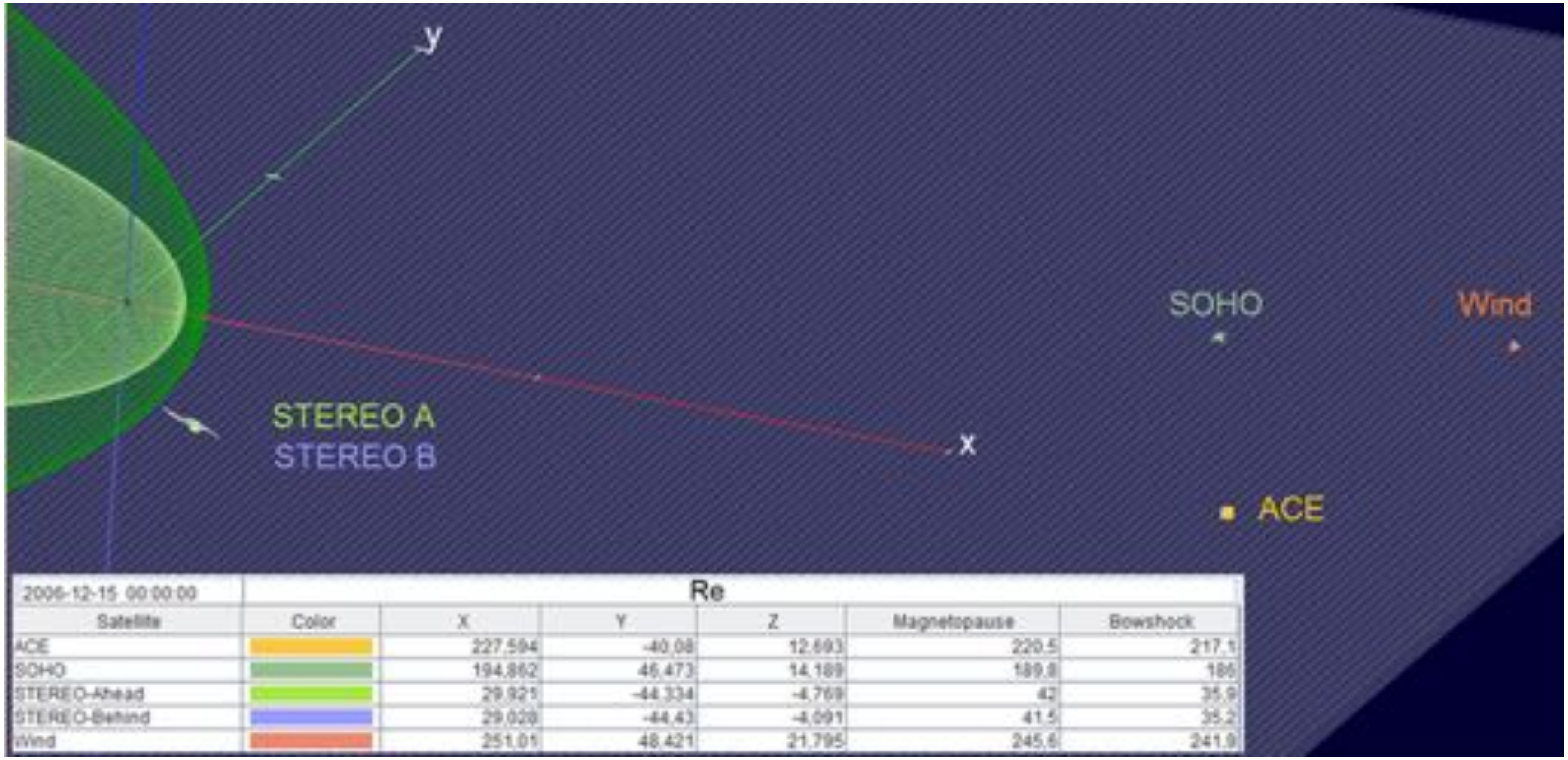
ICME Interaction with a Long-lived Coronal Hole Flow. Magnetic Cloud Distortion and Combined DSA-flux Rope Acceleration: 2006 December 13-15: Unusual SEP event



Strong increases in the energetic particle flux originating from solar active region 10930 (X3.4, W23°, 02:40 UT) (**black arrow**). A second increase with the peak at the ICME-related IS occurring on 2006 December 14 (**vertical line**). The next SEP event occurred on 2006/12/14 - DOY 348 (X1.5, W46°, 22:15 UT) nearly simultaneously with the magnetic cloud leading edge propagating through the spacecraft positions.

