SOLAR ENERGETIC PARTICLES: OBSERVATIONS, THE FLARE-CME ORIGIN AND CATALOGS

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Acknowledgements

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DNTS-Russia 01/6 (23-Jun-2017)

CONTENTS

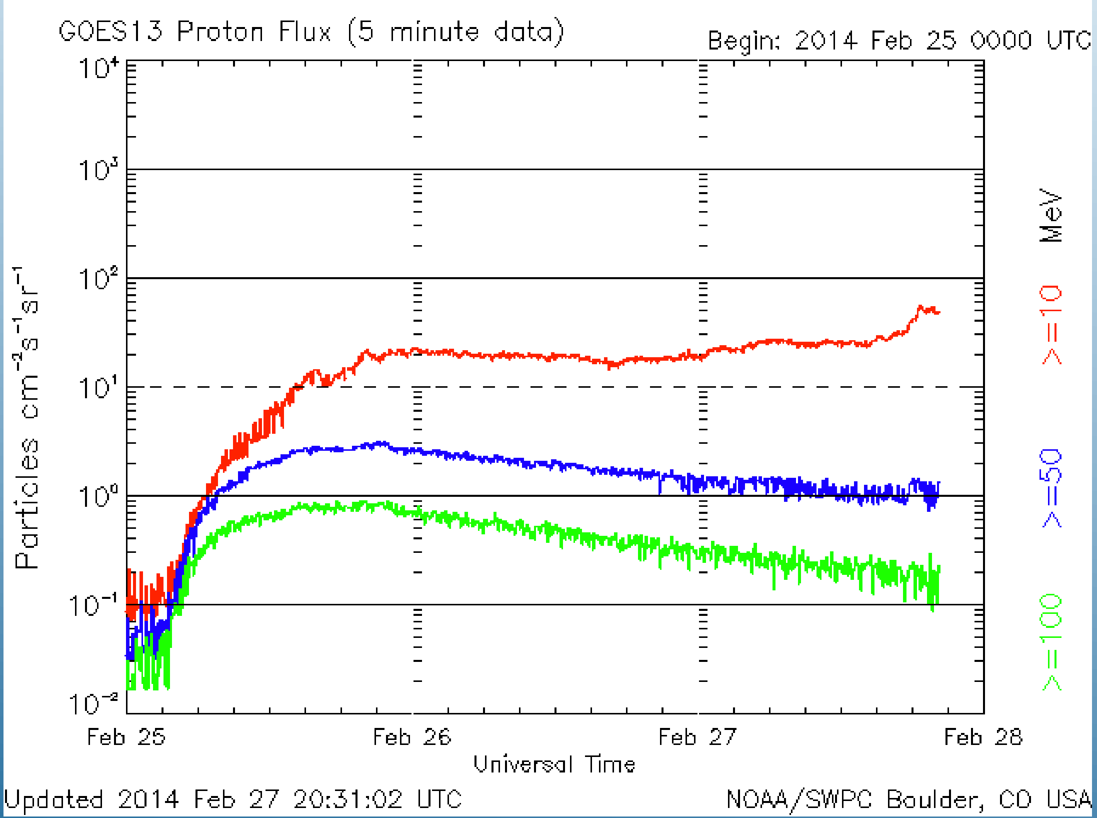
Selected reviews

- M. Desai and J. Giacalone (2016), Large gradual solar energetic particle events, Living Reviews in Solar Physics, Volume 13, Issue 1, article id. 3, 132 pp. https://link.springer.com/article/10.1007%2Fs41116-016-0002-5
- K.-L. Klein and S. Dalla (2017), Acceleration and Propagation of Solar Energetic Particles, Space Science Reviews, Volume 212, Issue 3-4, pp. 1107-1136, https://link.springer.com/article/10.1007%2Fs11214-017-0382-4
- HESPERIA book (2018), https://www.springer.com/gp/book/9783319600505, https://link.springer.com/book/10.1007%2F978-3-319-60051-2
- R. Schwenn (2006, 2010), 'Space Weather: The Solar Perspective', Living Rev. Solar Phys.
- T. Pulkkinen (2007), 'Space Weather: Terrestrial Perspective', Living Rev. Solar Phys.

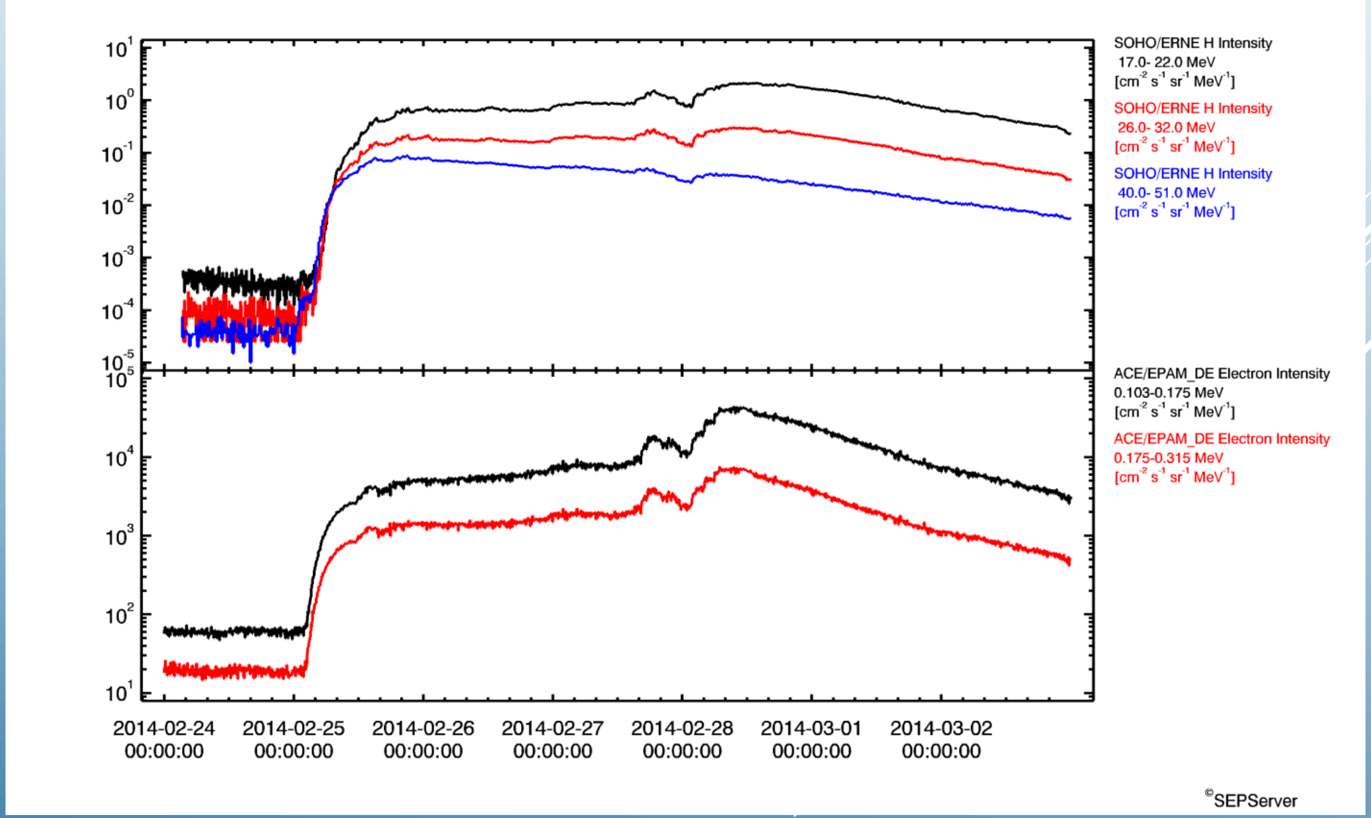
Solar energetic particles (SEPs)

→ protons (10s keV – GeV), electrons (keV) and heavy ions (MeV) with solar origin

→ follow in time solar activity and show velocity dispersion trends

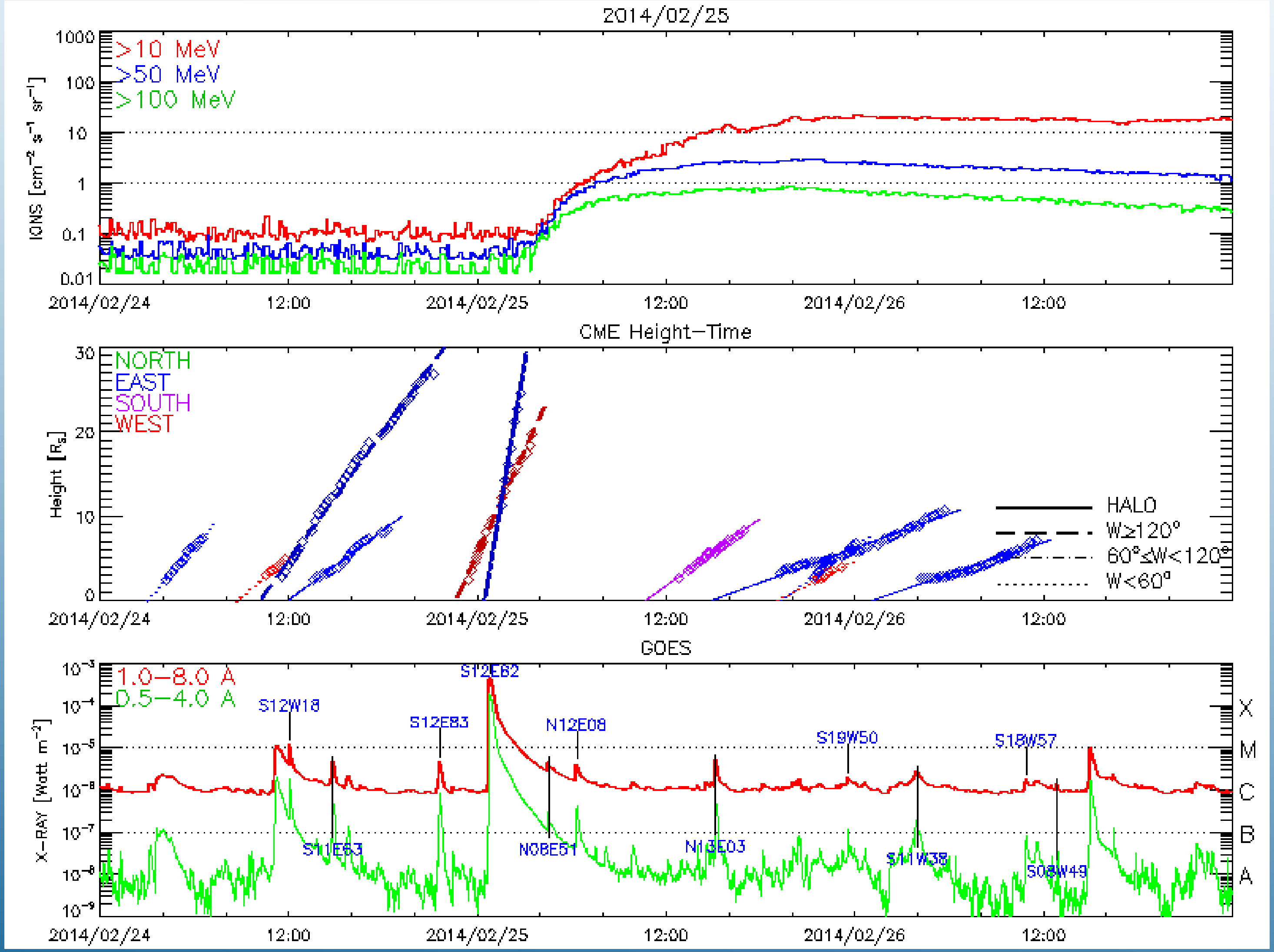


www.solarmonitor.org



server.sepserver.eu

Solar origin: flares and coronal mass ejections



Association criteria:

