Solar Energetic Particles: Science and Applications

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Working Group 6 on
'Solar Energetic Particles
(SEPs)'

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ISEST/MINIMAX24
WORKING GROUP 6, WG6:
'SOLAR ENERGETIC PARTICLES (SEPS)'

Scientific Objectives

The main objective of this Working Group, directly aligned with the ISEST science objectives, is the **improvement of our understanding of the origin, acceleration and transport of energetic particles in the heliosphere**, in association with **Coronal Mass Ejections (CMEs)** and **Corotating Interaction Regions (CIRs)** propagation and evolution.

SCIENTIFIC ISSUES ADDRESSED WITHIN ISEST/WG6 - RESULTS

- SEP release time and Radio bursts (Kouloumvakos et al., 2015)
- **Potential SEP acceleration by shock compression (Kozarev et al. 2015; Schwadron et al. 2015)**
- **Magnetic cavities, current sheets and magnetic islands as local sources of energetic particles in the solar wind (Khabarova et al. 2015, 2016, 2017, 2018; Malandraki et al. 2019)**
- Gamma-ray flare events and SEPs: FERMI era (Share et al. 2019)
- Triangulation of shocks in 3-D (Plotnikov et al. 2017)
- **Joint Ne/O and Fe/O analysis to diagnose large SEP events (Tan et al. 2017)**
- What governs the longitudinal spread of SEPs? (Cohen et al. 2017)
- 3-D Modeling of SEP propagation within the heliosphere (Dalla et al. 2017)
- ENLIL and 3-D test particle model (Thomas et al. 2018)
- Are abundance enhancements power-law in A/Q?
- Compare FIP plots of SEPs and slow solar wind (Reames et al. 2017)
- **Flare vs Shock Acceleration of high-energy protons in SEP events (Cliver et al. 2016)**
- **Extreme CME kinematics and SEP spectra: 2012 July 23, 2017 Sept 10 events (Gopalswamy et al. 2016, 2018)**
- **Extreme solar eruptions and their space weather consequences (Gopalswamy 2017)**
- The long-lasting injection during the widespread 2013 Dec 26 SEP event (Dresing et al. 2018)
- **SEP event forecasting:**
  - With Flare X-ray peak ratios (Kahler & Ling, 2018)
  - **ESPERTA-based forecast (Laurenza et al. 2018)**
  - **HESPERIA-based forecast (Malandraki et al. 2018; Nunez et al. 2017, 2018, *BBC SWS Regional Network*) HESPERIA REleASE forecast, 2017 Sept 10 SEP event**
- **Key Open Questions and Future Missions**

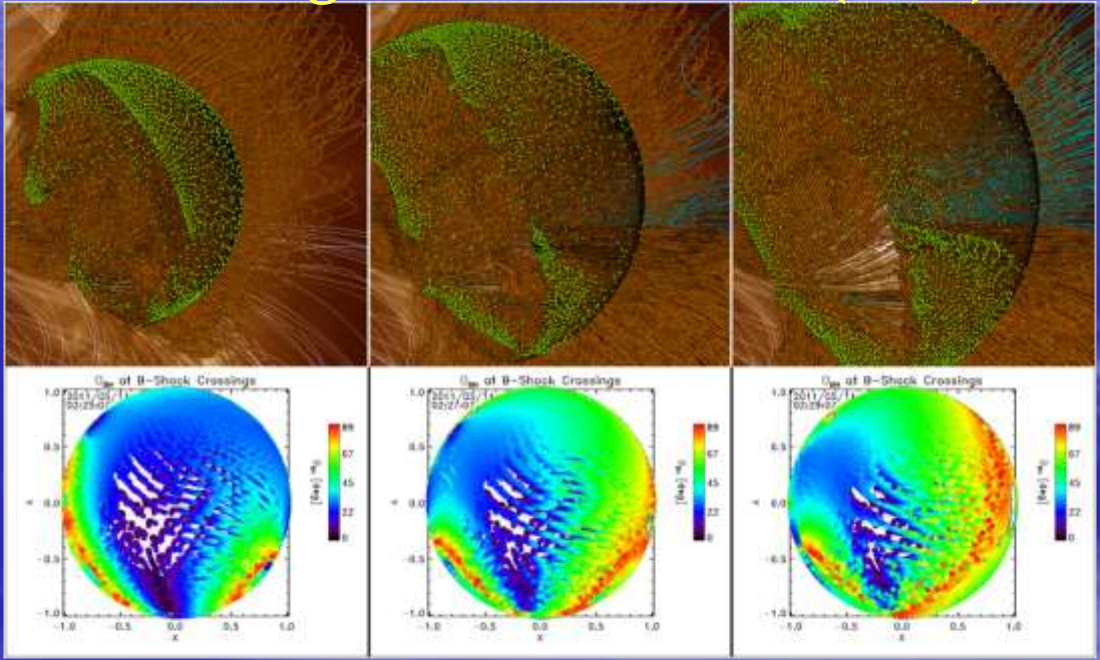
Understand the shock type at SEP injection site

METHOD: Estimate the shock normal angle to B-field via 3D reconstruction of shock envelope and B-field model (PFSS).

e.g. see Kozarev et al (2015)

- Estimates of θ_{Bn} in the low corona are possible.
- Can lead to better modeling (and understanding) of the SEP intensities/evolution.
- **Open Questions:**
  - What's the best B-field model to use?
    - PFSS is likely unreliable.
  - Needs to be validated with more events.

