A Benchmark Solar Energetic Particle Events Dataset

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Abstract

We develop a comprehensive and homogeneous dataset that can serve as a benchmark by integrating Solar Energetic Particles (SEPs) information from three primary catalogs: the National Oceanic and Atmospheric Administration solar proton events list, the geostationary solar energetic particle catalog (Rotti et al., 2022), and the one maintained by the Geophysical Center of the Russian Academy of Sciences. Despite the discrepancies among these catalogs, we conduct visual examinations, cross-referencing with the plasma and magnetic field properties to determine the correct inputs. 590 events are finally identified as SEP events, with a temporal coverage from 1970 up to now. Based on the dataset, we conduct statistical analysis to study the causality relations between the sources of SEP events and their properties detected at Earth. The dataset will facilitate the development of a more comprehensive and robust machine-learning model for the community, enabling more accurate SEP predictions in future space exploration.

Introduction & Motivation

- Solar Energetic Particles (SEPs): Energetic particles (mostly protons) emitted from the Sun and accelerated by solar eruptions, such as flares and Coronal Mass Ejections (CMEs)
- Hazard: Can pose severe radiation risks to space-borne assets and astronauts
- Aim: Predict the occurrence and properties of energetic particles
- Situation: Lack of a comprehensive and homogeneous dataset

Data

- Satellites & Detectors:

(Tab. 1)

Cycle	(Part of) SC 20							SC 21				SC 22		SC 23	SC 24	SC 25
Year	70	71	72	73	74	75	76	77	78	79-85	86	87-95	96	97-08	09-19	20-23 (Now)
Particles	IMP 5 Metero-1			IMP 6 Metero-1		IMP 7, 8 Metero-1				IMP 8 Metero-1	GOES/EPS (Energetic Particle Sensor)					
Flares	SOLRAD					GOES/XRS (X-Ray Sensor) SOON (Solar Observing Optical Network)										
CME	——												SOHO/LASCO			

- Catalogs integrated:
  - NOAA solar proton events list [1]
  - Geostationary solar energetic particle catalog (Rotti et al., 2022)
  - Solar proton events list maintained by the Geophysical Center of the Russian Academy of Sciences [2]

Criteria for Labeling SEP Events (Papaioannou et al., 2016)

- **Enhancement Threshold**: 0.01 #/cm^2/sr/s/MeV for candidates
- **Minimum Peak**: 0.5 pfu for possible events
- **Events Interval**: 2 hours between two consecutive candidate events
- **Minimum Duration**: 2 hours is required

Context in our Dataset

(Tab. 2)

Category	Header	Interpretations
Basic Information	Event_ID	Index of the SEP event
	msk_local	Mask of local acceleration
	date	Date of the event beginning
	doy	Day of year of the event beginning
	t_onset	Onset time of the SEP event
	t_max	Time when proton flux reaches its peak
	Jp	Peak proton flux in unit of pfu
	Fit_Index_γ	Index for the power-law fitting of flux versus energy
	E_quasi-max	Quasi-maximal energy of the protons at the peak
Flares	certainty	Certainty of the source, adapted from the RAS list
	t_onset_fH	Start time of the flare in Hα line
	t_max_fH	Time of the flare maximum in Hα line
	t_end_fH	End time of the flare in Hα line
	fImportance	Flare Importance in Hα line
	fClass	Flare X-ray class
	fLoc	Heliographic longitude and latitude of the flare
	t_onset_fX	Start time of the flare in X-ray
	t_max_fX	Time of the flare maximum in X-ray
	t_end_fX	End time of the flare in X-ray
	AR_ID	Active region index
CME	t_CME	First appearance time of the CME
	V_CME	CME linear speed in unit of km/s
	Δϕ_CME	Angular width of the CME in unit of degree
	MPA_CME	Measurement position angle of the CME in unit of degree
Others	note	Notes to the event

