Study of solar energetic particle associations with solar eruptions

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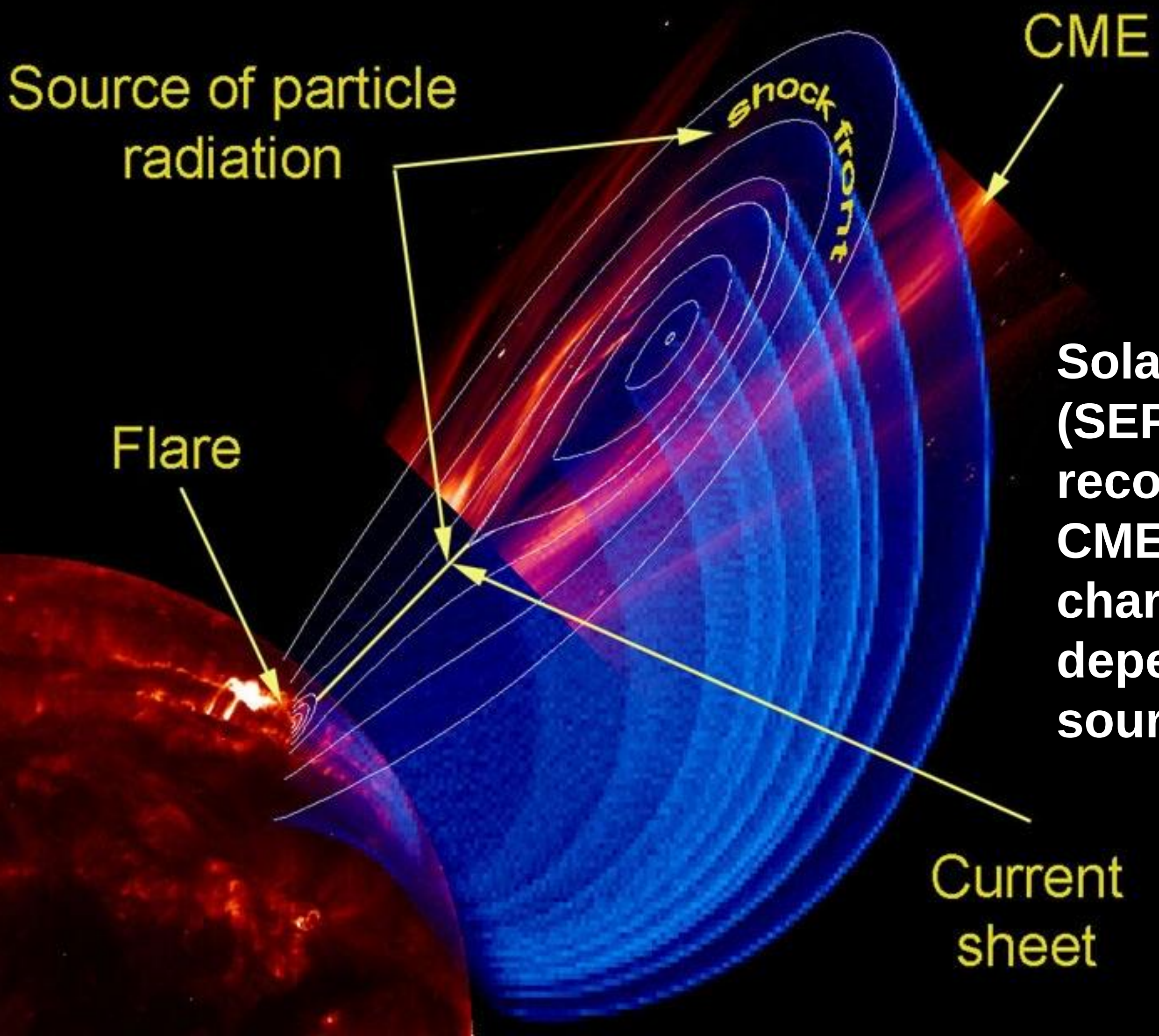
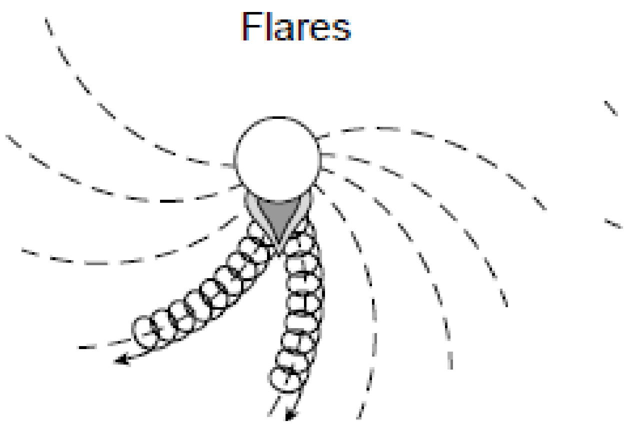
1.1 Introduction
Solar Energetic Particles (SEPs)



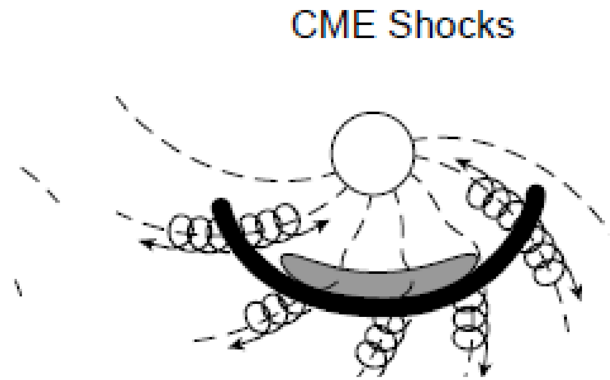
Solar energetic particles (SEPs) are accelerated in flare reconnection regions and by CME-driven shocks. The characteristics of the particles depend on their solar sources.

Impulsive



- H-alpha and X-ray flares
- Type III radio bursts
- Short duration,
  lasting several hours
- Magnetically
  well-connected
- Longitude cone : < 30°
- Electron-rich

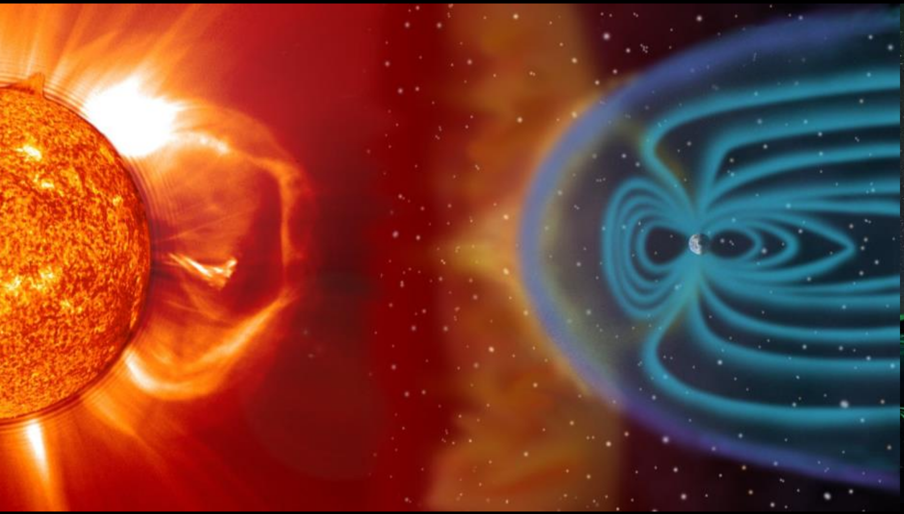
Gradual



- Gradual X-ray flares
  and the CME shock
- Type II and IV radio burst
- Long duration,
  lasting several days
- Board range of
  heliolongitude.
- Longitude cone : ~ 180°
- Proton-rich

This classification is not always accepted because SEPs with mixed characteristics are also observed, but it has been well accepted that the CMEs play an important role in generating strong particle acceleration.

