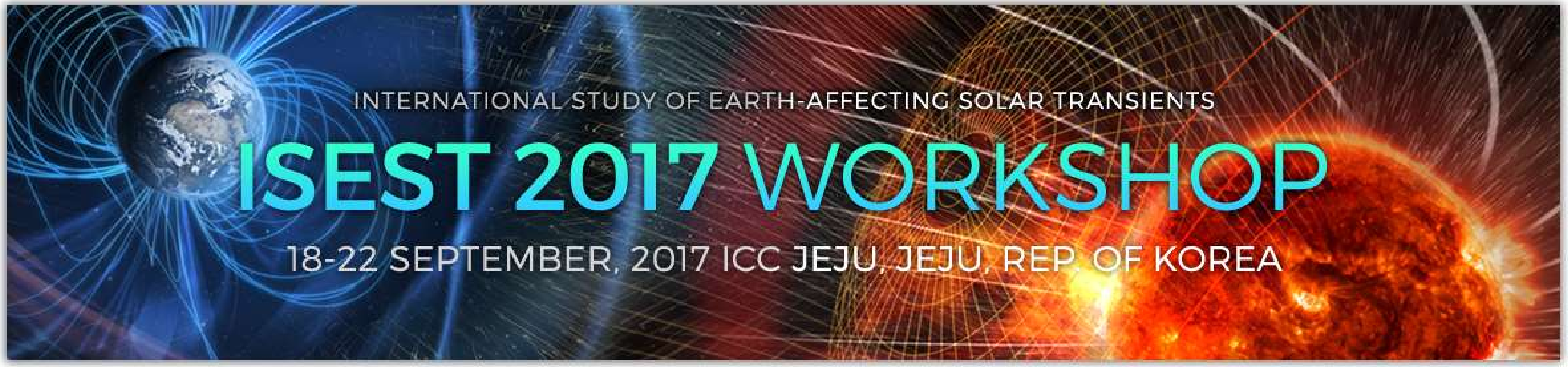


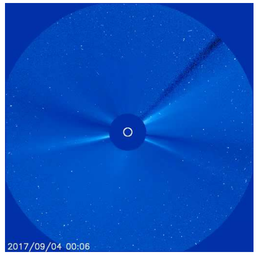
Working Group 6: Solar Energetic Particles

The Third Class of SEPs

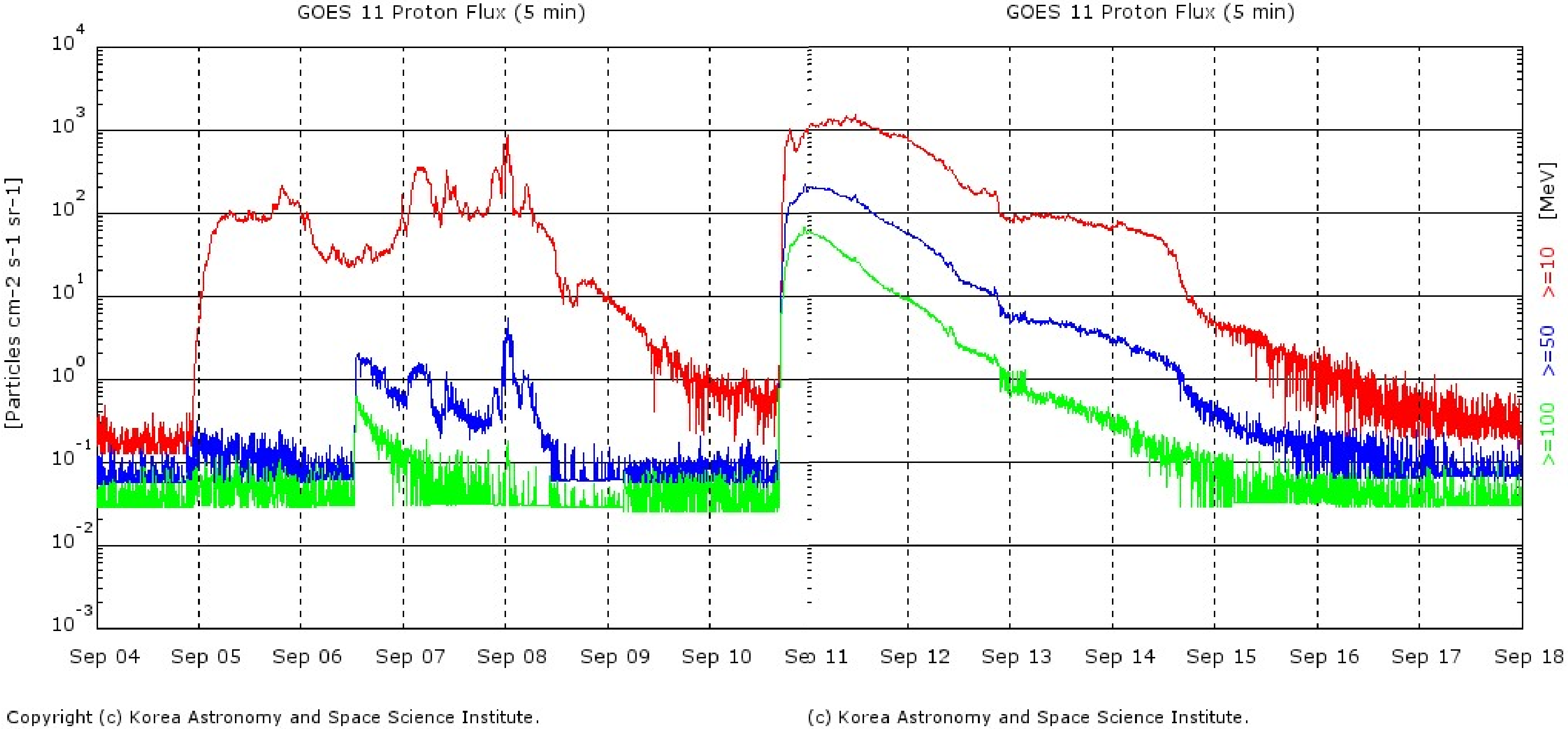
Roksoon Kim[1,2], Olga Malandraki[3] , Jin-hye Park [4]
[1]KASI, [2]UST, [3]NOA , [4]KHU

Reference: Malandraki & Crosby, Springer ASSL series, in press, 2017 : 'Solar Particle Radiation Storm Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and beyond'

Recent Solar Activities



- **During the early September**

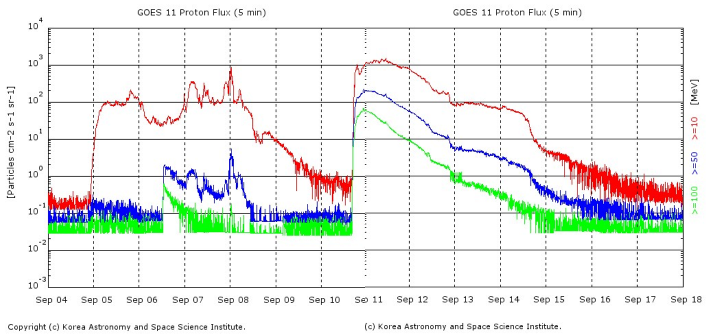


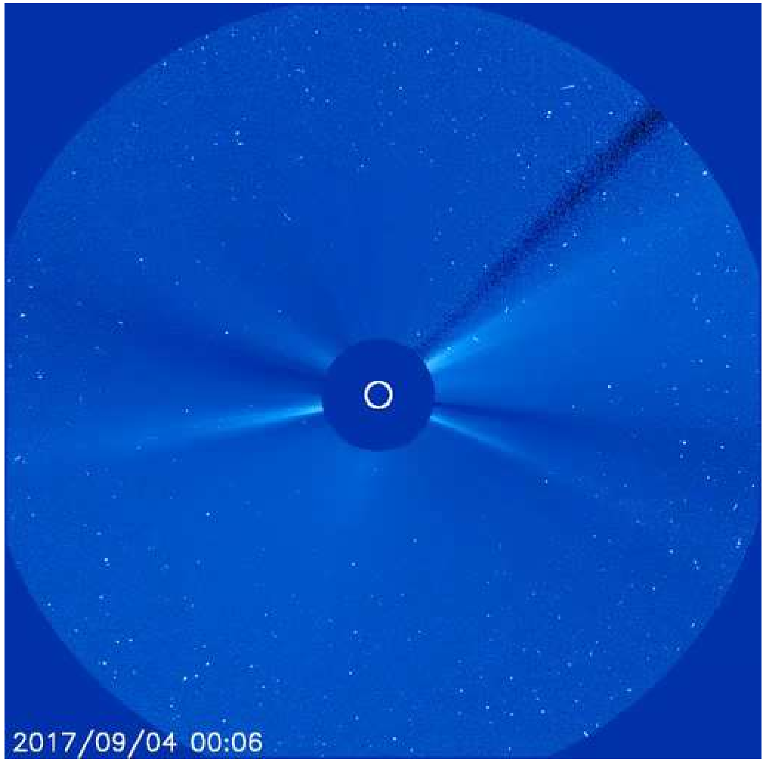
								12365
								12371
Jun 26/0350	Jun 27/0030	22		Asymmetric full halo/25 0836	25/0816	M7	N12W40	12371
Oct 29/0550	Oct 29/1000	23		Far-sided on W limb, S11/29 0236	(Farside)			12434
			2016					
Jan 02/0430	Jan 02/0450	21		SW limb event/02 2324	02/0011	M2	S21W73	12473
			2017					
Jul 14/0900	Jul 14/2320	22		Asymmetric full halo/14 0125	14/0209	M2	S06W29	12665
Sep 05/0040	Sep 08/0035	844		Asymmetric full halo/04 2042	04/2033	M5	S11W16	12673
Sep 10/1645	Sep 11/1145	1490		Asymmetric full halo/10 1600	10/1606	X8	S08W83	12673

https://umbra.nascom.nasa.gov/SEP/

Recent Solar Activities

- **During the early September**





https://umbra.nascom.nasa.gov/SEP/

			2015					
Jun 18/1135	Jun 18/1445	16		Narrow SW limb event/18 0125	18/0127	M1	SW limb	12365
Jun 21/2135	Jun 22/1900	1070		Full halo/21 0236	21/0236	M2	N13W00	12371
Jun 26/0350	Jun 27/0030	22		Asymmetric full halo/25 0836	25/0816	M7	N12W40	12371
Oct 29/0550	Oct 29/1000	23		Far-sided on W limb, S11/29 0236	(Farside)			12434
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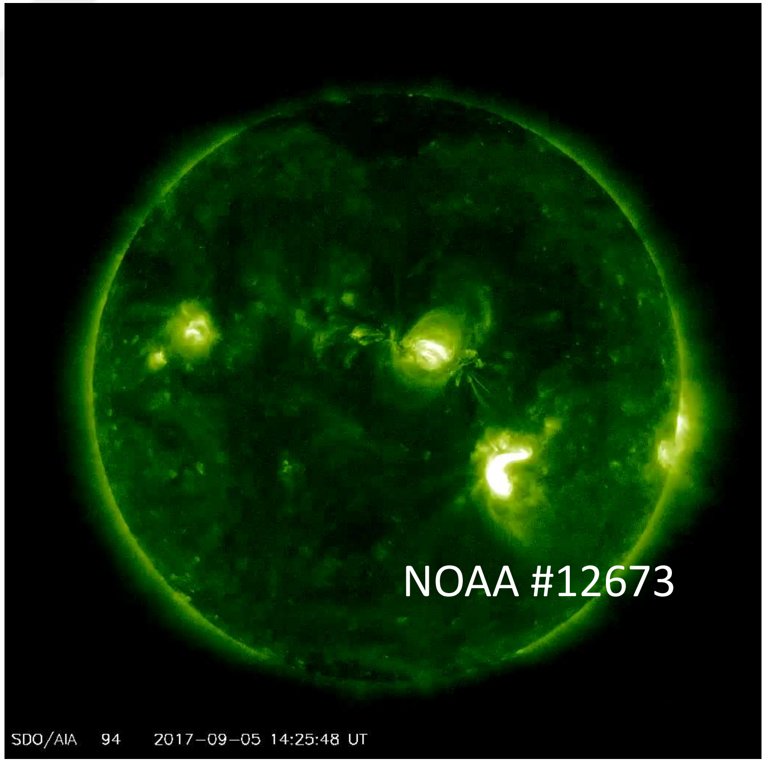
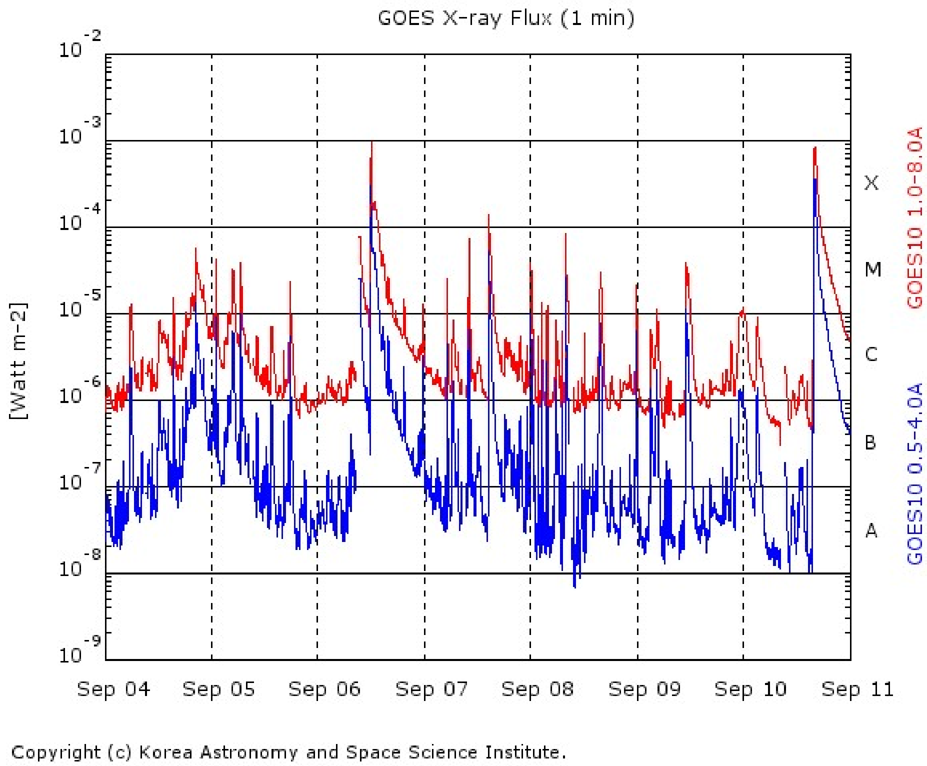
Recent Solar Activities