→ Strongest flare-CME pair prior the SEP onset

→ SEP profile shape

Western origin: fast rising

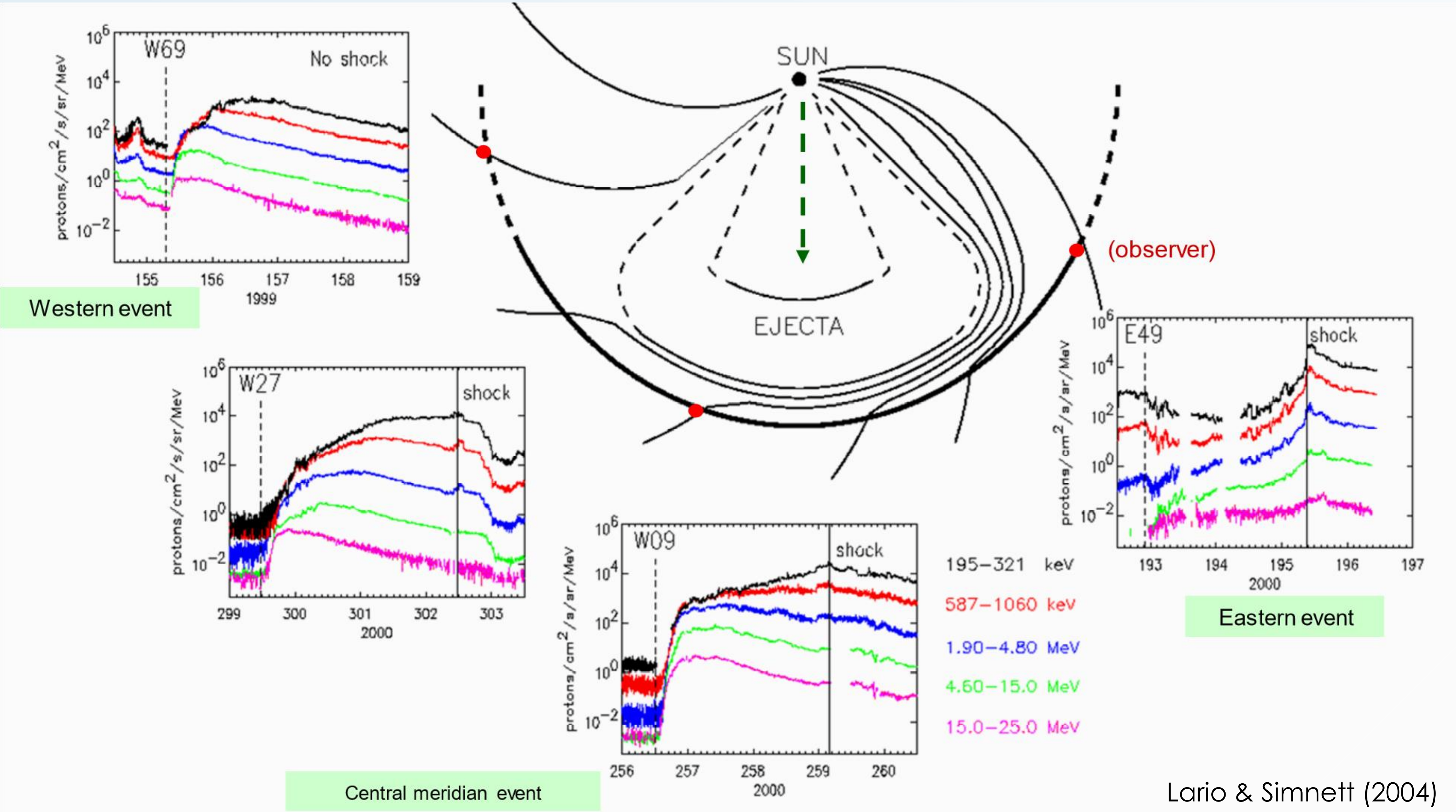
East origin: slowly rising

SOHO LASCO CME CATALOG

YEAR	MONTH											
1996	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1998	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2003	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2005	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2006	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2008	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2009	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2010	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2011	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2012	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2013	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2014	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2015	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2016	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2017	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

https://cdaw.gsfc.nasa.gov/CME_list/daily_plots/sephtx/2014_02/sephtx_20140225.png

Longitudinal variation SEP profile: Earth's perspective



Lario & Simnett (2004)
ACE & IMP-8

Longitudinal variation SEP profile: Earth & STEREO view

Western origin: fast rising
East origin: slowly rising, long durations, lower intensities

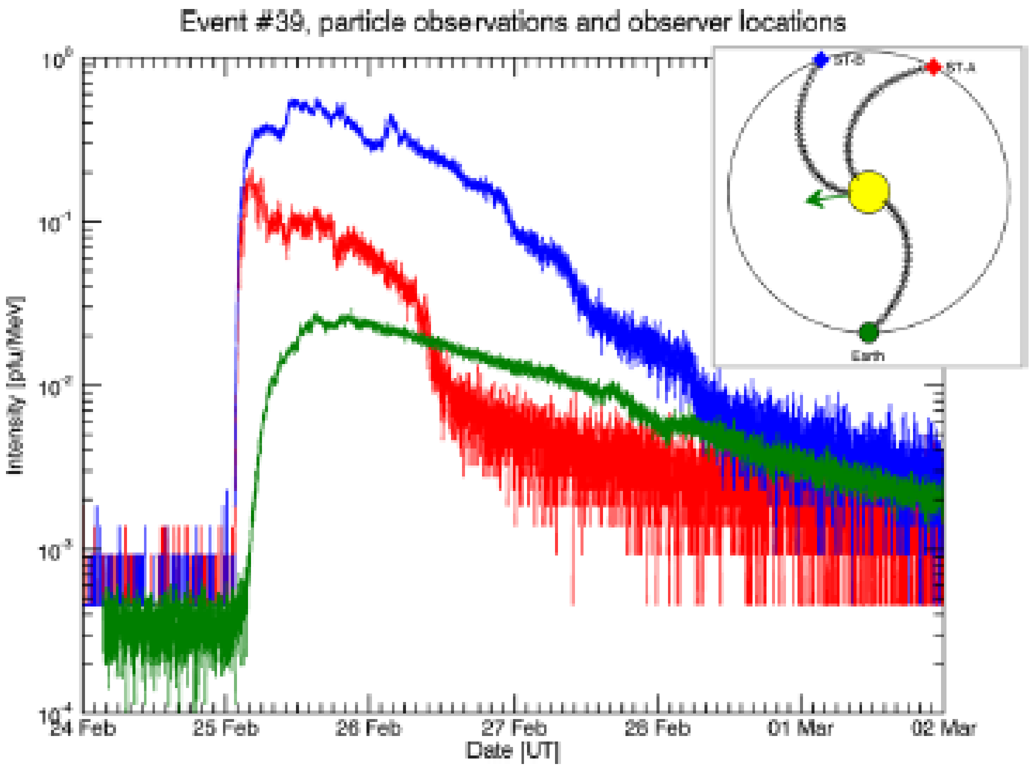


Figure 1 Detected proton intensities (*red* = STEREO-A/HET, *blue* = STEREO-B/HET, *green* = SOHO/ERNE) during event 39 (25 February 2014). *Inset*: relative locations of the STEREO spacecraft and the Earth during the event. The *arrow* pointing out from the Sun shows the location of the event-related flare (at E82), and the *asterisks* mark the nominal Parker spiral magnetic field lines connecting each observer to the Sun.

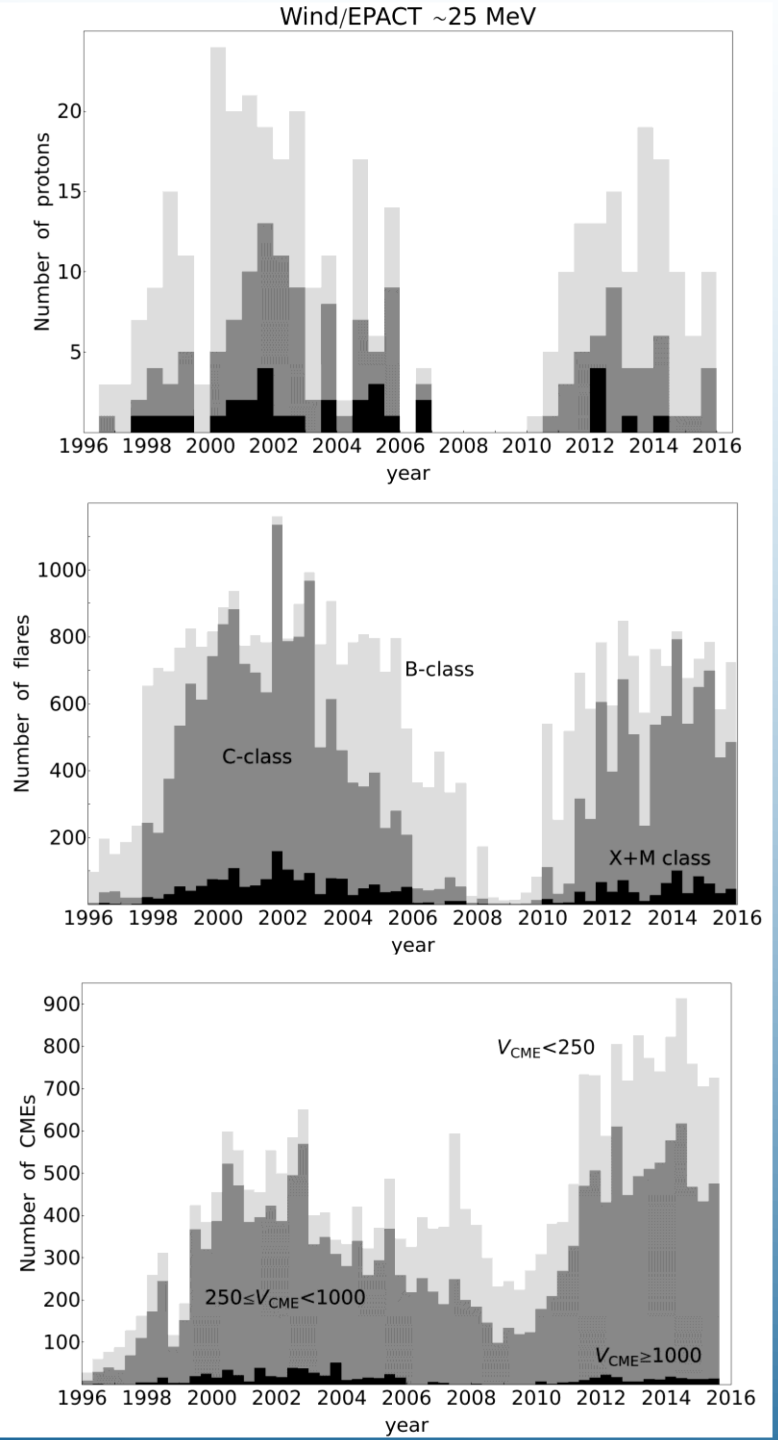
Paassilta et al. (2018)

Solar cycle variation

SEP yearly distribution follow in time the distribution of solar eruptive phenomena (flares and CMEs)