SEPs in terms of space weather



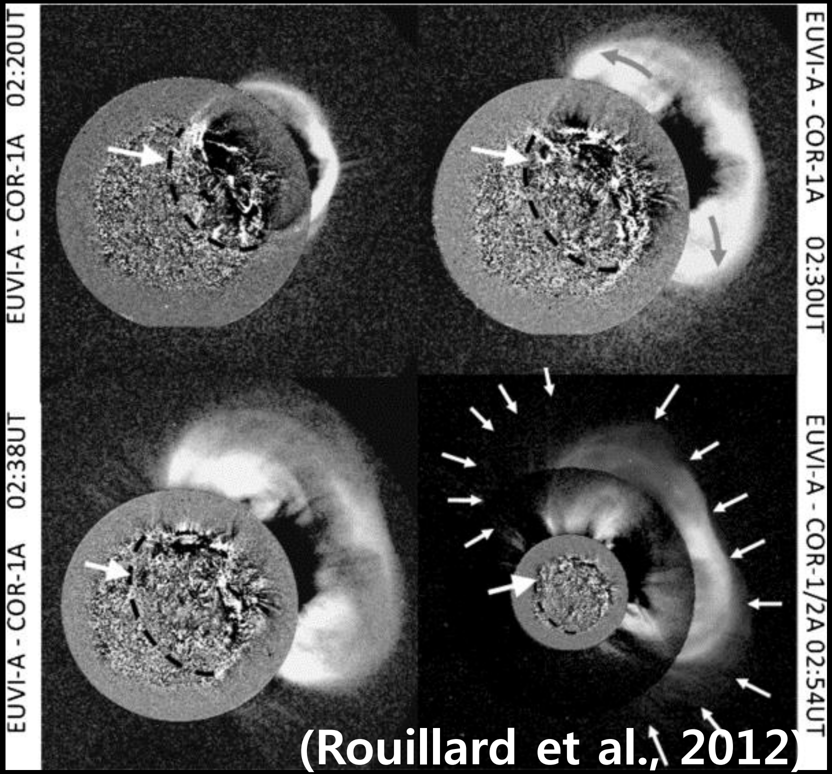

Strong SEPs are one of the most important phenomena in terms of space weather in that they could hazard human activities on the ground as well as in the space (Feynman and Gabriel, 2000).

- Commercial airlines
- HF communication
- Satellite launch
- Manned space flight

EUV waves

EUV waves (EIT wave),
large disturbances in the low corona region, were discovered
with EIT observations from SOHO (Moses et al., 1997; Thompson et al., 1998.

EUV (Extream Ultraviolet) waves are generated in solar eruptions (Thompson & Myers 2009; Warmuth 2010). They show up as faint fronts moving with velocities up to 1000 km/s with large dimming regions in their wakes.



(Rouillard et al., 2012)

Whether this edge is a wave front (Thompson et al. 1999; Patsourakos et al. 2009; Kozarev et al. 2011) or the rim of the region affected by magnetic reconfiguration associated with the CME (Cheng et al 2012; Attrill et al. 2007) is often not resolvable.

Relations between SEPs and EUV waves

One of the key issues is whether EUV waves are associated with SEP acceleration because the waves are thought to be a signature of CME-driven shocks.

The EUV waves are associated with the SEP acceleration!
(Rouillard et al., 2012; Park et al., 2013; Miteva et al., 2014...)

The associated EUV wave tracked the extent of the high pressure variations developing around the expanding CME

It is not responsible for the particle acceleration!
(Bothmer et al.,1997; Posner et al., 1997; Lario et al., 2014...)

Particle enhancement earlier than EUV wave

1.4 Motivation

This study is to investigate the relationship between 16 large gradual solar energetic particle (SEP) events and associated extreme ultraviolet (EUV) wave properties from 2010 August to 2013 May.

SEP onset (peak) time & Arrival time of EUV wave
at the spacecraft magnetic footpoint on the low corona region

SEP peak flux (spectral index) & EUV wave speed
from the source region to the spaceccraft magnetic footpoint on the low corona region

EUV wave & CME speed

2. Data and analysis

SEP

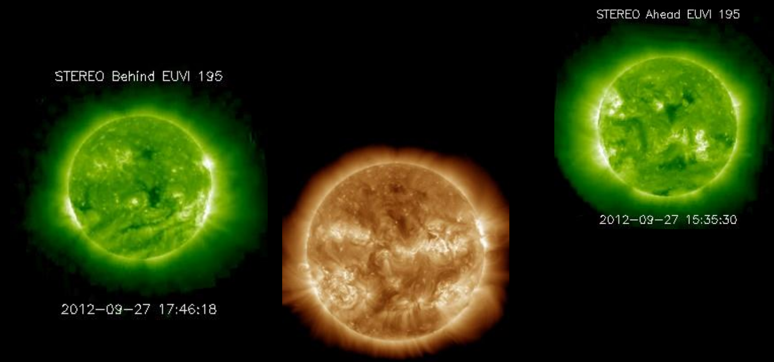
STEREO averaged over 10 min in the 6-10 MeV proton channel or by the Energetic and Relativistic Nuclei and Electron instrument on SOHO averaged over 10 min in the 6-10 MeV proton channel.

Flare, CME, solar wind

GOES X-ray flare catalogue

SOHO LASCO, STEREO SECCHI

ACE Solar Wind Electron Proton Alpha Monitor and the STEREO Plasma and Suprathermal Ion Composition measurements.

