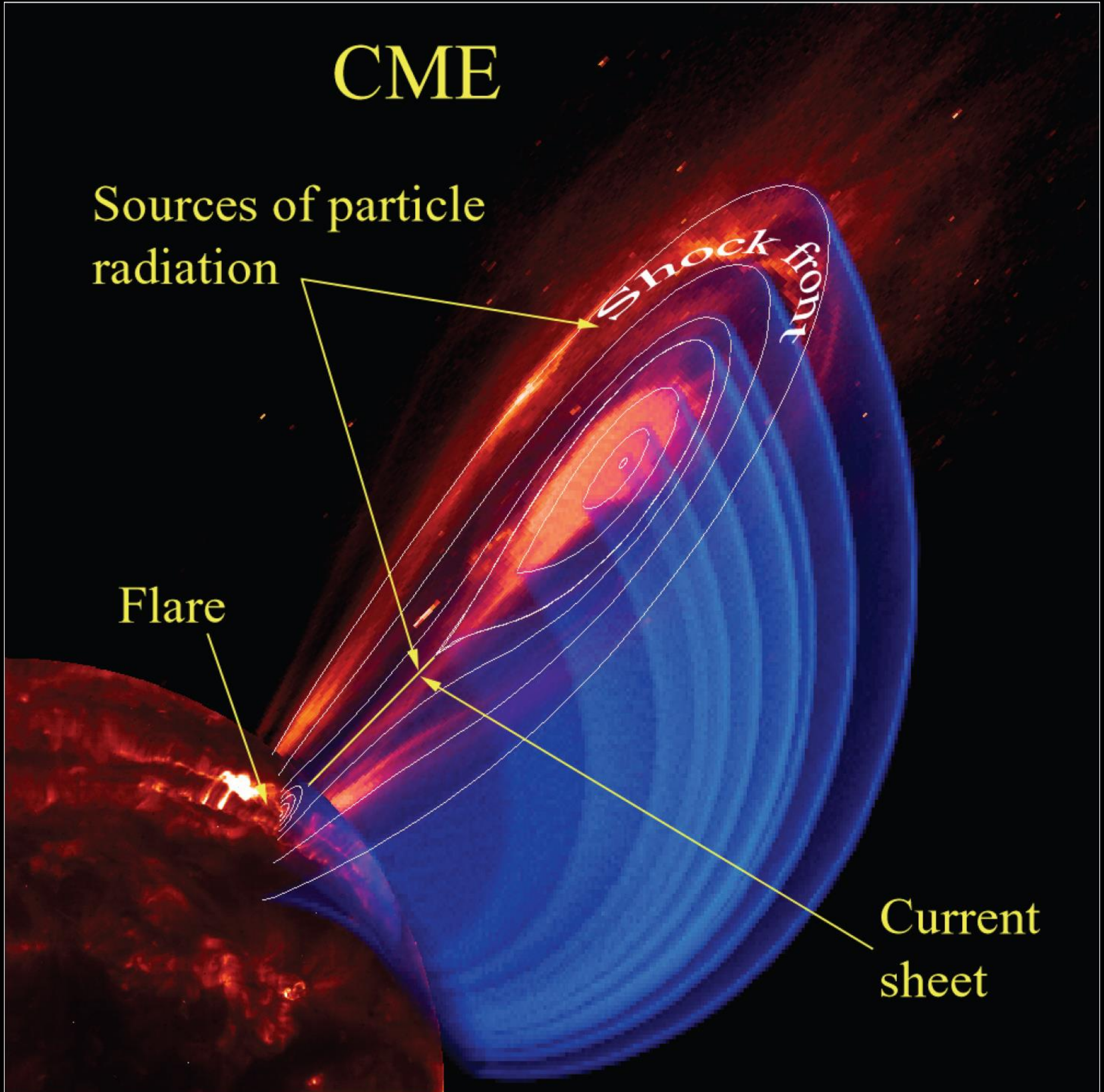
Forecasting and Analysis of Solar Energetic Particle Radiation Storms

Olga E. Malandraki[1], Michalis Karavolos[1], Arik Posner[2], Kostas Tziotziou[1], Henrik Droege[3], Bernd Heber[3], Patrick Kuehl[3]