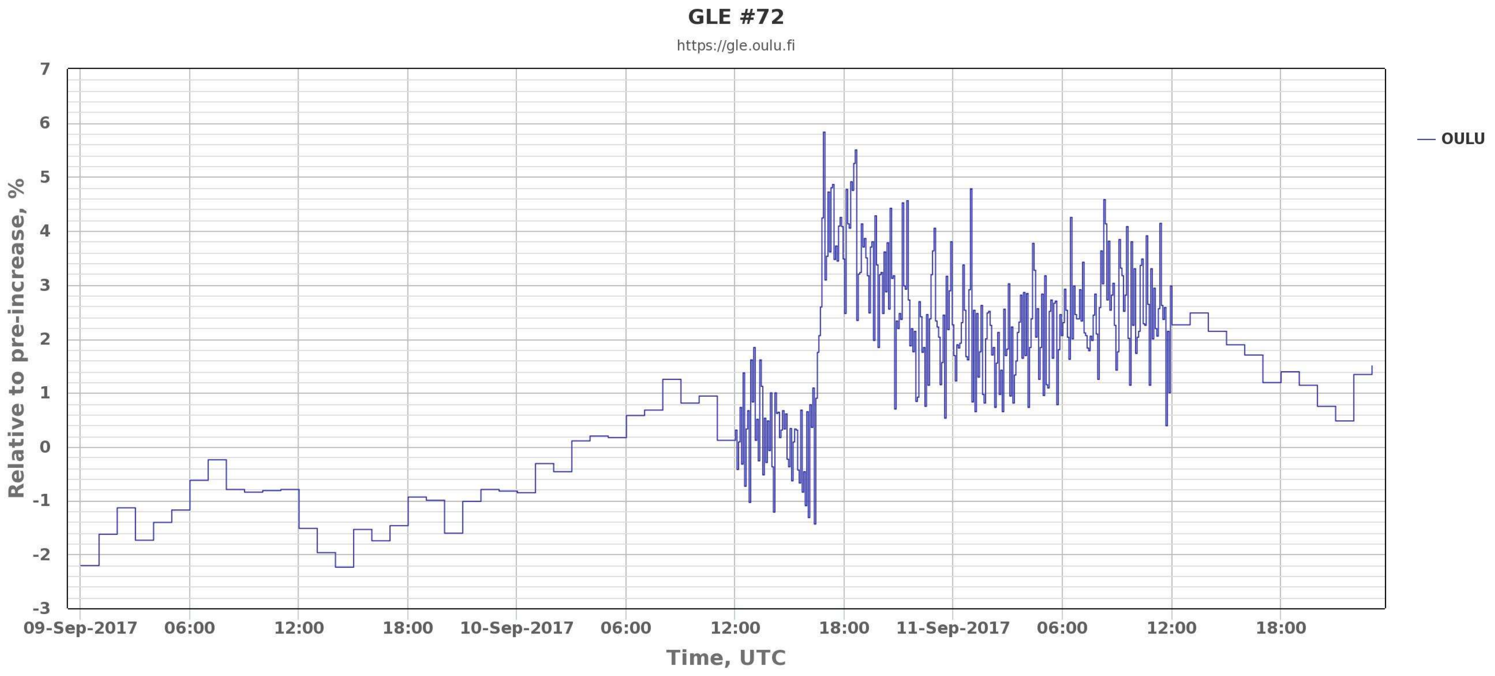
- **During the early September**





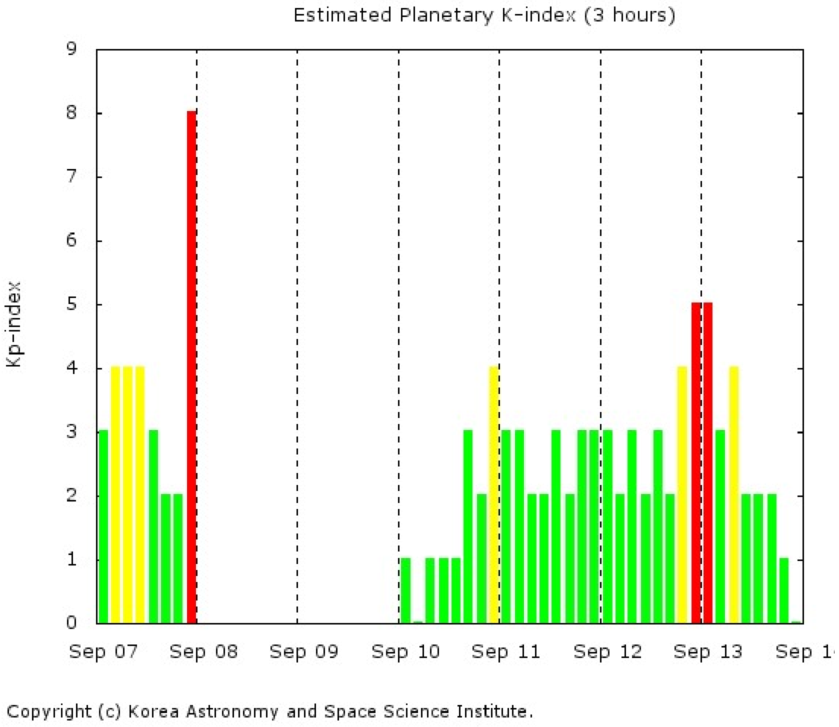
Recent Solar Activities

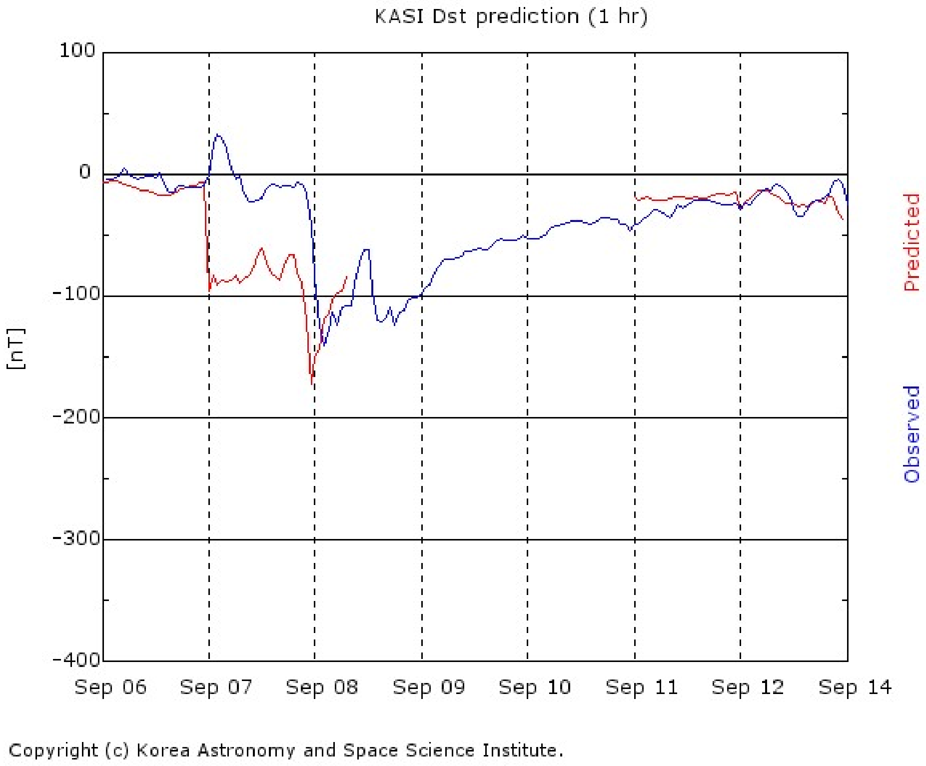
- **During the early September**



Recent Solar Activities

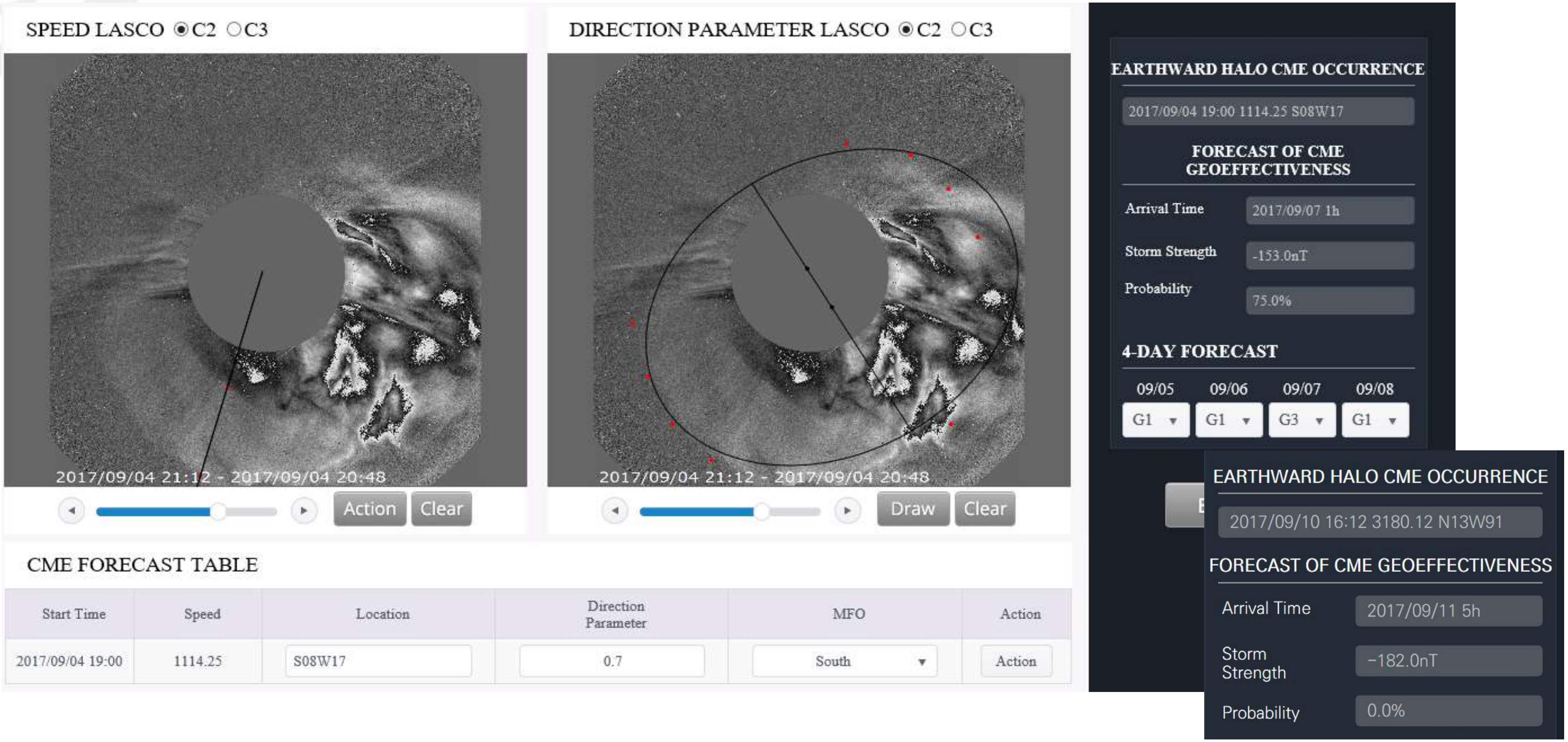
- **During the early September**





Recent Solar Activities

- **KASI's forecast using CME parameters (Kim et al., 2010)**
  - Semi-auto process to measuring CME speed and direction parameter.