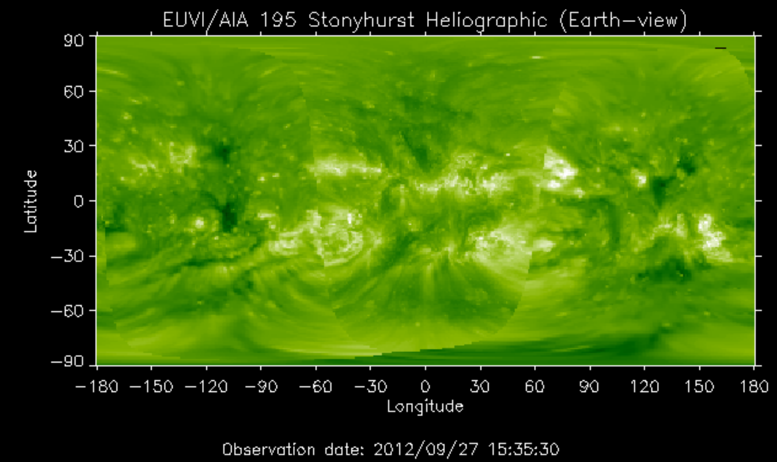


SDO AIA 193

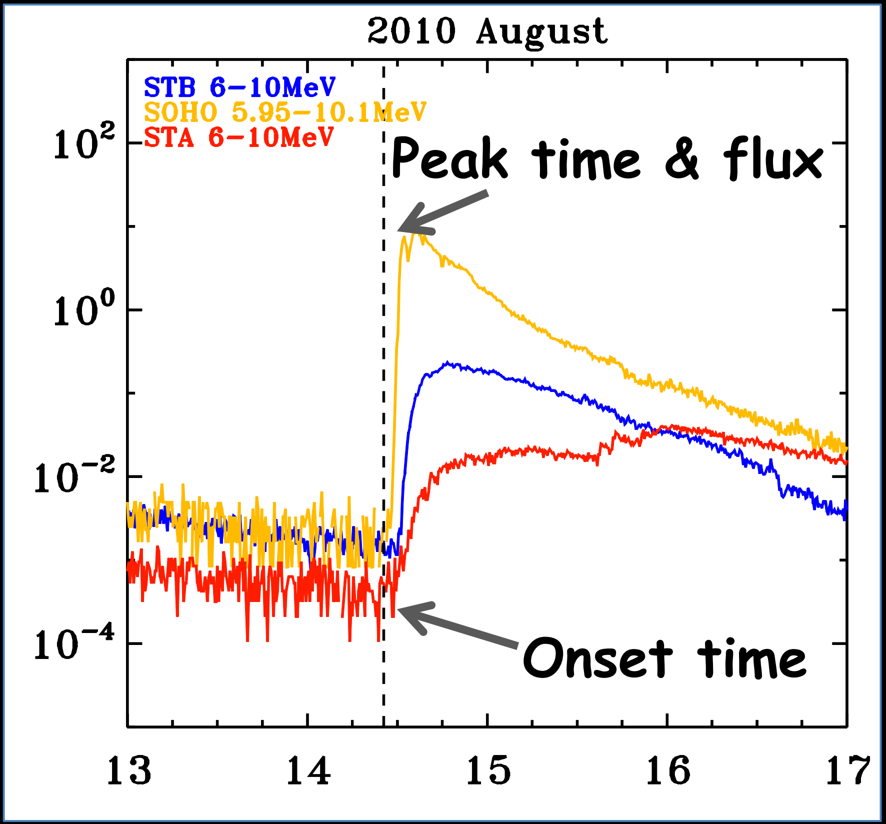
EUV wave

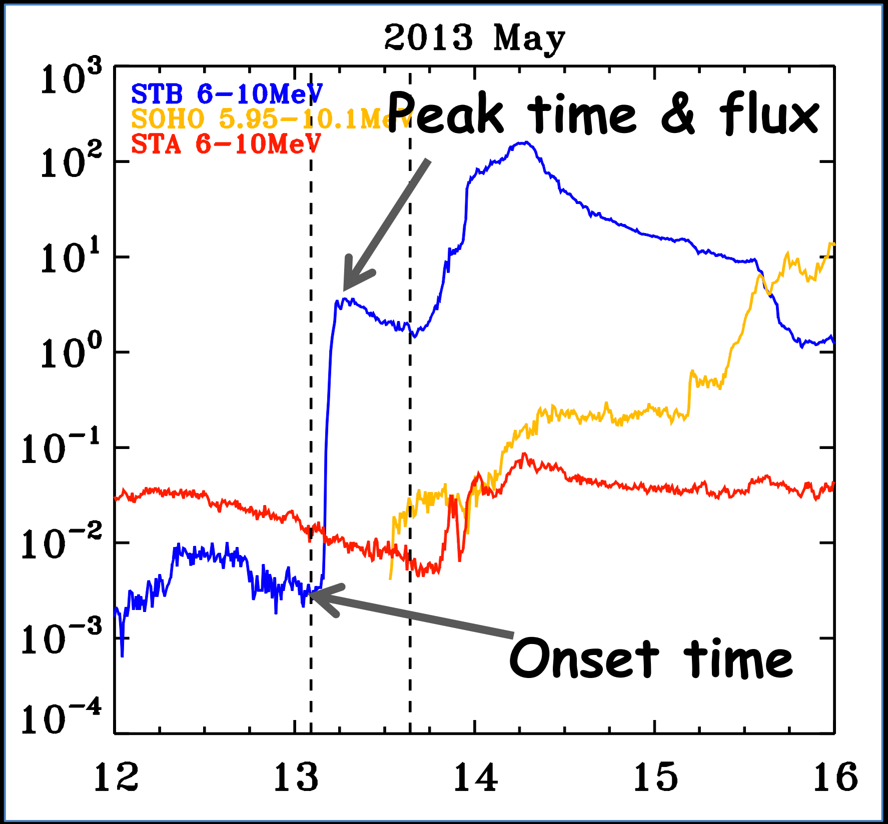
SDO AIA 195Å STEREO EUVI 193Å

Now with the high cadence full Sun extreme ultraviolet (EUV) images, we are able to look at the disturbance of EUV waves on the low corona region.



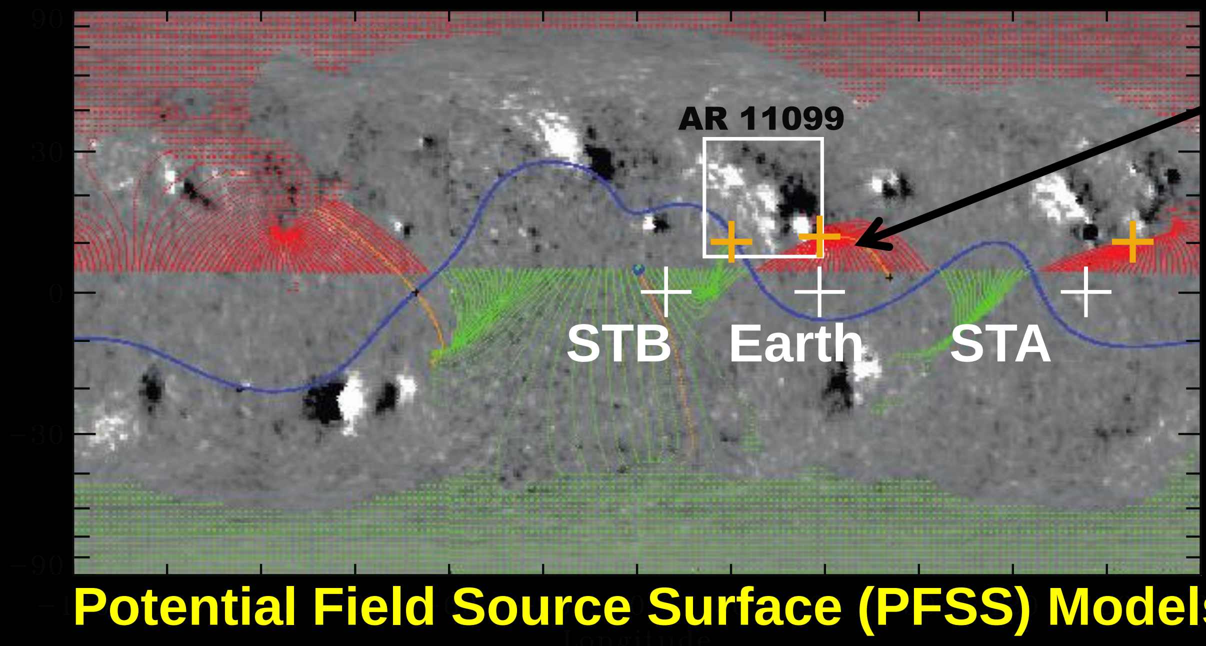
SEP onset time, peak time, peak flux





We estimate the three earliest consecutive times with increasing flux and mark the first of the three as its onset time. The peak times and peak fluxes are chosen as the points at the top of the of the steep flu x rise, which appeared just after the solar eruption.

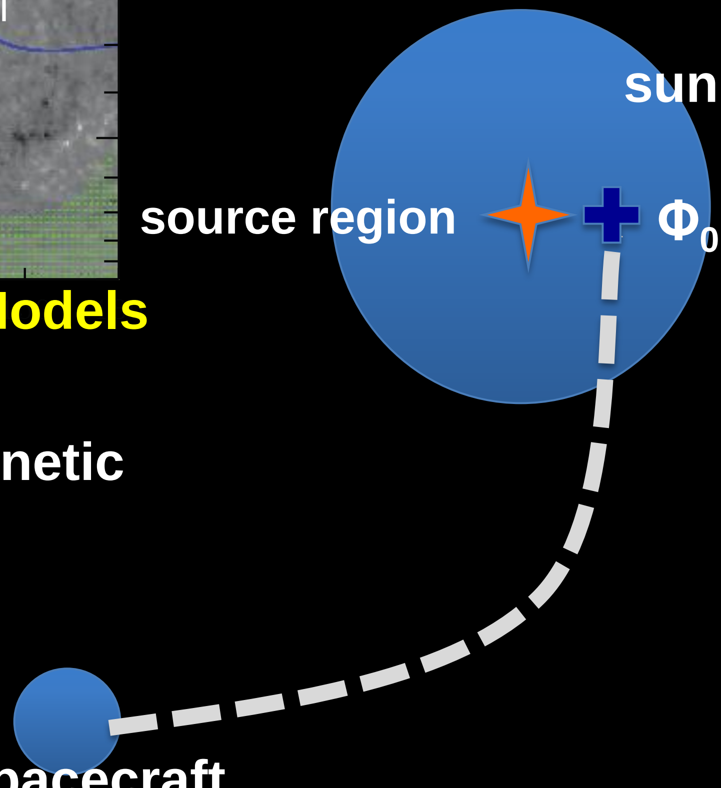
The magnetic footpoint of spacecraft and its connection with the open field line