2011 May 11 CME event



Top row: three snapshots of the time-dependent coupled PFSS+CSGS model, showing the interaction of the spherical geometric shock front model with the PFSS coronal fields. The AIA 193Å channel image is shown for reference, for each time step. On top of it the field lines were plotted—colored orange (closed) or blue (open) if interacting with the shock surface, white otherwise. The shock surface mesh is plotted in black. The points of interaction are shown in light green.

Bottom row: for each step of the shock evolution, a map of the position of the field interaction with the shock is produced. The colors correspond to the value of the angle θ_{Bn} between 0º and 90º. Open field-crossing symbols are open circles (their centers are white). θ_{Bn}, changes significantly throughout the evolution of the shock surface. Areas of higher θ_{Bn} values, which correlate with faster and stronger acceleration, occur preferentially near the flanks for the magnetic fields calculated by PFSS for this event.

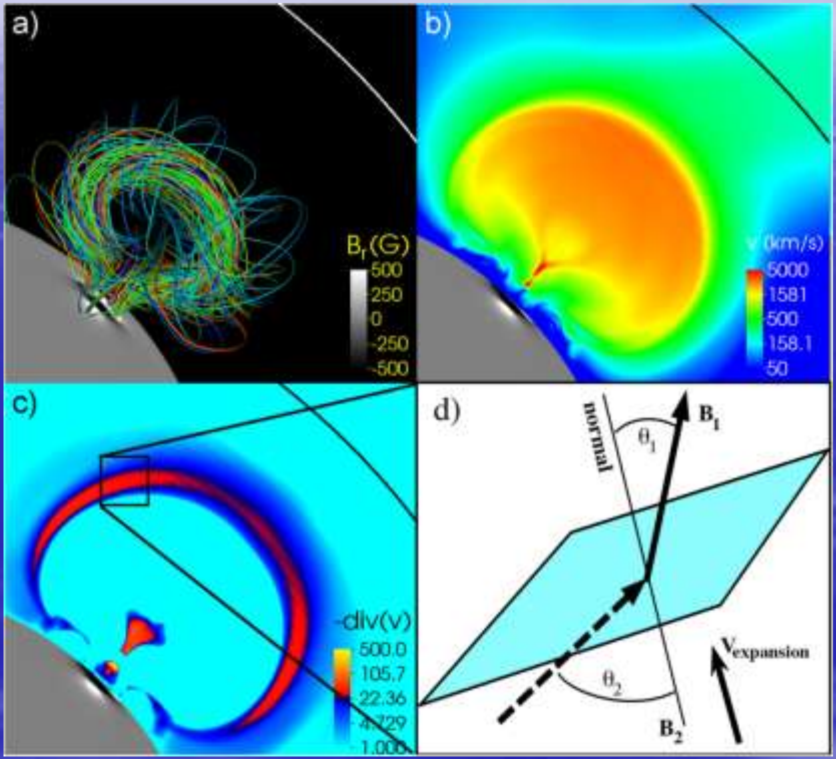
Methods used hold a significant potential for early characterization of coronal shock waves and forecasting of SEP spectra based on remote observations.

What is the role of compression on SEP production?

METHOD: Measure CME lateral expansion low in the corona

- Lateral expansion of the CME, low in the corona, drives shocks or compressions and accelerates particles.
- Validates early interpretations from Patsourakos et al. (2009) and Patsourakos, Vourlidas, & Kliem (2010).
- **Open Questions:**
  - How common is this mechanism?
  - Is an EUV bubble (shock proxy) a necessary condition for SEPs?
  - What is the role of the flare-accelerated particles?

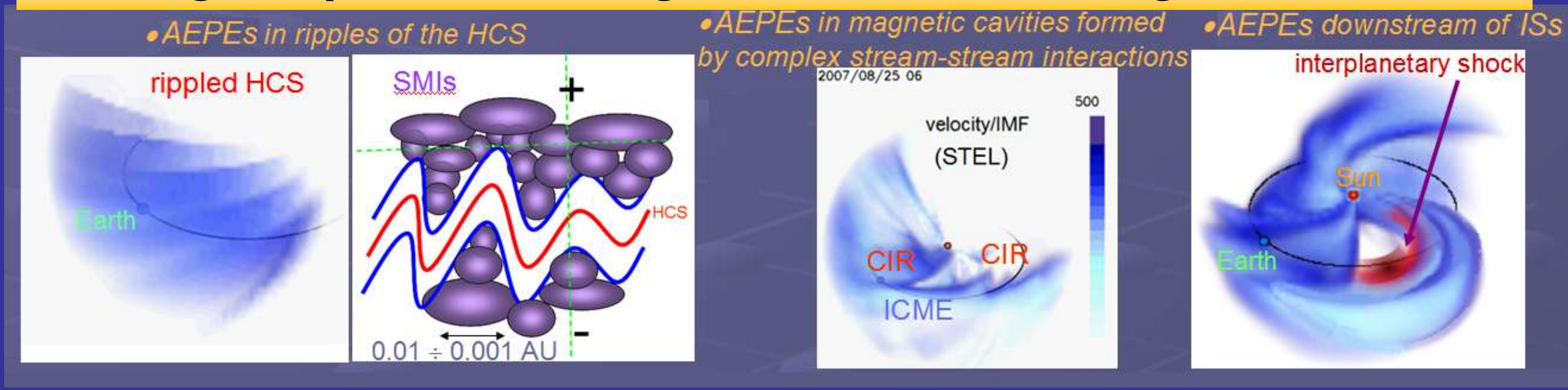
Schwadron et al (2015)