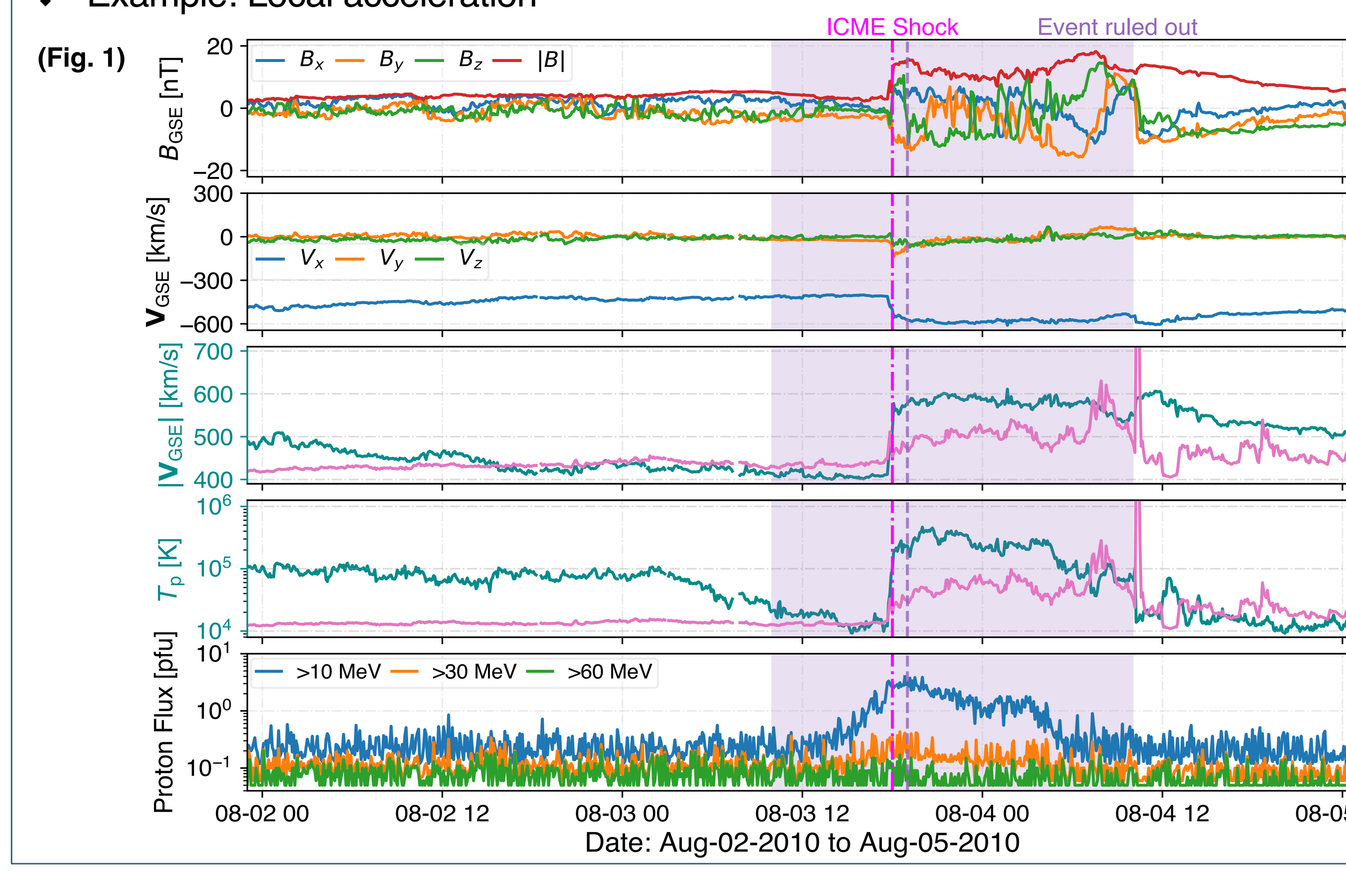
SEP Events Counts

Events	Large Events (Jp ≥ 10 pfu)						Weak Events (Jp < 10 pfu)						Total
Cycle	SC 20	SC 21	SC 22	SC 23	SC 24	SC 25	SC 20	SC 21	SC 22	SC 23	SC 24	SC 25	
Proton Flux Enhancement	32	58	84	114	50	9	28	89	76	50	65	0	655
With Local Acceleration	0	3	4	12	2	2	0	2	9	13	18	0	65
SEP Events	**32**	**55**	**80**	**102**	**48**	**7**	**28**	**87**	**67**	**37**	**47**	**0**	**590**