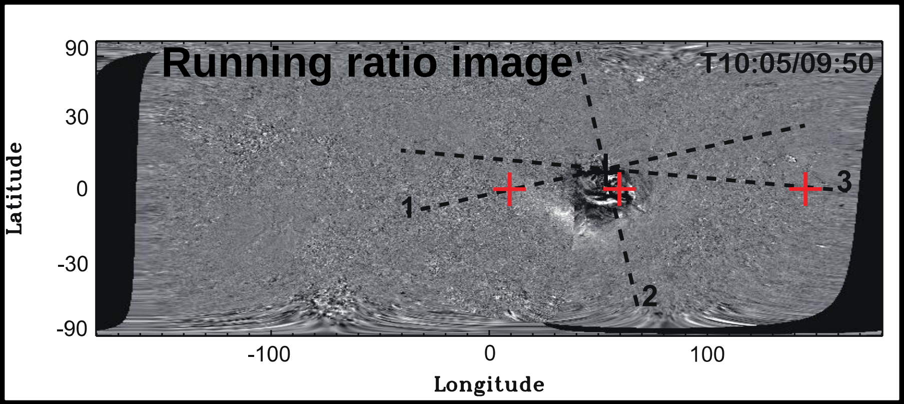
Potential Field Source Surface (PFSS) Models
Synoptic Ecliptic-Plane Field Plot

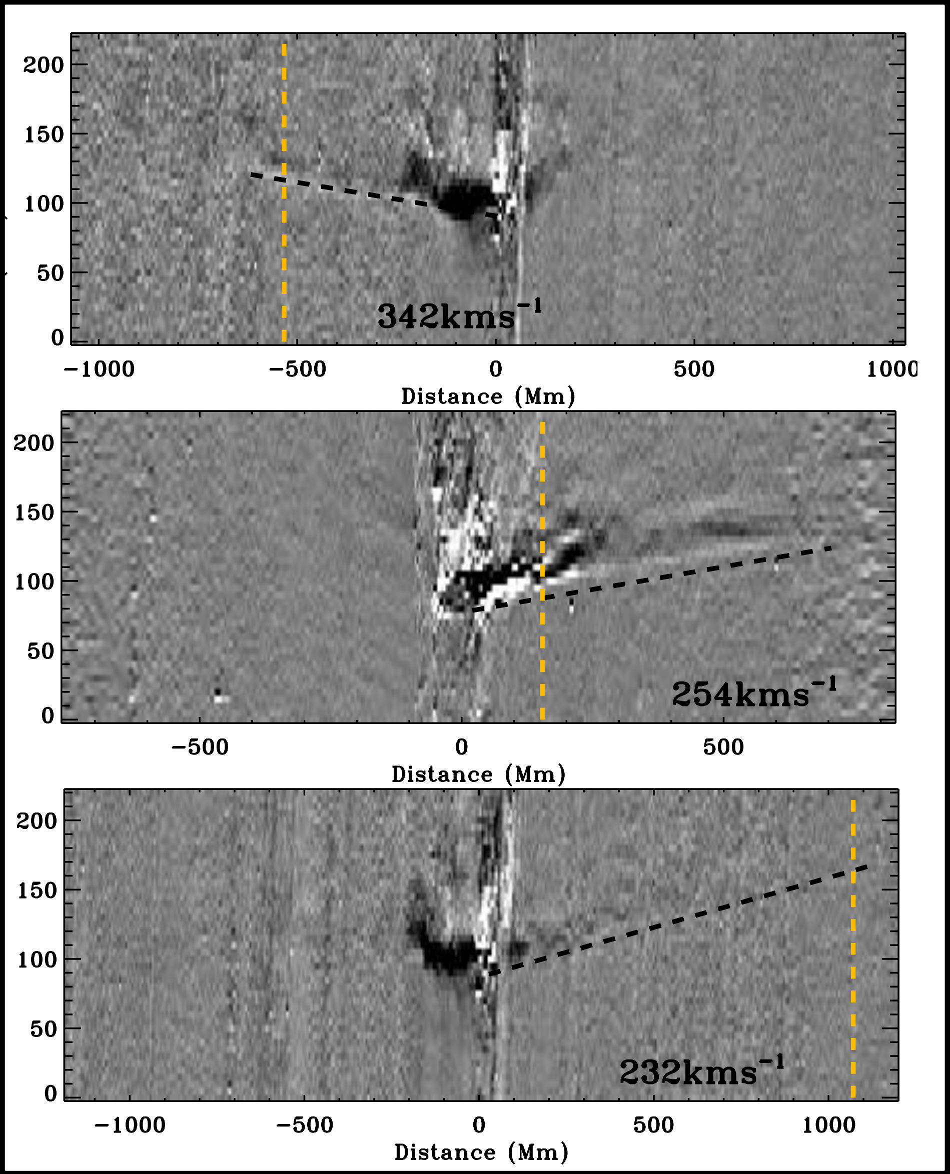
It give a good approximation of the magnetic field up to 2.5 Rsun.

The magnetic footpoints of three spacecraft calculated by Parker spiral field formula considering solar wind speed.



Arrival time of EUV wave and EUV wave speed





EUVI/AIA Heliographic (Earth-view) images (5 minutes)

obtained by SDO AIA 193 Å, STEREO A, and B EUVI 195 Å

The EUV wave arrival times and their speeds from the source sites to the spacecraft footpoints in the photosphere are determined by space-time plots from the full Sun heliographic images created by combining STEREO-A, B 195Å and SDO 193Å images.

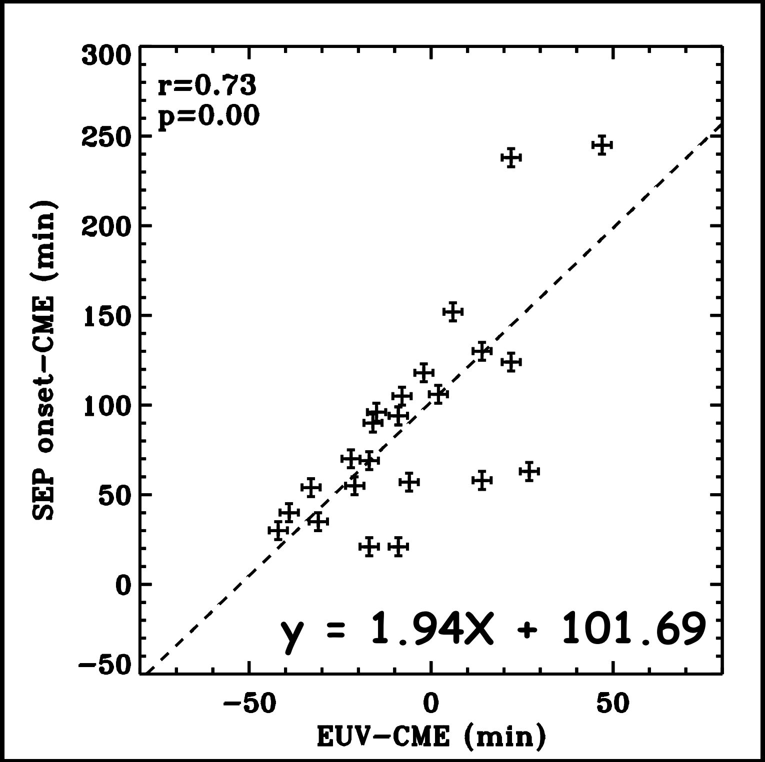
16 SEPs and their associated solar eruptions