Configuration in the low corona based on MAS simulations (Schwadron et al. 2014) showing a strong compression driven by the expansion of a CME. The strong compressions on the flank of the CME create the conditions that lead to rapid particle acceleration. The configuration of the erupting magnetic flux rope (panel (a)) is shown with associated photospheric field strength B_r in grayscale on the solar surface. The CME accelerates rapidly to plasma speeds (panel (b)) of thousands of km s^{-1} low in the corona. As a result of the CME's rapid acceleration, strong compressions and shocks are formed showing a large negative velocity divergence, (panel (c)) expressed in code units corresponding to 7×10^{-4} s^{-1}. The box in panel (c) is blown out (panel (d)) to indicate the plane of the shock or compression and a magnetic flux bundle piercing the shock. In panel (d), note the magnetic field normal angles θ_1 and θ_2 upstream and downstream from the shock or compression. The expansion velocity driving these compressions is also shown

CME expansion and acceleration in the low corona may naturally give rise to particle acceleration and broken power-law distributions in large SEP events

- energetic particles- magnetic cavities – magnetic islands


•AEPEs in ripples of the HCS

•AEPEs in magnetic cavities formed by complex stream-stream interactions

•AEPEs downstream of ISs

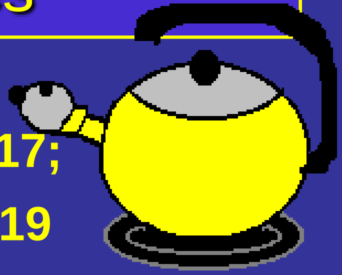
New paradigm

- pre-acceleration via magnetic reconnection at current sheets or other mechanisms of particle acceleration +

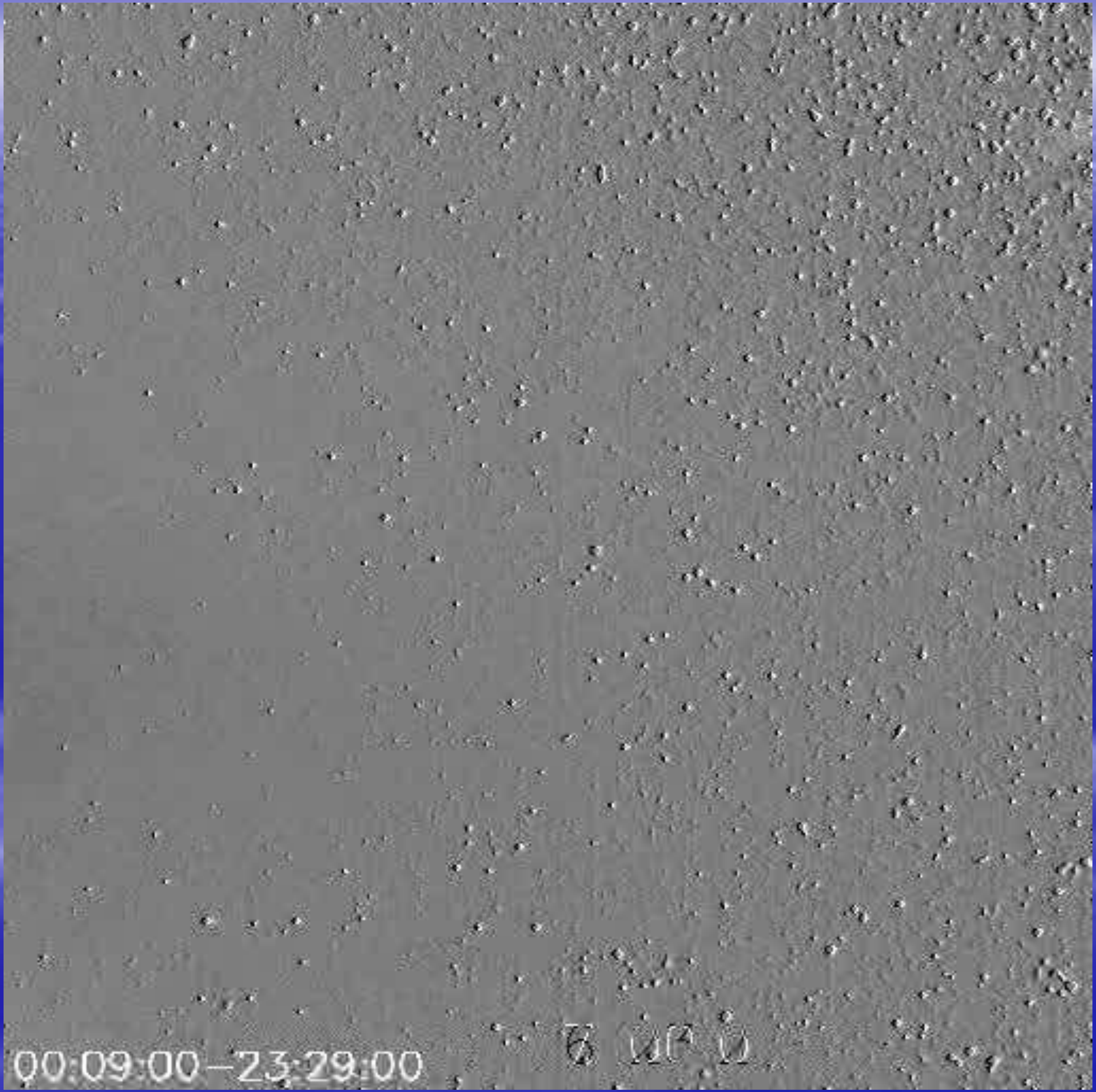
- additional acceleration of energetic particles in magnetically confined areas filled with dynamically evolving small-scale magnetic islands (*l* ~ 0.001AU-0.01AU).