The variations associated with the magnetic cloud passage have been treated as being of solar origin or being due to acceleration at the ICME shock, but propagating along different magnetic field lines, for example, inside two interwoven magnetic flux tubes. von Rosenvinge et al. (2009) noticed the occurrence of at least one strong current sheet inside the magnetic cloud.

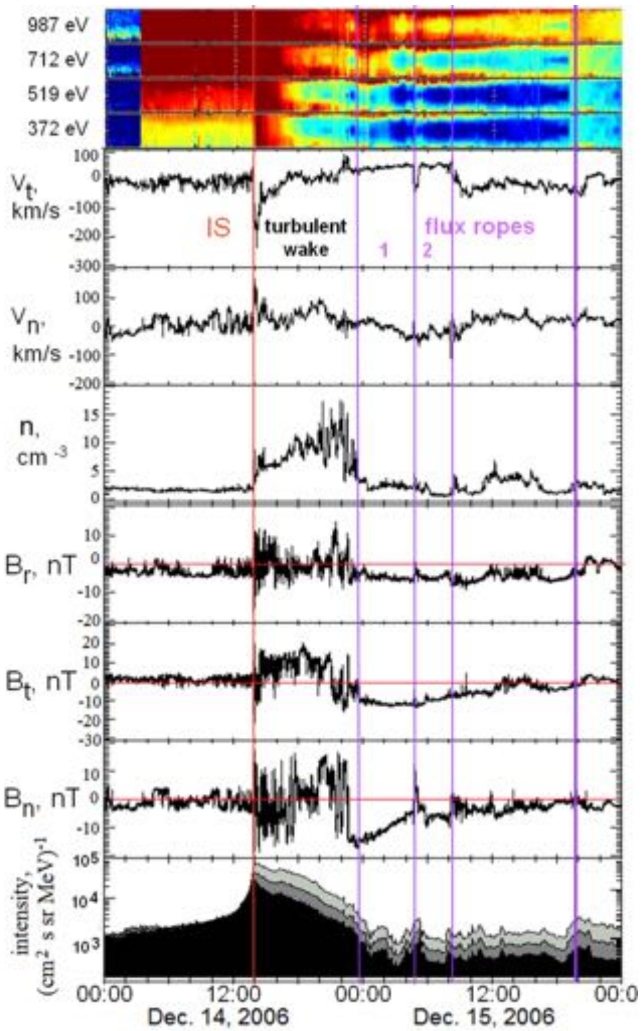
The most intriguing fact about this event is that the variations highlighted in the figure occurred inside the ICME body with ~20 minutes delay between the spacecraft at L1 and STEREO, and were not detected inside the magnetosphere.



2006-12-15 00:00:00	Re					
Satellite	Color	X	Y	Z	Magnetopause	Bowshock
ACE		227.594	-40.08	12.693	220.5	217.1
SOHO		194.862	46.473	14.189	189.8	186
STEREO-Ahead		29.921	-44.334	-4.769	42	35.9
STEREO-Behind		29.028	-44.43	-4.091	41.5	35.2
Wind		251.01	48.421	21.795	245.6	241.9