Date	Flare[a] Start	Max	Class	Location	AR
20100814*	09:38	10:05	C4.4	N17W52	11099
20100818*	04:45	05:48	C4.5	N17W91	11099
20110307*	19:43	20:12	M3.7	N24W59	11164
20110321*	02:04	···	···	N22W132	···
20110804*	03:41	03:57	M9.3	N15W49	11261
20110921*	21:35	···	···	N15W120	···
20110922*	10:28	11:01	X1.4	N11E74	11302
20111103*	21:40	···	···	N05E160	···
20120123*	03:38	03:59	M8.7	N28W36	11402
20120526	···	···	···	N15W120	11482
20120718	05:55	06:02	C3.0	N15W170	···
20120723	···	···	···	S17W135	11520
20120831	19:45	20:43	C8.4	S19E42	11564
20130315	05:46	06:58	M1.1	N11E12	11692
20130411	06:55	07:16	M6.5	N09E12	11719
20130513	01:53	02:17	X1.7	N08E89	11748

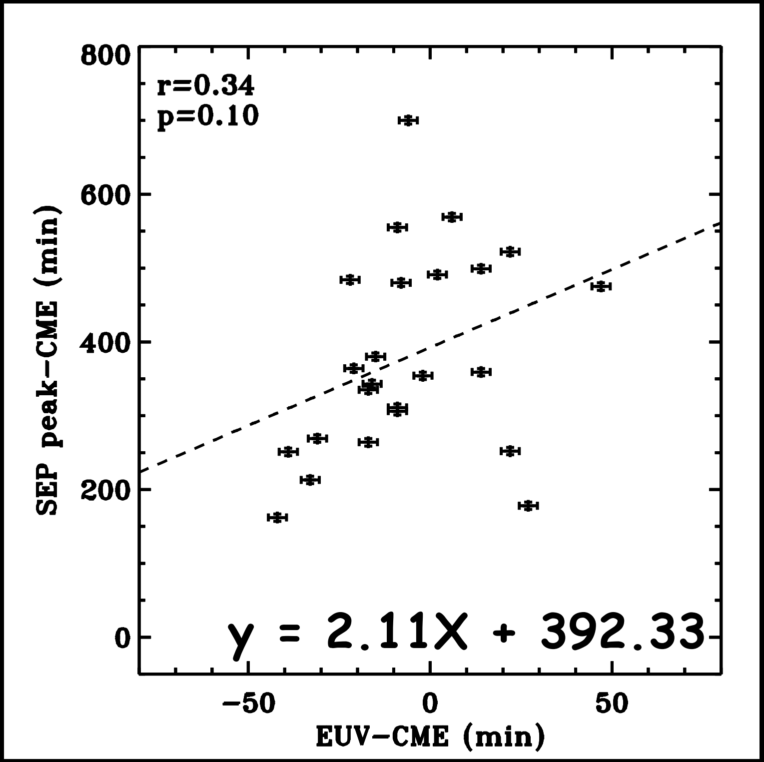
- ✓ **SEP peak flux:** 0.01 ~ 300 cm^{-2} s^{-1} sr^{-1} MeV^{-1}
- ✓ **Flare flux:** C3.0 ~ X2.0
- ✓ **Flare location:** 11 in the frontside and 5 behind the limb
- ✓ **CME linear speed:** 1000 ~ 2000 km/s
- ✓ **Radio burst Type II:** 15 events
- ✓ **EUV wave speed:** 180 ~ 680km/s

1.3 Result

SEP onset/peak time and EUV wave arrival time



EUV arrival time and SEP onset time



EUV arrival time and SEP peak time

It shows the relationship between the 6-10 MeV proton travel times from the solar sources to the spacecraft in interplanetary space (proton onset time/ peak time - CME appearance time) and the EUV wave arrival times from the solar sources to the footpoints in the low corona (EUV wave arrival time - CME appearance time).

SEP onset and peak time and EUV wave arrival time (Park et al. 2013)

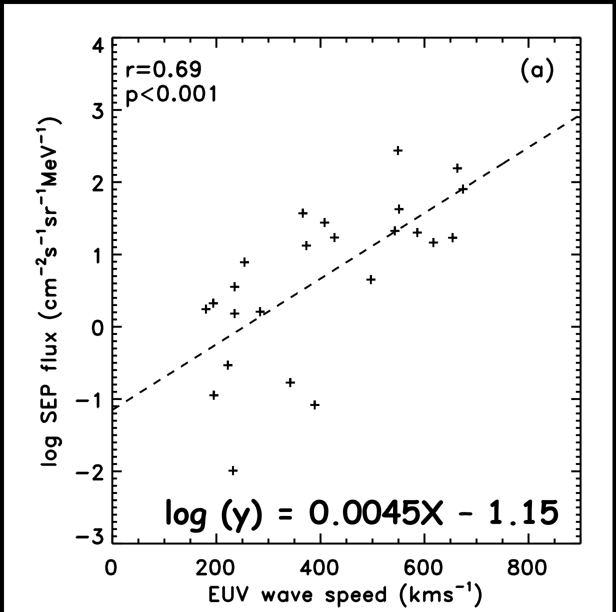
	SEP	a	b	r
Flare	e	1.01	40.73	0.60
	p	2.25	112.92	0.61
CME	e	1.17	42.65	0.69
	p	1.98	148.31	0.61
Type III	e	1.20	38.79	0.63
	p	2.30	134.06	0.62

Notes. The Linear Regression Coefficients ($y = ax + b$) and correlation coefficients.

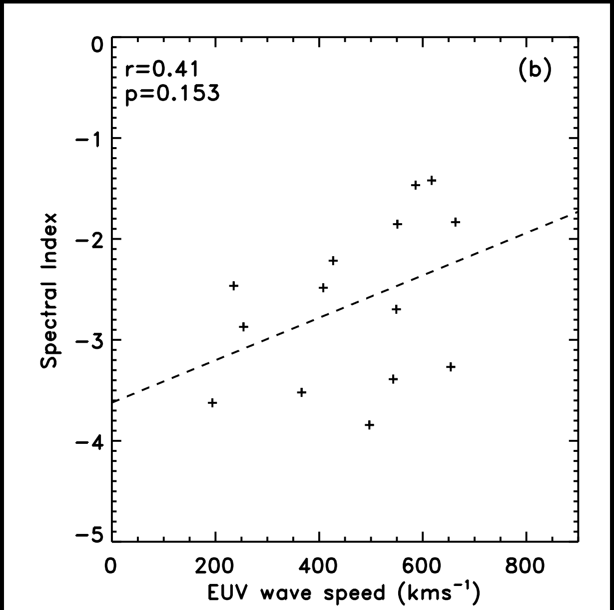
12 events observed in the 1.90-3.06 MeV proton channel and in the 175-315 keV electron channel from 2010 August to 2012 January.

It shows that electron onsets are more responsive to the EUV wave arrival times because the electrons are accelerated more quickly from the footpoints compared with protons.