Contents

- **Review**
  - What are SEPs and SPEs?
    - ✓ Historical perspective of SEP events and their observations
  - Why do we care?
    - ✓ SEP effects on human and technology and several forecast models
  - Series of processes from sun to earth by solar activity
    - ✓ According to the conventional two classes of SEPs

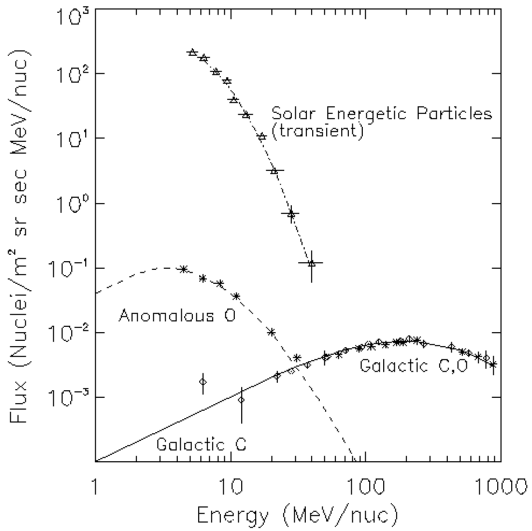
- **Refined Classification of SEPs**
  - When and how do they accelerate? – Condition and Mechanism
  - Considering SPE onset time and energy enhancement pattern (Kim et al., 2014)
  - Characteristics of four SPE groups (Kim et al., 2015)
  - Hybrid events as the third class of SEPs – Scenarios

- **Remarks**
  - Unsolved questions
  - Future projects to understand SEPs

Review

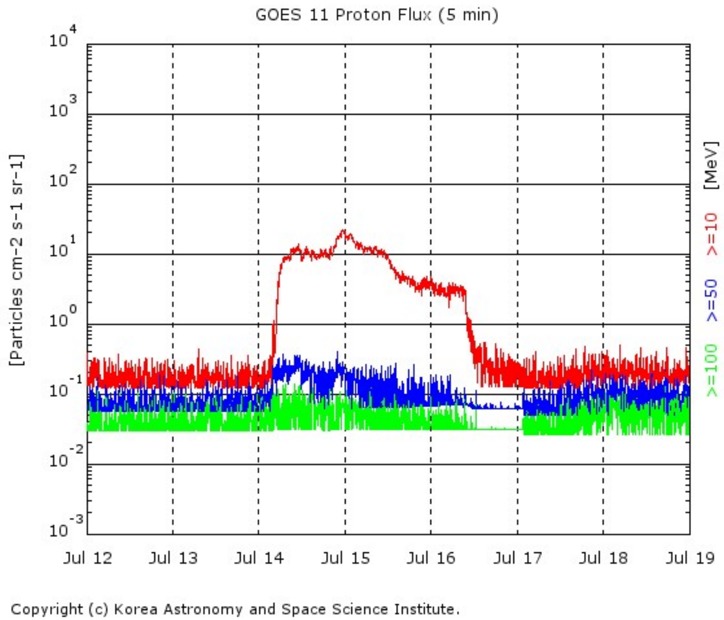
What are SEPs and SPEs?

- **Solar Energetic Particles (SEPs)**
  - Solar originating energetic particles from a few keV up to GeV observed in interplanetary (IP) and near Earth space.
  - Accelerated in the location of
    - ✓ Solar flares
    - ✓ CME-driven IP shocks



Major particle populations in space (SRL, Caltech)

- **Solar Proton Events (SPEs)**
  - When the solar originating proton count of >10 MeV exceeds 10/sec.



Historical Perspective of SEP events

1940s The First Indirect Observation

The earliest detection of solar particles related with flare (Forbush, 1946).
- By ground-based ionization chambers and Neutron Monitors (NMs) indirect measurement.
- Solar cosmic rays which are have the analogy to galactic cosmic rays.

1950s Analysis of Big Events

The analysis of the particle flux of the 23 February 1956 SPE (Parker, 1956).
- Only the solar magnetic field was capable of accelerating protons in the quantities and to the detected energy level.
- Both flares and CMEs derive their energy from the same solar magnetic field.

1960s Relation with Solar Radio Bursts

(A) type III radio bursts – electron acceleration
(B) type II bursts – shocks – proton acceleration

1980s The First Detection in Space

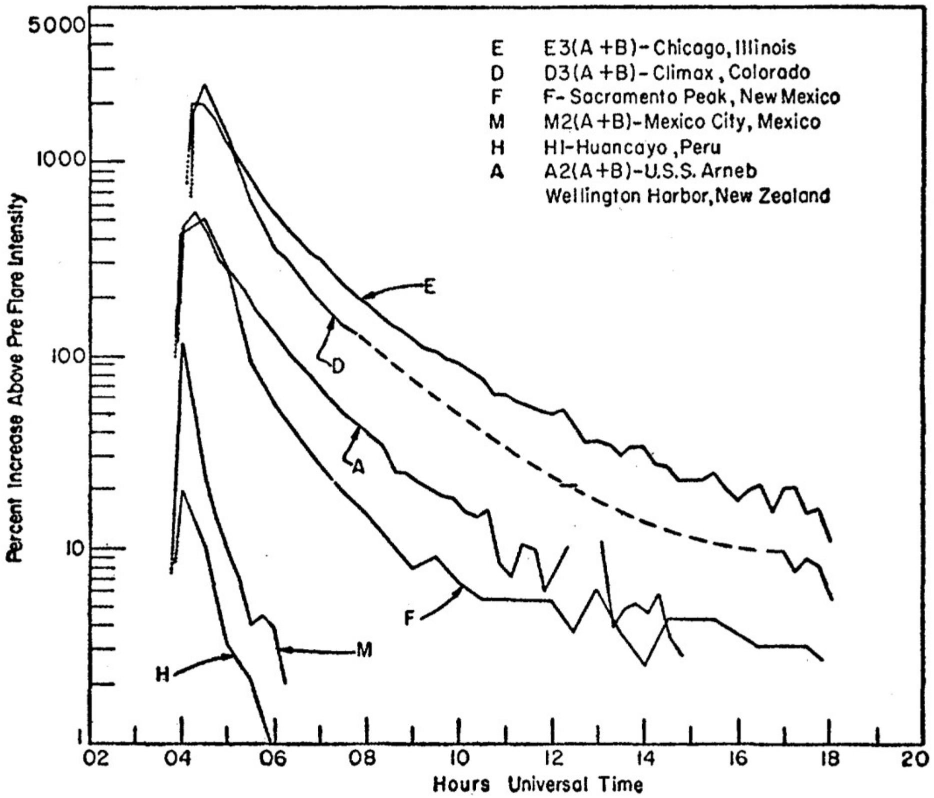
The first detection of solar neutrons at 1 AU
- Gamma Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) following an intense impulsive solar flare.

1990s Two Class Paradigm

According to acceleration mechanisms
- Flare-related impulsive events and gradual events as the results of diffusive acceleration at CME-driven shocks.

Observations on the Ground

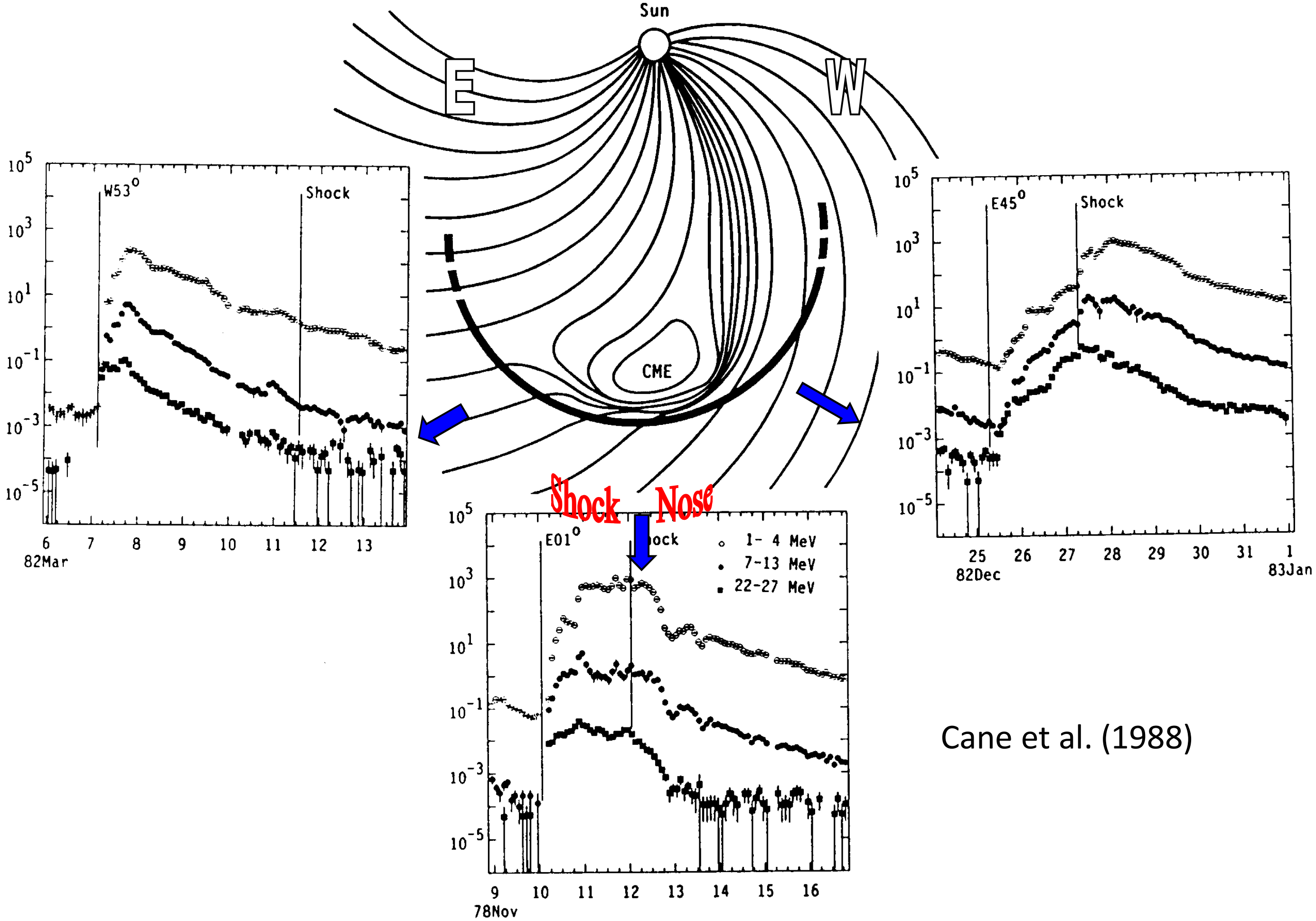
- **Ground Level Enhancements (GLEs)**
  - Sudden increase in the counting rate primarily detected by Neutron Monitors (NMs) at the Earth surface



Meyer, Parker and Simpson (1956)

Observations in Space

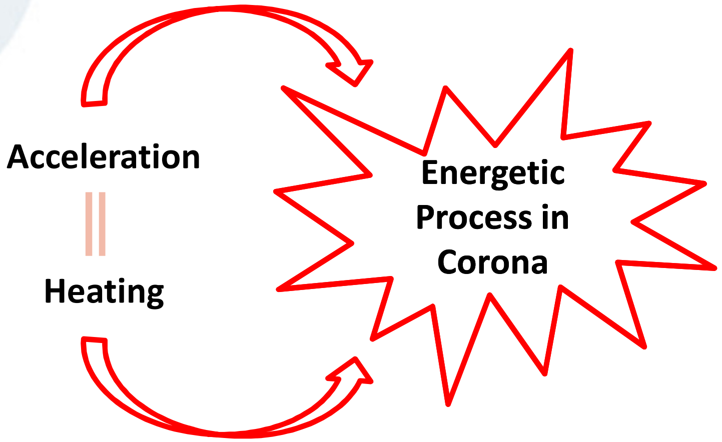
- **Multi-Point Observation**

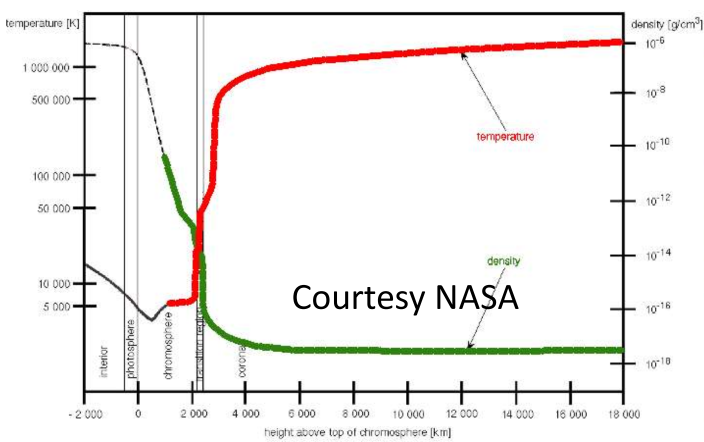


Cane et al. (1988)

Why Do We Care?

