Constructing a Basis of SEP Event Characteristics Based on Source and Solar Wind Plasma Conditions

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Abstract

Solar energetic particle (SEP) events have been observed by the Parker Solar Probe (PSP) spacecraft since its launch in 2018. These events include solar flares and coronal mass ejections. Onboard PSP is the IS⊙IS instrument suite that measures ions and electrons over a range of decades of energy via the EPI-HI and EPI-LO detectors. Here we conduct a cumulative systematic study of SEP events with similar particle signatures to construct a basis of expected values for local plasma conditions throughout each event. This can help determine which set of parameters can be used to predict specific characteristics common over these solar storms. An implication of such a study may contribute to the capability of predicting plasma conditions of SEP events only from observed particle signatures in the lack of supplementary remote and in-situ observations.

Background

- Previous work to compile in-situ signatures of coronal mass ejections (CMEs).
- PSP IS⊙IS, FIELDS, and SWEAP data can optimize and extend upon these parameters.
- We intend to focus on signatures pertaining to the magnetic field, plasma dynamics, composition and energetic particle categories

TABLE I

In-situ signatures of ICMEs (description applies to ~1 AU heliospheric distance) in the magnetic field (B), plasma dynamics (P), plasma composition (C), plasma waves (W), and suprathermal particles (S)

Signature	Description	Selected references
B1: B Rotation	$\gg 30°$, smooth	Klein and Burlaga (1982)
B2: B Enhancement	>10 nT	Hirshberg and Colburn (1969); Klein and Burlaga (1982)
B3: B Variance decrease		Pudovkin *et al.* (1979); Klein and Burlaga (1982)
B4: Discontinuity at ICME boundaries		Janoo *et al.* (1998)
B5: Field line draping around ICME		Gosling and McComas (1987); McComas *et al.* (1989)
B6: Magnetic clouds	(B1, B2 and $\beta = \frac{\sum nkT}{B^2/(2\mu_0)} < 1$)	Klein and Burlaga (1982); Lepping *et al.* (1990)
P1: Declining velocity profile/expansion	Monotonic decrease	Klein and Burlaga (1982); Russell and Shinde (2003)
P2: Extreme density decrease	≤ 1 cm^{-3}	Richardson *et al.* (2000a)
P3: Proton temperature decrease	$T_p < 0.5 T_{exp}$	Gosling *et al.* (1973); Richardson and Cane (1995)
P4: Electron temperature decrease	$T_e < 6 \times 10^4$ K	Montgomery *et al.* (1974)
P5: Electron Temperature increase	$T_e \gg T_p$	Sittler and Burlaga (1998); Richardson *et al.* (1997)
P6: Upstream forward shock/"Bow Wave"	Rankine-Hugoniot relations	Parker (1961)
C1: Enhanced α/proton ratio	$He^{2+}/H^+ > 8\%$	Hirshberg *et al.* (1972); Borrini *et al.* (1982a)
C2: Elevated oxygen charge states	$O^{7+}/O^{6+} > 1$	Henke *et al.* (2001); Zurbuchen *et al.* (2003)
C3: Unusually high Fe charge states	$\langle Q \rangle_{Fe} > 12$; $Q_{Fe}^{\geq 15+} > 0.01$	Bame *et al.* (1979); Lepri *et al.* (2001); Lepri and Zurbuchen (2004)
C4: Occurrence of He^+	$He^+/He^{2+} > 0.01$	Schwenn *et al.* (1980); Gosling *et al.* (1980); Gloeckler *et al.* (1999)
C5: Enhancements of Fe/O	$\frac{(Fe/O)_{CME}}{(Fe/O)_{photosphere}} > 5$	Ipavich *et al.* (1986)
C6: Unusually high $^3He/^4He$	$\frac{(^3He/^4He)_{CME}}{(^3He/^4He)_{photosphere}} > 2$	Ho *et al.* (2000)
W1: Ion acoustic waves		Fainberg *et al.* (1996); Lin *et al.* (1999)
S1: Bidirectional strahl electrons		Gosling *et al.* (1987)
S2: Bidirectional ~MeV ions	2nd harmonic > 1st harmonic	Palmer *et al.* (1978); Marsden *et al.* (1987)
S3: Cosmic ray depletions	Few % at ~ 1GeV	Forbush (1937); Cane (2000)
S4: Bidirectional cosmic rays	2nd harmonic > 1st harmonic	Richardson *et al.* (2000b)

Zurbuchen+Richardson, SSR 2006

Research Questions

Can a more detailed basis set of parameters enable predictions of in-situ conditions only given particle and source signatures of an SEP event? Can a radial trend of these in-situ conditions be attained?