SEP peak flux and EUV wave speed



EUV wave speed Vs SEP peak flux

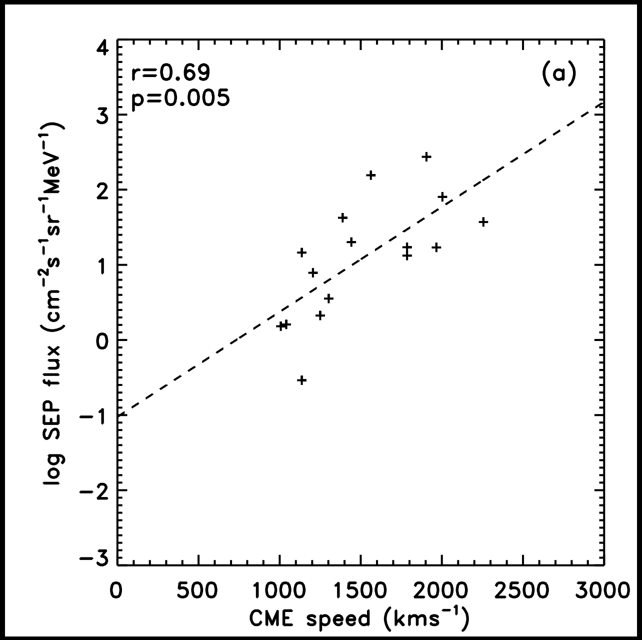


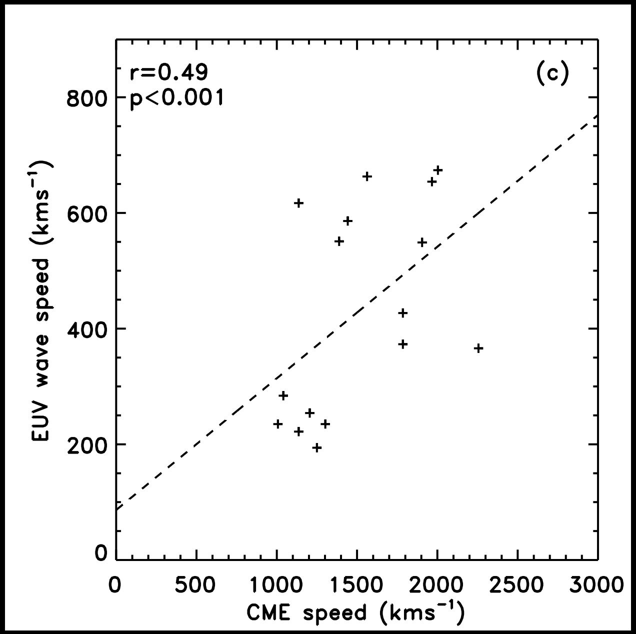
EUV wave speed Vs spectral index

The speeds of EUV waves seen in the low corona give a direct measure of their energies.

The two-point power-law spectral indices of SEP events are obtained at the proton peak fluxes in the SOHO ERNE 20.8-26.0 MeV and 34.8-40.5 MeV and the STEREO HET 20.8-23.8 MeV, and 35.5-40.5 MeV channels.

CME speed and SEP peak flux





CME speed Vs SEP peak flux

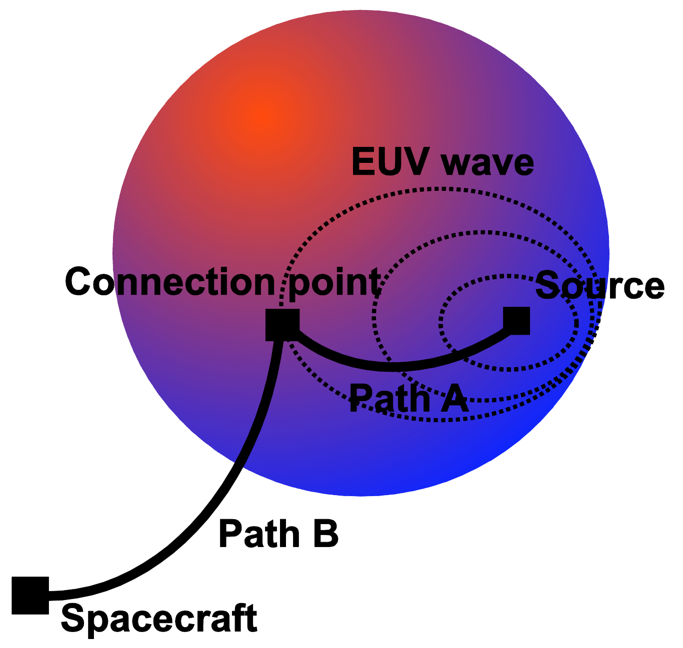
CME speed Vs EUV wave speed

It shows the relationship between the associated CME linear speeds and the SEP peak fluxes for the 16 events.
In case SEP events were observed by more than two instruments, we selected the highest flux among them.

The correlation coefficient (r=0.49) is meaningful even though the propagations of two parameters ar e not in the same direction.

1.4 Summary

- ✓ We study the relationship between 16 large gradual solar energetic particle (SEP)events and associated EUV wave properties.
- ✓ The results have shown strong correlations between EUV wave arrival times and SEP onset time (r=0.73) as well as SEP peak flux and EUV wave speed (r=0.69).
- ✓ There is tendency that the spectral index become harder with the EUV wave speed. It means higher energetic particle fluxes are associated with faster EUV waves.



EUV wave trajectory from the source region to the connection point (Path A) and SEP propagation from the connection point to the spacecraft (Path B)

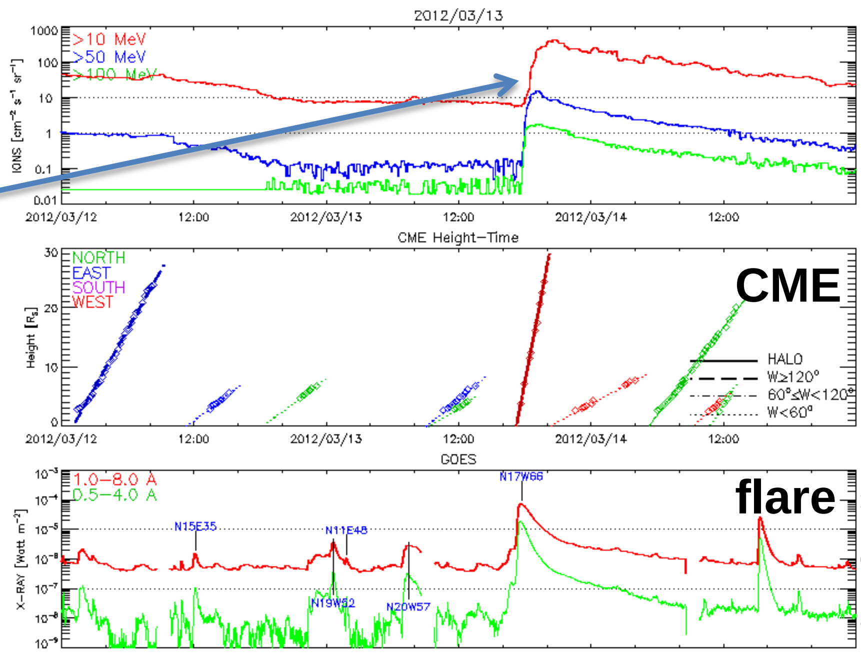
- ✓ The present study shows SEPs are associated with EUV waves, which are considered as the lateral expansions of CME-driven shocks in the low corona.

2. Study of solar proton events associations with flares and CMEs

2.1 Introduction

In this study we examine the occurrence probabilities of solar proton events (SPEs) and their peak fluxes depending on both flare and CME parameters: flare peak flux, longitude, impulsive time, CME linear speed, and angular width.

Solar proton event (SPE)
SPEs threshold
10 pfu (protons/cm^2 s sr at > 10 MeV).