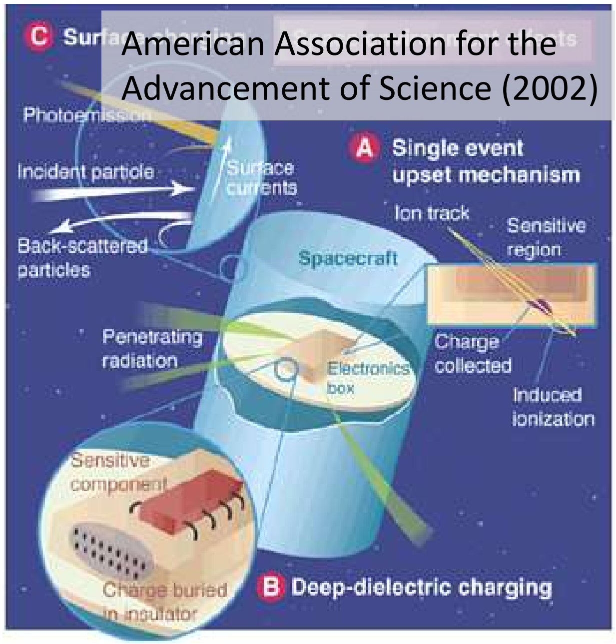
- **Particle acceleration**





Courtesy NASA

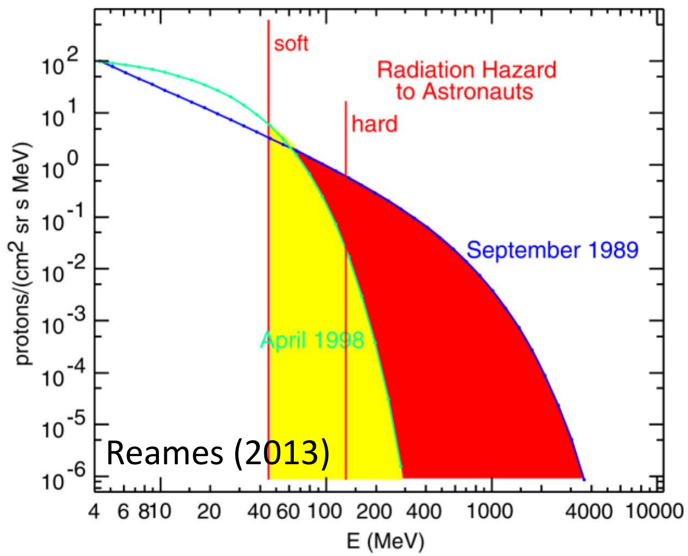
- **Practical space weather effects**
  - To avoid possible space hazards to human and technology
  - → Annual dose limit for a radiation worker in US is 20 mSv.
  - → If there is a severe event, astronauts may receive more than limit.



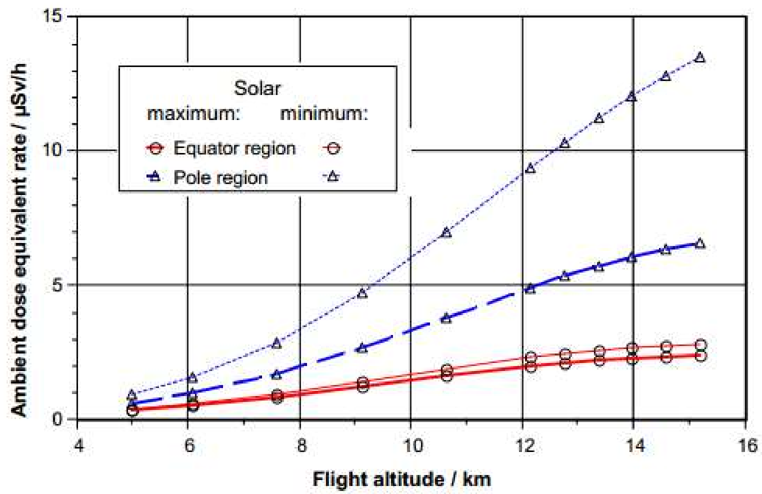
American Association for the Advancement of Science (2002)

SEP Effects on Human

- **Radiation effects on astronauts**
  - Deterministic effects
    - ✓ Due to exposure to a large dose of radiation for a limited time, hair loss, nausea, acute sickness, death
  - Stochastic effects
    - ✓ Due to accumulated random radiation, changes at DNA molecule level like cancer.

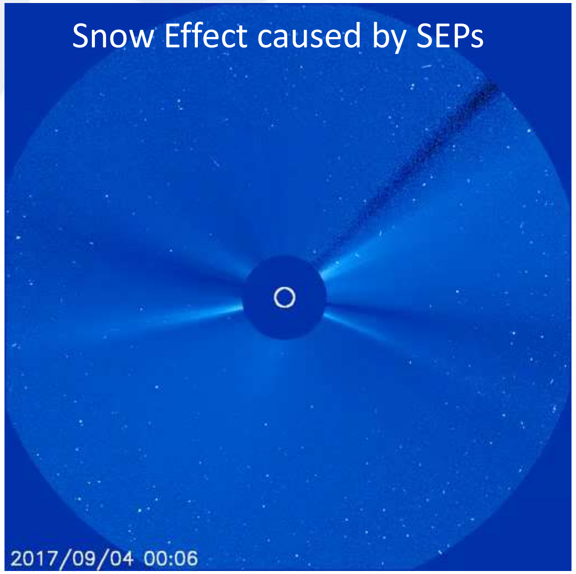


- **Radiation effects on aviation altitudes**
  - Radiation dose received by passengers on high latitude (> 50˚N), especially on polar route (> 78˚N) can increase.
  - For commercial aviation this can be a risk for frequent flyers and particularly for aircrew.
  - Protons (>10 MeV) are monitored and taken into account when planning extra-vehicular activities.



SEP Effects on Technology

- **Snow effect on the coronagraph**



- **Single Event Effects (SEEs)**
  - Single Event Upset: a bit switching from an initial logical state to an opposite logical state occurring in logical circuits.
  - Single Event Burnout: a condition that can cause device destruction due to a high current state in a power transistor.

- **Polar Cap Absorption (PCA)**
  - Intense ionization of the D-layer of the polar ionosphere by strong (>10 MeV) SEP events results in problems for communications and navigation position errors.

- **Total Electron Content (TEC)**
  - TEC enhancement can also effect signal propagation between Earth and satellites.

- **Secondary particles**
  - They may be more of an obstacle for the satellite designer than the primary SEPs themselves, since they can have more profound effects on sensitive space-borne instrumentation.

Forecast Models Related SEPs

- **Physics-based numerical models**
  - Earth-Moon-Mars Radiation Environ-ment Module (EMMREM)
  - Predictions of radiation from REleASE
  - EMMREM and Data Incorporating CRaTER
  - COSTEP and other SEP measurements (PREDICCS)
  - Solar Energetic Particle MODel (SEPMOD)
  - SO-Lar Particle ENgineering Code (SOLPENCO)

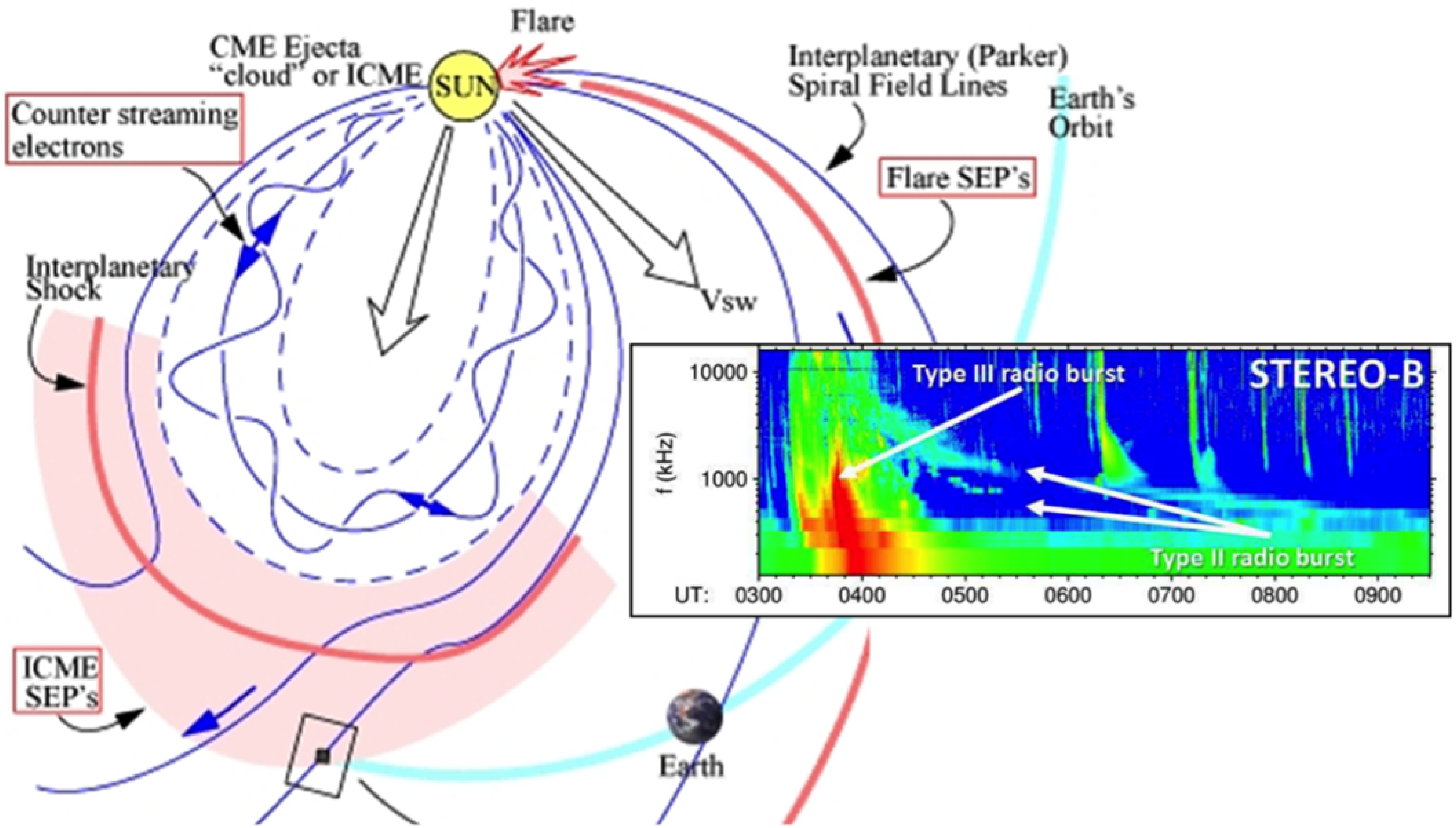
- **Empirical models**
  - University of Malaga Solar Energetic Particle (UMASEP) system
  - Relativistic Electron Alert System for Exploration (RE-leASE)
  - Proton Prediction System (PPS)
  - PROTONS system
  - GLE Alert Plus

- **Both**
  - SEPForecast tool built under the EU FP7 COMESEP project (http://www.comesep.eu/alert/).

- **Future project**
  - The EU H2020 HESPERIA project (https://www.hesperia.astro.noa.gr/) developed two novel real-time SEP forecasting tools based on the UMASEP and REleASE proven concepts.