Solar Wind Parameters

$$\beta_p = \frac{8\pi n_p k_B T_p}{B^2}$$

$$w_p = \sqrt{\frac{k_B T_p}{m_p}}$$

$$c_s = \sqrt{\frac{\gamma Z k_B T_e}{m_p}}$$

$$V_A = \frac{B}{\sqrt{4\pi n_p m_p}}$$

$$M_t = \frac{\delta v_{rms}}{c_s} = \frac{\delta v_{rms}}{V_A}\sqrt{\frac{2}{\gamma \beta_p}}$$

$$M_s = \frac{V_{SW}}{c_s}$$

$$M_A = \frac{V_{SW}}{V_A}$$

$$\sigma_c = \frac{\langle (z^+)^2 \rangle - \langle (z^-)^2 \rangle}{\langle (z^+)^2 \rangle + \langle (z^-)^2 \rangle}$$

$$d_i = \frac{c}{\omega_{p,i}} = \frac{228}{\sqrt{n_p}}\ [\text{km}]$$

Magnetic Field

$$\mathbf{B} = \mathbf{B}_0 - \mathbf{b}$$

Proton Density

$$n_p = n_{p,0} + \delta n_p$$

Solar Wind Bulk Velocity

$$\mathbf{V}_{SW} = \mathbf{V}_{SW} - \mathbf{v}$$

Proton Thermal Speed

$$w_p$$

Elsässer Variables

$$\mathbf{z}^{\pm} = \mathbf{v} \pm \mathbf{b}_A$$

Ion Inertial Length

$$d_i$$

Above/below are the solar wind parameters/particle signatures we intend to use for our prediction basis.

Energetic Particle Considerations

Event Type
(CME, Solar Flare, or both)

Radio Burst
(If yes, what type(s))

Pitch Angles
(Angle between particle trajectory and local magnetic field)

Fluence
(Time-integrated Flux)

Ion Composition/Abundances

Different times throughout event to average solar wind parameters (based on SEP signatures):