- confinement of magnetic islands in magnetic cavities

Zank et al., ApJ, 2014, 2015; le Roux et al., ApJ, 2015, 2016; Khabarova et al., ApJ, 2015, 2016, 2017; Khabarova & Zank, ApJ 2017; Khabarova et al. 2018; Zhao et al. ApJ, 2018; Adhikari et al. ApJ, 2019

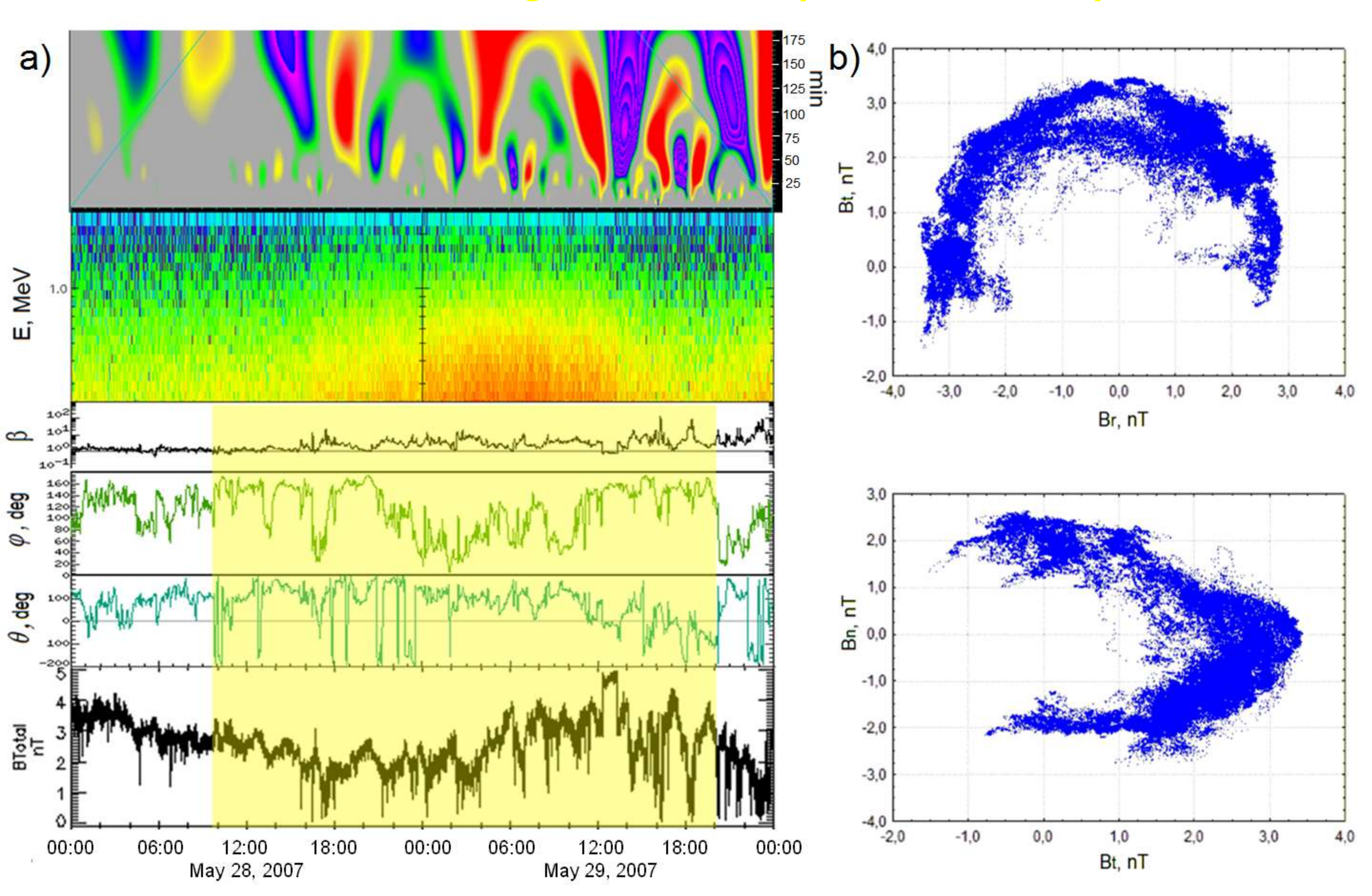


Magnetic cavities formed due to unstable streaming from a long-lived coronal hole