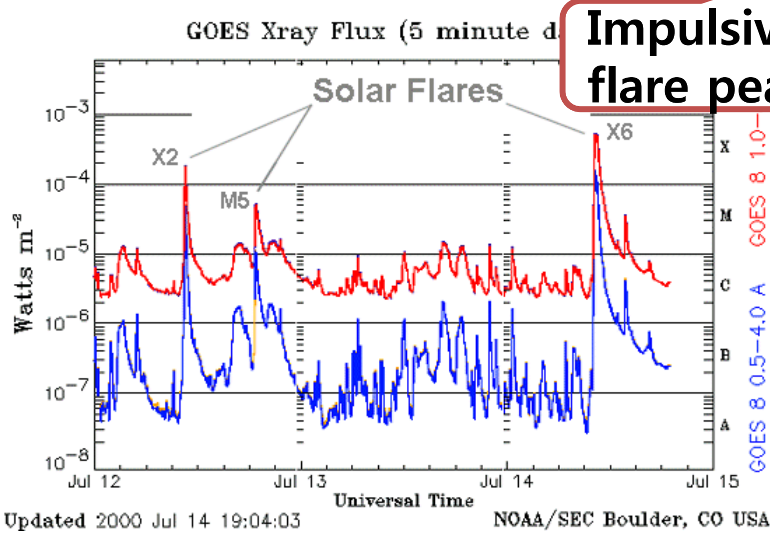
SOHO/LASCO CME catalog, PHTX plot

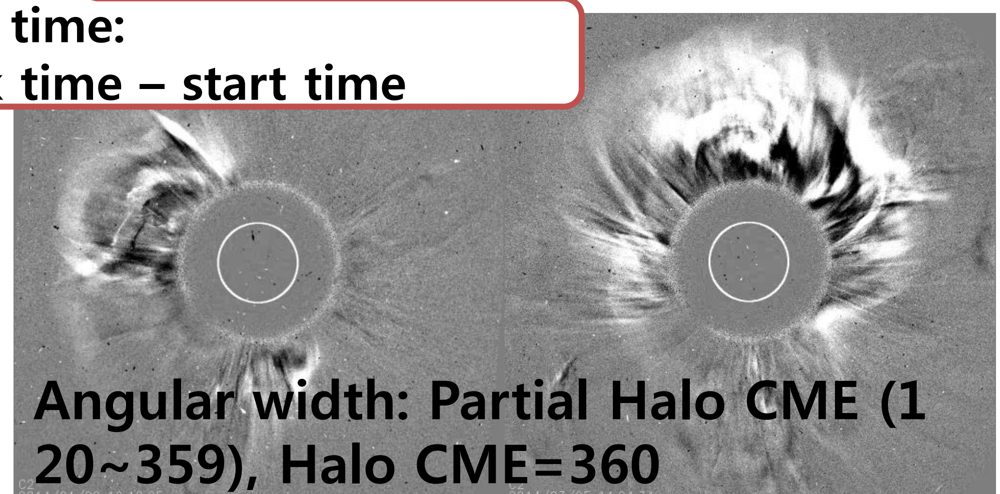
2.2 Data

NOAA solar proton event list
SOHO LASCO CME online catalogue
NOAA NGDC GOES X-ray flare catalogue

Flare & CME Parameters 1997-2011 65 SPEs 484 flare 484 CMEs	CME speed	400≤V<1000km/s and V>1000km/s
	Angular width	partial halo CME and full halo CME
	Flare flux	C1< f < M5 and f ≥ M5
	Longitude	east (-90 ~0°) and west (0~90°)
	Impulsive time	T < 0.4h and T ≥ 0.4h

Impulsive time:
flare peak time – start time





2.3. Result: SPE occurrence probability depending on flare and CME parameters

(# of SPEs/ # of solar eruptions)

- Flare flux, location, CME speed, and angular width

Full Halo

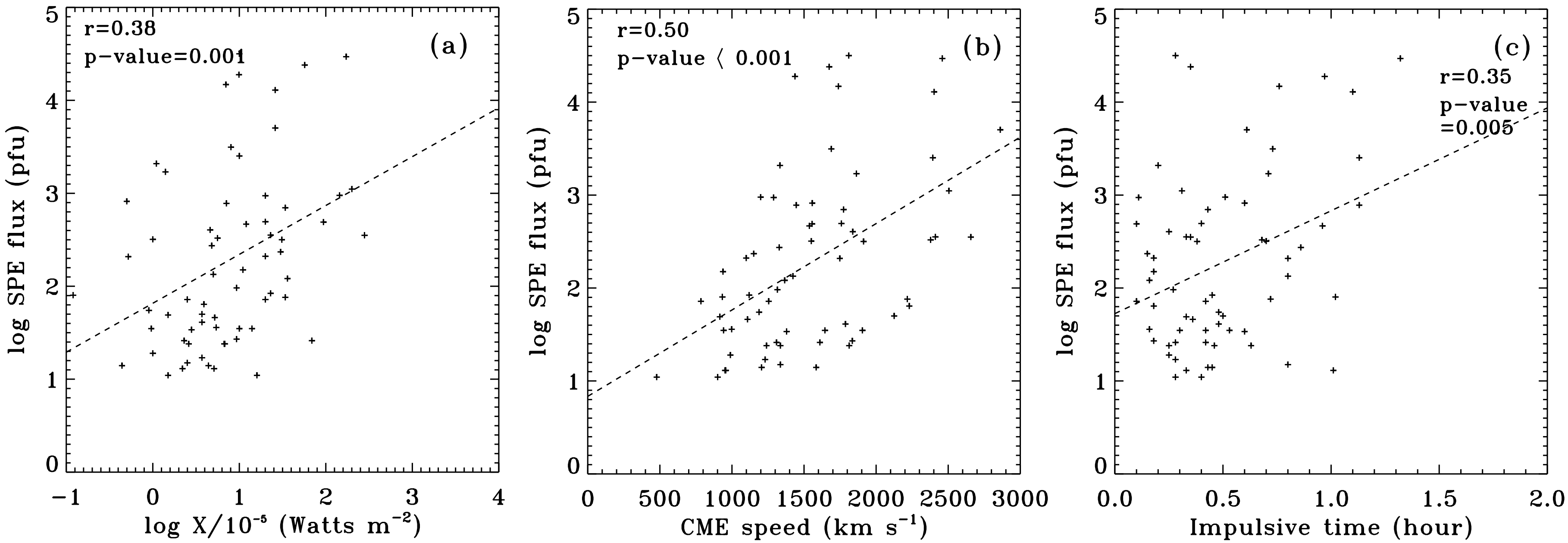
		400 ≤ V < 1000km/s	V ≥ 1000km/s
West	f≥M5	33% (6/18)	57% (20/35)
	F<M5	11% (4/37)	32% (11/34)
East	f≥M5	0% (0/9)	30% (8/27)
	F<M5	0% (0/40)	17% (4/23)

Partial Halo

		400 ≤ V < 1000km/s	V ≥ 1000km/s
West	f≥M5	8% (1/13)	42% (5/12)
	F<M5	4% (3/82)	11% (3/28)
East	f≥M5	0% (0/2)	0% (0/11)
	F<M5	0% (0/90)	0% (0/23)

(Park et al., 2013)