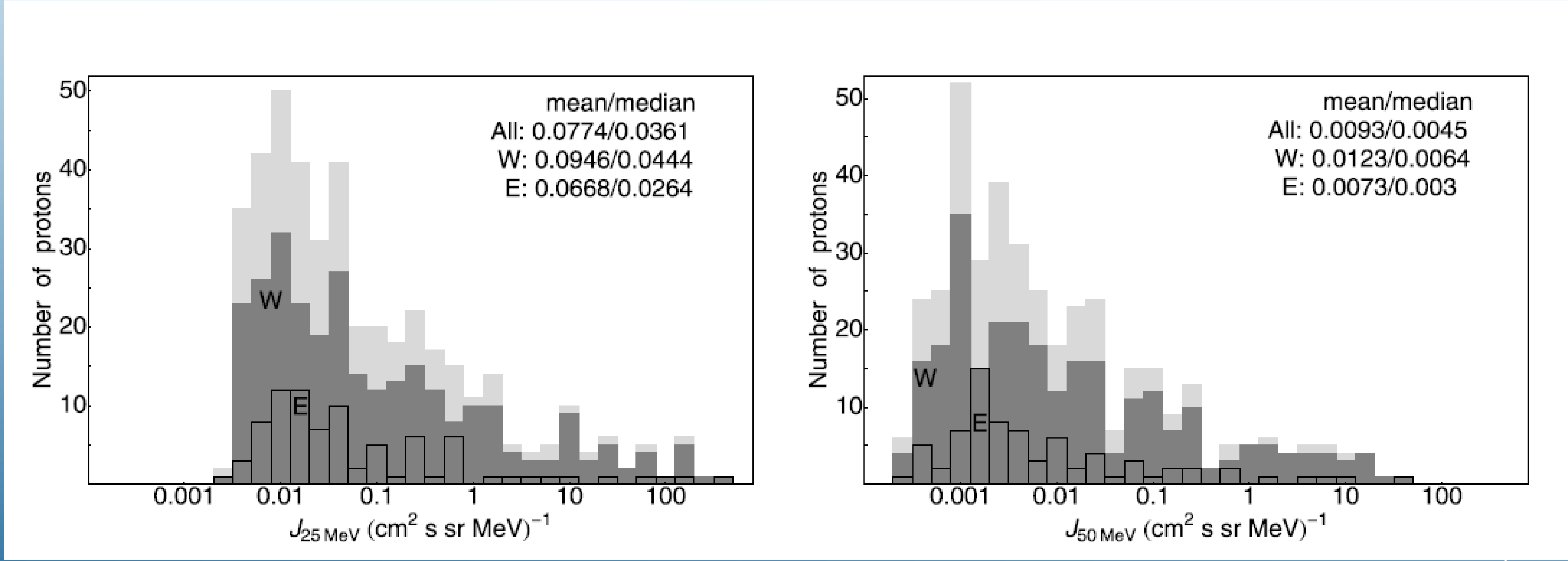
Decreasing trend:
all SEPs (25%, small SEPs – 65 %, large SEPs),
all flares (33%, c-class to 44%, X-class) and
all CMEs (33% ***increase*** for slow CMEs, but 46% drop for faster than 1000 km/s) in SC24 compared to SC23.

Miteva et al. (Sun&Geosphere 2017),
http://newserver.stil.bas.bg/SUNGEO/



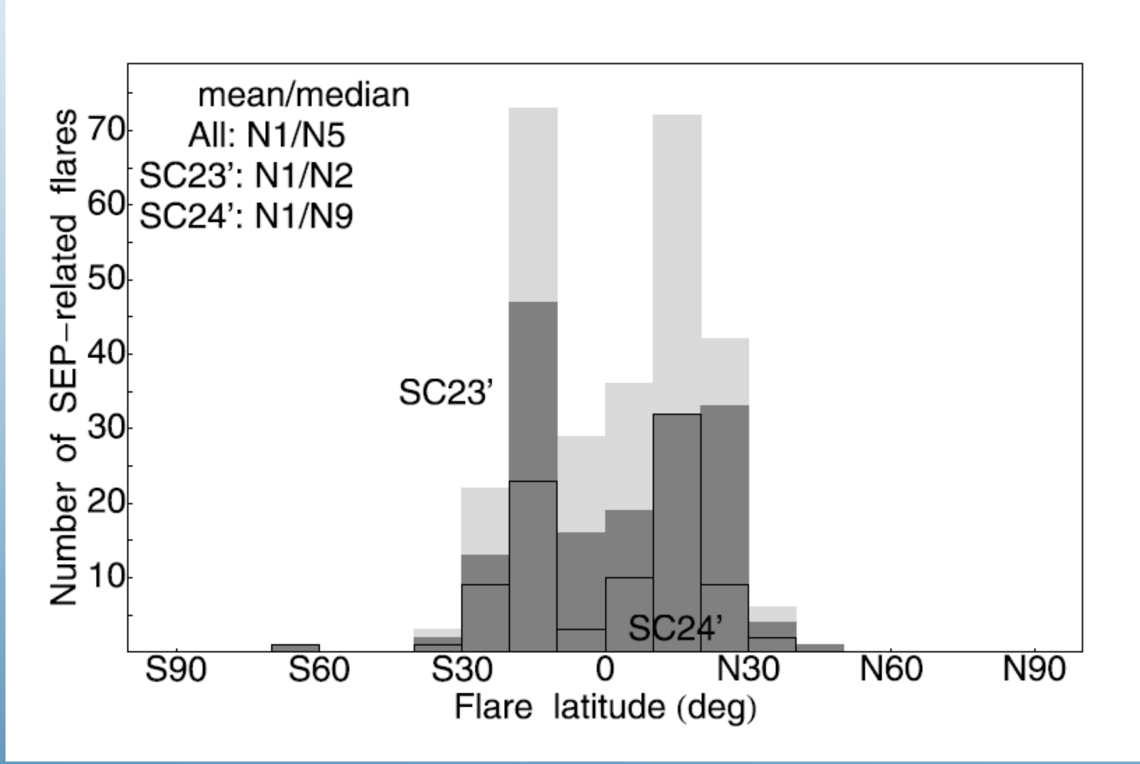
II. OBSERVATIONS WHAT IS KNOWN

70-to-30 % dominance of western origin events



Miteva et al. (2018), Wind/EPACT catalog

Southern (SC23) to northern (SC24) hemisphere asymmetry



Miteva et al. (2018), Wind/EPACT catalog
for strong SEPs: SC23 – southern; SC24 – northern

Chandra et al. (2013)
SC23 rise – southern source region
SC24 rise – northern

Garcia (1990): SC20, SC21
Joshi & Joshi (2004): SC21, SC22 (north), SC23 (south)

Multi-spacecraft observations

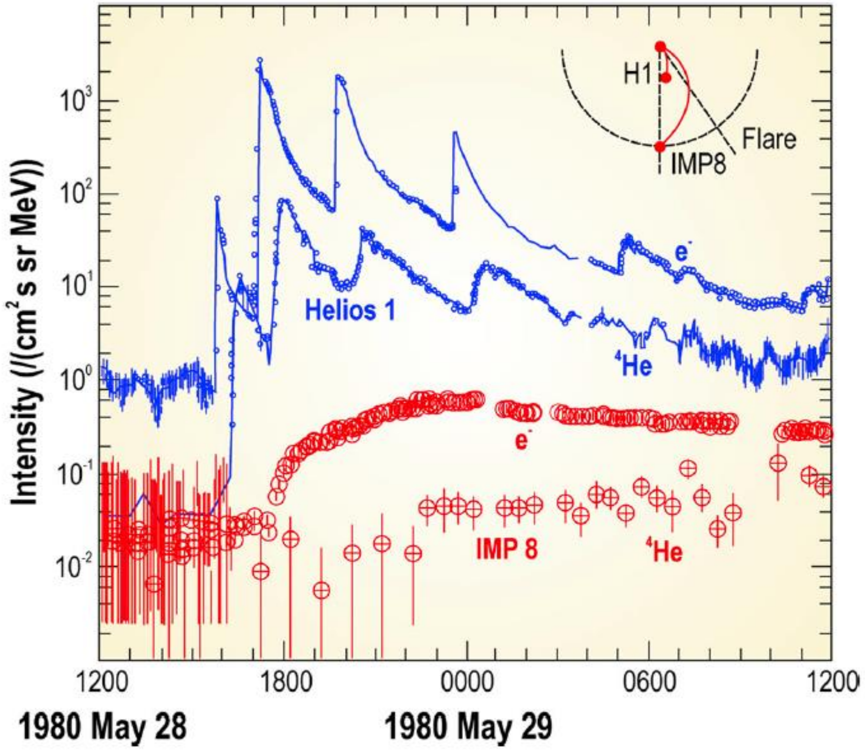


Fig. 68 Electron (e) and He (α) time profiles from Helios 1 (0.3 AU) and IMP 8 (1 AU) during five SEP events in 1980. Magnetic connections to the flare site are indicated at *upper right*. Helios 1 observed five separate injections, while IMP 8 observed only one. Future missions, SPP and SolO, will enable us to separate the effects of transport by making key near-Sun measurements where SEP acceleration takes place. Image adapted from Wibberenz and Cane (2006)

Desai & Giacalone (2016)

Dalla et al. (2003)