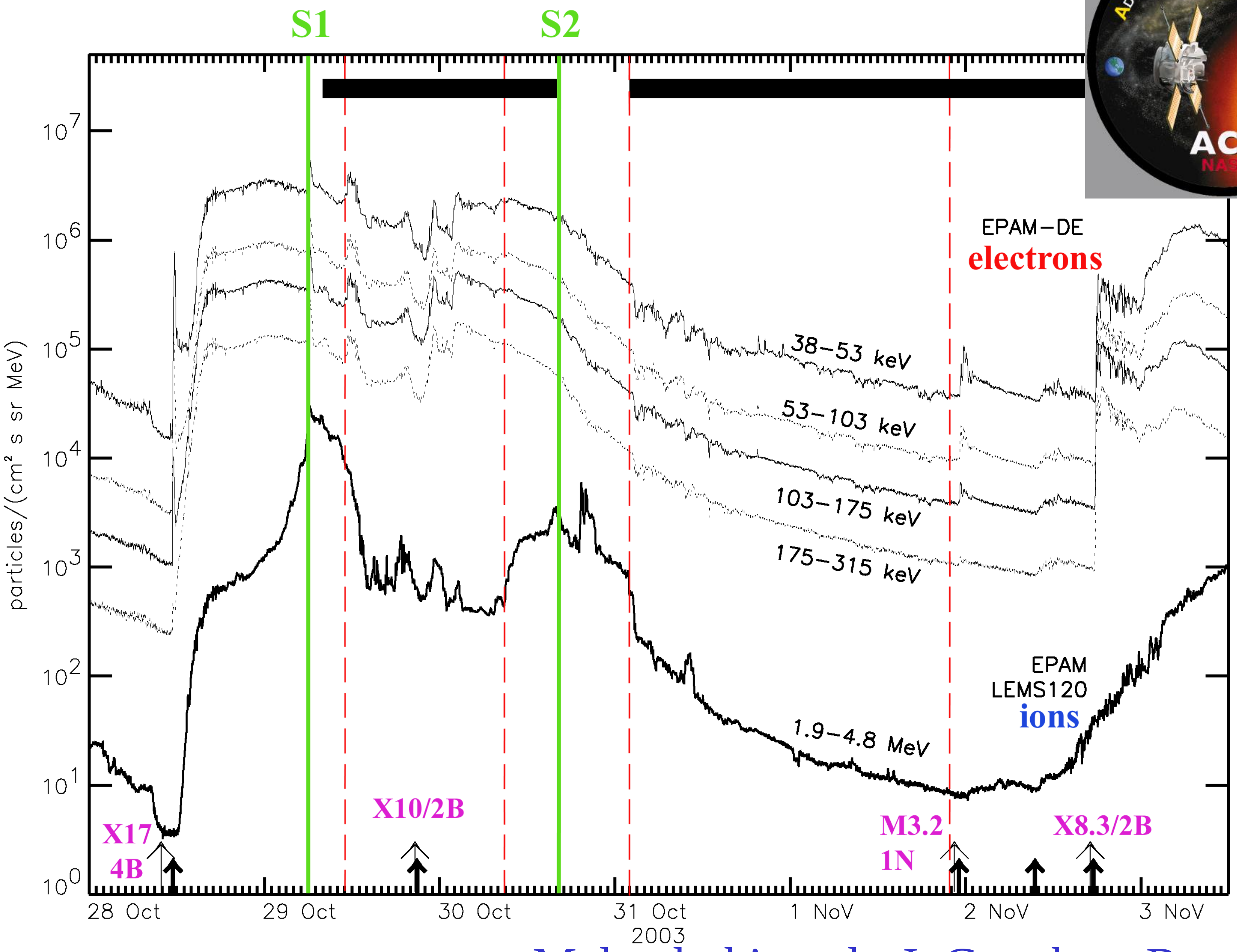
[1]National Observatory of Athens, IAASARS, Athens, Greece, [2]NASA Headquarters, USA, [3]Christian-Albrechts-Universität zu Kiel, Germany

United Nations/Germany Workshop on the International Space Weather Initiative: *Preparing for Solar Maximum*

Solar Energetic Particles, (SEPs)