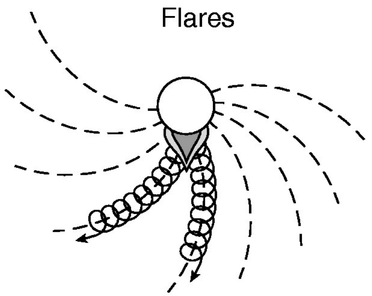
Series of Processes from Sun to Earth by Solar Activity

- **According to the conventional two classes of SEPs**

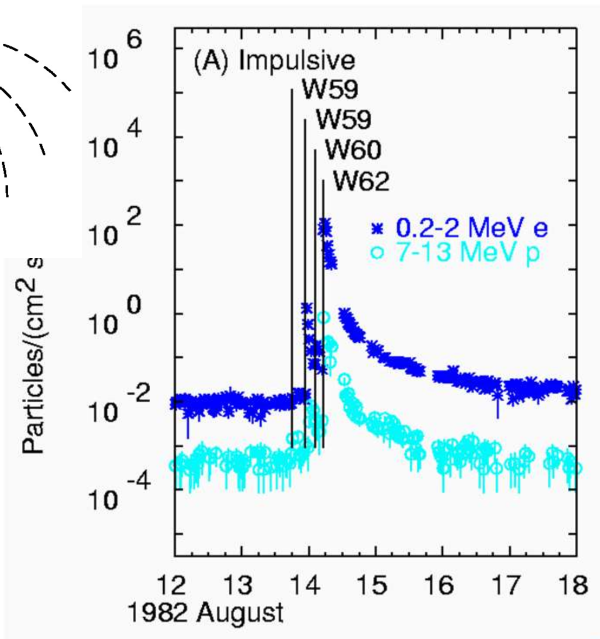


Main Trigger, Flux Profile, and Composition

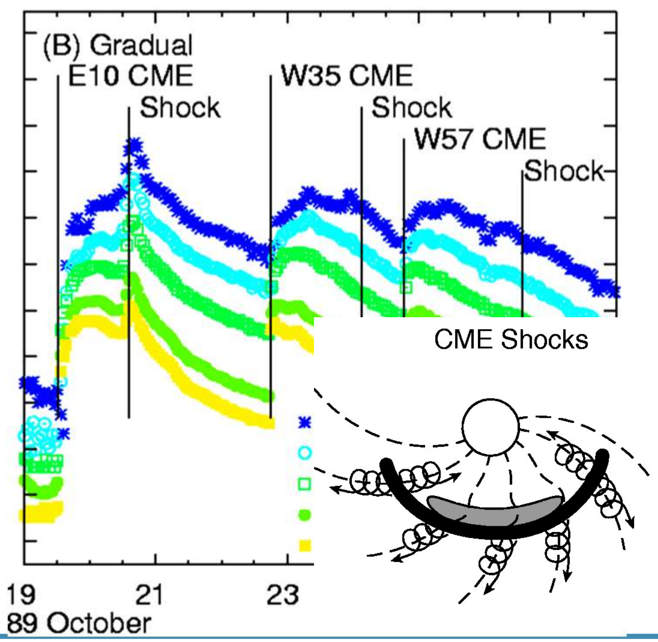
- **Impulsive events**
  - Associated with impulsive Hα and X-ray flares or jets and mostly occurred in the western region.
  - Short durations (~several hrs).
  - Electron-, 3He-rich events



Reames (1999)

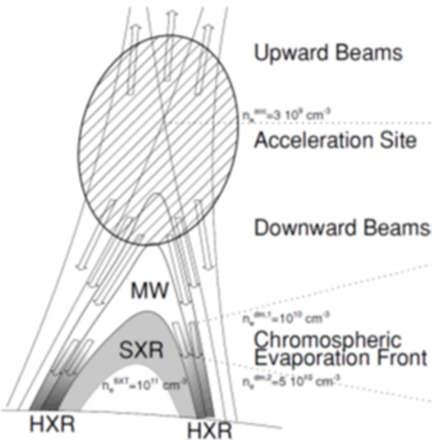


- **Gradual events**
  - Associated with fast CMEs and occurred in broad range of longitude.
  - Long durations (~several days).
  - Proton-rich, and normal coronal abundance and charge states corresponding to typical quiet coronal temperatures.

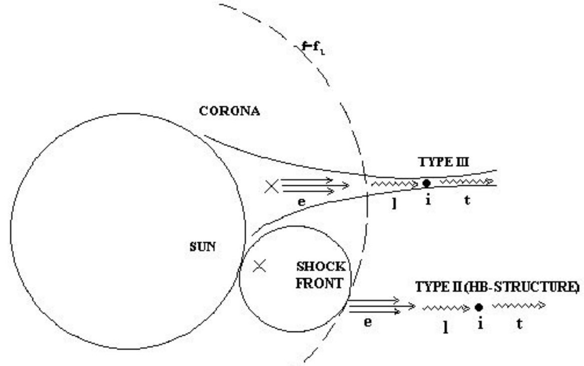


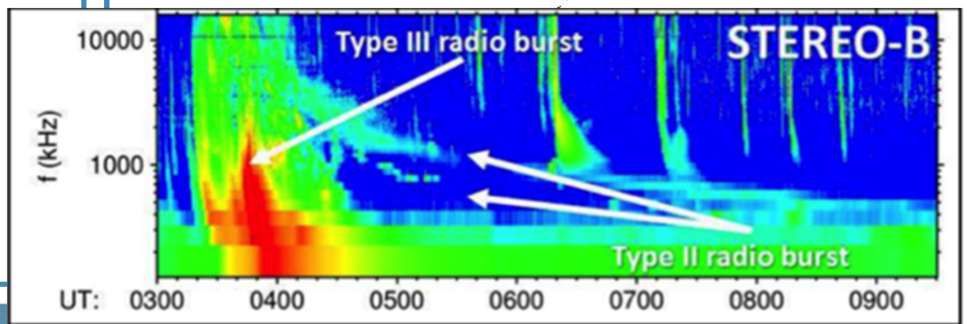
Electron Acceleration

- **In the flare sites**
  - Magnetically well-connected events with type III radio bursts
  - Flare-accelerated particles were likely able to escape from the corona when microwave bursts occurred with simultaneous type III bursts → contribute to the SEPs.
  - Type III bursts: Ideal tracers of the escape of energetic electrons (Reames, Dennis, Stone, & Lin).



- **In the CME-driven shocks**
  - Type II and type IV radio bursts.
  - IP shock theory –self-amplified waves (Lee, 1983)
  - Large SEP events 96% associated with CMEs (Kahler et al., 1984)
  - SEP intensities correlated with CME speed (Kahler, 2001)



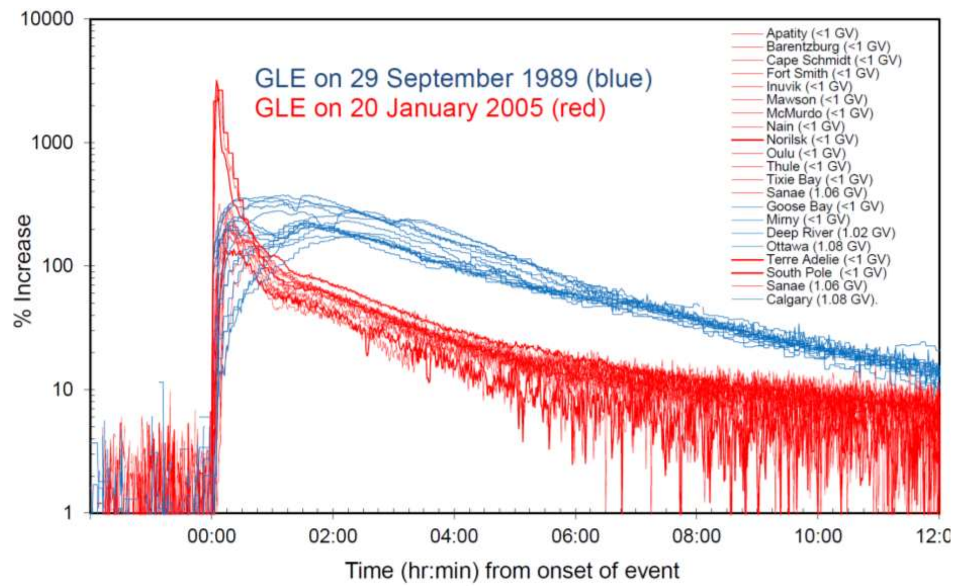


GLE

- **GLE #69 (20 Jan. 2005)**
  - The largest GLE
  - Perfectly connected to the Earth, so it was dominated by flare acceleration.

- **GLE #42 (29 Sep. 1989)**
  - 3rd largest GLE
  - Originate behind western limb, only particles accelerated on an extended CME shock front could have reached the Earth

- **High-energy SEPs (>500 MeV) and GLEs**
  - GLEs can result in secondary radiation caused by particles interacting with space craft shielding and other material.
  - This results in lower energetic protons, neutrons, and pions that in some cases may be more of an obstacle for the space craft designer than the primary SEPs themselves.



Moraal and Caballero-Lopez (2014)

Refined Classification of SEPs

When and How Do They Accelerate?

- **Acceleration mechanisms and condition**
  - Reconnection or MHD shock
- **Key factors to determine the strength of SEPs**
  - Strength of related solar eruptive event
    - ✓ Flare intensity and source location
    - ✓ CME angular width and expanding speed

- **Previous Studies**
  - Contributions of flares and CMEs to major SEP events (Trottet et al., 2015)
    - ✓ Correlation coefficients for flare-related (SXR peak flux) and CME-related (speed) parameters are low and similar so far. → Solar parameters are not independent.
  - Correlations between the SEP intensities and quantities characterizing solar activity (Kocharov et al., 2015)
    - ✓ The SEP pe… …ificantly better w… …into… …uences) and CM… …flux. → CME s… …t fluence.

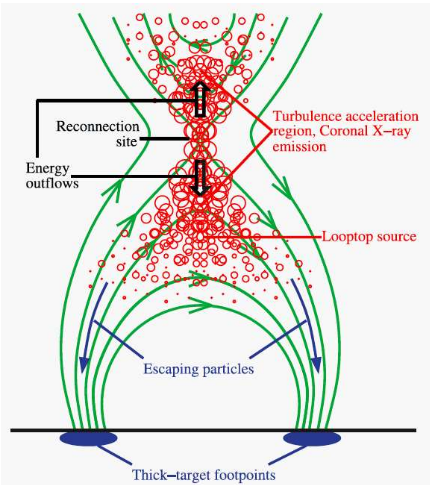
Velocity Dispersion Analysis

Multi-channel energy evolution

→ Analysis of onset timing and energy evolution for corresponding events

When and How Do They Accelerate?

- **Impulsive events**
  - Magnetic reconnection in solar flare
  - Rapid acceleration of particles to high energies within short timescale (Miller et al., 1990)
  - → Acceleration starts from the lower energy.



Liu 2013

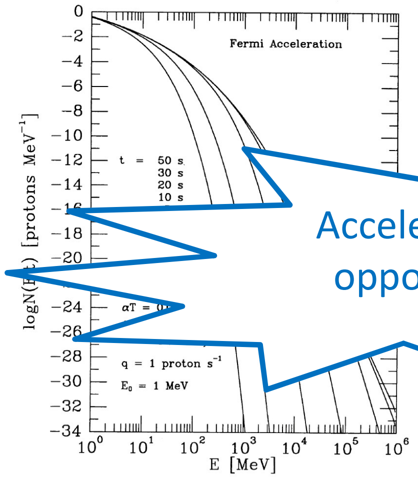
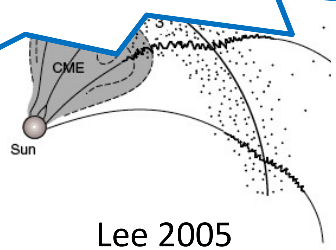


FIG. 4.—Proton energy spectra at various times t after the start of a continuous injection pf protons at energy E_0, showing the approach to equilibrium. Here $\alpha T_{esc} = 0.04$ with $\alpha = 0.04$ s^{-1} and $T_{esc} = 1$ s. The lowest curve corresponds to $t = 1$ s, and the highest curve corresponds to $t = 50$ s.

(Miller et al., 1990)

- **Gradual events**
  - Fast mode MHD shocks formed by CME
  - Gradual acceleration in which energetic particles are dominant in the initial stage, and low energy particles arise later as the shock propagates further into the solar wind (Zank et al., 2000).
  - → Acceleration starts from the higher energy.

Acceleration patterns are opposite to each other.



Lee 2005

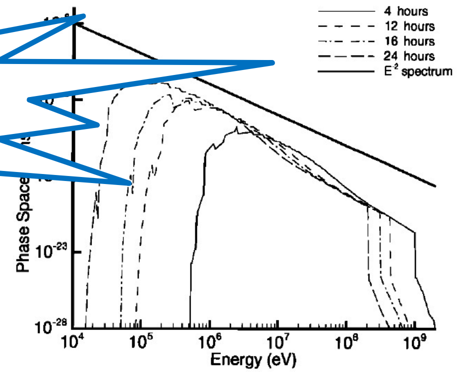


Figure 11. Particle distributions observed at 1 AU, at different times, prior to the shock arrival. Time is measured with respect to the initiation of the shock at 0.1 AU. An E^{-2} spectrum is included to guide the eye.