A) Before onset of inverse velocity dispersion

B) During inverse velocity dispersion but before peak flux of event

C) During peak flux of event

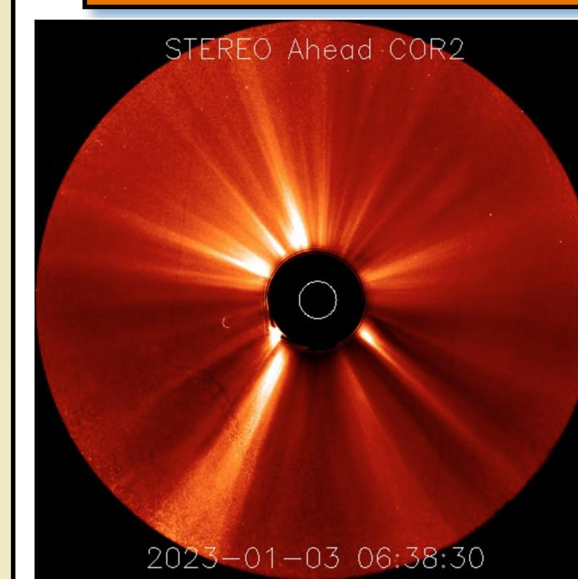
D) After peak flux of event

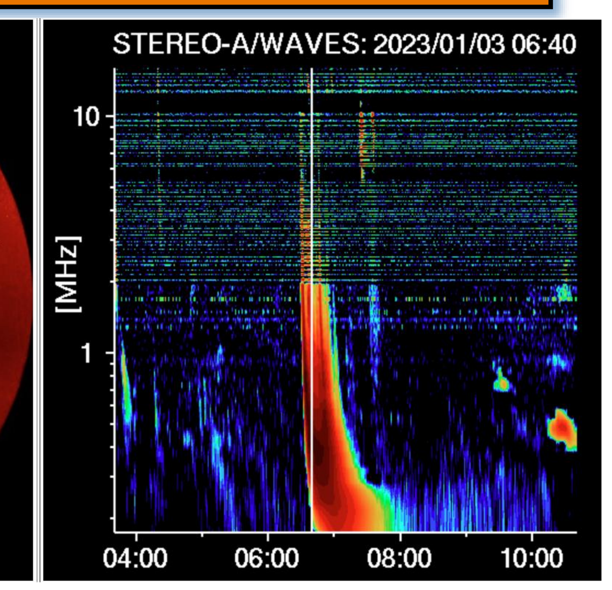
Events to Consider

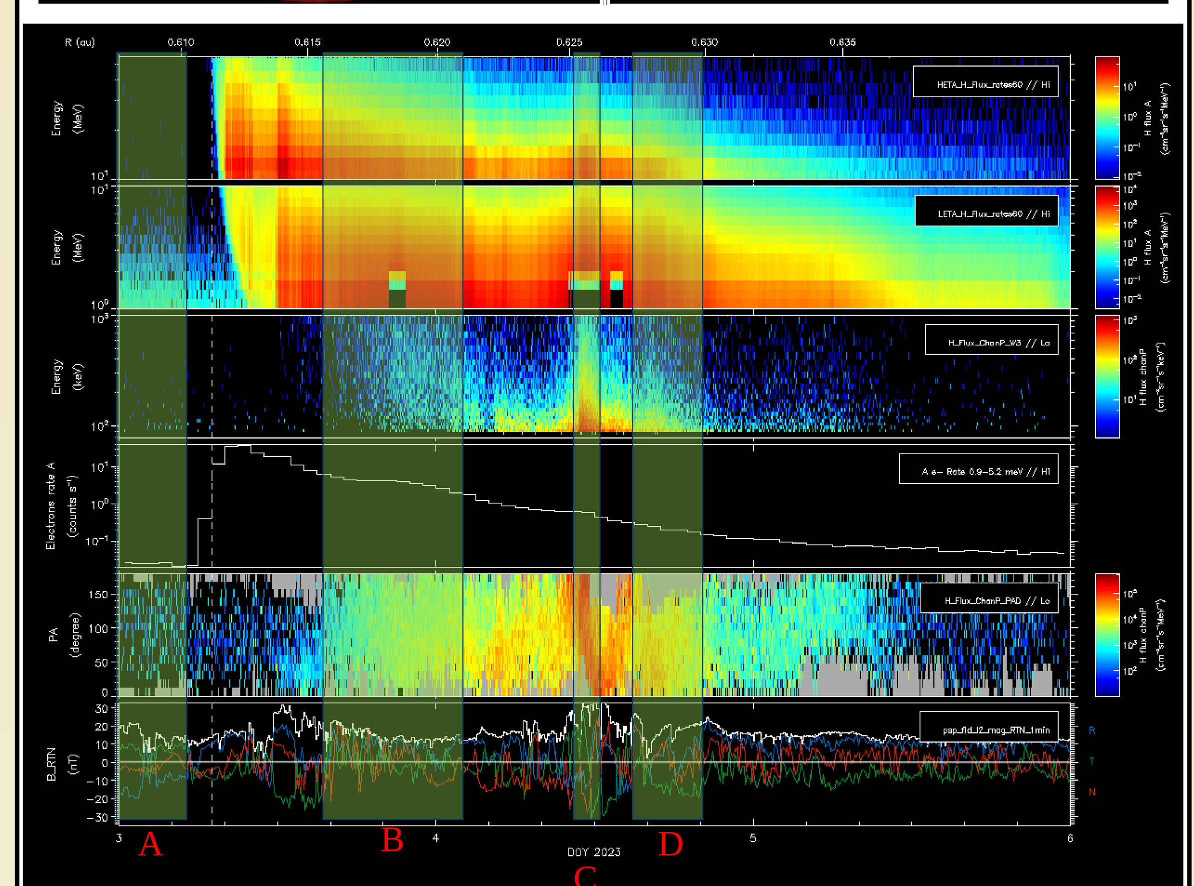
Must have inverse velocity dispersion leading into surge of ions.
CIR crossings during CME passing may obscure trends but will still be selected for analysis.

If no sufficient plasma parameters are available, cannot use such event in constructing the basis. Can, however, use such event to test prediction basis.