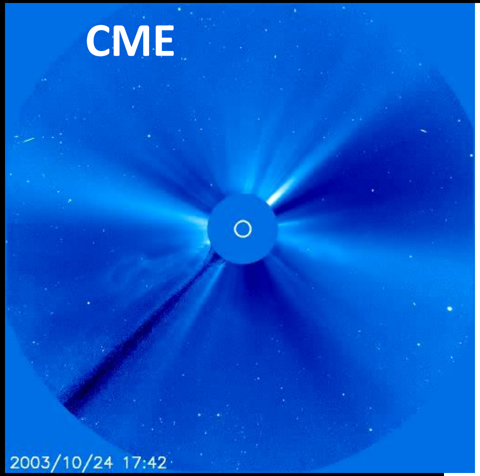


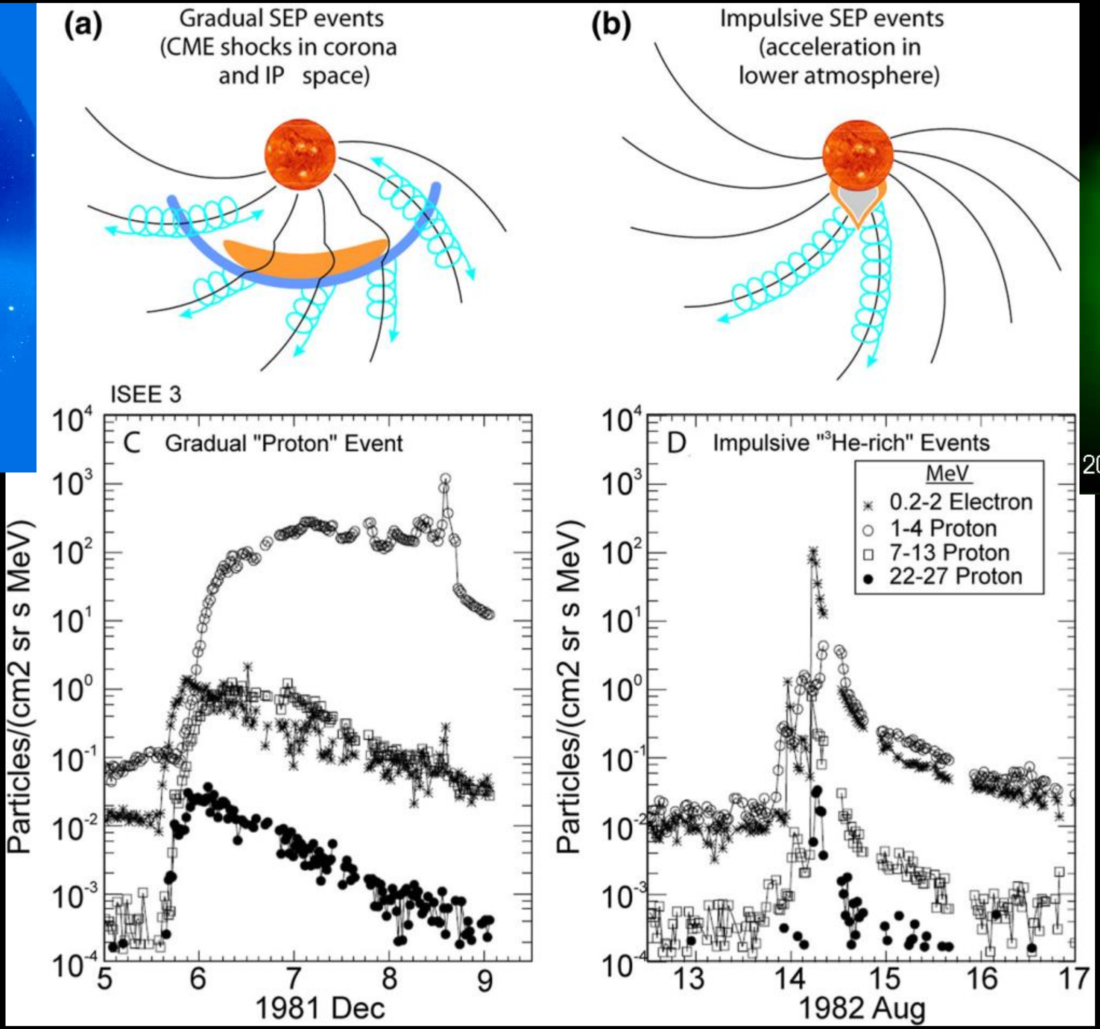
October/November 2003 SEP events

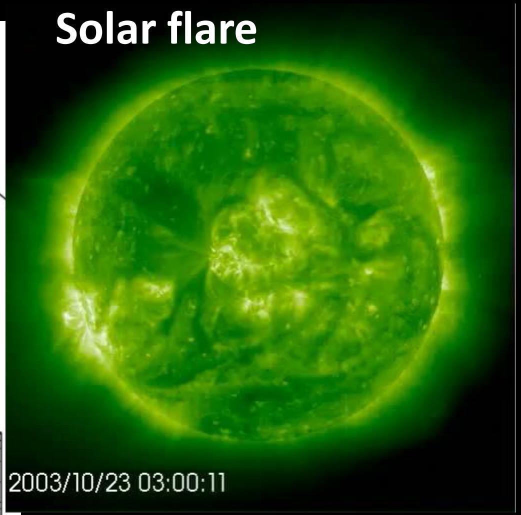


Malandraki et al., J. Geophys. Res, 2005

Solar Energetic Particle Events







Large Gradual SEP events accelerated at CME-driven shocks

^{3}He-rich SEP events accelerated during solar flares via magnetic reconnection

Malandraki & Crosby, 2018,
Springer Astrophysics and Space Science Library (ASSL) series: 'Solar Particle Radiation Storm Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and beyond'

SPACE WEATHER IMPACT AND EFFECTS

Near-Earth environment – Interplanetary Space

Malandraki and Crosby, Springer Book, ASSL, *2018*

SEP effects on Technology

SEPs can penetrate Earth's magnetic field and enter the ionosphere, especially near the poles where magnetic field lines are open.

This renders the highly-inclined LEO satellites and the International Space Station (with a 51.64° orbital inclination) vulnerable to SEPs.

SEPs affect signal propagation between Earth and satellites, primarily due to protons with energies between 1 to 100 MeV (30-80 km altitude), leading to increased ionization that absorbs HF and VHF radio waves. This causes communication issues and navigation problems, especially in the polar regions.

SPACE WEATHER IMPACT AND EFFECTS
Near-Earth environment - IP Space

SEP effects on Human Health

Protons with high energies (>30 MeV) are a health risk for astronauts. The effects are sub-classed into two categories:

Deterministic (early) Effects: Due to exposure to a large dose of radiation for a limited time (ranges from hair loss, nausea, acute sickness, death).

Stochastic (late) Effects: Due to random radiation-induced changes at the deoxyribonucleic acid (DNA) molecule level (cancer).

SEP events reach aviation altitudes and they become also a concern for human health as the radiation dose received can increase. This specifically applies to high-latitude flights (> 50°N) and polar routes (> 78°N). For commercial aviation can be a risk for frequent flyers and particularly for aircrew.

Malandraki and Crosby, Springer Book, ASSL, *2018*

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Advances in Space Research xxx (xxxx) xxx

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ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Particle radiation environment in the heliosphere: Status, limitations, and recommendations

Jingnan Guo[a,b,*], Bingbing Wang[c], Kathryn Whitman[d], Christina Plainaki[e], Lingling Zhao[c,f], Hazel M. Bain[g,h], Christina Cohen[i], Silvia Dalla[j], Mateja Dumbovic[k], Miho Janvier[l,m], Insoo Jun[i], Janet Luhmann[n], Olga E. Malandraki[o], M. Leila Mays[p], Jamie S. Rankin[q], Linghua Wang[r], Yihua Zheng[s]

[a] *Deep Space Exploration Laboratory/School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China*
[b] *Collaborative Innovation Center of Astronautical Science and Technology, Harbin 150001, China*
[c] *Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, AL 35899, USA*
[d] *University of Houston, 4800 Calhoun Road, Houston, TX 77204, USA*

COSPAR COMMITTEE ON SPACE RESEARCH

International Space Weather Action Team - ISWAT Cluster
"H3: Radiation Environment in the Heliosphere"
https://www.iswat-cospar.org/h3

- Limitations in knowledge and open questions on SEP science
- Recommendations related to the improvement of both observational and modeling capabilities

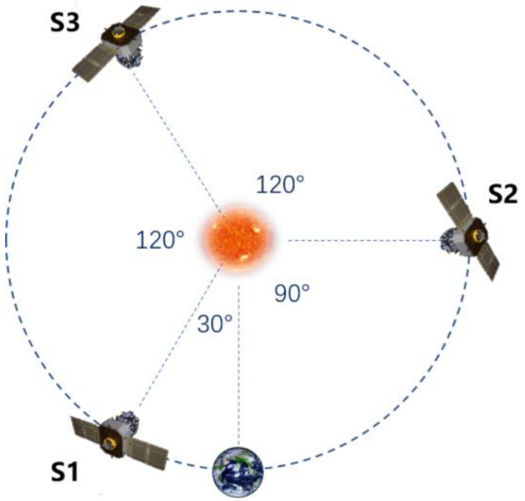
Guo,…,Malandraki et al., 2024, Advances in Space Research, in press