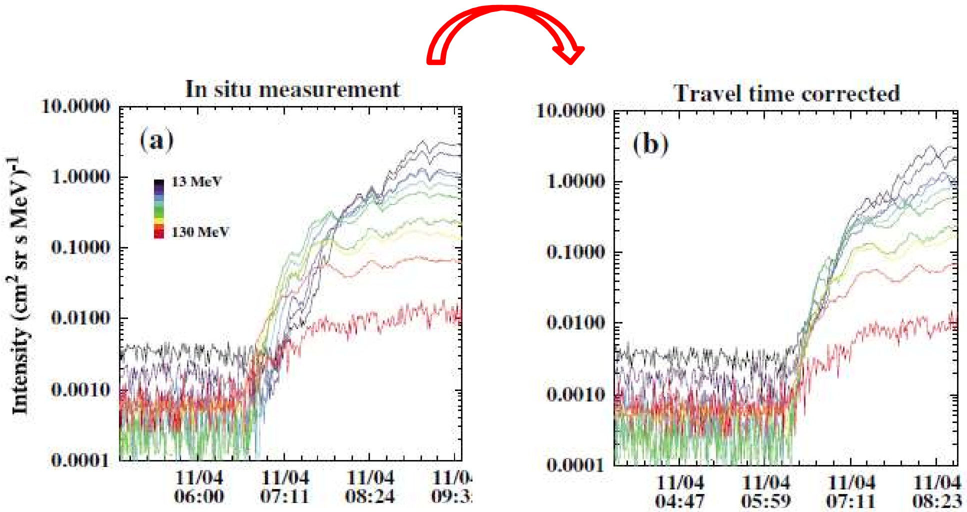
(Zank et al., 2000)

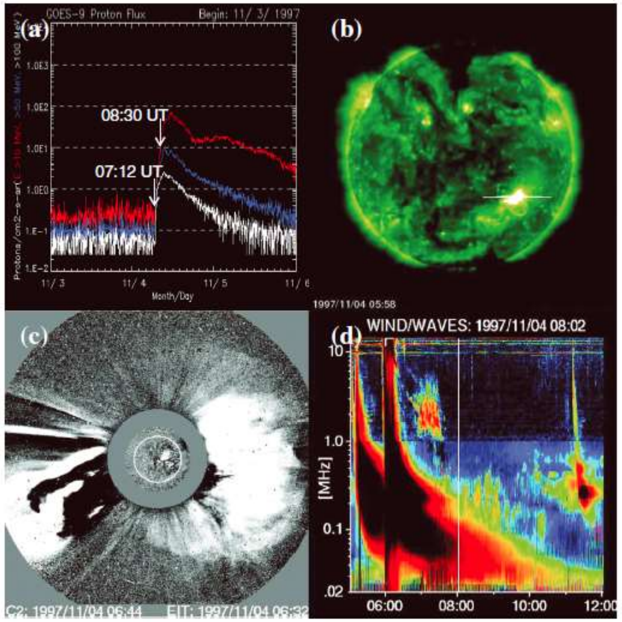
Refined Classification of SPEs (Kim et al., 2014)

- **Data and methods**
  - 42 SPEs observed with SOHO/ERNE multi-energy channel detector from 1997 to 2012
  - Velocity dispersion analysis: estimation of the SPE onset times at the solar vicinity
  - Onset time comparison: SPEs, and associated flares, CMEs, and type II radio bursts.

$$t_{onset} = t_{obs} - t_{tr} + t_c$$

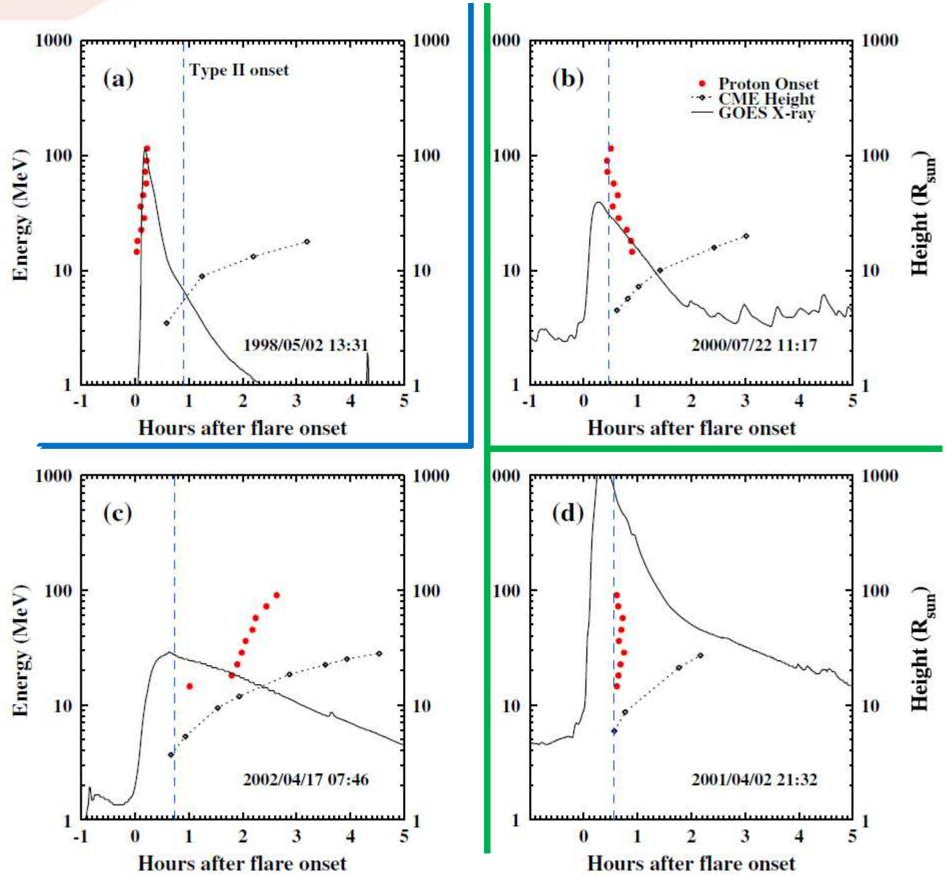
t_c → 8.3 min
L → Path length (Magnetic-field-line length)
v → Proton velocity
corresponding each energy channel
$t_{tr} \propto \beta^{-1} = \frac{c}{v} \rightarrow t_{tr} = t_c$, where v=c

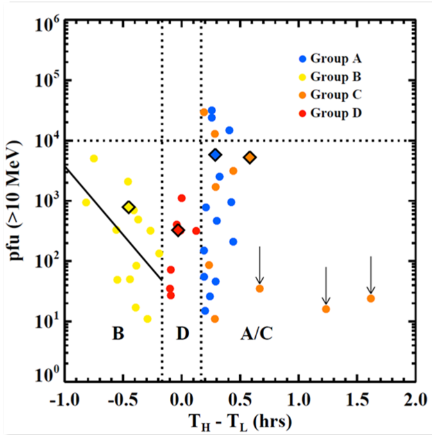




Refined Classification of SPEs (Kim et al., 2014)

- **SPE classification by two criteria of**
  - SPE onset timing relative to flare peak time
  - Flux enhancement sequences ($T_H - T_L$) according the energy levels

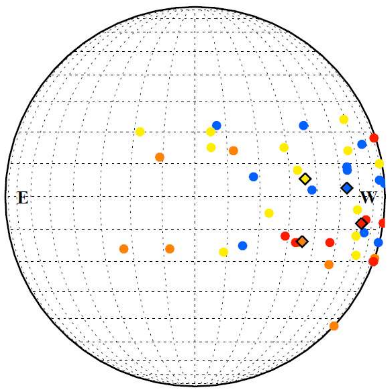


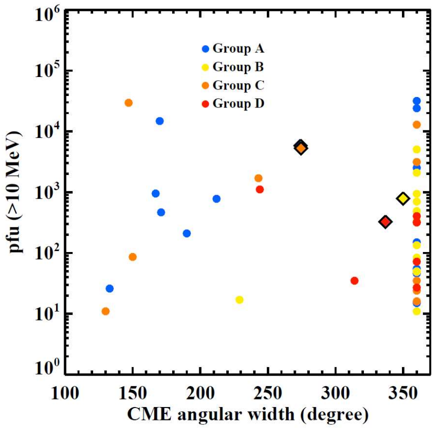


Group	Event #	Association	Acceleration Direction	$T_H - T_L$ (Average)
A	13 (31%)	Flare	Low → High	17 min
B	13 (31%)	CME	High → Low	−26 min
C	9 (21%)	CME	Low → High	35 min
D	7 (17%)	CME	Simultaneous	−1.8 min

Refined Classification of SPEs (Kim et al., 2014)

- **Association with Flare or CME**
  - Flare intensity: no strong dependence
  - Source location
    - ✓ Groups A and D: western limb
    - ✓ Groups B and C: wider distribution
  - Angular width
    - ✓ Groups B and D: full halo CMEs
    - ✓ Groups A and C: mean=274˚
  - CME Speed: Group D is the fastest.

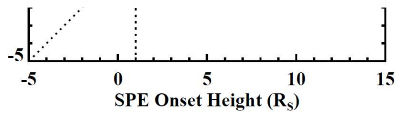




- **Acceleration Heights, H**
  - Based on extrapolation of CME height
    - ✓ H_p: proton acceleration height
    - ✓ H_e: type II burst start height
  - Only for group A, H_p is lower than 1 Rs
    - → No or less relation with CME
  - Groups B and C in beneath the line
    - → Electron accelerates first then proton is later.

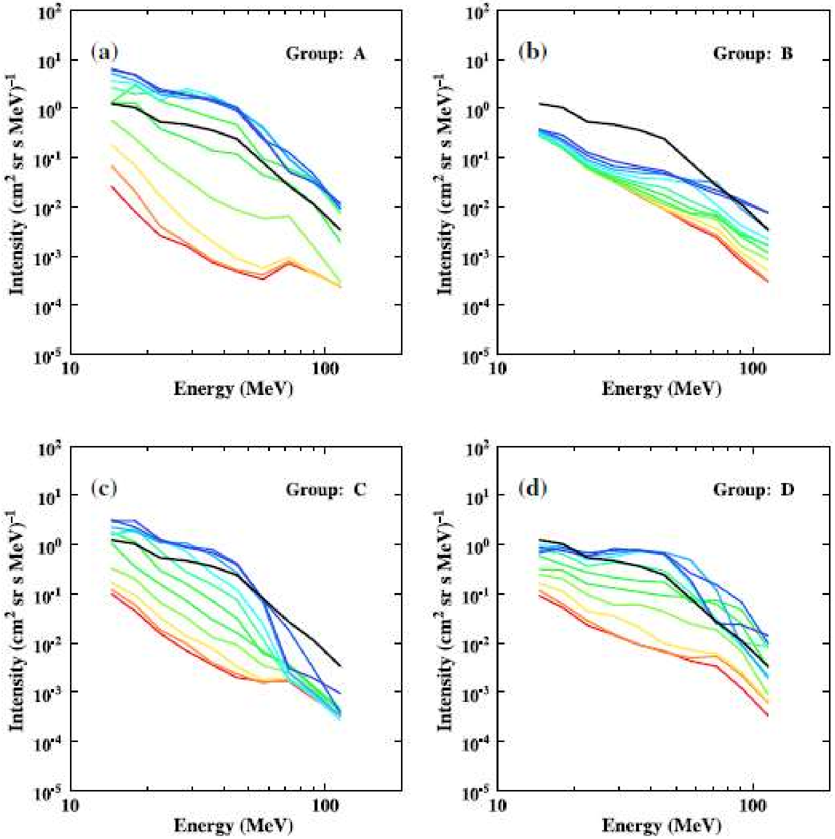
→ For impulsive events, release of GLE particles during the flare X-ray phase, the acceleration occurs at 1.05 Rs (Aschwanden, 2012)

→ Release of GLE particles occurs when the CMEs reach an average height 3 Rs for well-connected events, and 5Rs for poor-connected ones (Gopalswamy et al., 2012)



Refined Classification of SPEs (Kim et al., 2014)

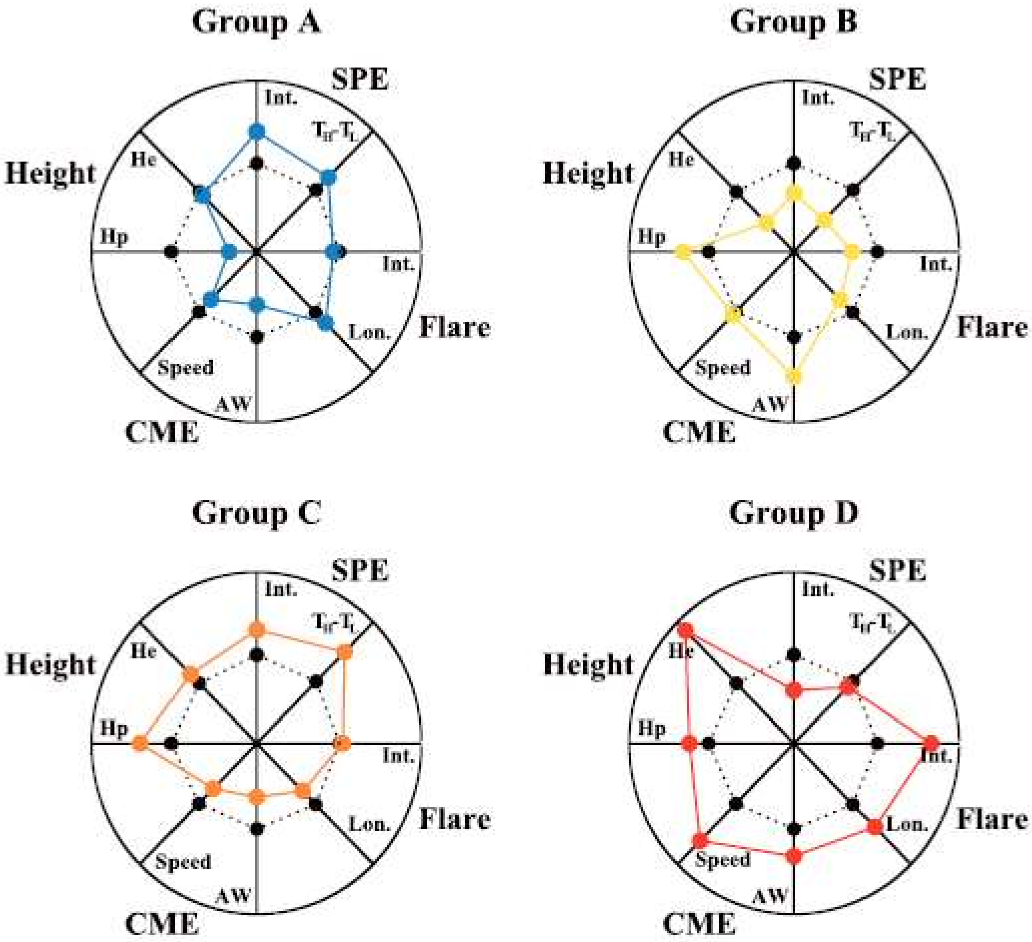
- **Dominant enhancement in energy evolutions**