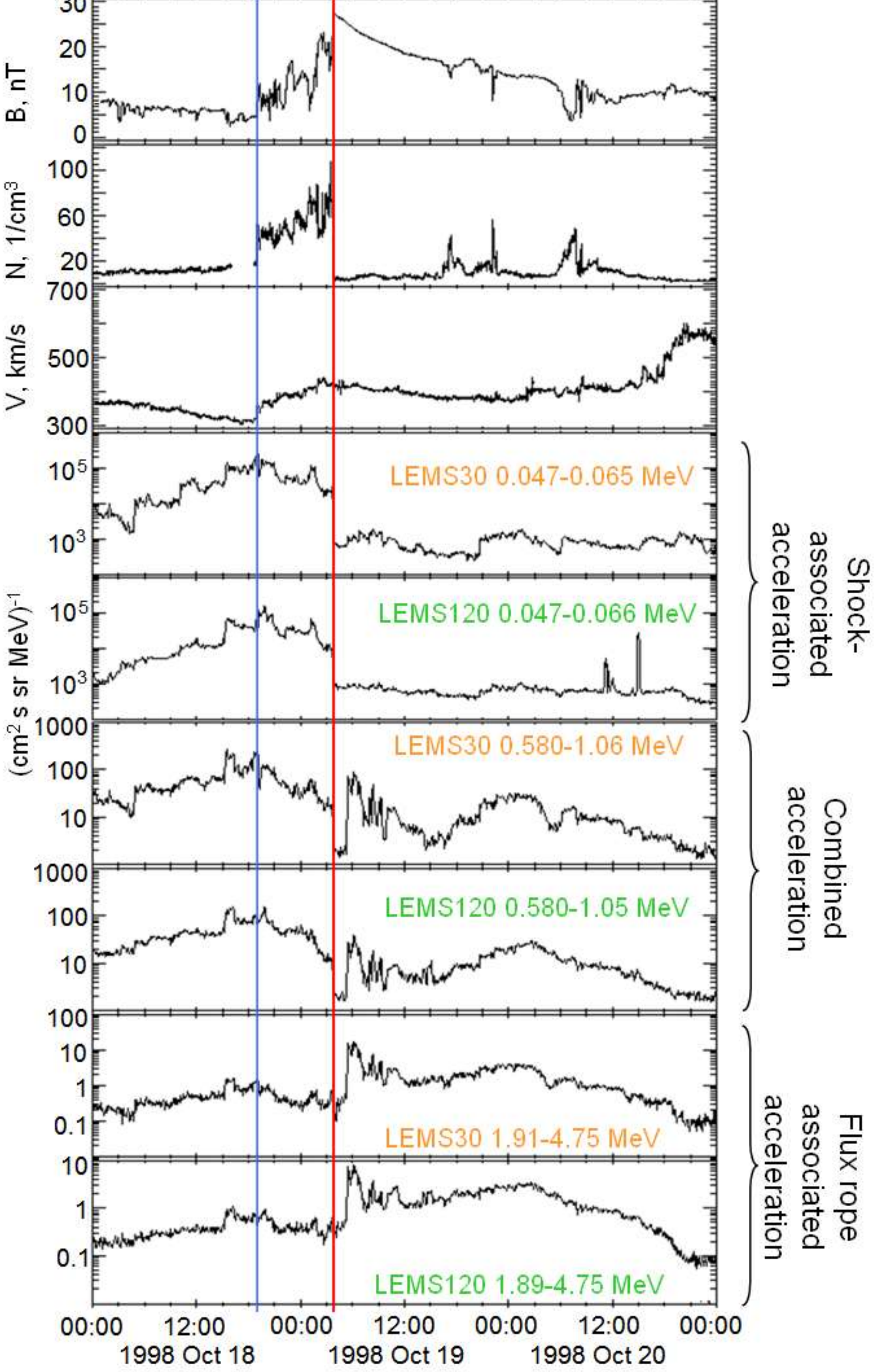


Khabarova et al, ApJ, 2016

Magnetic cavity formed due to unstable streaming from a long-lived coronal hole + magnetic islands (l~0.001-0.01 AU)