Flares (Hα) available	27	47	75	76	31	0	19	75	58	26	22	0	456
Flares (X-ray) available	19	47	77	98	43	7	15	75	62	34	37	0	517
CME available	—	—	0	93	48	6	—	—	0	34	46	0	227

(Tab. 3)

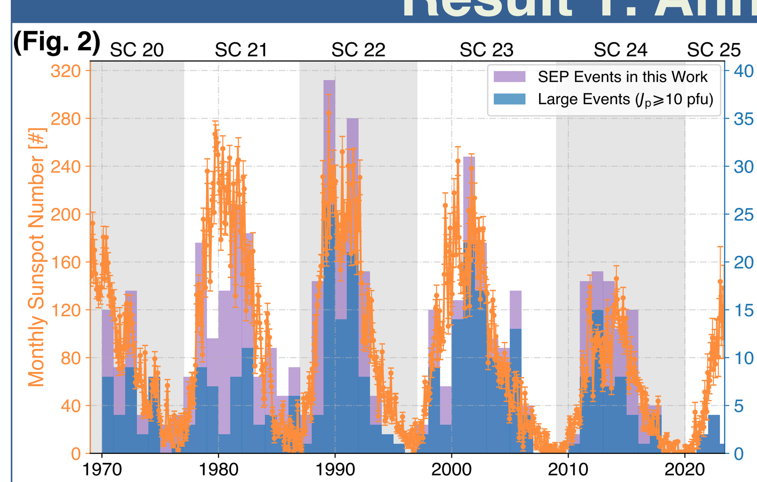
- 590 enhancements are labeled as SEP events
- CME information is available by the end of SC 22 in our study
- Example: Local acceleration

(Fig. 1)

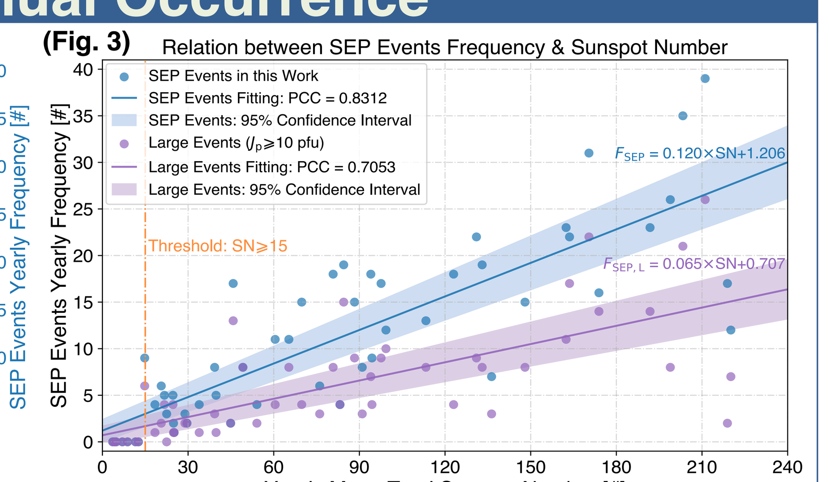


Result 1: Annual Occurrence

(Fig. 2)