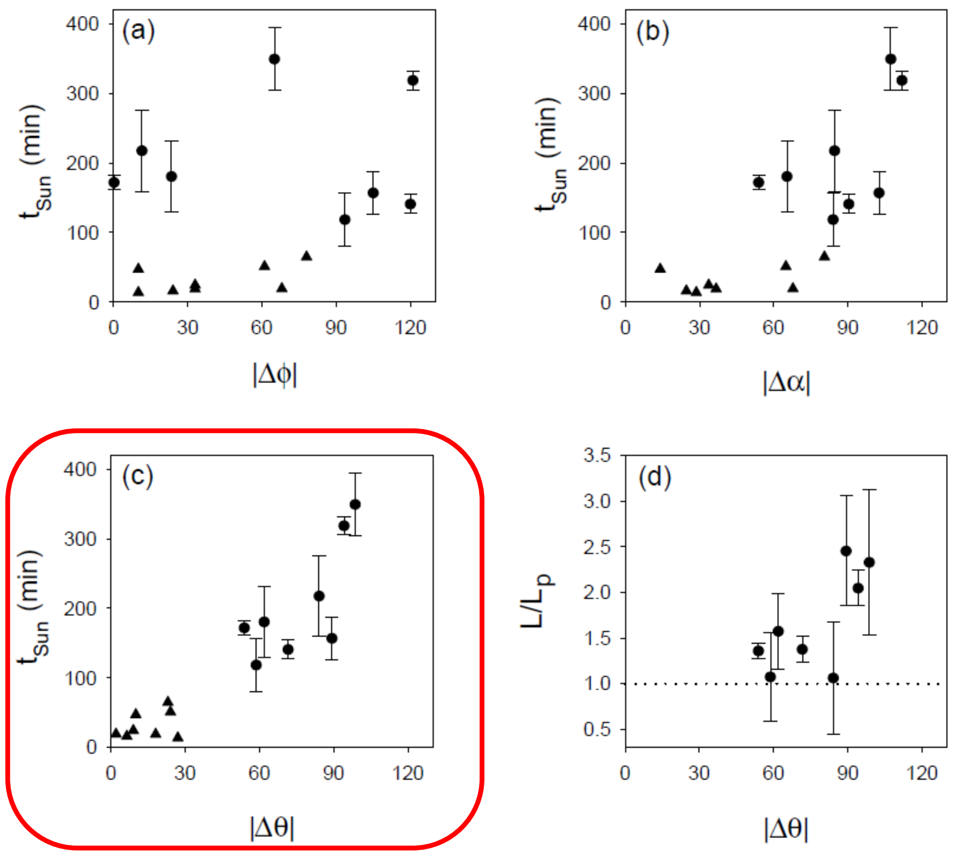


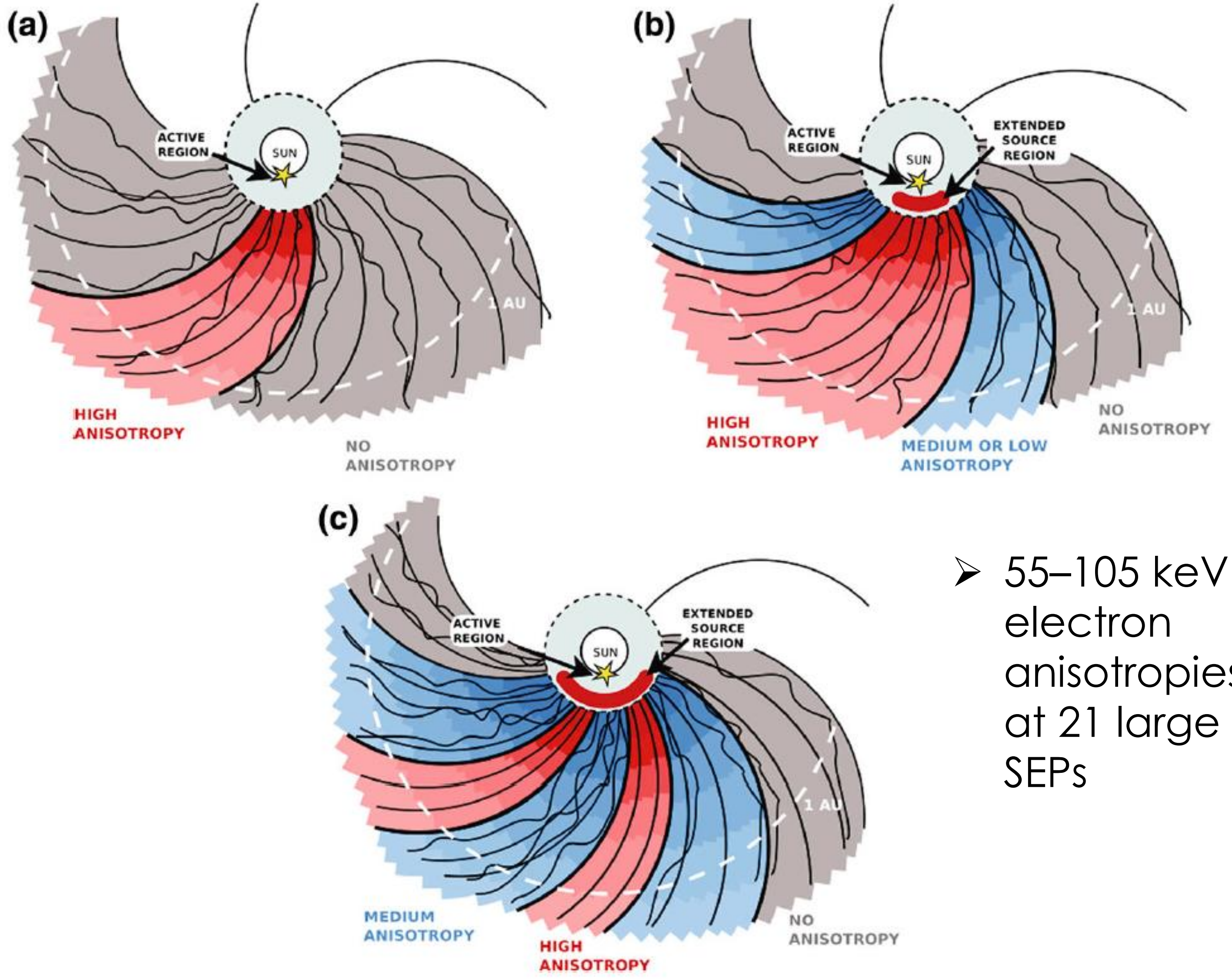
Fig. 6. Release time t_{Sun} versus angular separations between the spacecraft footpoint and the flare locations. Circles are Ulysses data points and triangles are Wind data points. **(a)** t_{Sun} versus difference in longitudes $|\Delta\phi| = |\phi_{footpt} - \phi_{flare}|$; **(b)** versus great circle angular separation $|\Delta\alpha|$ between footpoint and flare; **(c)** versus difference in latitude $|\Delta\theta| = |\theta_{footpt} - \theta_{flare}|$. Also given in panel **(d)** is the ratio L/L_p versus $|\Delta\theta|$. Plots are given for only 8 SEP events because the flare location was not known for 1 event.

Multi-spacecraft observations

a) Flare injection into narrow region

b) CME injection into IP space over broad region near the Sun

c) CME injection near the Sun with cross-field diffusion or CME/IP structures interactions



- 55–105 keV electron anisotropies at 21 large SEPs

Fig. 56 Three possible causes of the large longitudinal spread of SEP events as observed by the STEREO s/c. Image reproduced with permission from Dresing et al. (2014), copyright by ESO

Desai & Giacalone (2016)

Solar origin: impulsive vs. gradual SEP classification

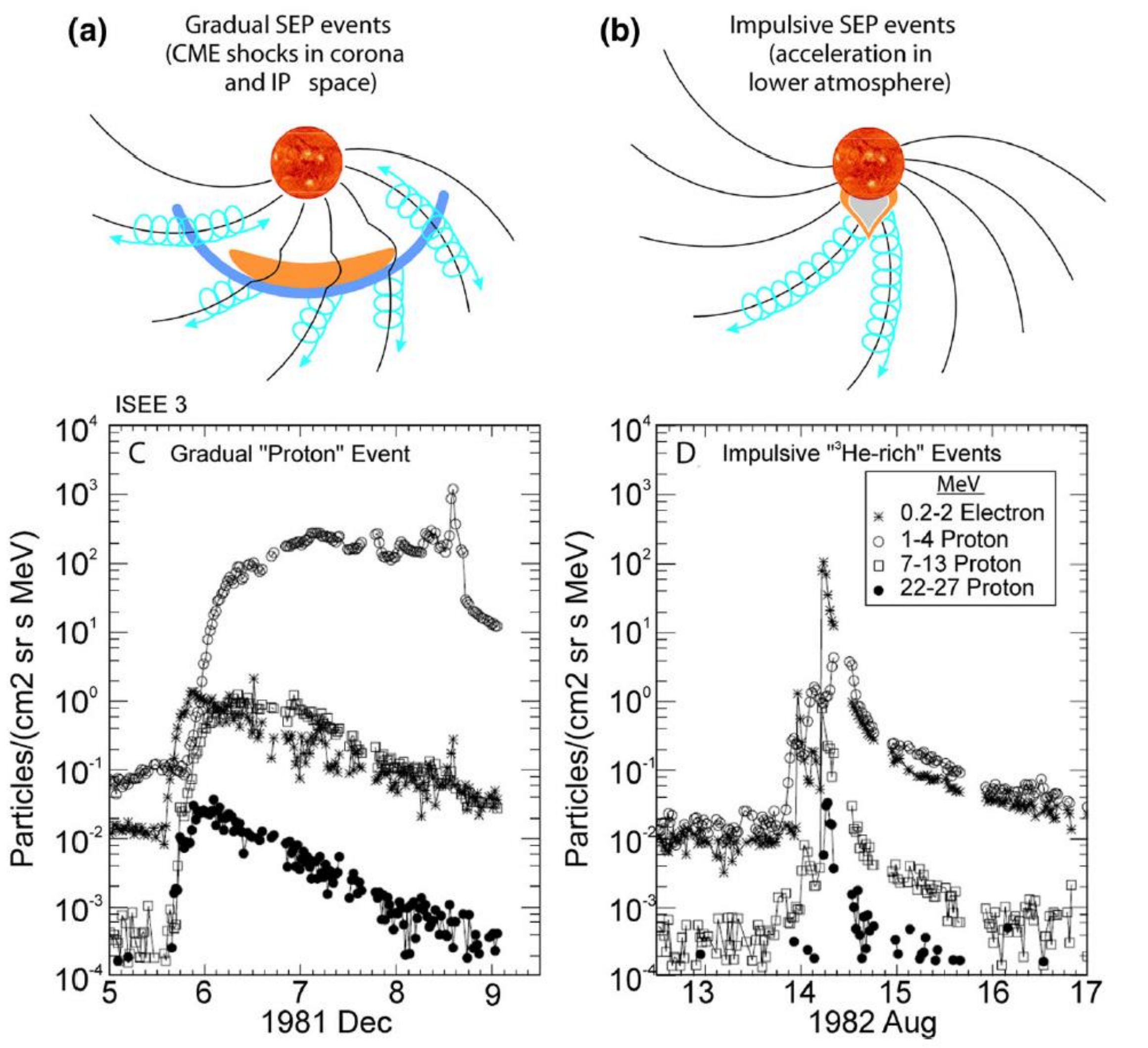


Fig. 3 The two-class picture for SEP events where **a** the gradual event is produced by a large-scale CME-driven shock wave that accelerates the SEPs and populates interplanetary magnetic field (IMF) *lines* over a large longitudinal area, and **b** the impulsive event is produced by a solar flare that populates only those IMF lines well-connected to the flare site. Intensity-time profiles of electrons and protons in **c** a large gradual SEP event, and **d** a small impulsive SEP event (adapted from Reames 1999)

Desai & Giacalone (2016)

Solar origin: impulsive vs. gradual SEP classification

Table I: Two-class Paradigm for SEP Events

	IMPULSIVE	GRADUAL
Particles:	Electron-Rich	Proton-Rich
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
H/He	~10	~100
Q_{Fe}	~20	~14
Duration	Hours	Days
Longitude Cone	< 30°	~ 180°
Radio Type	III,V (II)	II, IV
X-Rays	Impulsive	Gradual
Coronograph	—	CME
Solar Wind	—	IP Shock
Events/Year	~1000	~10

Reames (1999, 2013) & Cliver (2009)

Table II: Revised SEP Event Classification[a]

	Flare	Shock	
		Quasi-Perp	Quasi-Par
H Upper Limit[b]	~3 pr	~10^3 pr	~10^4 pr
e/p[b]	~10^2-10^4	~100	~50
$^3He/^4He$[c]	~10^3-10^4	~10^1-10^2	~1
Fe/O[d,e]	~8	~3	<1
Z(>50)/O[d,f]	~10^2-10^3	~10^{-1}-10^1	~10^{-1}-10^1
Ion Spectra[g]	—	Power-law	Exp. Rollover
QFe[h]	~20	~20	~11
SEP Duration	<1-20 hr	~1-3 days	~1-3 days
Longitude Cone[i]	<30-70°	~100°	~180°
Seed Particles	N/A	Flare STs	Coronal STs
Radio Type[j]	III	II (III)	II (III)
X-ray Duration	10-60 min	~1 hr	>1 hr
Coronagraph[k]	*	CME	CME
Solar Wind	—	IP Shock	IP Shock

Plateau-like distribution of SEPs Cane et al. (2010)