Khabarova et al, ApJ, 2016

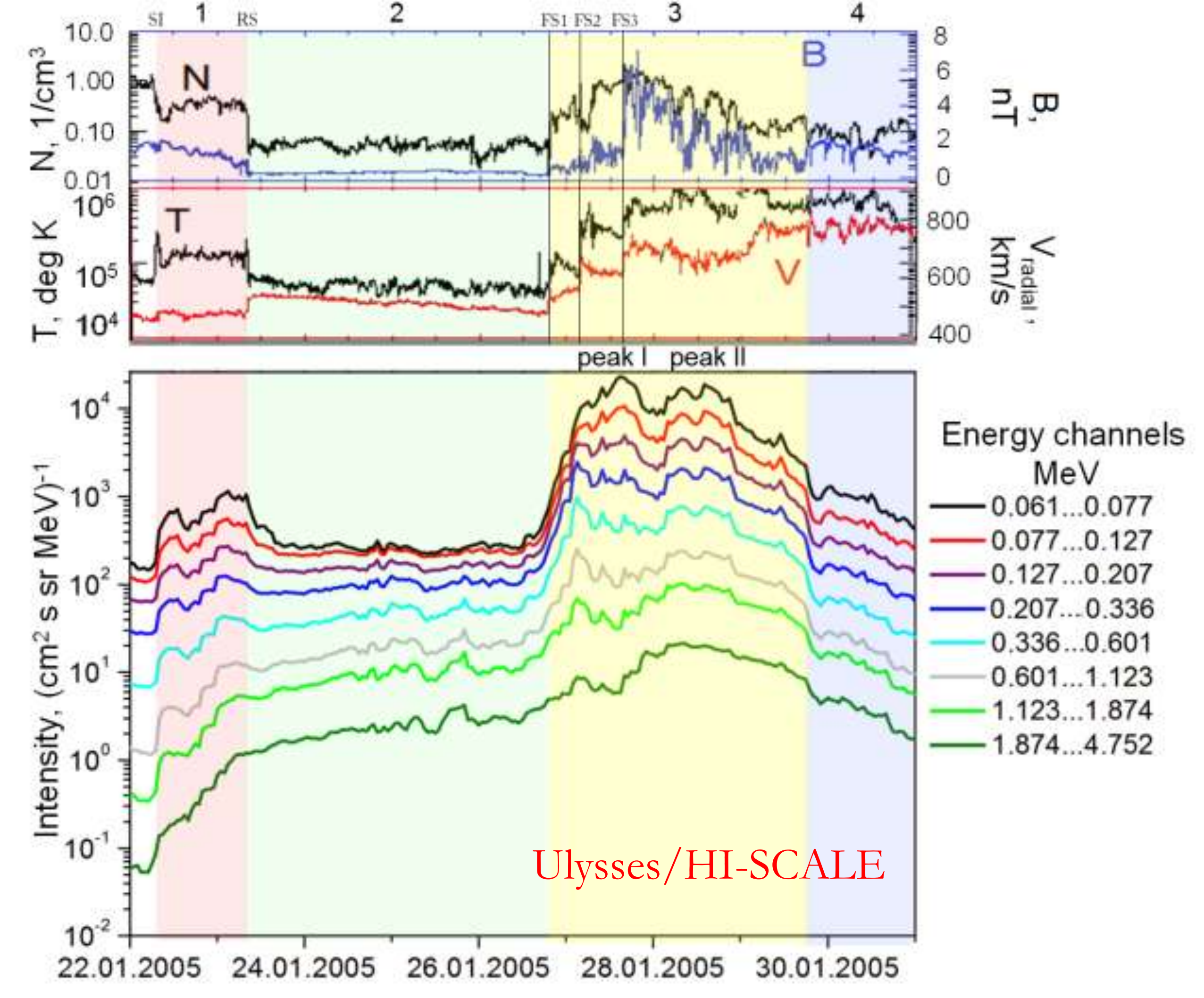


The shock (blue line) accelerates particles effectively up to hundreds of keV.
Dynamical magnetic islands accelerate particles up to 5 MeV.
There is an energy range in which both sources contribute.

Different mechanisms of particle acceleration can act simultaneously and interplay in the solar wind

Khabarova & Zank, ApJ, 2017

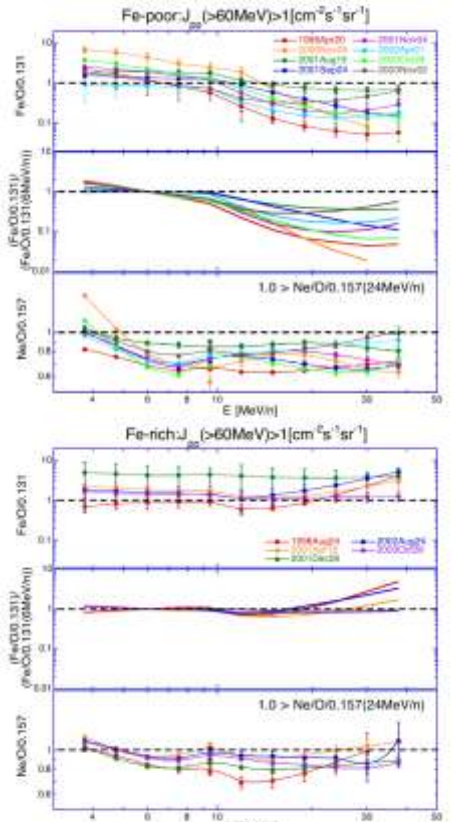
Current sheets, magnetic islands and associated particle acceleration in the solar wind observed by Ulysses near the ecliptic plane



Malandraki et al., ApJ, in press, 2019

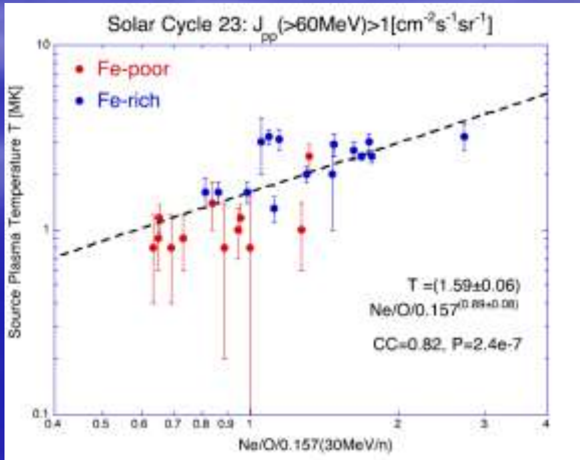
- AEPEs downstream of the merged ICME shocks are characterized by a flux amplification factor exceeding 1, which points to the existence of a mechanism of particle acceleration apart from DSA
- Evidence that local particle acceleration in the regions is governed not only by shocks but also by dynamical magnetic islands and stochastically reconnecting current sheets.