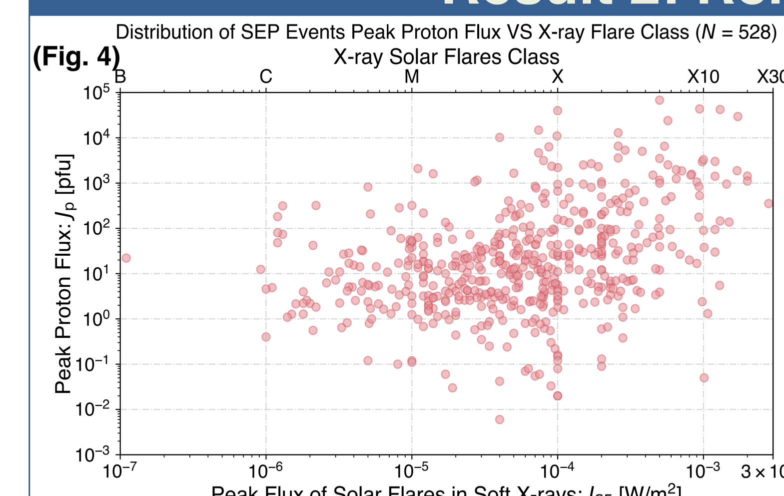
(Fig. 3)



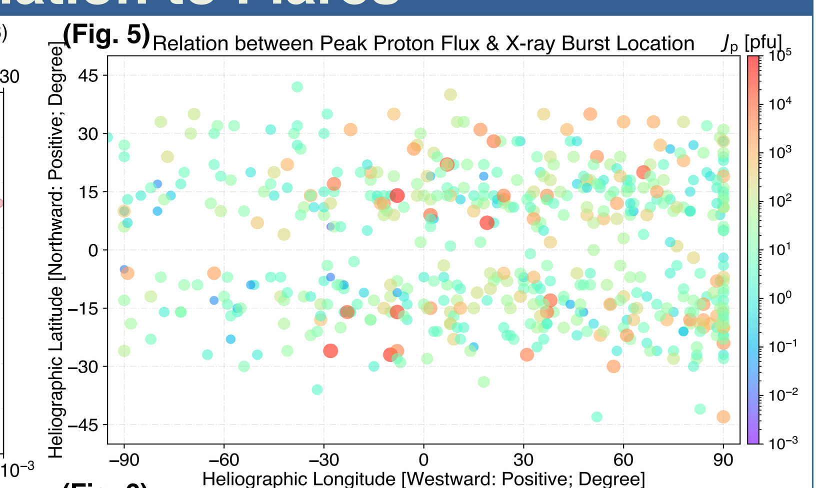
- Annual occurrence is **well-fitted** with the Sunspot Number (SN)
- Threshold of the SN for the SEP events to occur: ***SN ≥ 15***
- Non-ideal correlation may occur at some epochs (e.g., SC 21 Maximum)

Result 2: Relation to Flares

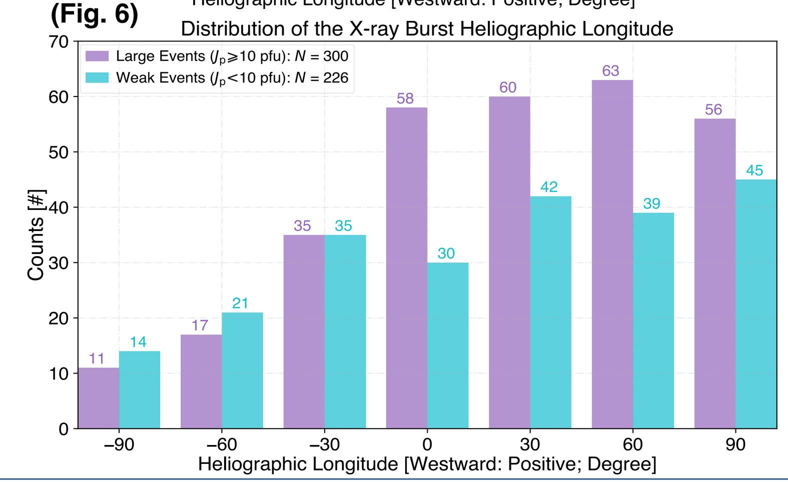
(Fig. 4)