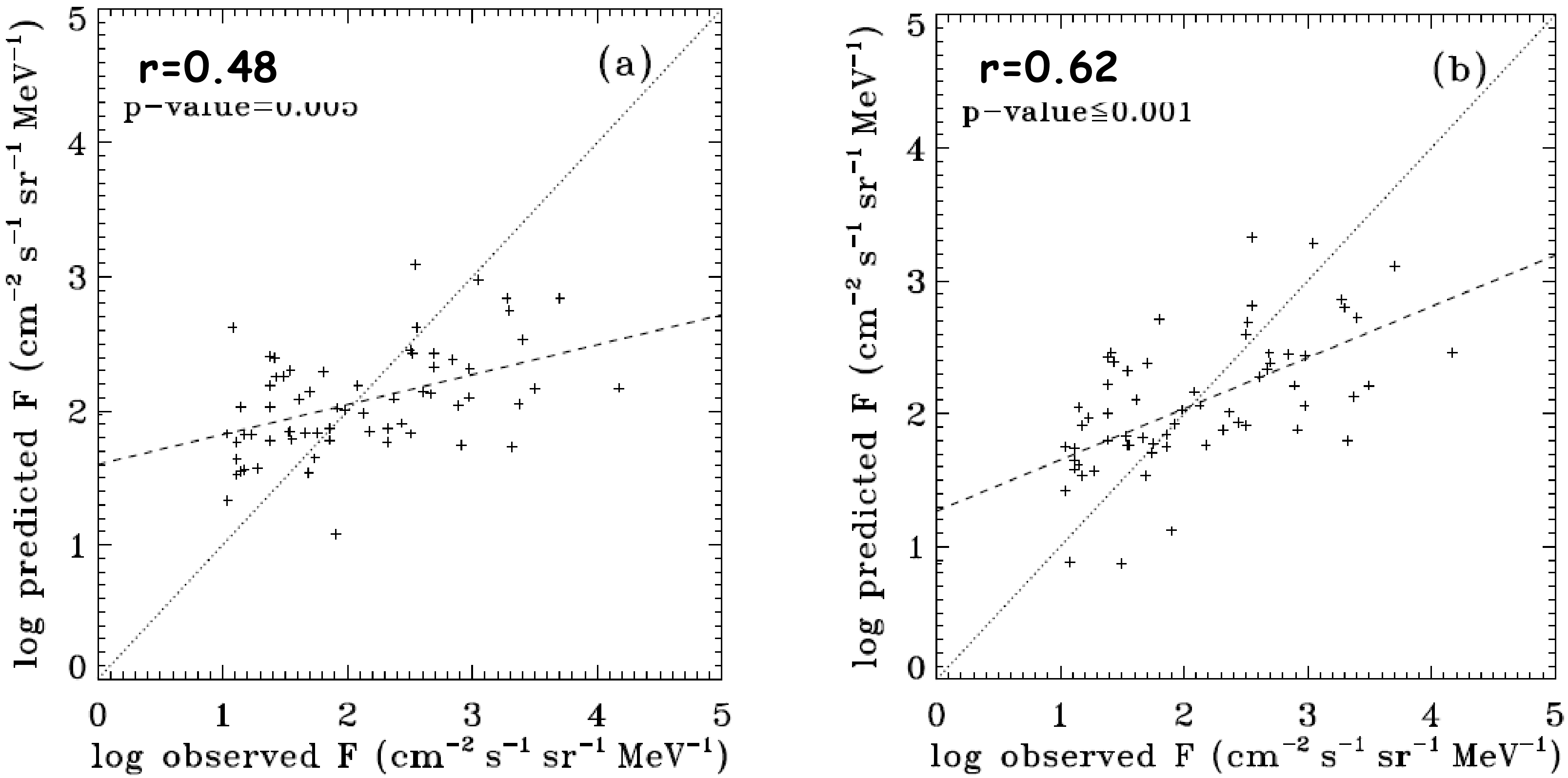
The relationship between SPE peak flux and flare peak flux/CME speed/impulsive time



**The correlation coefficients are 0.38 for flare and 0.50 for CME. SPE peak fluxes have a moderate relationship with impulsive times (*r* = 0.35) but not with longitudes (*r* = 0.02). There is no correlation between the SPE peak fluxes and the angular width (*r* = −0.05) b
ecause almost half of the SPEs are associated with full halo CMEs.**

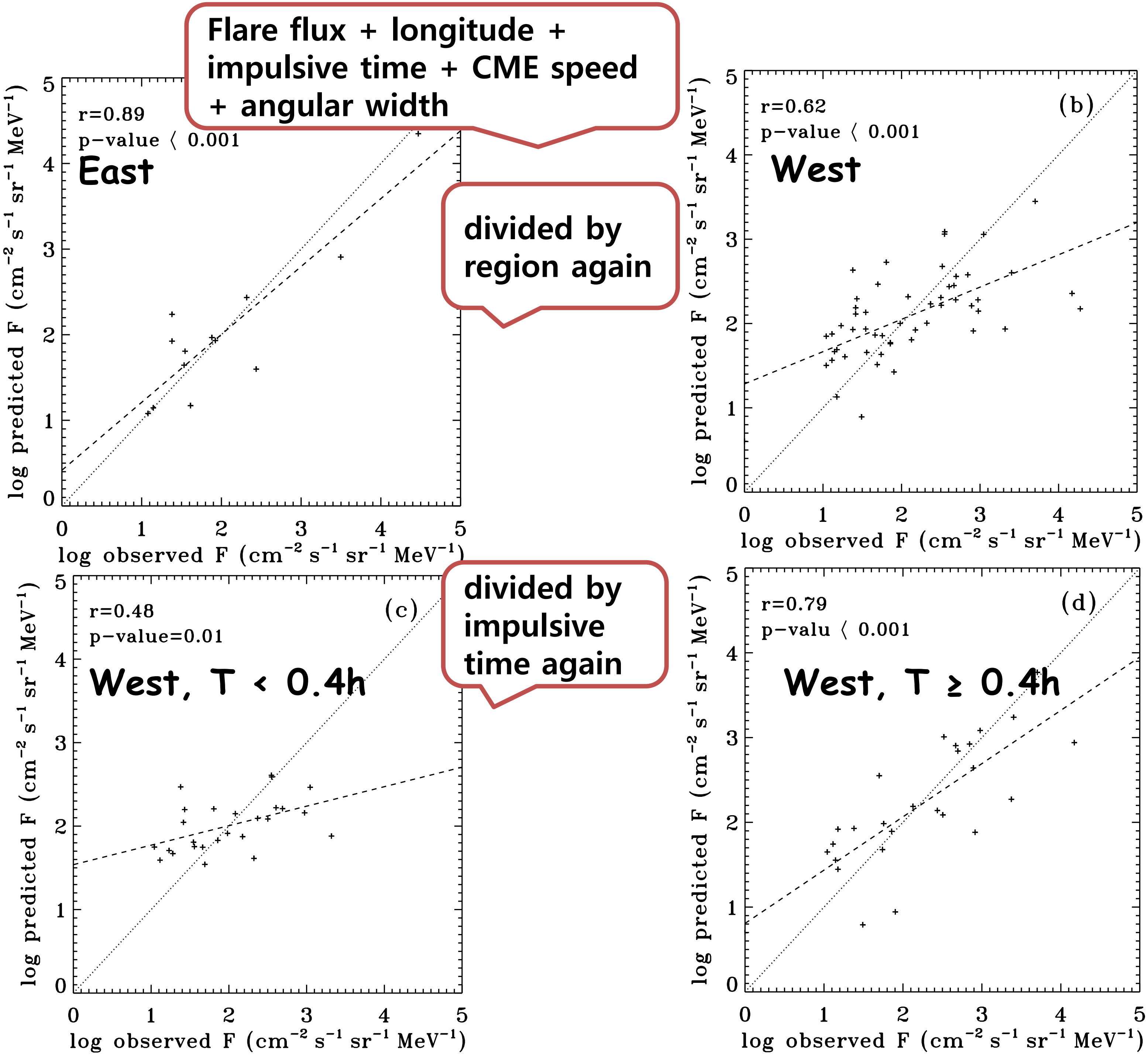
Predicted SPE Peak Flux using Combined Parameters

- Combined parameters



Flare flux + CME speed

Flare flux + longitude + impulsive time + CME speed + angular width



Flare flux + longitude + impulsive time + CME speed + angular width
divided by region again
divided by impulsive time again
r=0.89
p-value 〈 0.001
East
r=0.62
p-value 〈 0.001
(b)
West
r=0.48
p-value=0.01
(c)
West, T < 0.4h
r=0.79
p-valu 〈 0.001
(d)
West, T ≥ 0.4h
log predicted F (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
log observed F (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)

2.4 Summary

- ✓ In the study, we have made the contingency table for SPE probability considering four solar parameters and examined the relationship between SPE peak flux and flare/CME parameter.

- ✓ The three highest probabilities are found for the following subgroups : 1) fast full halo (55.3%) and fast partial halo (42.9%), CMEs associated with strong flares from the western region and 2) slow full halo CMEs associated with strong flares from the western region (31.6%).

- ✓ It is noted that the events whose SPE probabilities are nearly 0% belong to the following subgroups: 1) slow and fast partial halo CMEs from the eastern region, 2) slow partial halo CMEs from the western region, and 3) slow full halo CMEs from the eastern region.

- ✓ When the subgroups are separately considered by flare impulsive time and source longitude, the correlation coefficients between the observed and the predicted SPE peak fluxes are greatly improved.

Thanks for your attention!

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