Key Process	Key Physics	Existing Key observations	Limitations and Open questions
Energization	Shock acceleration (Shock drift acceleration, Diffusive shock acceleration)	EUV Shock waves, Coronagraphs of CMEs, Radio emission, IP shock strength & orientation, SEP composition & spectral properties	• What is the key physics at scales and locations that cannot yet be observed? • How to distinguish CME-associated SEPs from flare-accelerated ones? • Where exactly does the flare acceleration takes place? How are particles released? • What is the exact role of current sheet & turbulence during reconnection? • What is the shock condition? How does the shock distribute in space and evolve in time? How does the shock condition affect the acceleration process? • What determines the starting and ending energy of the accelerated SEPs? • How to explain observed energy-dependence of composition in some cases? • How the variability of the SEP events (size, composition, spectral features) is correlated to the acceleration process?
	Reconnection acceleration (current sheet, turbulence, magnetic islands)	Remote-sensing images (flare, jets, flux-rope, coronal dimming), Multi-wavelength obs (EUV, X-ray, γ-ray, Radio emission), SEP composition (enhanced 3He, Ultra heavy ions)	
Transport	Field aligned	Magnetic connectivity, Pitch angle, Anisotropy (with limited resolution), onset time, spectral information and spatial distribution by multi-view observers (not yet sufficient)	• What is the actual field connectivity (especially with SW disturbances)? • How the field evolves dynamically in space and time? • What is the relative role of extended source and cross-field transport? • What is the relative role of particle scattering and field meandering? • How are the SEP properties modified during the propagation? • How to explain observations opposite to the existing acceleration/transport theories?
	Cross field		
Conditions	Plasma + Structures	Solar observation (magnetic field of the photosphere, Coronal holes) Insitu SW disturbance, Near-Sun and in-situ observations of CMEs	• How to identify the properties of the SEP source at the back-side of the Sun? • What is the IMF and SW condition at close solar distances? • What are the strength, orientation & structure of disturbances missing the observer?
	Seed population	Composition, Relative abundance, Energy spectra	• What are the composition & spectrum of super-thermal particles? • What is the seed population variability? What are their properties close to the Sun? • What is the spatial distribution (longitudinal, radial) of seed particles?

Multi-view real-time forecasting capabilities are crucial

- **ESA** approved mission Vigil: s/c deployed at the L5 point of the Sun-Earth system to enable remote sensing of the Sun and IP space and in situ measurements of solar wind plasma and high-energy solar particle events

- **Chinese scientists** have proposed the Solar Ring mission: includes 3 s/c at positions somewhat shifted from the L3, L4, and L5 points to observe the Sun and carry out in situ observations



Guo,…,Malandraki et al., 2024, ASR, in press

Table 12
SEP models that are running in operational and real time environments.

Model	Date of Implementation	Location	End Users
		Operational Models	
AFRL PPS	1987 (as early as 1976)	USAF Space Weather Analysis and Forecast System (SWAFS)	USAF Space Weather Operations Center (SpWOC)
COMESEP	2013 (real time), 2016 (operations)	ESA Space Weather Service Network	ESA space weather stakeholders, PECASUS global center for aviation users
PROTONS	1998 (earlier version running from at least 1983)	NOAA SWPC	NOAA SWPC
HESPERIA REleASE	real time since 2008, operational since 2016	ESA Space Weather Service Network, HESPERIA, CCMC iSWA, SEP Scoreboard	ESA space weather stakeholders, NASA SRAG, public
UMASEP	real time since 2011, operational since 2016	ESA Space Weather Service Network, HESPERIA, University of Malaga, CCMC iSWA, SEP Scoreboard	ESA space weather stakeholders, NASA SRAG, public

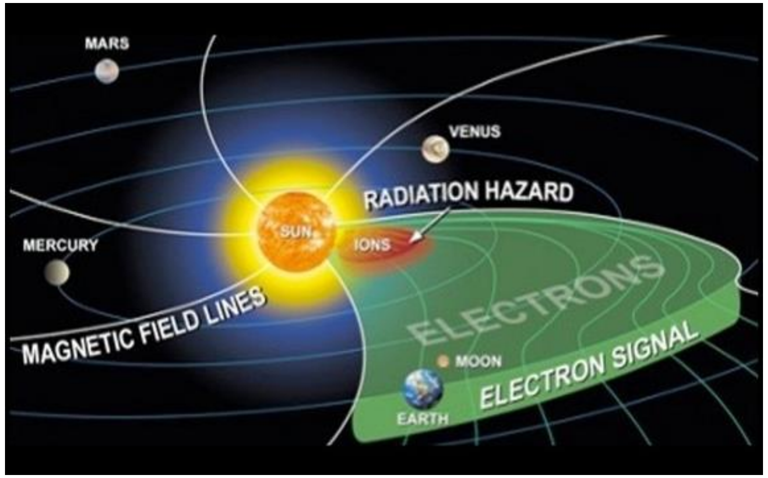
Model	Date of Implementation	Location	End Users
		Real Time Models	
FORSPEF	2015	NOA	registered users
MAG4	2019 (various real time locations from 2011)	SEP Scoreboard	NASA SRAG, public
SAWS-ASPECS	2022	SEP Scoreboard, NOA	NASA SRAG, public
SEPMOD	2020	SEP Scoreboard	NASA SRAG, public
SEPSTER	2020	SEP Scoreboard	NASA SRAG, public
SEPSTER2D	2021	SEP Scoreboard	NASA SRAG, public
SPRINTS	2022	SEP Scoreboard	NASA SRAG, public