(Fig. 5)



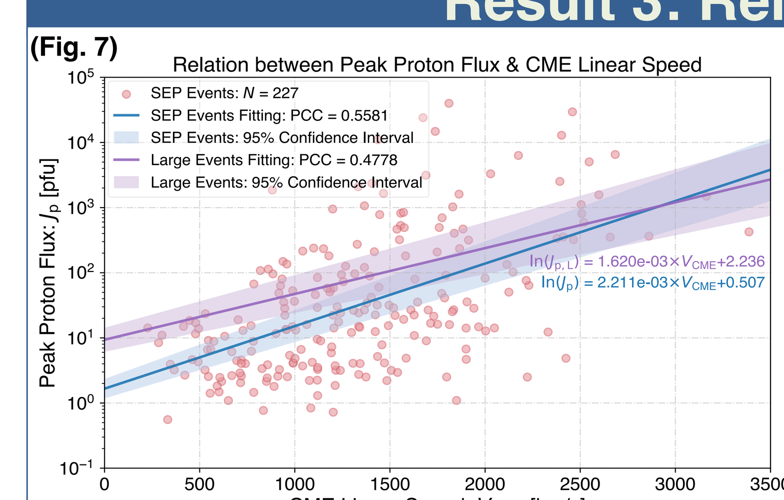
(Fig. 6)



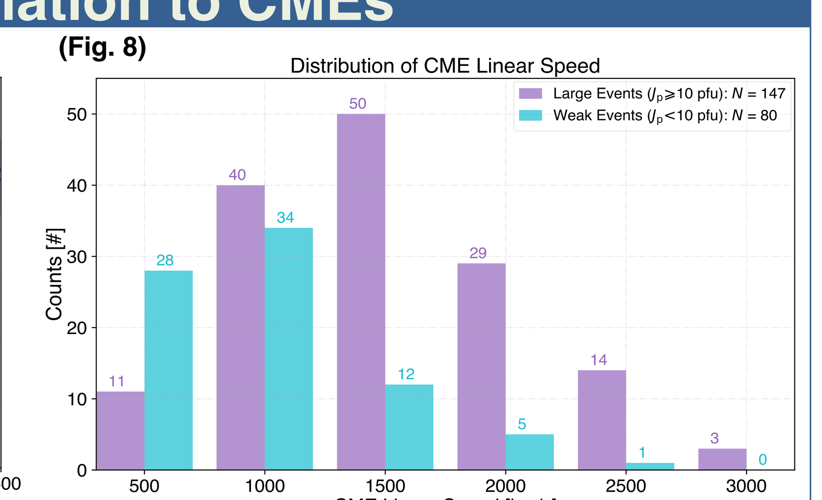
- X-ray Flares: $J_p \sim I_{SF}$ has a **broad** distribution and is not well linearly correlated in logarithmic scale (PCC = 0.36 for all events, and 0.41 for large events)
- Extremely large events (high J_p: large and warm dots in Fig. 5) tend to correspond to flares at **30°E ~ 60°W**
- Flares that act as a source tend to occur in the **center/westward**

Result 3: Relation to CMEs

(Fig. 7)