Group	Event #	Association	Energy Spectrum: Dominant Energy Band	Energy Spectrum: Enhancement
A	13 (31%)	Flare	Low and Middle	$\sim 10^4$
B	13 (31%)	CME	High	$> 10^2$
C	9 (21%)	CME	Low	$\sim 10^3$
D	7 (17%)	CME	Middle and High	$\sim 10^2$

Characteristics of Four SPE Groups (Kim et al., 2015)

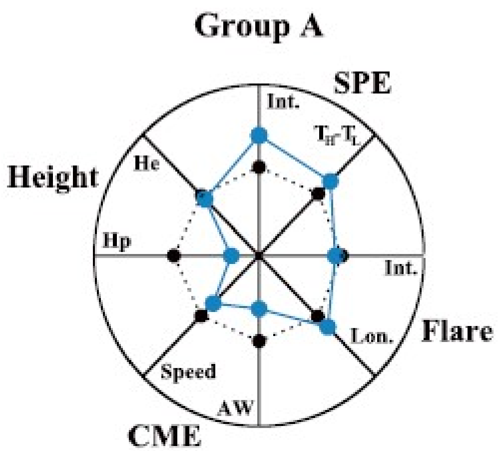
- **Considering parameters**
  - SPE: intensity and energy evolution pattern
  - Flare: intensity and source location
  - CME: angular width and speed
  - Acceleration heights
    - ✓ Proton (SPE)
    - ✓ Electron (Type II)



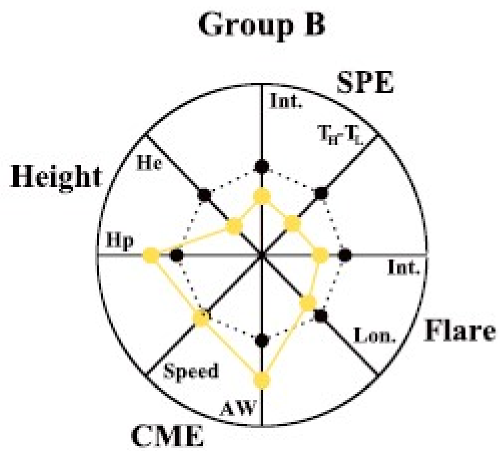
- **General**
  - Group A and C include strong SPEs
  - Group D has weak SPEs

Characteristics of Four SPE Groups (Kim et al., 2015)

- **Group A (Flare-associated reconnection)**
  - Proton flux increases during the flare X-ray intensity is increasing .
  - Large flux enhancements starting from the lower energy in relatively short time
  - Strong SPE flux in spite of week X-ray intensity.
  - Its CME properties of speed and angular width are also weaker than average values and low acceleration height and western biased longitudes.

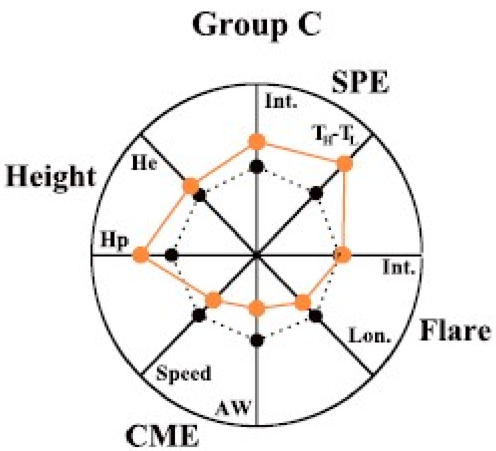


- **Group B (CME-driven shock)**
  - Well coincident onsets with the first appearance of CMEs in LASCO FOV.
  - Relatively weak and slow flux enhancements
  - Weak flare and SPE intensities, but wide angular width and fast speed with higher proton acceleration site and wider longitude of flaring site.

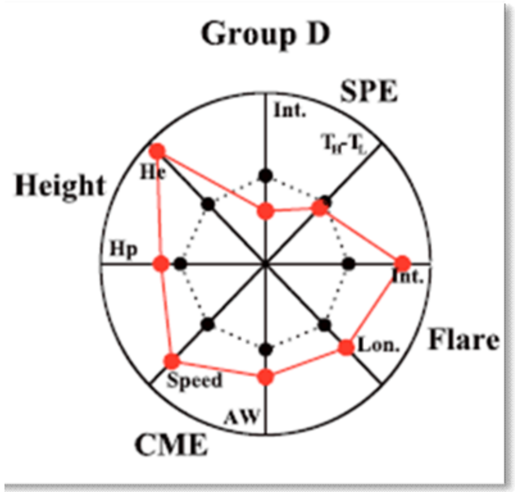


Characteristics of Four SPE Groups (Kim et al., 2015)

- **Groups C (CME-associated reconnection?)**
  - Well coincident onsets with the first appearance of CMEs in LASCO FOV.
  - Relatively weak and slow flux enhancements
  - Strong SPE intensity in spite of weak flare and CME.



- **Group D**
  - Immediate flux enhancement in all energy channels within ~2 m
  - Association with very strong flares and CMEs.
  - Acceleration sites of proton and electron are relatively higher.
  - However the proton intensity is very weak.



Summary

- **If the proton acceleration starts from a lower energy (Group A and C),**
  - → A SPE has a higher chance to be a strong event (> 5000 pfu) even if the associated flare and CME are not so strong.
  - Group A: acceleration sites are very low (~1 Rs) and close to the western limb.
  - Group C: relatively higher (mean=6.05 Rs) and wider acceleration sites.

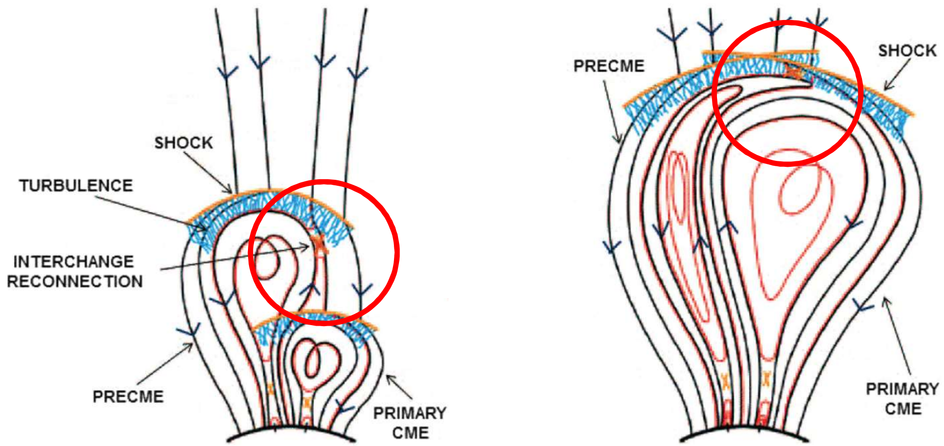
- **When the proton acceleration starts from the higher energy (Group B),**
  - → A SPE tends to be a relatively weak event (< 1000 pfu), in spite of its associated CME is relatively stronger than previous group.

- **SPEs with simultaneous acceleration in whole energy range within 10 minutes (Group D)**
  - → Acceleration heights are very close to the locations of type II radio bursts.
  - → Weakest proton flux (mean=327 pfu) in spite of strong related eruptions.

Hybrid Events as the Third Class of SEPs

- **Hybrid or mixed events (Kallenrode, 2003)**
  - Observations have indicated that there are ‘hybrid’ or ‘mixed’ event cases, where both mechanisms appear to contribute, with one accelerating mechanism operating in the flare while the other operates at the CME-driven shock.

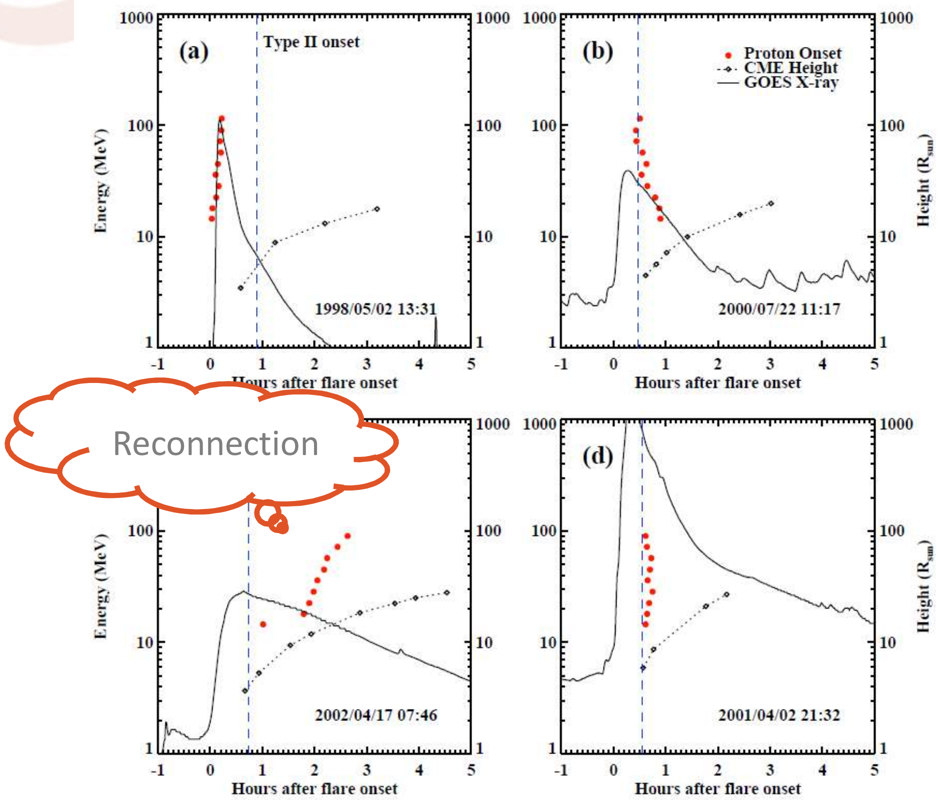
- **Possible scenarios**
  - Re-acceleration
    - ✓ Of remnant flare supra-thermals by shock waves (Mason et al., 1999; Desai et al., 2006)
    - ✓ From the interaction of CMEs (Gopalswamy et al., 2002)
    - ✓ In a magnetic interchange reconnection region of multi-CMEs (Ding et al., 2013)

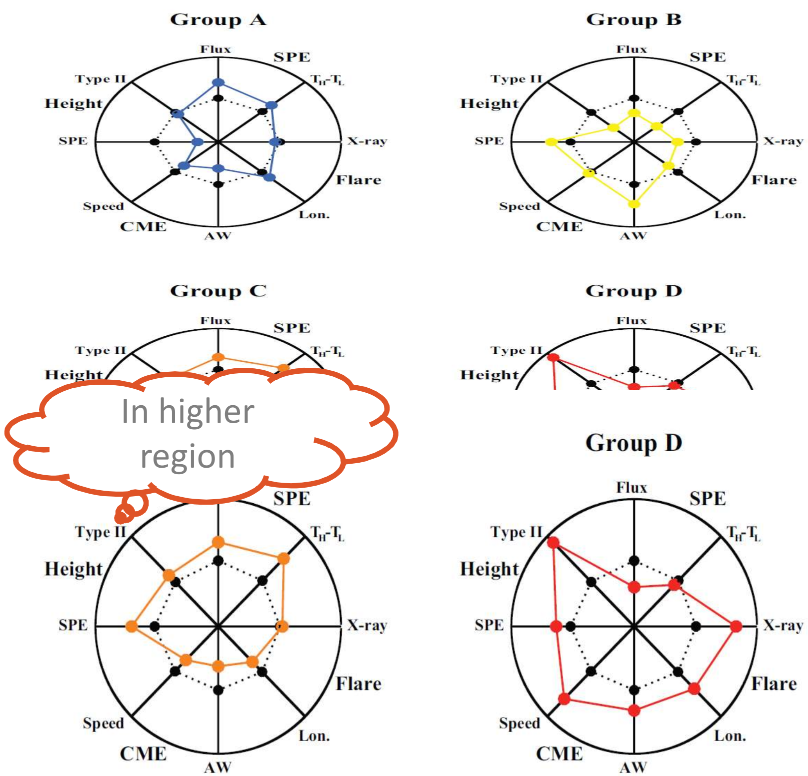


Li et al., (2012)

Hybrid Events as the Third Class of SEPs

- **Reconnection process in higher region**



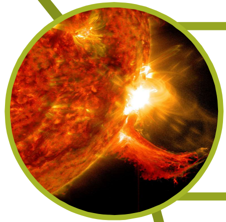


2+1 classes of SEPs (?)