Joint Ne/O and Fe/O Analysis to Diagnose Large SEP Events during Solar Cycle 23



- An improved ion ratio calculation was carried out by re-binning the ion intensity into the form of equal bin widths in the logarithmic energy scale
- Because of the similarity of mass-to-charge (A/Q) ratios between Ne and O ions, we see no substantial time variation of Ne/O ratios ⇒ the Ne/O measurement is more accurate and the explanation of Ne/O observations is more straightforward
- In particular we observe a good correlation of the high-energy Ne/O ratio with the source plasma temperature T recently reported by Reames, 2016. Therefore the $(Ne/O)_n$ value at high energies should be a proxy of the injection energy in the shock acceleration process, and hence the shock θ_{Bn} according to the models of Tylka & Lee, 2005 and Schwadron et al., 2015.

- We clarify the explanation on the correlation of Fe/O ratios with the event duration at higher energies. We find that the apparent correlation between $(Fe/O)_n$ and the event duration is caused by a large difference of average $(Fe/O)_n$ values between the Fe-poor and Fe-rich event groups



Tan, Malandraki, Shao, ApJ, 2017

Flare vs Shock Acceleration of high-energy protons in Solar Energetic Particle Events

This study was motivated by three recent papers by

- Dierckxsens et al. (2015)
- Grechnev et al. (2015)
- Trottet et al. (2015)

that provided correlative evidence for a role for a significant contributory, or dominant, flare-resident particle acceleration mechanism in the generation of high-energy protons in large SEP events.

Focused on the Grechnev et al. (2015) study that examined >100 MeV proton events.

E. W. Cliver

E. W. Cliver (2016)

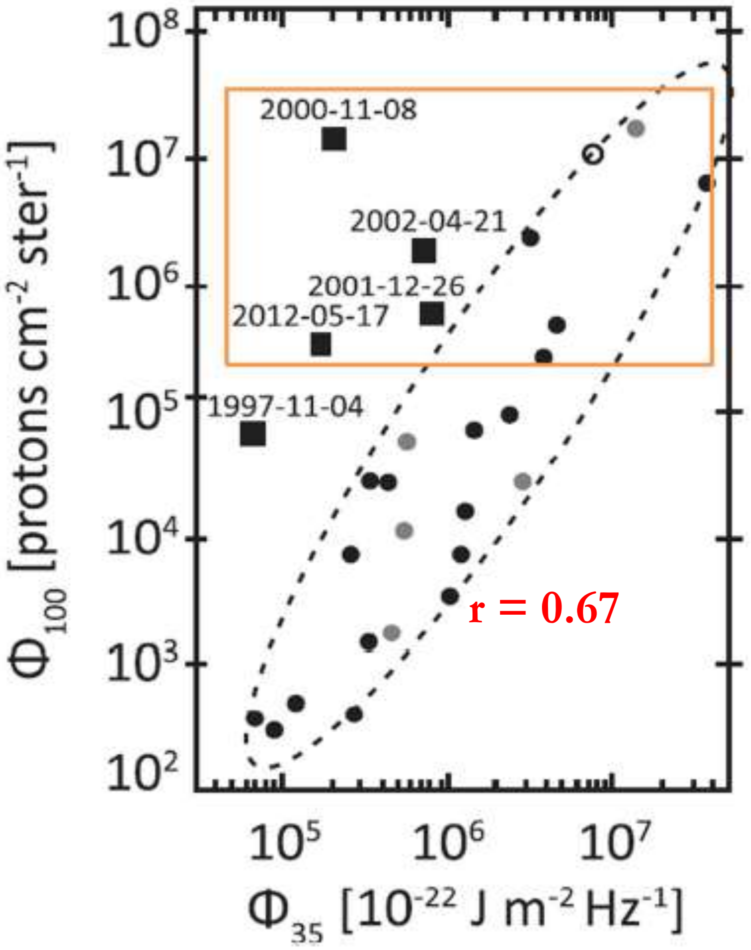


Figure 1. Scatterplot of longitude-corrected >100 MeV proton fluence (Φ_{100}) vs. 35 GHz fluence (Φ_{35}) for solar proton events from 1996 to 2014, adapted from Grechnev et al. (2015; black circles and squares (W21–W90); gray circles (E30–W20); open circles (<E30)). The orange rectangle isolates events with $\Phi_{100} > 2 \times 10^5$ pfu s.

Grechnev et al. argued that the events indicated by black squares in the figure were events in which CME-driven shocks dominated acceleration of >100 MeV protons while a flare-resident acceleration process dominated the events depicted by circles.

Excluding the “squares” => r = 0.67

In the next slide we compare the CME properties of the square (outliers) and circle events (main sequence) in the orange rectangle.

Grechnev et al. (2015)