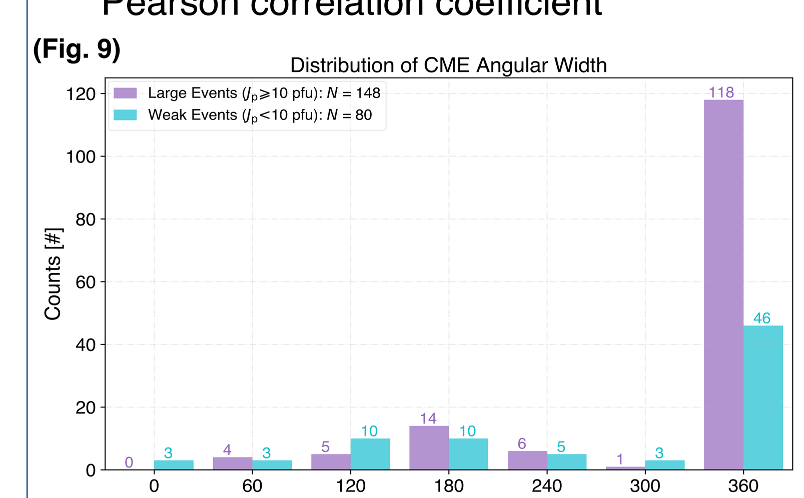


(Fig. 8)

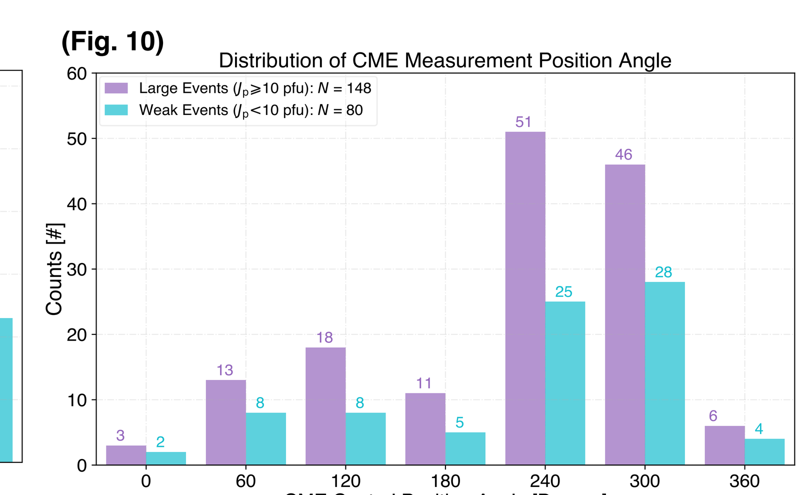


- J_p tends to be **better correlated** with the **CME speed** than the X-ray flare class
- Large events: tend to be associated with a **higher CME linear speed**, but with a lower Pearson correlation coefficient

(Fig. 9)



(Fig. 10)



- CME tends to be a **halo** (57.5% for all events, 79.7% for large events), with an ***MPA > 180°***

Conclusions and Future Work

- A benchmark SEP dataset is developed with flares and CMEs information, local acceleration events ruled out, and temporal coverage from 1970 up to now.
- The SEP annual occurrence has a good correlation with the sunspot number, particularly for the hazardous large events, which be applied for future prediction.
- Relation between the peak proton flux and X-ray flare class has a broad distribution, and the large events tend to occur in the center/westward of the sun.
- CMEs that act as sources of SEP events tend to be halos, with an MPA > 180° and a better relation between its linear speed and the peak proton.
- *Future: Explore causality relations between SEP events and the sources using developed models, compare them with the existing results, and get ready for ML models.*

References

1. Rotti, Sumanth, et al. "Integrated Geostationary Solar Energetic Particle Events Catalog: GSEP." The Astrophysical Journal Supplement Series 262.1 (2022): 29.
2. Papaioannou, Athanasios, et al. "Solar flares, coronal mass ejections and solar energetic particle event characteristics." Journal of Space Weather and Space Climate 6 (2016): A42.

Footnotes

[1] https://www.ngdc.noaa.gov/stp/space-weather/interplanetary-data/solar-proton-events/ [2] http://www.wdcb.ru/stp/solar/solar_proton_events.html.

Acknowledgments

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