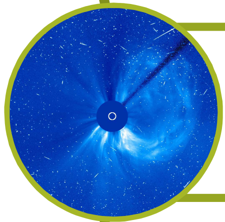
- **Further studies are needed.**
  - We checked
    - ✓ Energy evolution (acceleration mechanisms)
    - ✓ Related solar eruption (source heights)
  - We need to check
    - ✓ Type III relationship
    - ✓ Composition
    - ✓ And so on …

Remarks

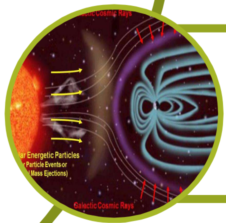
Unsolved Questions



Origins : seed populations and physical conditions necessary for energetic particle acceleration



Acceleration: role of shocks, reconnection, waves and turbulence in accelerating energetic particles

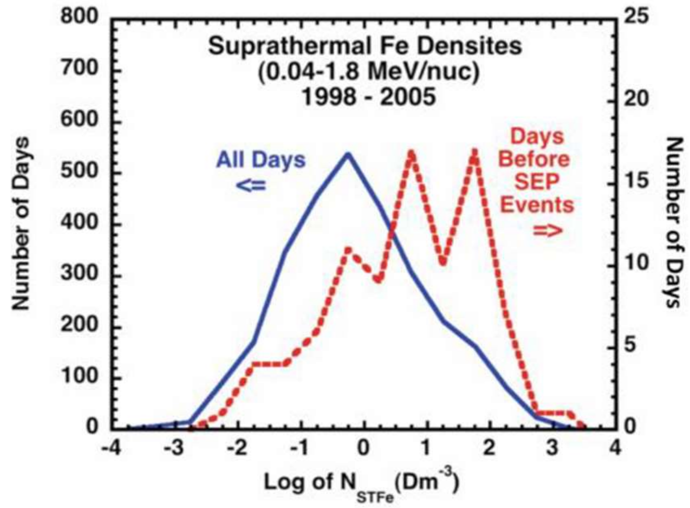


Transport: how energetic particle propagate from the corona out into the heliosphere.

Seed Population

- **Presence or absence of pre-events**
  - The intensity of ambient energetic particles originated from impulsive flares or preceding CMEs can be another deciding factor for the generation of a large SEP event as the enhanced seed population is leading to a more efficient shock acceleration process (Kahler et al., 2000).

- **Pre-existing Suprathermal Density**
  - The suprathermal Fe densities are significantly greater before the occurrence of these large SEP events with respect to all other days, strongly suggesting the large fluences of Fe in SEP events only occurred when there was a pre-existing high density of suprathermal Fe (Mason et al., 1999; Dasai et al., 2006).

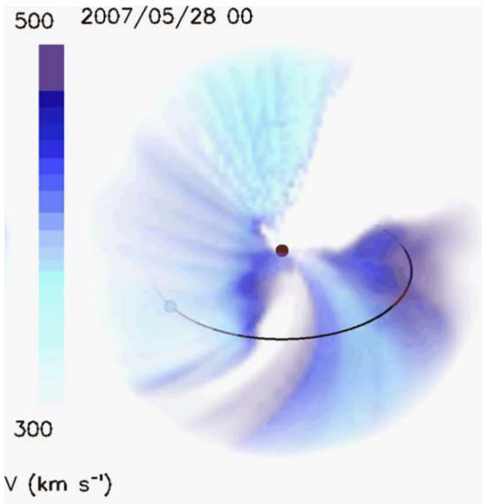


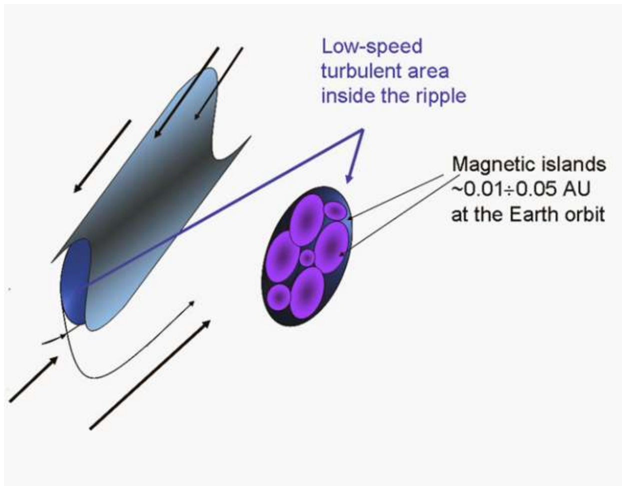
- **For 59 western large SEPs and 67 no SEPs in solar cycle 23 (Ding et al., 2014)**
  - 73% of SEPs (43/59) have preceding CMEs with V >300 km/s within 9 hr.
  - Twin-CME leading to a large SEP event is 61% (43/71)
  - Single fast CME leading to a large SEP events is 29% (16/55)

	SEPs	No SEPs	Total
Twin-CME	43	28	71
Single-CME	16	39	55
Total	59	67	126

Small Scale Magnetic Islands

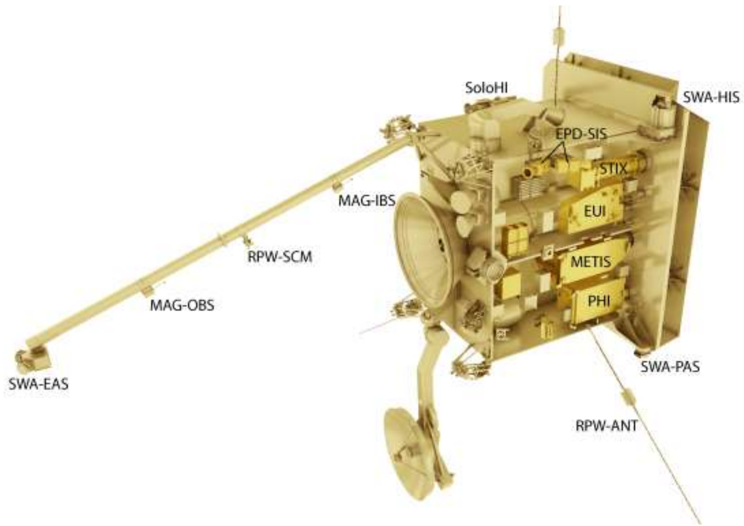
- Small-scale magnetic islands inside the ripples of the HCS (Khabarova et al., 2015; 2016)
  - Magnetic islands experience dynamical merging in the solar wind and that increases of energetic particle fluxes in the keV-MeV range and the interaction of ICMEs with the heliospheric current sheet (HCS) can lead to significant particle acceleration due to plasma confinement.
  - The rippled structure of the HCS, which confines plasma, can make energization of particles trapped inside small-scale magnetic islands.
  - → Although initial particle acceleration due to magnetic reconnection at the HCS may be insufficient to obtain high energies, the presence of magnetic islands inside the ripples of the HCS or between two CSs with a strong guide field offers the possibility of re-accelerating particles.





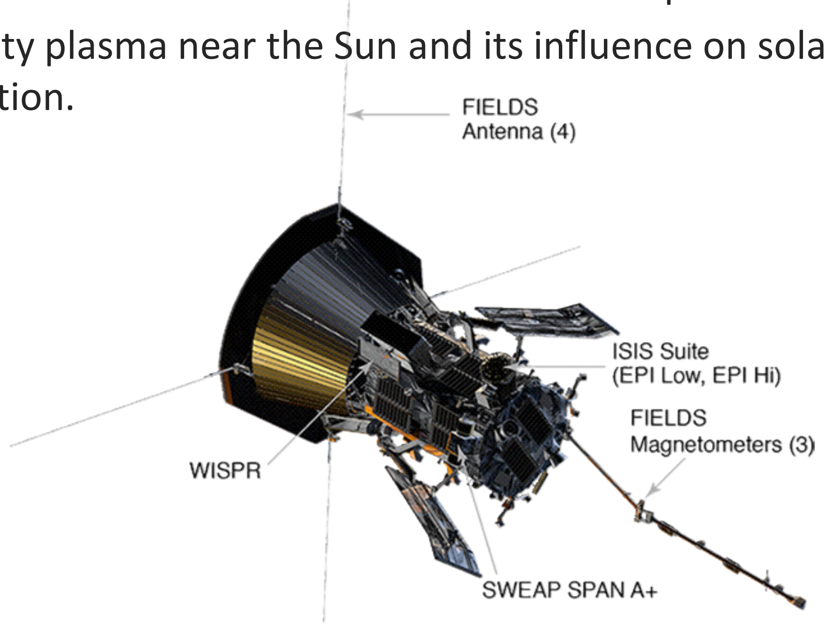
Future Projects to Understand SEPs

- Solar Orbiter (SolO: ESA/NASA, 2019)
  - It will operate both in and out of the ecliptic plane. Solar Orbiter will measure solar wind plasma, fields, waves and energetic particles close enough to the Sun to ensure that they are still relatively pristine.
  - Scientific Goal: how do solar eruptions produce energetic particle radiation that fills the heliosphere
    - ✓ What are the seed populations for energetic particles?
    - ✓ How and where are energetic particles accelerated at the Sun?
    - ✓ How are energetic particles released from their sources and distributed in space and time?



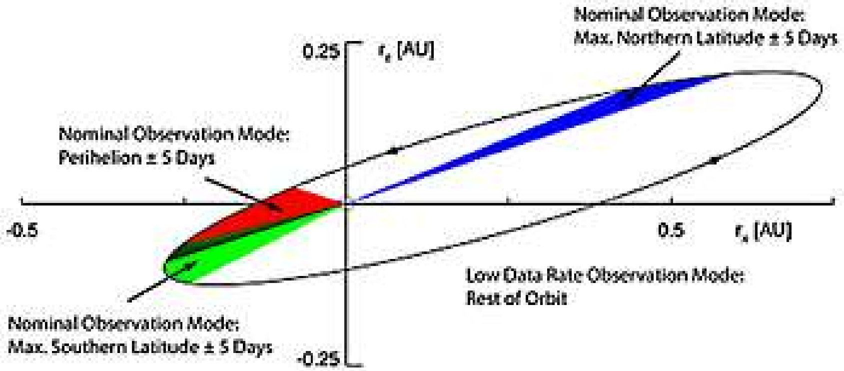
Future Projects to Understand SEPs

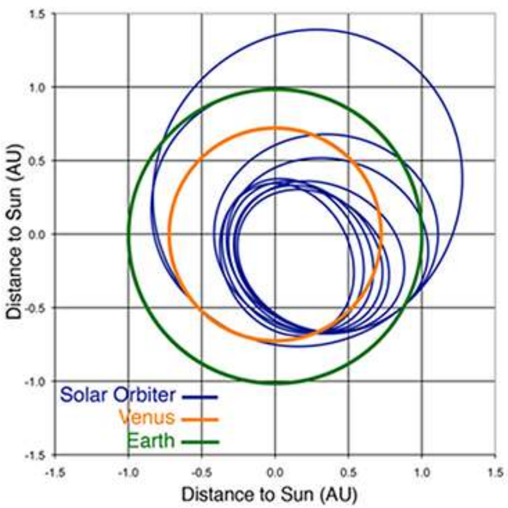
- Parker Solar Probe (former Solar Probe Plus: NASA, 2018)
  - Not only to unlock the mysteries of the corona, but also to protect a society that is increasingly dependent on technology from the threats of space weather.
  - Scientific goals
    - ✓ To determine the structure and dynamics of the magnetic fields at the sources of solar wind.
    - ✓ To trace the flow of energy that heats the corona and accelerates the solar wind.
    - ✓ To determine what mechanisms accelerate and transport energetic particles.
    - ✓ To explore dusty plasma near the Sun and its influence on solar wind and energetic particle formation.



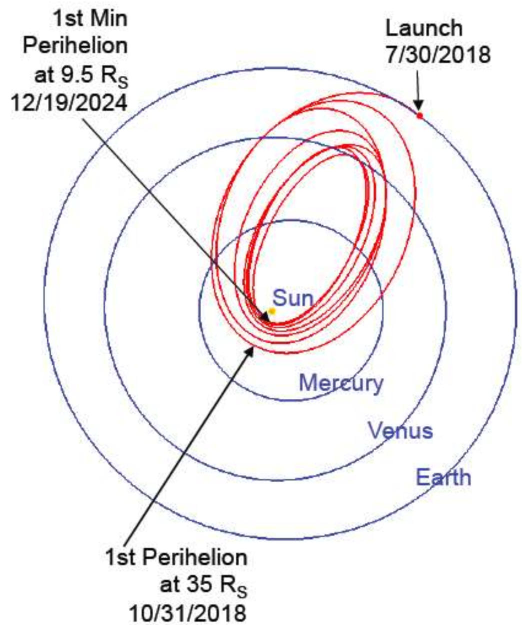
Future Projects to Understand SEPs

- Solar Orbiter
  - Orbit closely to the perihelion and high inclination





- Parker Solar Probe
  - Fly within 9 Rs of the Sun's surface.



Thank You

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Korea Astronomy & Space Science Institute