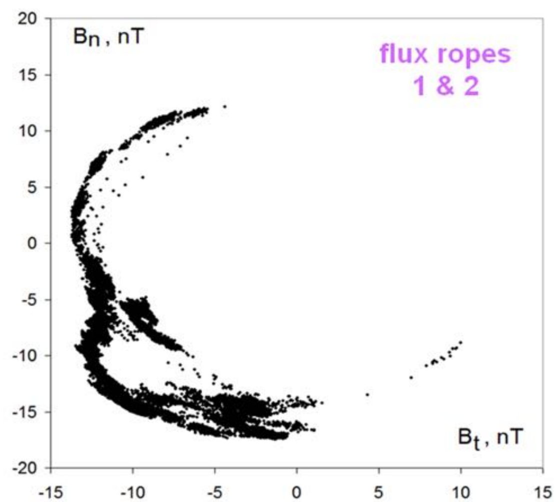
Spacecraft positions on 2006-12-15. The STEREO pair was closer to the Earth than the other spacecraft and located below the ecliptic plane XY (GSE). ACE, SOHO and Wind were above the ecliptic plane, shown by grid lines. GOES 11 (do not appear here) was inside the magnetosphere.

2006 December 13-15: Unusual SEP event



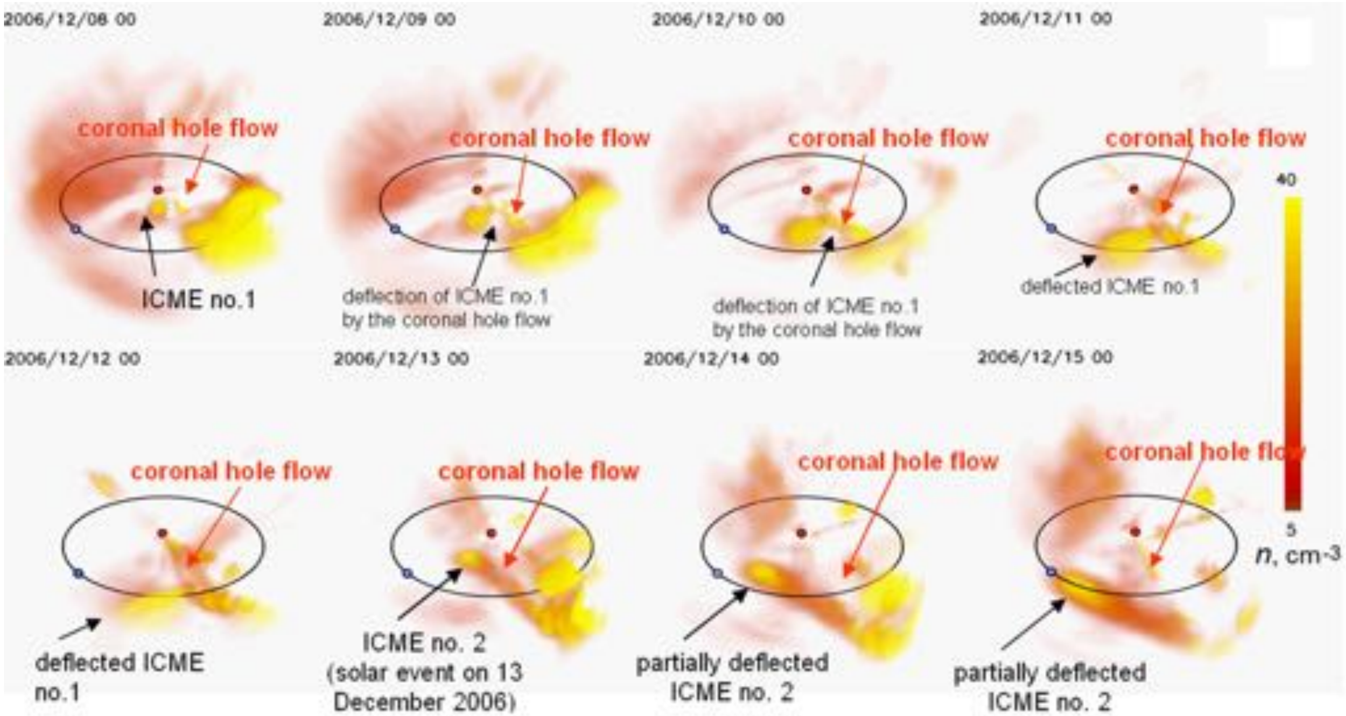
Khabarova et al. ApJ, 2016

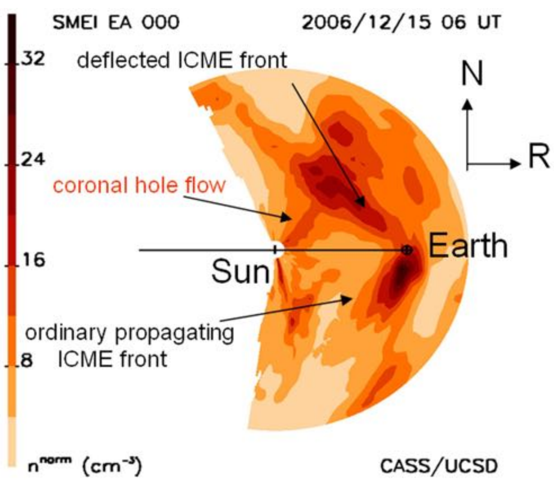
- Two middle-size magnetic clouds can be identified inside the ICME body from the analysis of the IMF data shown in figure.
- The ICME is characterized by a prolonged period of post-shock turbulent solar wind (a turbulent wake behind the IS), and instead of one large magnetic cloud, a complex region filled with flux ropes can be identified.
- Simultaneous variations in the suprathermal electron pitchangle distributions (PADs), the solar wind tangential and normal speed components, and in the plasma density, confirm that clouds 1 and 2 are separated by a strong current sheet.
- Thick vertical purple line: final current sheet separating the area filled with clouds/flux ropes from the remaining ICME trailing edge.
- Occurrence of Bi-directional strahls during the ICME confirms the existence of closed magnetic structures.



The IMF hodogram clearly illustrates independent rotation of the IMF vector in the tangential-normal plane (RTN co-ordinates) inside the two identified clouds.

2006 December 13-15: Unusual SEP event, SMEI observations





SMEI observations: Deflection of two ICME fronts by a long-lived low latitude coronal hole flow produced two interacting Magnetic clouds within the same 2006 December 14-15 event observed in situ.

Important feature revealed according to SMEI: the ICME was completely detached from the Sun.