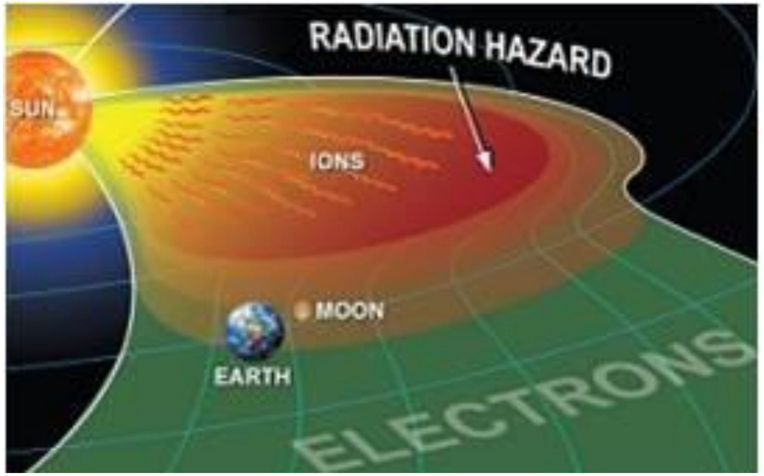
SEP forecasting models

Whitman,…,Malandraki et al., 2023, Advances in Space Research

- 36 SEP models ranging from physics-based to empirical to ML approaches
- 5 Operational SEP Models

HESPERIA REleASE

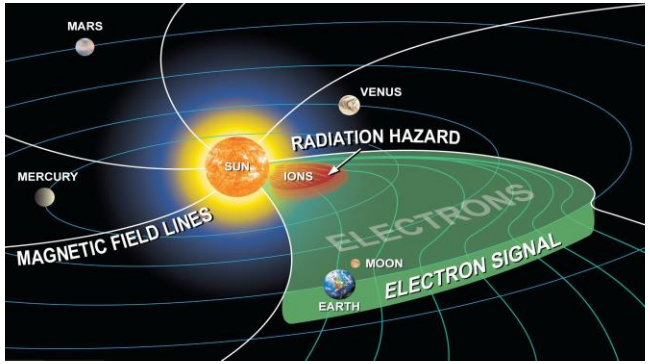




Predicting 30-50 MeV SEP events by using the Relativistic Electron Alert System for Exploration (REleASE) scheme

- This tool implemented and evaluated a real-time SEP predictor by using the REleASE scheme (Posner, 2007)
- The implemented model infers the maximum proton intensity and onset at 30-50 MeV based on near relativistic and relativistic electron intensity time profiles measured by SOHO/EPHIN and ACE/EPAM
- The tool provides advanced forecasting methods
- Validation: POD, FAR, and average warning time.

HESPERIA REleASE



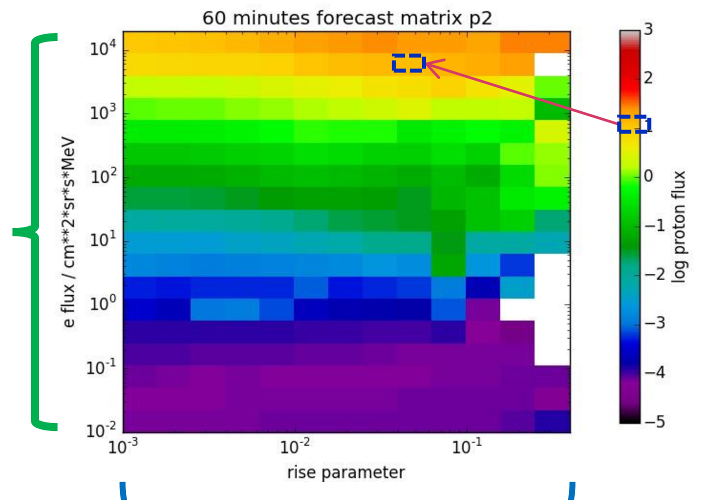
The REleASE scheme (Posner 2007)

Near relativistic **electrons travel faster than ions** and are present in SEP events. **The faster electrons arrive at L1 30-90 min before the slower protons**

The REleASE scheme uses this effect to **<u>predict the proton flux</u>** by utilizing:

1) The **actual electron flux**

2) The **increase of the electron flux** in the last **60 minutes**



HESPERIA REleASE

Development

- REleASE utilizes an empirical matrix to predict the proton intensity (30, 60, 90 min)
- Real-time SOHO/EPHIN electron data (0.25-1.0 MeV) are available:

  Advantage

  – 1-min resolution

  Disadvantages

  – limited time data coverage (less than 4 hours per day)

  – if no real-time data are available → no forecast produced

- **HESPERIA Innovation:** Real-time electron intensities by **ACE/EPAM** in a comparable energy range (0.175-0.315 MeV) adapted to the existing REleASE forecasting matrix.

  Advantage

  – Very good data coverage

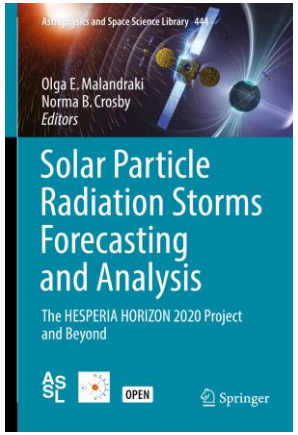
  Disadvantages

  – 5-min resolution

HESPERIA RElеASE

Validation

- The largest time interval possible with EPHIN was selected (2009-2016) to calculate POD, FAR, and AWT.
  - The obtained POD using both data sources (EPHIN/EPAM) was **63.2%**.
  - The FAR using EPHIN and EPAM were **29.4%**, and **35.1%** , respectively.
  - The AWT (Advanced Warning Time) using EPHIN and EPAM was 107 and 123 min, respectively.