Ion charge, composition, abundances

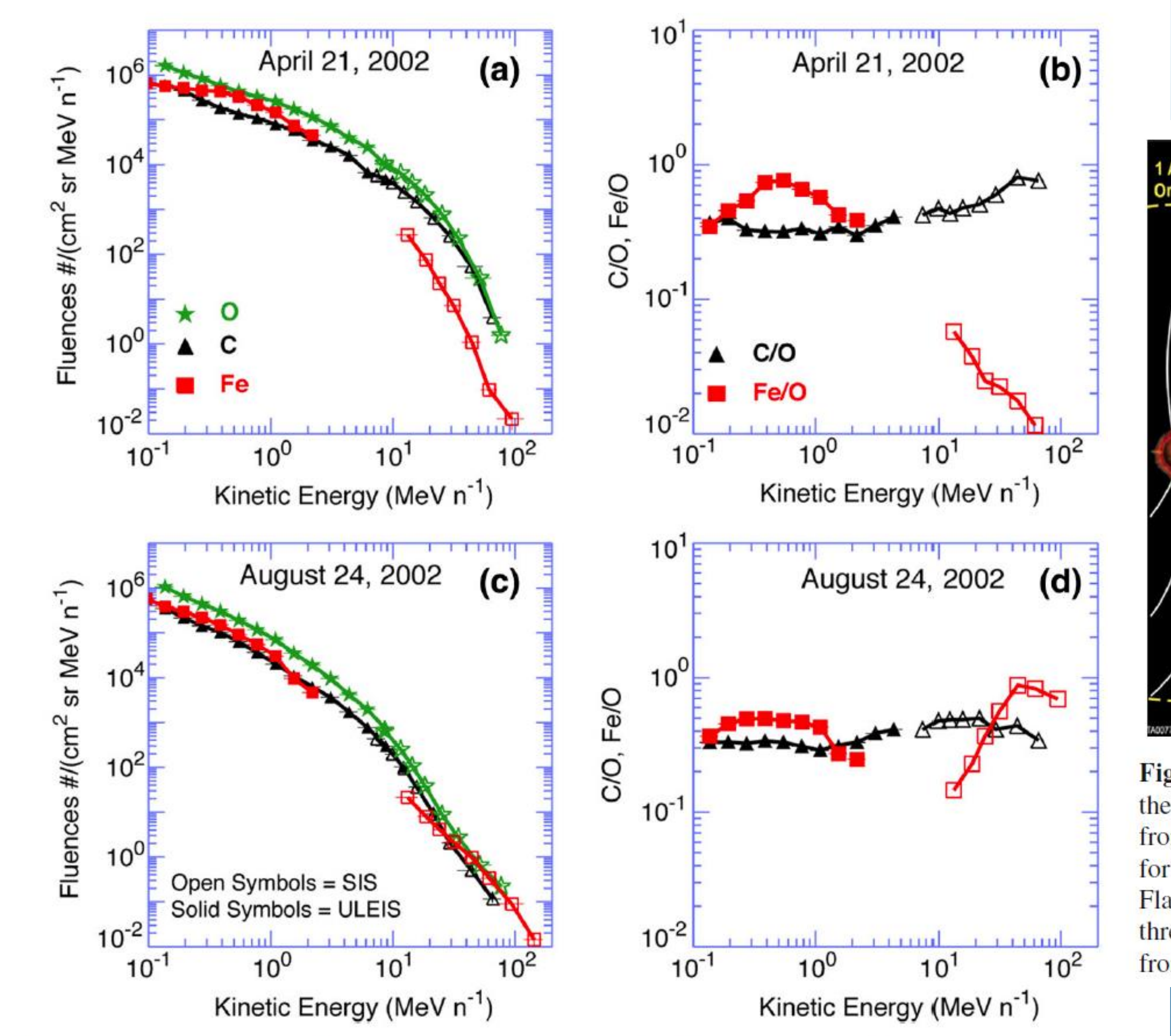


Fig. 11 *Left* Event-integrated fluence spectra of C, O, and Fe. *Right* C/O and Fe/O ratios in two large SEP events measured by the Ultra Low Energy Isotope Spectrometer (ULEIS) and the Solar Isotope Spectrometer (SIS) on board ACE (adapted from, Tylka et al. 2005; Desai et al. 2006a)

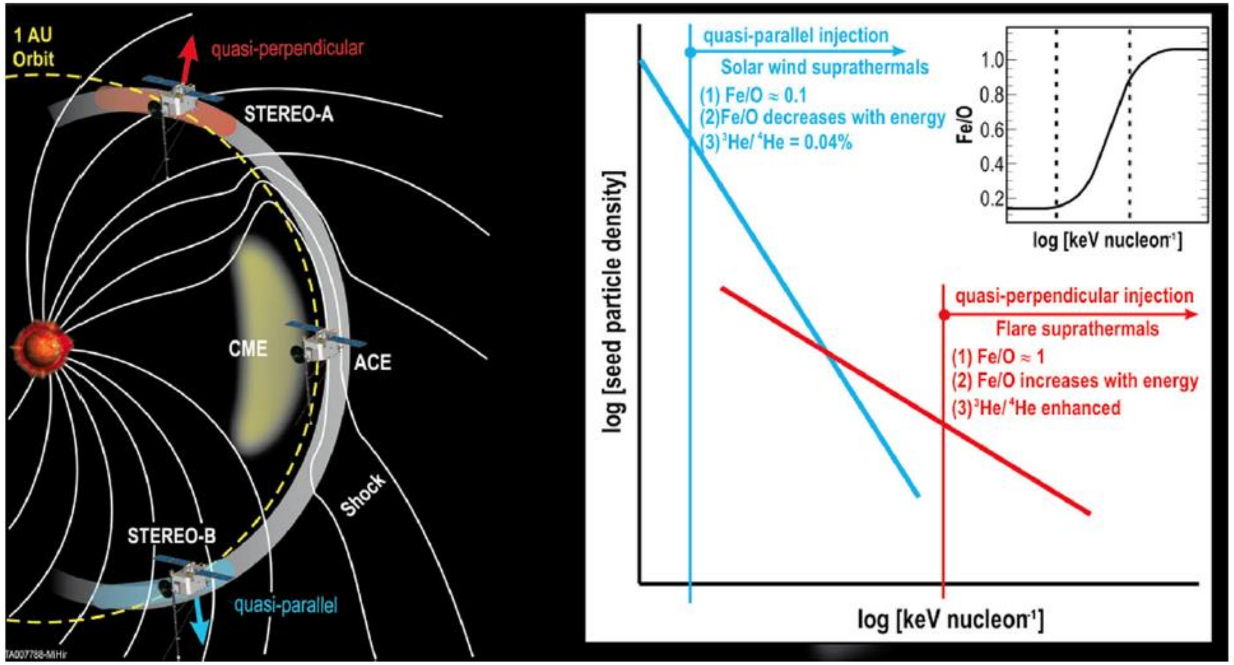


Fig. 17 *Left* Schematic of a CME-driven shock as seen at azimuthally-separated 1 AU spacecraft illustrating the variation in shock obliquity and the corresponding regions of variable injection threshold speeds (adapted from Zank et al. 2006). *Right* According to the Tylka and Lee (2006) model, the suprathermal seed population for shock-accelerated ESPs and SEPs comprises both coronal (or solar wind) and flare-accelerated ions. Flare suprathermals are more likely to be accelerated at quasi-perpendicular shocks with higher injection thresholds. The inset shows the energy-dependence of Fe/O ratio in the accelerated population (adapted from Tylka et al. 2005)

Desai & Giacalone (2016)

Energy dependence and solar origin

Dierckxsens et al. (2015) **as a function of energy!**

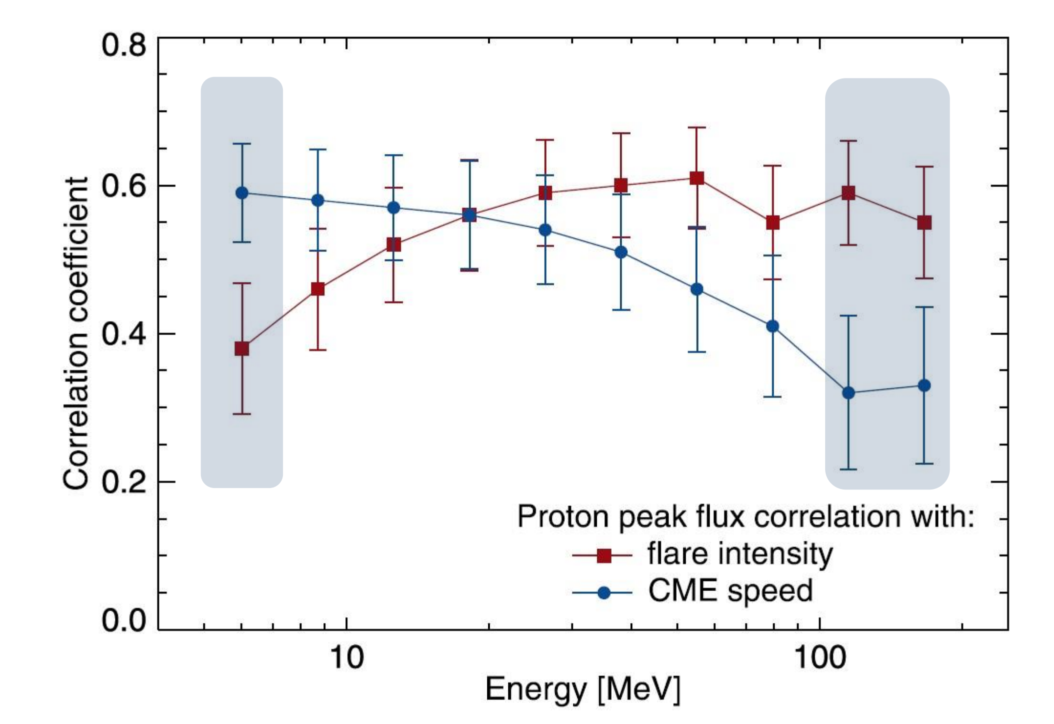


Table 3 Open questions, possible causes, and contributions from future inner heliospheric missions

Open questions	Possibilities/effects	SPP and SolO contributions
What causes event-to-event variations in SEPs?	Seed populations, Twin CMEs, shock properties, flare contributions	Identify variations in seed populations and determine how they affect CME shock acceleration efficiency and SEPs
Do self-excited proton-generated Alfvén waves exist, and how do they affect SEPs?	Q/M-dependence of low-energy spectral flattening; radial and energy dependence of peak intensities	Study properties of events with self-excited waves, and correlate with associated increases in streaming-limited peak intensities and the possible lack of spectral flattening
How does scattering during transport modify SEPs?	Rigidity-dependent scattering and associated variations or direct flare contributions	Identify and quantify the contributions of flares to large SEP events as transport-related time variations diminish
How do coronal and interplanetary magnetic field configurations affect SEPs?	SEP acceleration and transport in the presence of CMEs, shocks, and other large-scale structures in the low corona and interplanetary medium	Determine CME shock formation and propagation, properties of evolving CMEs, shocks, and other large-scale coronal and IP structures and their relationships with ambient turbulence spectra and SEP properties
Where are the highest energy SEP protons accelerated?	CME shocks in the low corona or flares	Use onset-time analyses to reduce uncertainties and identify source regions in individual SEP events

III. OPEN ?S

Desai & Giacalone (2016)

- **Empirical models**

e.g. REleASE (Posner 2007)
PPS (Kahler et al. 2007)
PROTONS (Balch 2008)
Laurenza et al. (2009); ESPERTA
UMASEP (Nunez et al. 2011–2018)
FORSPEF (Papaioannou et al. 2018)
Zucca et al. (2018)

- **Physics based models**

e.g. SOLPENCO (Aran et al. 2006)
EMMREM (Schwadron et al. 2010)
SEPMOD (Luhmann et al. 2010)
PREDICCS (Schwadron et al. 2012)
SOLPENCO2 (Crosby et al. 2015)