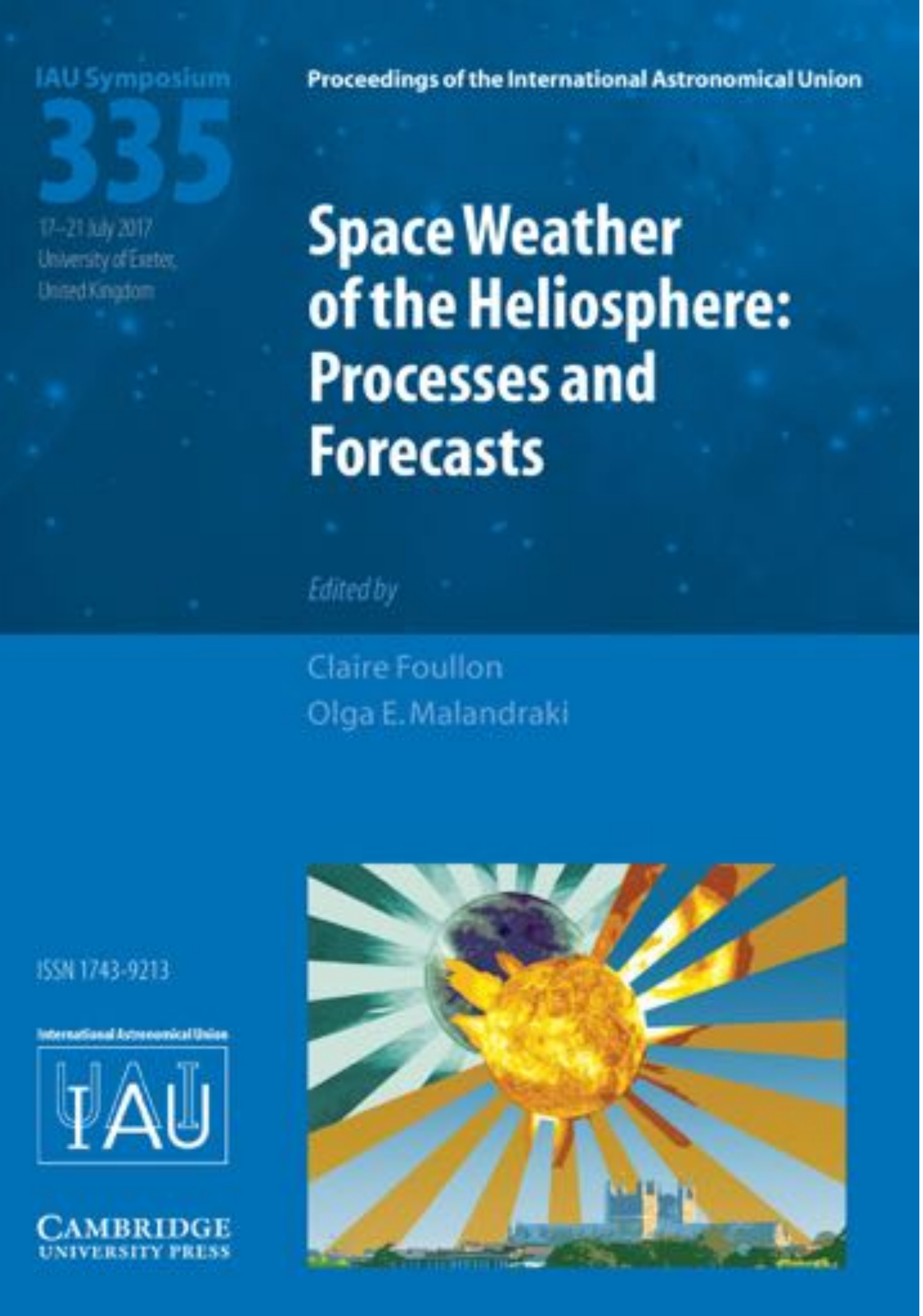
Summary

- Observed variations in proton fluxes measured by ACE EPAM correspond very well to the crossings of IMF/plasma structures showing enhancements near the edges of magnetic islands, i.e. near current sheets

- The efficiency of particle acceleration in dynamical magnetic islands depends to a high degree on (i) typical sizes of magnetic islands (flux ropes), (ii) Energies of pre-accelerated particles (the seed population) and (iii) the manner of magnetic confinement

- We suggest that the formed magnetic clouds in a large scale, the existence of seed particles pre-accelerated via Diffusive Shock Acceleration, the occurrence of additionally ejected energetic particles from the flare on 2006 December 14, and the magnetic confinement of magnetic clouds inside the ICME body all contributed to the observed acceleration of particles and flux modulation associated with magnetic clouds.

Khabarova et al. ApJ, 2016



Re-Acceleration of Energetic Particles in Large-Scale Heliospheric Magnetic Cavities

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Abstract. Case studies show that some energetic particle flux enhancements up to MeV/nuc. observed at 1 AU cannot be treated as a consequence of particle acceleration at shocks or during flares. Atypical energetic particle events (AEPEs) are often detected during crossings of magnetic cavities formed by strong current sheets of various origins in the solar wind. Such cavities confine small-scale magnetic islands (SMIs) produced by magnetic reconnection. SMIs, in turn, trap and re-accelerate energetic particles according to predictions based on the theory of Zank *et al.* describing stochastic particle energization in the supersonic solar wind via numerous dynamically interacting SMIs. AEPEs possess energies that overlap SEP events and can be an important component in understanding space weather.

Keywords. Solar wind, particle acceleration, magnetic islands, current sheets

1. Introduction

Energetic particle flux enhancements (EPFEs) observed at 1 AU in the keV-MeV energy range are predominantly treated as a phenomenon that has a distant origin. Some EPFEs are classical solar energetic particle (SEP) events, produced by particle acceleration near the Sun, which result from either solar flares or diffusive particle acceleration at shocks associated with interplanetary coronal mass ejections (ICMEs). The same diffusive shock acceleration (DSA) mechanism is usually considered to be responsible for 1 AU EPFEs observed in quiet (non-flare) times and associated with long-lived corotating

Khabarova, O.V., Malandraki, O.E., Zank, G.P., Li, G., le Roux, J., Webb, G.M., 2018