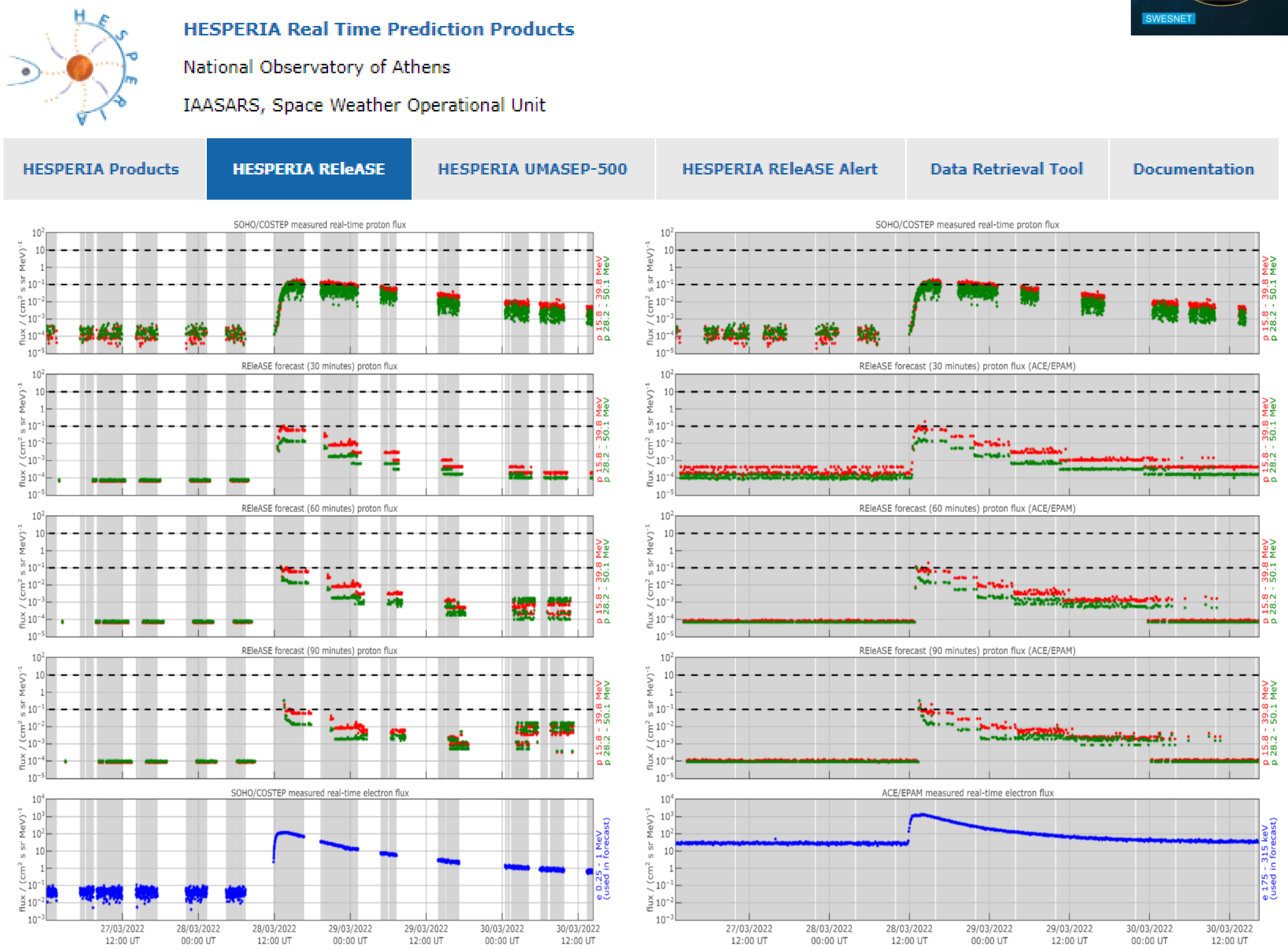


- The results are satisfactory (low FAR, high POD, high AWT).

- We conclude that the RElеASE forecasting scheme can be used with ACE/EPAM data, and can probably be used with **other near relativistic electron flux measurements**.

HESPERIA REleASE

ESA SWE Network (SWESNET) – ESA Space Safety Programme



Real-time SEP predictions are available via the HESPERIA Products website through ESA's SWE

https://swe.ssa.esa.int/noa-hesperia-federated

HESPERIA REleASE Alert

Federated products from the Institute for Astronomy, Astrophysics, Space Applications & Remote Sensing (NOA)

HESPERIA Real Time Prediction Products

National Observatory of Athens

IAASARS, Space Weather Operational Unit

HESPERIA Products | HESPERIA REleASE | HESPERIA UMASEP-500 | **HESPERIA REleASE Alert** | Data Retrieval Tool | Documentation

E-mail: REleASE Alert system | Risk level: ALERT FOR "EPHIN"

"**EPHIN**" exceeded its threshold and generated an alert at

22-03-28 12:52:12 UT

based on our server timestamp.

The raw data of "**EPHIN**" refer to

2022-03-28 12:45:06 UT

based on the HESPERIA REleASE timestamp.

Visit our HESPERIA REleASE product web page to view details of the event forecast.

If you want to unsubscribe you have to visit the subscription web page of the HESPERIA REleASE Alert product and check the unsubscribe checkbox.

You can access the HESPERIA products webpage here.

Best Regards,

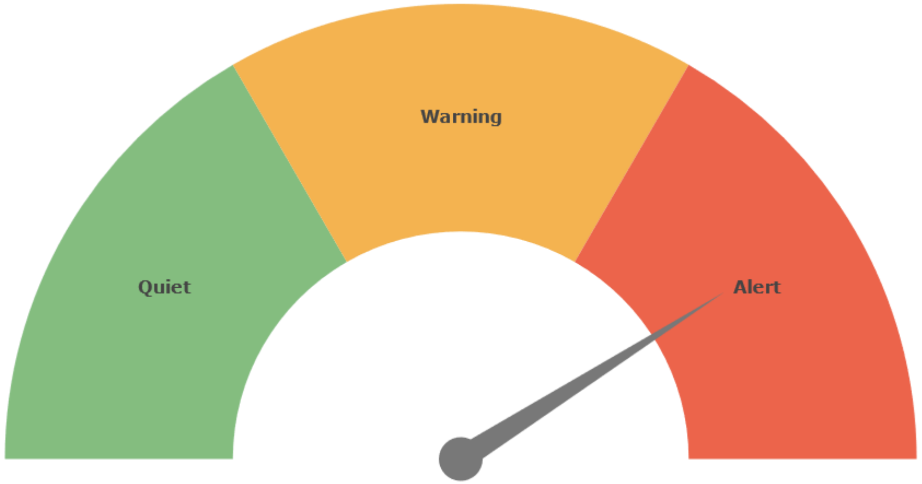
National Observatory of Athens

Access the ESA SWE Portal here: sw e.ssa.esa.int

For further product-related information or enquiries contact helpdesk.