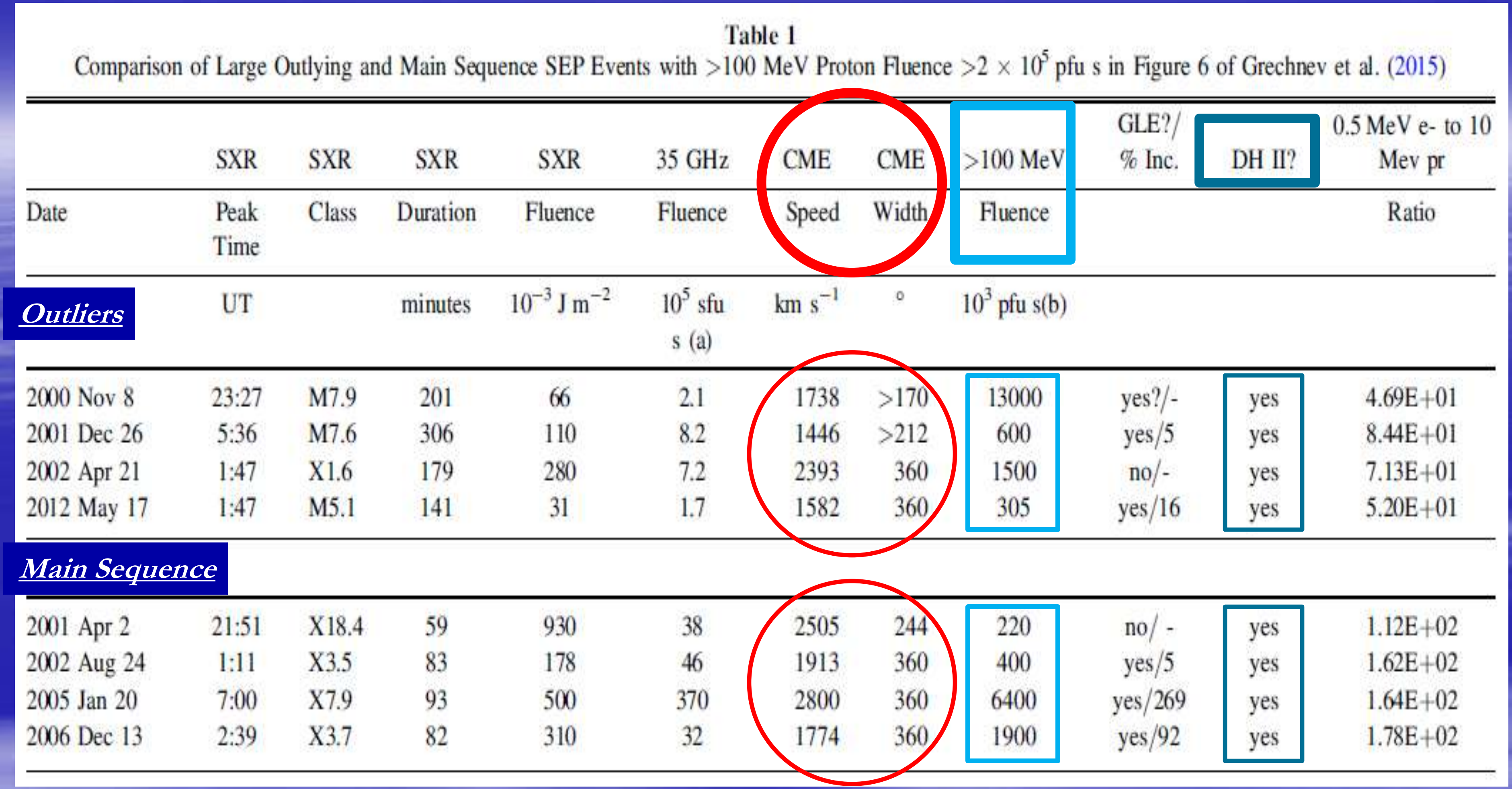


Table 1

Comparison of Large Outlying and Main Sequence SEP Events with >100 MeV Proton Fluence $>2 \times 10^5$ pfu s in Figure 6 of Grechnev et al. (2015)

Date	SXR Peak Time UT	SXR Class	SXR Duration minutes	SXR Fluence 10^{-3} J m^{-2}	35 GHz Fluence 10^5 sfu s (a)	CME Speed km s^{-1}	CME Width °	>100 MeV Fluence 10^3 pfu s(b)	GLE?/ % Inc.	DH II?	0.5 MeV e- to 10 Mev pr Ratio
Outliers											
2000 Nov 8	23:27	M7.9	201	66	2.1	1738	>170	13000	yes?/-	yes	4.69E+01
2001 Dec 26	5:36	M7.6	306	110	8.2	1446	>212	600	yes/5	yes	8.44E+01
2002 Apr 21	1:47	X1.6	179	280	7.2	2393	360	1500	no/-	yes	7.13E+01
2012 May 17	1:47	M5.1	141	31	1.7	1582	360	305	yes/16	yes	5.20E+01
Main Sequence											
2001 Apr 2	21:51	X18.4	59	930	38	2505	244	220	no/ -	yes	1.12E+02
2002 Aug 24	1:11	X3.5	83	178	46	1913	360	400	yes/5	yes	1.62E+02
2005 Jan 20	7:00	X7.9	93	500	370	2800	360	6400	yes/269	yes	1.64E+02
2006 Dec 13	2:39	X3.7	82	310	32	1774	360	1900	yes/92	yes	1.78E+02

The main sequence events, attributed to flare-resident SEP acceleration, have slightly faster/wider **CMEs** than the outliers. Both groups of events have associated **DH type II radio bursts** and comparable **>100 MeV proton fluences**.

As noted by Grechnev et al., including the outliers in Figure 1 => r = 0.09.

Summary *Cliver, ApJ, 2016*

(1) The correlation between flare electromagnetic emissions and associated >100 MeV proton events is poor because of a class of large proton events with relatively weak flare emissions (e.g. FE/SEP events – Gopalswamy et al. 2015)

(2) Classic flare-associated impulsive events are poor producers of >100 MeV protons

(3) The existence of >100 MeV proton events associated with weak flares that have fast CMEs and associated DH type II bursts argues that shock acceleration dominates high-energy proton acceleration in solar flares (e.g., Cliver, 1983, 1989)