Results: 2023-01-03

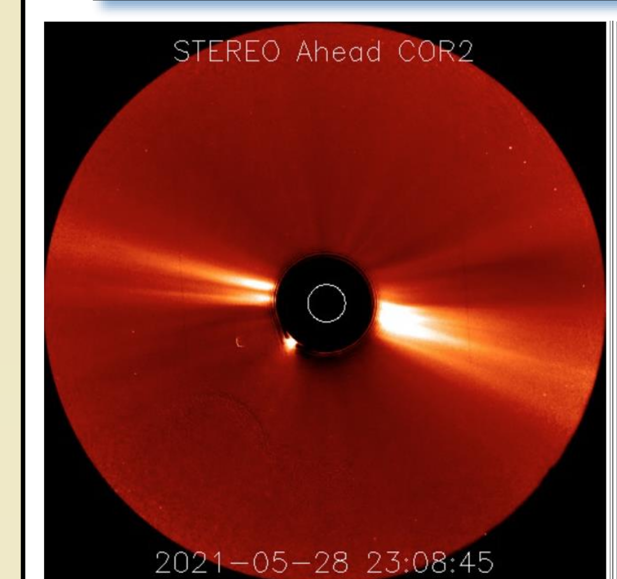


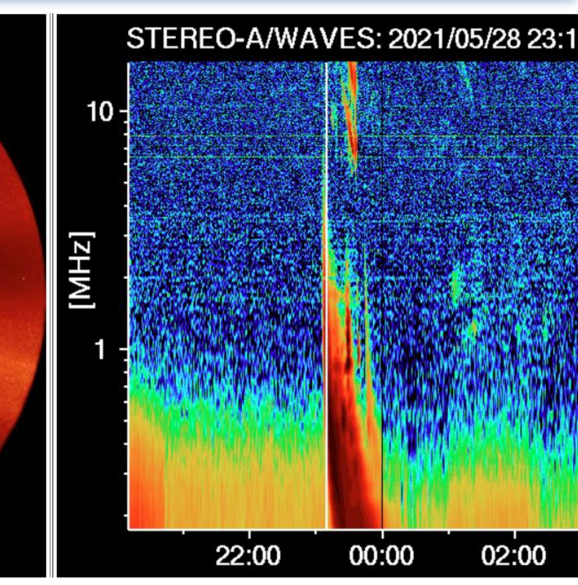


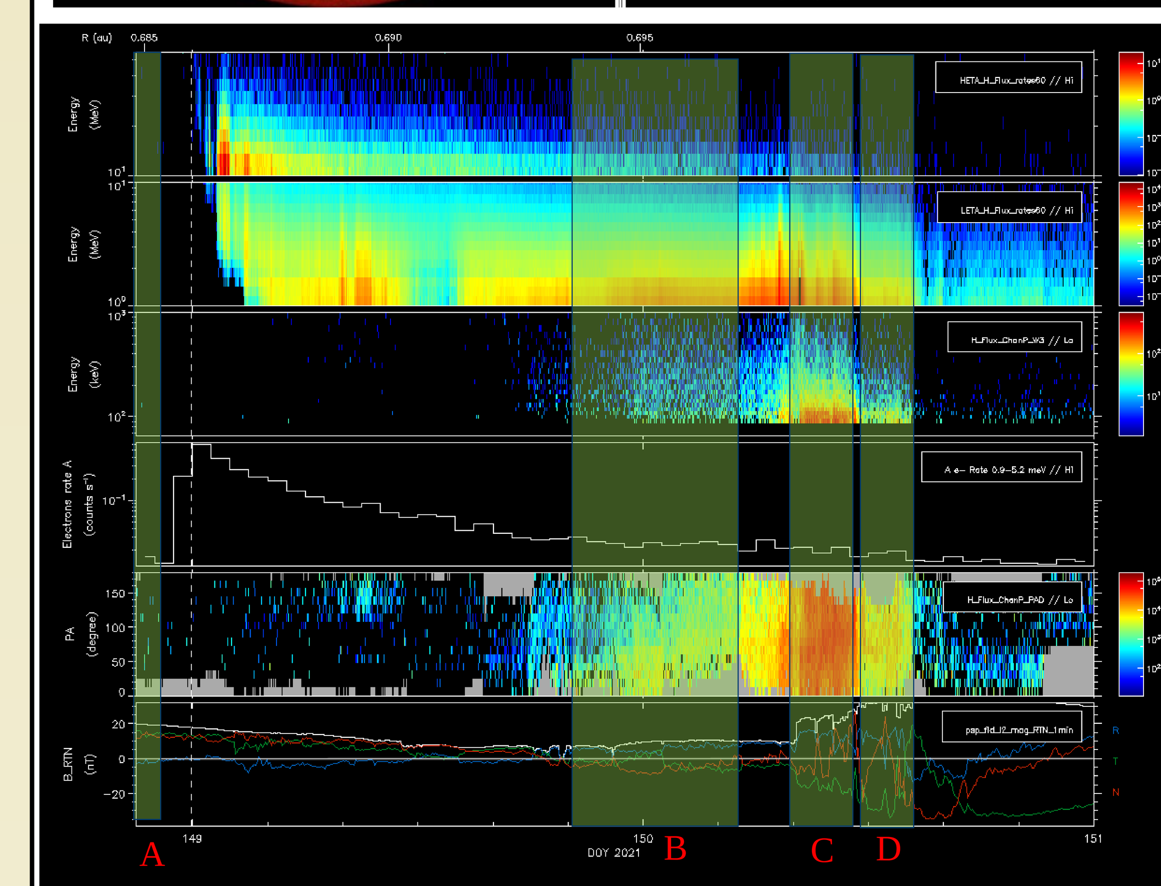


	Before Dispersion (A)	During Dispersion (B)	During Peak (C)	After Peak (D)
B_0	14.8	15.7	26.5	17.2
δb_{rms}	0.23	0.23	0.12	0.20
$n_{p,0}$ [/cc]	38.5	18.3	13.0	16.9
$\delta n_p / n_{p,0}$	0.08	0.13	0.22	0.21
β_p	1.06	0.87	0.24	0.75
V_{SW} [km/s]	317	544	810	638
V_A [km/s]	64.5	81.7	188.9	115.9
c_s [km/s]	33.1	63.9	52.3	43.8
T_p	7.4 eV = 85718 K	27 eV = 313062 K	19.5 eV = 225712 K	14.2 eV = 164470 K
M_t	1.00	0.43	0.64	0.82
M_s	12.0	9.0	19.9	20.3
σ_c	9.3e-6	-1.3e-5	-2.9e-6	2.2e-6
d_i [km]	41.7	55.3	71.0	68.0

Results: 2021-05-28

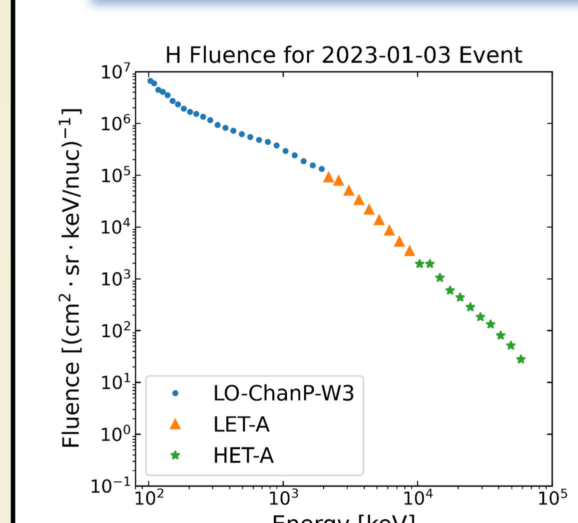


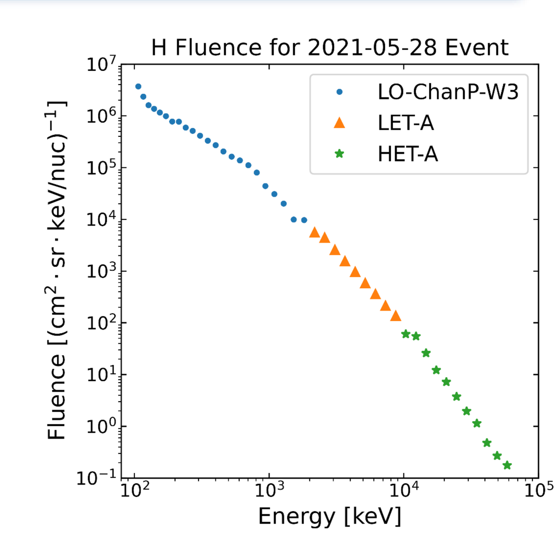




	Before Dispersion (A)	After Dispersion (B)	During Impulse (C)	After Impulse (D)
B_0	18.0	10.2	22.0	33.2
δb_{rms}	0.10	0.17	0.08	0.05
$n_{p,0}$ [/cc]	6.54	5.64	14.62	10.4
$\delta n_p / n_{p,0}$	0.32	0.37	0.18	0.28
β_p	0.02	0.13	0.63	0.33
V_{SW} [km/s]	396	374	544	665
V_A [km/s]	171	102	166	273
c_s [km/s]	20.4	26.5	80.1	107.0
T_p	2.77 eV = 32091 K	5.00 eV = 58003 K	46.6 eV = 540871 K	75.2 eV = 872400 K
M_t	0.64	0.57	0.21	0.13
M_s	20.9	17.4	9.00	6.89
σ_c	7.1e-6	-6.0e-6	-4.2e-6	-3.9e-6
d_i [km]	98.9	104.4	75.7	85.5

Fluence





Directions for Future Research

Further investigate particle data to include analysis of ion abundances, relative durations of dispersion to surge, SPAN-E for electron strahl behavior, and fluence spectrum comparisons before and after shock arrival.
Also, we intend to investigate as many available SEP events to determine solar wind parameter trends with some reasonable statistical significance.

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