E-mail: helpdesk.swe@ssa.esa.int

HESPERIA REleASE Alert Meter



2022-03-28 12:00:00 UTC

Table 1. HESPERIA REleASE Alert Gauge Meter's States and Flux / Conditions.

State	Flux/Condition
Quiet	flux is $< 10^{-3}$ $(cm^2$ sec sr $MeV)^{-1}$
Warning	$10^{-3} \leq$ flux $< 10^{-1}$ $(cm^2$ sec sr $MeV)^{-1}$
Alert	flux $\geq 10^{-1}$ $(cm^2$ sec sr $MeV)^{-1}$

The HESPERIA REleASE Alert System can generate alerts which are distributed to registered users. You can register **here**.

E-mail: REleASE Alert system | Risk level: ALERT FOR "EPAM"

"**EPAM**" exceeded its threshold and generated an alert at

22-03-28 12:12:50 UT

based on our server timestamp.

The raw data of "**EPAM**" refer to

2022-03-28 11:50:00 UT

based on the HESPERIA REleASE timestamp.

Visit our HESPERIA REleASE product web page to view details of the event forecast.

If you want to unsubscribe you have to visit the subscription web page of the HESPERIA REleASE Alert product and check the unsubscribe checkbox.

You can access the HESPERIA products webpage here.

Best Regards,

National Observatory of Athens

Access the ESA SWE Portal here: swe. ssa.esa.int

For further product-related information or enquiries contact helpdesk.

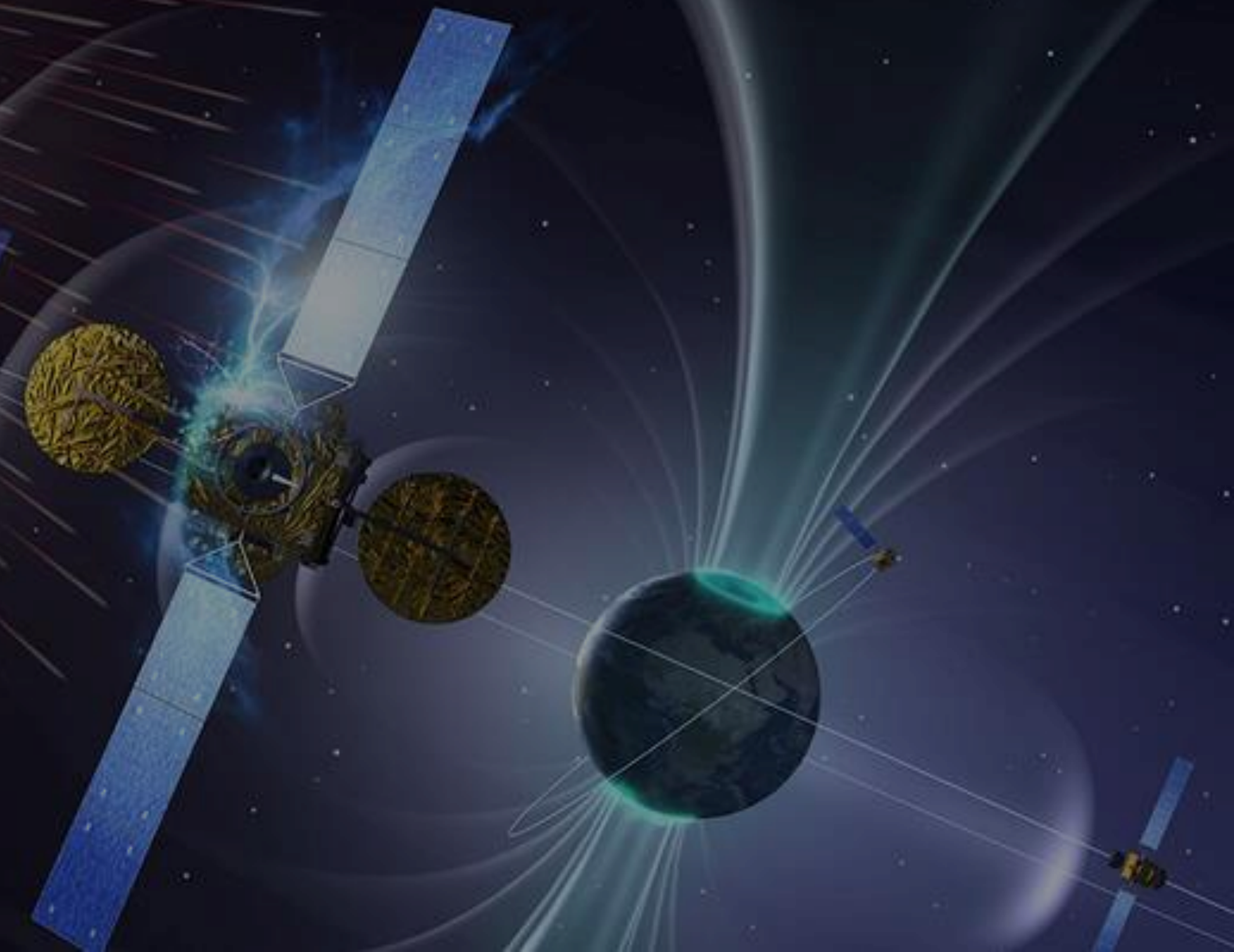
E-mail: helpdesk.swe@ssa.esa.int

HESPERIA REleASE

iSWA – CCMC/M2M

Assets of HESPERIA REleASE

- **No need for any prior solar flare (soft X-ray observations) to issue forecasts**
- **Providing forecasts also in the case of backside flares which most other schemes cannot provide**
- **25% of the SEP events observed at Earth's orbit are due to backside solar events (Richardson et al., 2014)**