- **Mixed models**

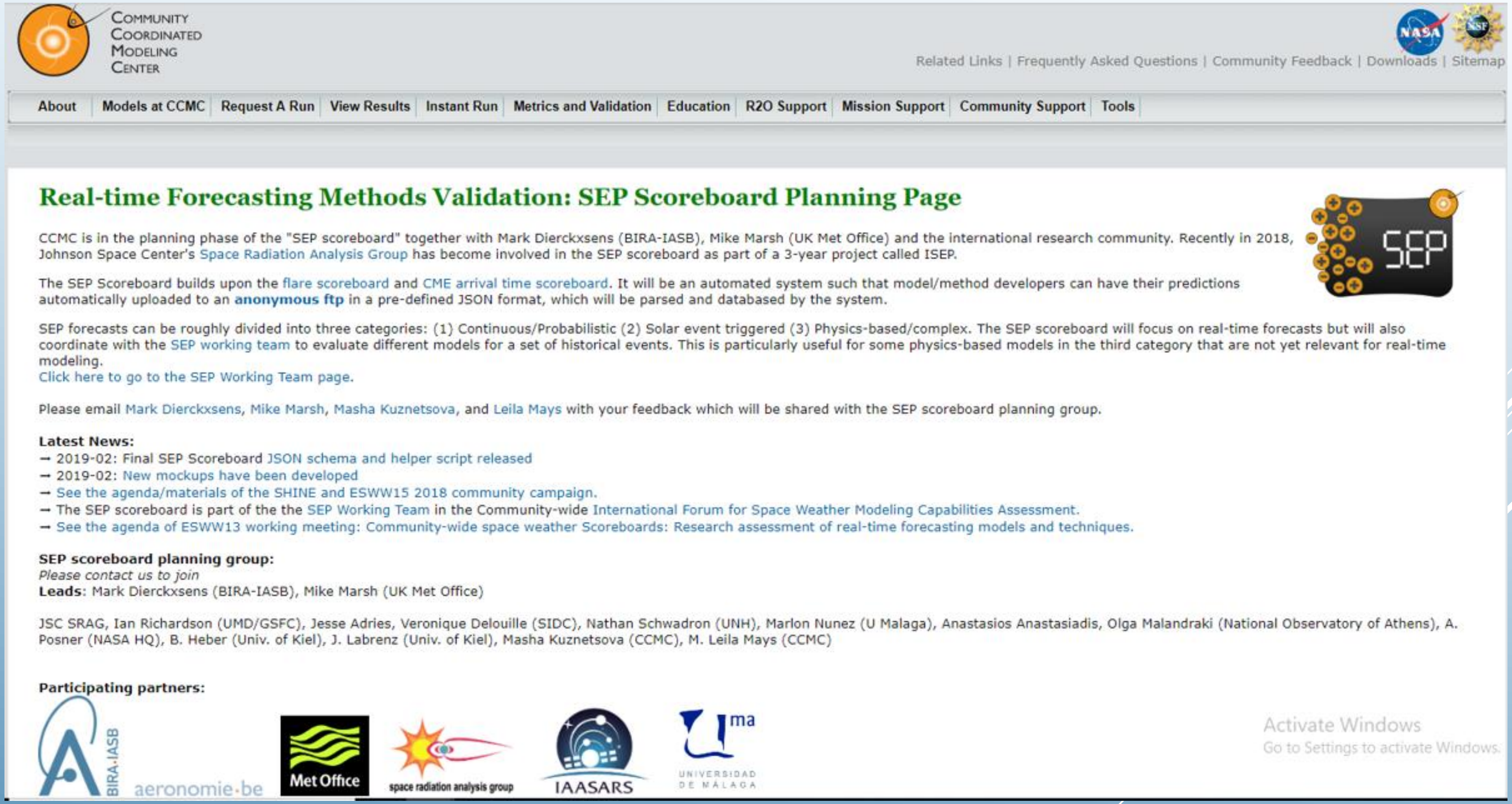
e.g. COMESEP(Crosby et al. 2015)

- **Recycled models**

e.g. HESPERIA project, book

- **Neural network models**

(not a complete list)


Community Coordinated Modeling Center

Related Links | Frequently Asked Questions | Community Feedback | Downloads | Sitemap

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Real-time Forecasting Methods Validation: SEP Scoreboard Planning Page

CCMC is in the planning phase of the "SEP scoreboard" together with Mark Dierckxsens (BIRA-IASB), Mike Marsh (UK Met Office) and the international research community. Recently in 2018, Johnson Space Center's Space Radiation Analysis Group has become involved in the SEP scoreboard as part of a 3-year project called ISEP.

The SEP Scoreboard builds upon the flare scoreboard and CME arrival time scoreboard. It will be an automated system such that model/method developers can have their predictions automatically uploaded to an **anonymous ftp** in a pre-defined JSON format, which will be parsed and databased by the system.

SEP forecasts can be roughly divided into three categories: (1) Continuous/Probabilistic (2) Solar event triggered (3) Physics-based/complex. The SEP scoreboard will focus on real-time forecasts but will also coordinate with the SEP working team to evaluate different models for a set of historical events. This is particularly useful for some physics-based models in the third category that are not yet relevant for real-time modeling.
Click here to go to the SEP Working Team page.

Please email Mark Dierckxsens, Mike Marsh, Masha Kuznetsova, and Leila Mays with your feedback which will be shared with the SEP scoreboard planning group.

Latest News:
- 2019-02: Final SEP Scoreboard JSON schema and helper script released
- 2019-02: New mockups have been developed
- See the agenda/materials of the SHINE and ESWW15 2018 community campaign.
- The SEP scoreboard is part of the the SEP Working Team in the Community-wide International Forum for Space Weather Modeling Capabilities Assessment.
- See the agenda of ESWW13 working meeting: Community-wide space weather Scoreboards: Research assessment of real-time forecasting models and techniques.

SEP scoreboard planning group:
Please contact us to join
Leads: Mark Dierckxsens (BIRA-IASB), Mike Marsh (UK Met Office)

JSC SRAG, Ian Richardson (UMD/GSFC), Jesse Adries, Veronique Delouille (SIDC), Nathan Schwadron (UNH), Marlon Nunez (U Malaga), Anastasios Anastasiadis, Olga Malandraki (National Observatory of Athens), A. Posner (NASA HQ), B. Heber (Univ. of Kiel), J. Labrenz (Univ. of Kiel), Masha Kuznetsova (CCMC), M. Leila Mays (CCMC)

Participating partners:

BIRA-IASB aeronomie.be | Met Office | space radiation analysis group | IAASARS | Universidad de Málaga

Activate Windows
Go to Settings to activate Windows.

https://ccmc.gsfc.nasa.gov/challenges/sep.php

Online

NOAA preliminary listing (1976–present): https://umbra.nascom.nasa.gov/SEP/

SEPEM reference event list (1973–2013): http://dev.sepem.oma.be/help/event_ref.html

ERNE major proton events (1996–1999): https://srl.utu.fi/erne_data/events/proton/HED/eventlist.html

SOHO/ERNE particle events (1996–2007): https://srl.utu.fi/SEPCatalog/index.php

SEPserver event catalogs (several, 1997–2012/2015): http://server.sepserver.eu/

Solar proton events (1970–2008): http://www.wdcb.ru/stp/online_data.en.html#ref113

SRTI-BAS proton events (1996–2018): http://newserver.stil.bas.bg/SEPcatalog

Online

V. CATALOGS ELECTRONS

NRIAG electron catalog (1997–2018):

http://www.nriag.sci.eg/aceepam-electron-event-catalog-2/

Fourth ArAS School for Astrophysics
ArAS SfA-4
October 19-26, 2019
Kottamia Astronomical Observatory
Egypt

2030 EGYPT VISION

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ACE/EPAM
Electron Event Catalog

@ NRIAG Last modified 31/10/2018

Solar Cycle 23: (1996-2008) | Solar Cycle 24: (2009-Present)

This catalog lists the electron enhancements from the ACE/EPAM instrument since 1996 in two energy channels. The catalog is organized as a table that presents the solar energetic particles (electrons) observed during solar cycle 23 (1996-2008) and the ongoing solar cycle 24 (since 2009). The catalog provides the following information: onset, peak times (in UT) and peak electron intensity at 103-175 keV energy channel and also the peak electron intensity at 175-315 keV energy channel. In addition, the solar sources (flares and coronal mass ejections) of the electron events are identified, where possible, with their properties noted. Further information is given as a comment. Extensions of the catalog (or corrections if needed) will appear regularly online.

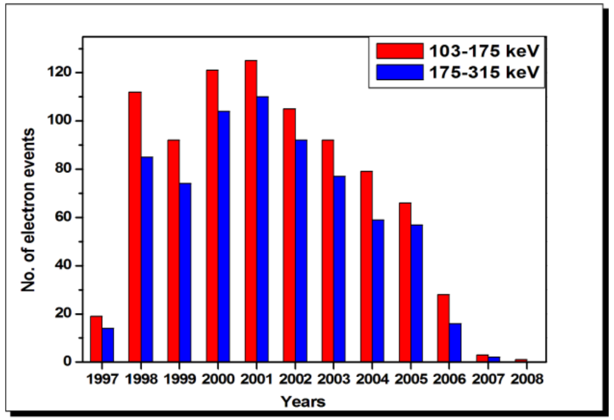
ACE/EPAM
Electron Event Catalog

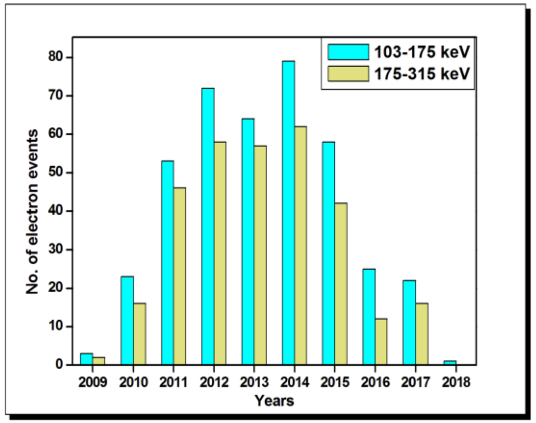
Solar cycle 23: 1996-2008

@ NRIAG 2018 Last modified 31/10/2018

Back to: Home Page | Solar Cycle 24: (2009-Present)

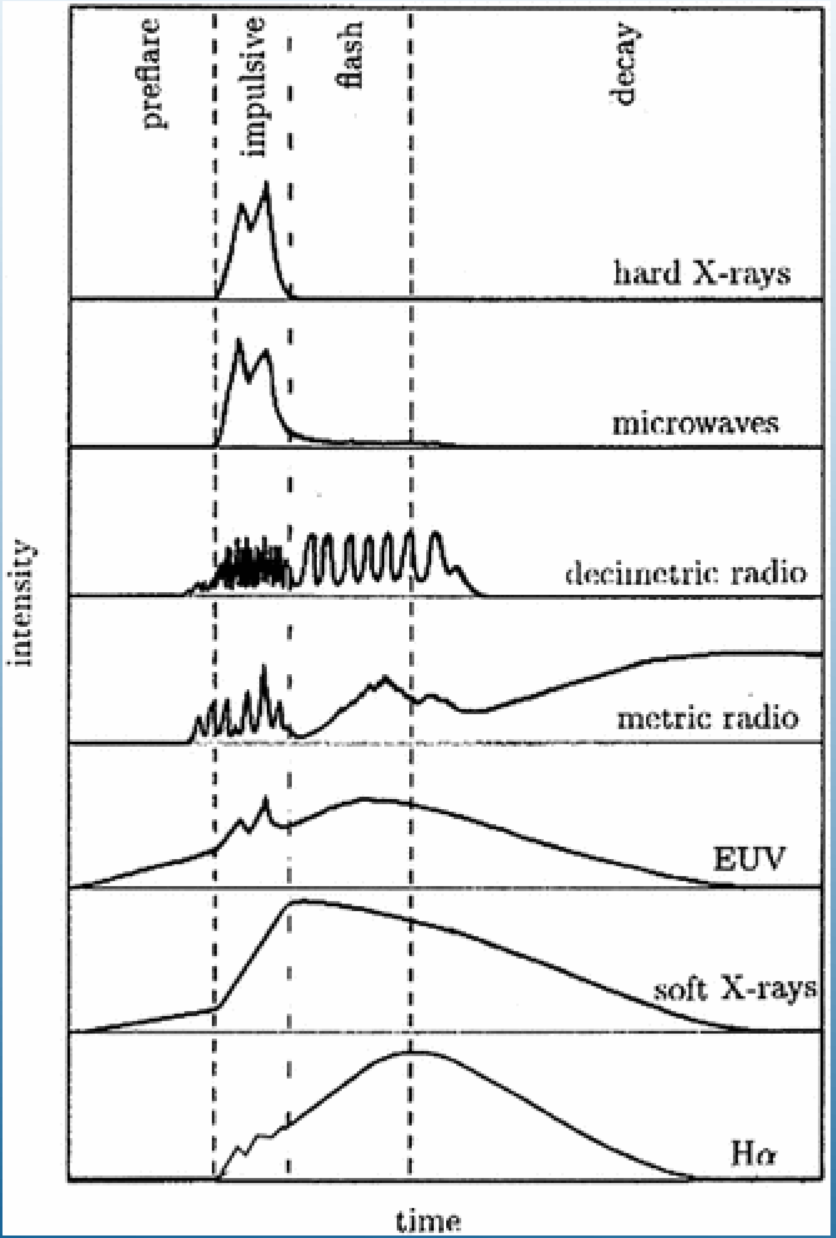
Event date	103-175 keV			175-315 keV	Flare	CME	Comment
yyyy-mm-dd	onset time (UT)	peak time (UT)	J_p /(cm^2 s sr MeV)$^{-1}$	J_p (cm^2 s sr MeV)$^{-1}$	SXR class/ onset time (UT)/ location	time (UT)/ speed (km s^{-1})/ width (deg)	
1997-09-09	20:59	23:00	158.33	68.662	B7.1/20:04/u	20:06/726/101	
1997-09-18	00:41	01:00	417.66	–	M1.0/17:45^{pd}/ N21W84	18:18^{pd}/613/46	
1997-09-18	17:18	19:24	248.12	–	B5.8/16:04/u	16:53/112/38	
1997-09-18	20:10	22:29	496.13	–	C1.5/17:05/u	18:03/285/55	
1997-09-20	03:55	06:22	368.15	70.204	B8.0/00:27/u	00:44/522/39	
1997-09-20	10:33	10:53	355.75	76.684	C2.3/09:49/u	10:20/777/97	
1997-09-24	03:45	5:40	182.34	74.592	M5.9/02:43/ S31E19	03:38/532/76	





➢ **for direct comparison with EM emission**

Bulgaria–Austria bilateral collaboration project



new, under completion

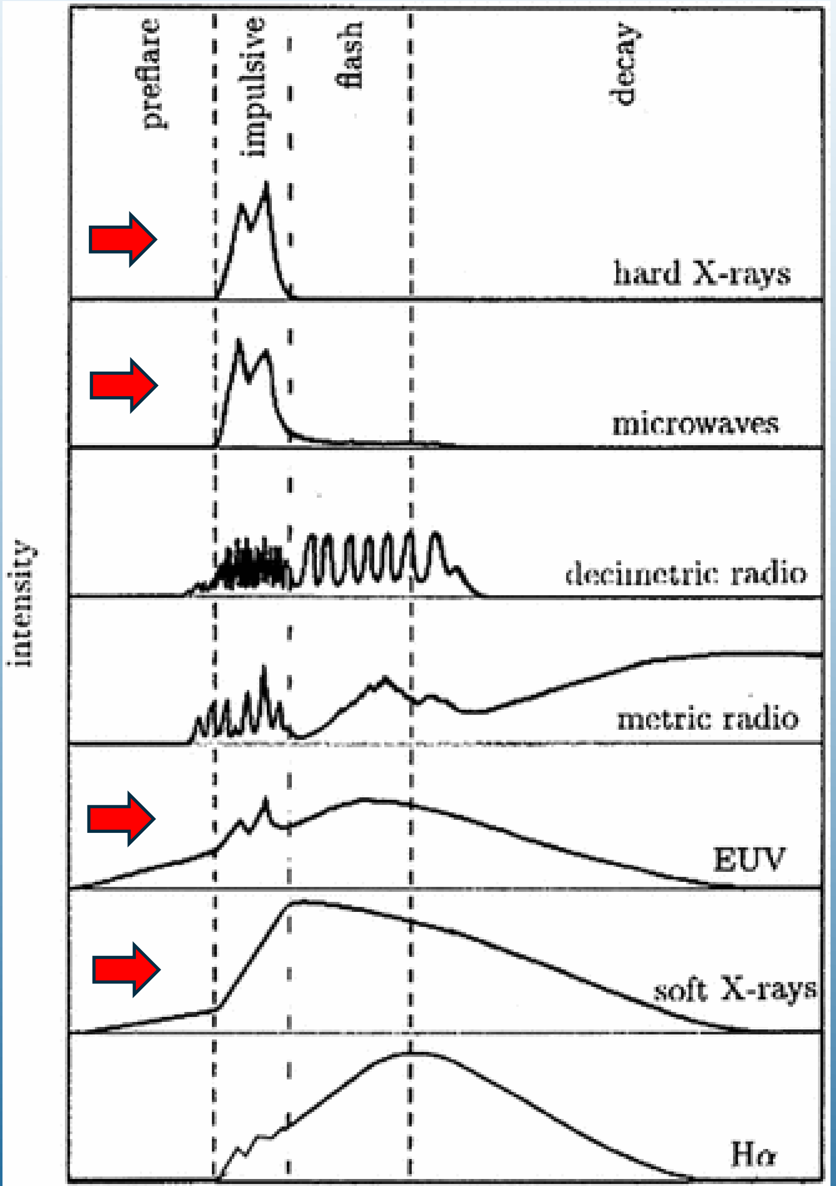
planned

new, under completion

standard, completed

Benz (2002)

Bulgaria–Austria bilateral collaboration project



Benz (2002)

17–22 MeV proton events (http://newserver.stil.bas.bg/SEPcatalog/) in 1996–2017: ~660 events

Flare association: ~400 events

➢ RHESSI coverage of onset-to-peak (http://sprg.ssl.berkeley.edu/~tohban/browser/): 70 events;

(background-subtracted) analysis of 70 events also done in:

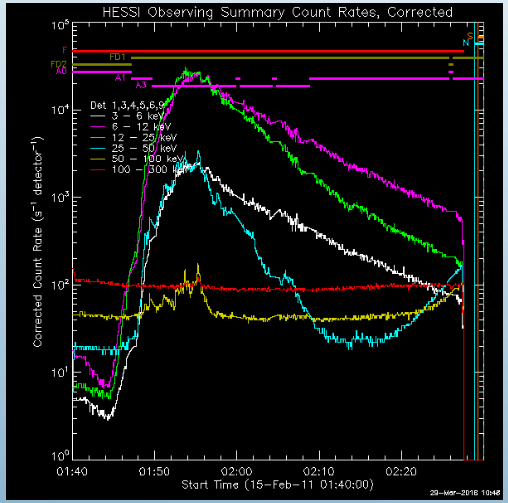
✓ GOES SXR (incl. derivative)

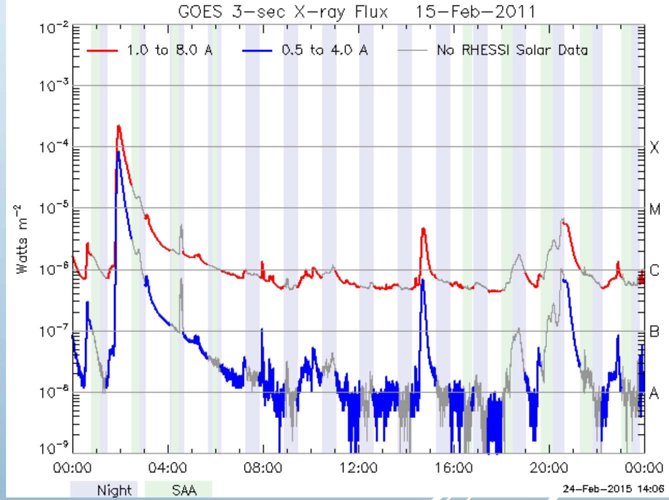
✓ SDO/AIA (1600 Å)

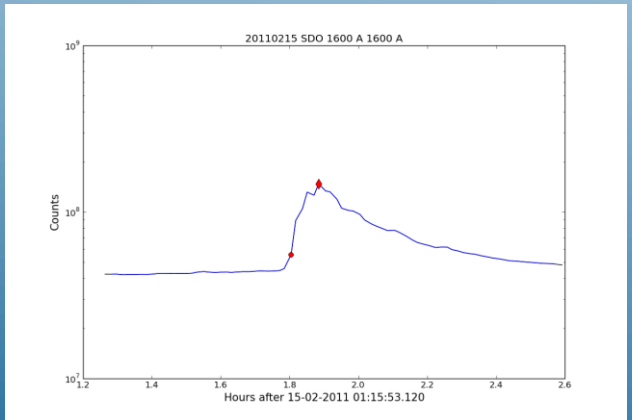
✓ RSTN (15.4 GHz)

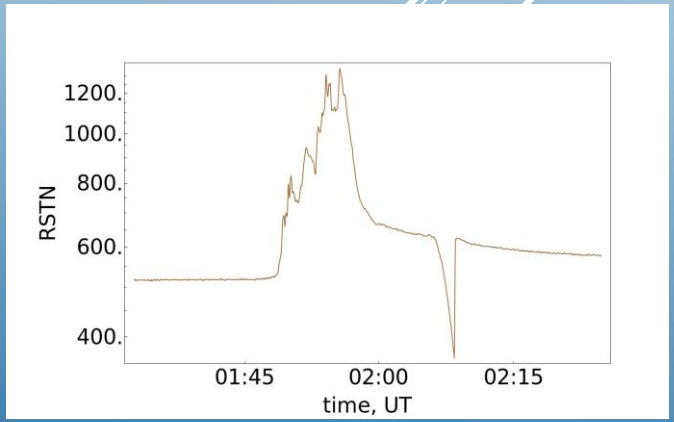
➢ EVE coverage (2010-2018)

➢ RSTN coverage (1996-2018)









ESA's project

Title: Development of a *physics-based* prototype model chain for *SEP acceleration and transport forecasting for the inner heliosphere*

PI: Kamen Kozarev

Duration: 2019-2020

- ✓ Coronal shocks: CASHeW model (Kozarev et al 2017)
- ✓ Diffusive shock-acceleration due to CMEs
- ✓ Heliospheric transport: EPREM code (Schwadron et al. 2010, 2015, Kozarev et al. 2010, 2013)
- ✓ 2D coronal plasma maps (Zucca et al. 2014)
- ✓ Database of typical parameters to be used in the forecasting
- ✓ Validation

Radiation hazard (RAD instrument/Curiosity rover)

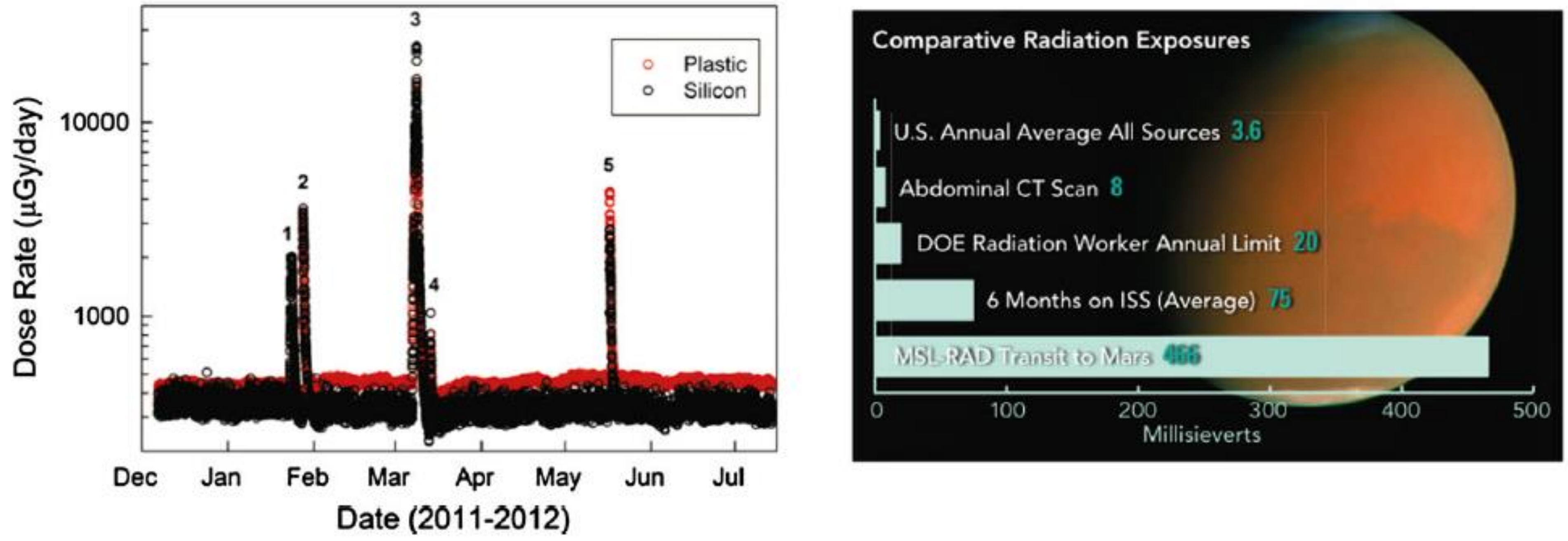
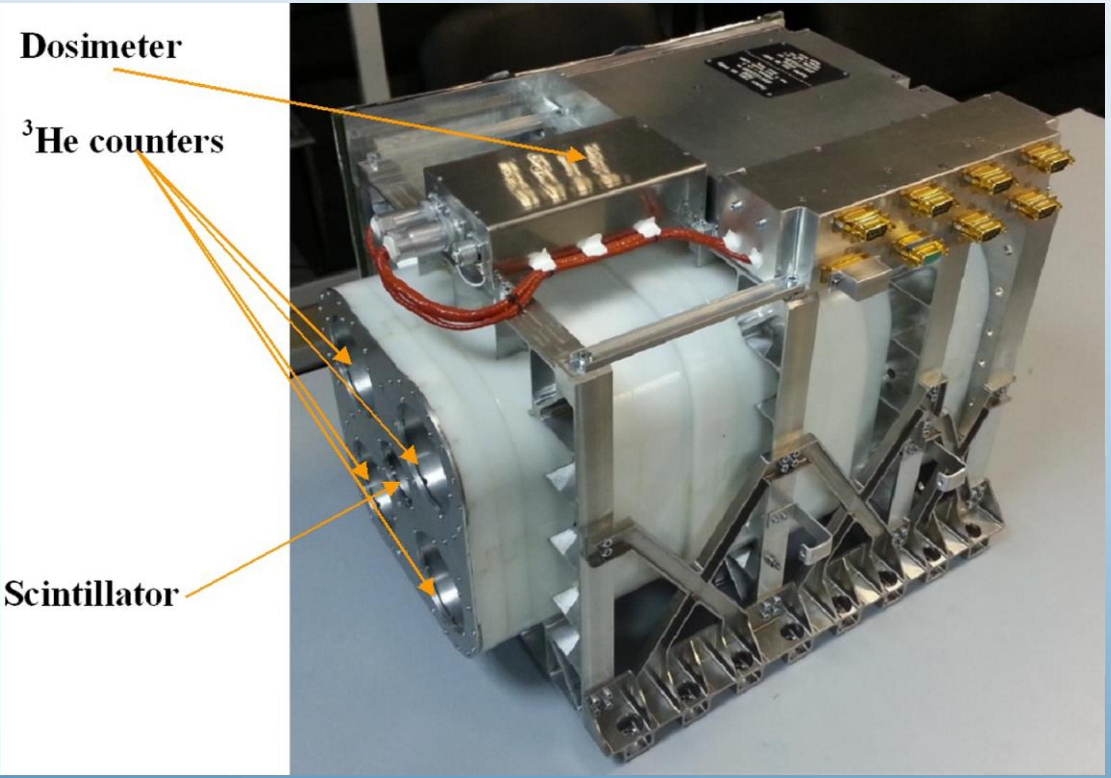


Fig. 45 *Left* Dose rates (~16-min averages) recorded by MSL-RAD in a silicon detector (*black circles*) and in a plastic scintillator (*red circles*) during MSL's journey to Mars. Five SEP events were observed during the cruise phase. For a given incident flux, the dose rate in silicon is generally less than the dose rate in plastic because of the comparatively large ionization potential of silicon. *Right* Radiation exposure compared with that measured by MSL-Rad on its way to Mars. Image reproduced with permission from Zeitlin et al. (2013) and Kerr (2013), copyright by AAAS

≤ 1 Sv during astronaut's career

Desai & Giacalone (2016)

Radiation hazard (Liulin-MO/ExoMars Trace Gas Orbiter)



http://www.esa.int

≤ 1 Sv during astronaut's career

Semkova et al. (2018), Icarus

"Data show that **during the cruise to Mars and back** (6 months in each direction), taken during the declining of solar activity, the crewmembers of future manned flights to Mars will **accumulate at least 60% of the total dose limit for the cosmonaut's career** in case their shielding conditions are close to the average shielding of Liulin-MO detectors – about 10 g cm^{-2}."

Parker Probe Plus

http://parkersolarprobe.jhuapl.edu
https://www.nasa.gov/content/goddard/parker-solar-probe
→close-up (~9 sol. radii) observations

Image credit: NASA
https://www.youtube.com/watch?v=UQ-E1icMpVw

SWEAP
The Solar Wind Electrons Alphas and Protons investigation gathers observations using two complementary instruments: the Solar Probe Cup, or **SPC**, and the Solar Probe Analyzers, or **SPAN**.

The instruments count the most abundant particles in the solar wind – electrons, protons and helium ions – and measure such properties as velocity, density, and temperature to improve our understanding of the solar wind and coronal plasma.

Solar Orbiter

http://sci.esa.int/solar-orbiter/
→close-up (0.28 AU) and high-latitude (33°/sol. eq.) observations

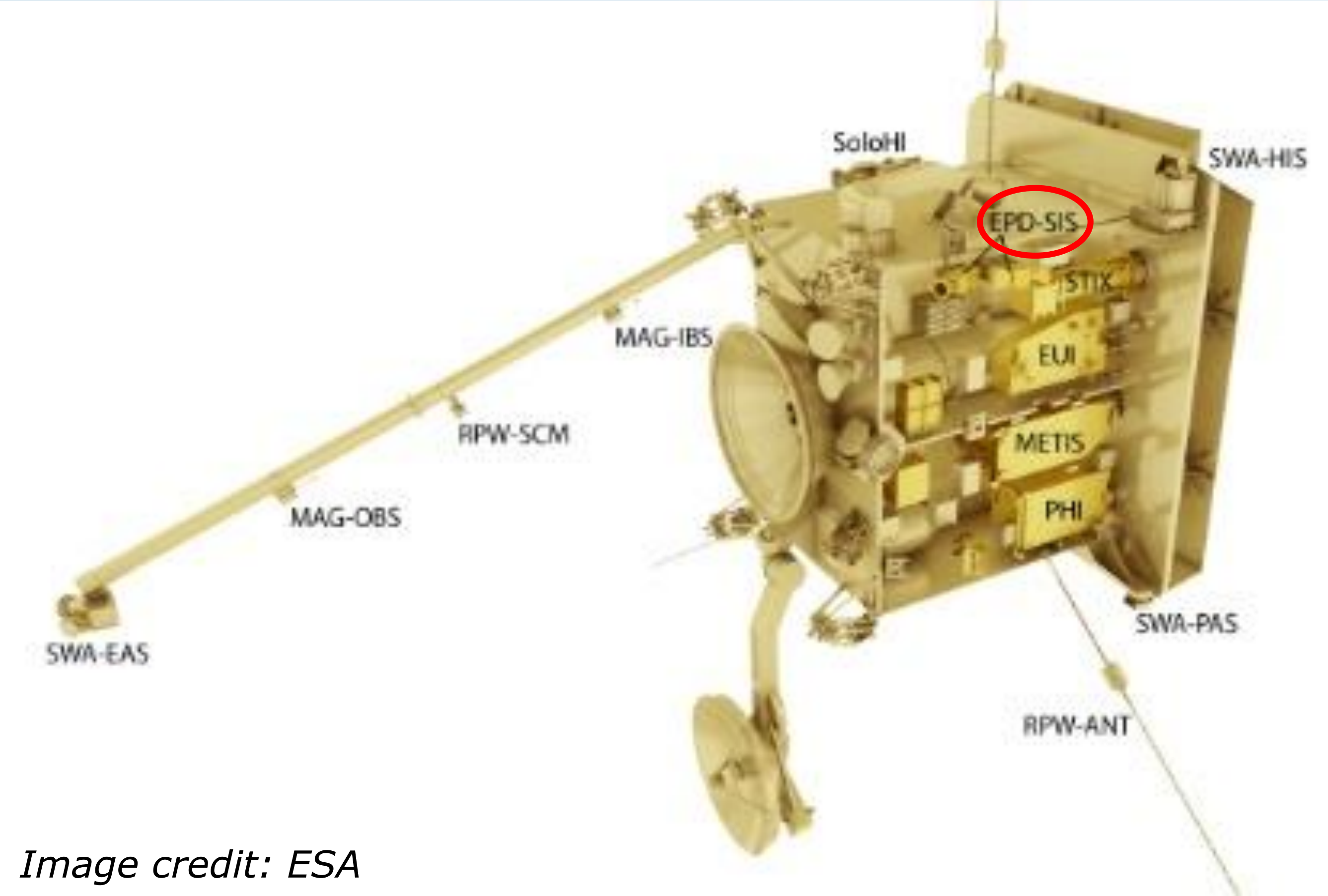


Image credit: ESA

EPD: Energetic Particle Detector
Principal Investigator: Javier Rodríguez-Pacheco, University of Alcala, Spain
Collaborating countries (hardware): Spain, Germany, USA, ESA

EPD will measure the composition, timing and distribution functions of suprathermal and energetic particles.
Scientific topics:
sources, acceleration mechanisms, and transport processes of these particles.

http://newserver.stil.bas.bg/SEPorigin/

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SEP origin project

SEP origin project

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The origin of solar energetic particles:
solar flares vs. coronal mass ejections

List of seminars and lectures for students

Solar physics group seminar at IGAM/University of Graz, Graz, Austria

12 March 2019 (coming soon)

Solar energetic particles: observations, the flare-CME origin and catalogs by *R. Miteva* (in English)

Sofia University 'St. Kliment Ohridski', Faculty of Physics, Astronomy Department

Master degree "Astronomy and Astrophysics" winter semester 2018-2019 by *Rositsa Miteva* (presentations in Bulgarian)

Physics of the Sun and solar activity

1. Overview of the Sun and the solar atmosphere
2. Observations of the Sun: ground-based and space-borne
3. Sunspots and solar activity cycle
4. Solar flares
5. Coronal mass ejections

International workshop "Eruptive energy release processes on the Sun and stars: origins and effects" ISW2018

12 October 2018

Solar energetic particles and space weather by *R. Miteva* (in English)

WEB:

List of popular lectures

Workshop on Astronomy at the Department of Astronomy, Faculty of Physics

WEB:

in Bulgarian