Significant SPEs and relevant HESPERIA REleASE Alerts

September 2021 – December 2023

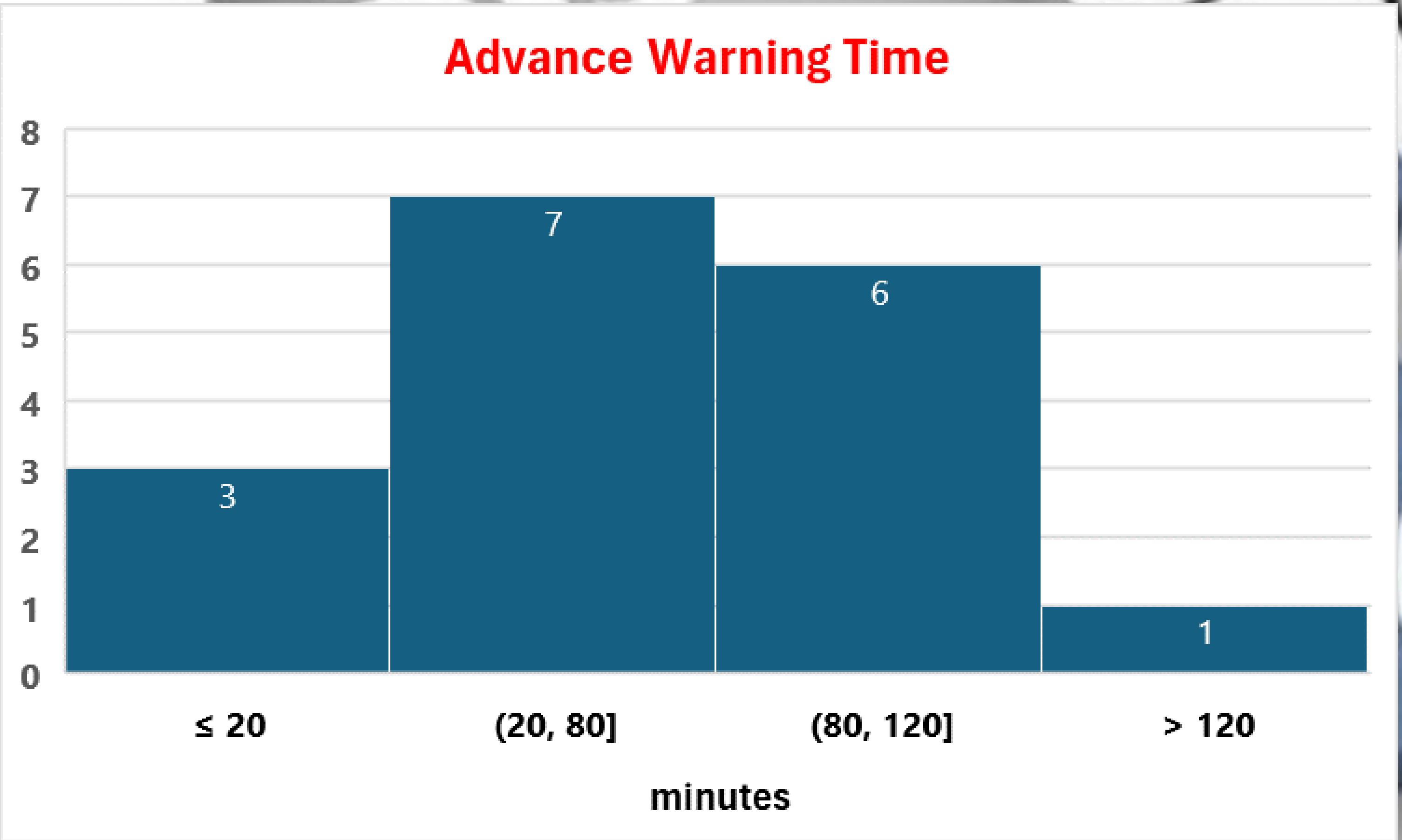
		Electron event Onset Time [in UT]		Proton flux threshold crossing [in UT]		Proton Alert Time (PA) [in UT]		Advance Warning Time (min)
A/A	**Date**	**EPHIN**	**EPAM**	**P3**	**P4**	**EPHIN**	**EPAM**	
1	28/10/2021	15:54	16:24	18:08	17:55	16:08	17:20	107
2	20/01/2022	06:06		8:07	7:47	06:19		88
3	28/03/2022	11:53	11:50	13:44	13:53	11:59	12:00	105
4	02/04/2022		13:39	14:38	14:39	14:03	13:39	35
5	09/07/2022	13:51	14:04	15:22	15:23	14:15		67
6	27/08/2022	03:20		10:32	13:52	10:30		2
7	13/01/2023	00:13		04:36				-
8	25/02/2023		19:50	21:26	21:29	19:58	20:00	88
9	13/03/2023	04:28		11:19	14:04			-
10	14/03/2023		08:30	10:44	15:13	09:48	10:24	56
11	23/04/2023	16:58	17:05	17:28	17:44	17:02		26
12	08/05/2023		09:05	13:12	7:23			-
13	09/05/2023	22:15	20:00	22:24	22:52	22:17	22:24	7
14	17/07/2023	18/07/2023 00:00	23:40	18/07/2023 1:06	18/07/2023 1:12	18/7/2023 00:06	23:54	60
15	28/07/2023	16:24	16:19	18:58	19:23	17:07	17:09	111
16	05/08/2023	07:42	07:40	10:03	10:14		09:59	4
17	05/08/2023	22:27	22:25	23:34	23:34	22:34		60
18	07/08/2023	21:32	21:00	22:09	22:19	21:33		36
10	01/09/2023	03:31	03:30	05:05	05:05	03:33	03:34	92
20	15/12/2023			15:09	15:09	11:07		242

20 significant proton events (P3/P4 proton flux exceeding 0.1 cm^{-2} s^{-1} sr^{-1} MeV^{-1}) *during the period Sep 2021 – Dec 2023 with:*

- *derived threshold-crossing and proton alert times*
- *associated electron event onsets*
- *Advance Warning Time*

Advance Warning Time

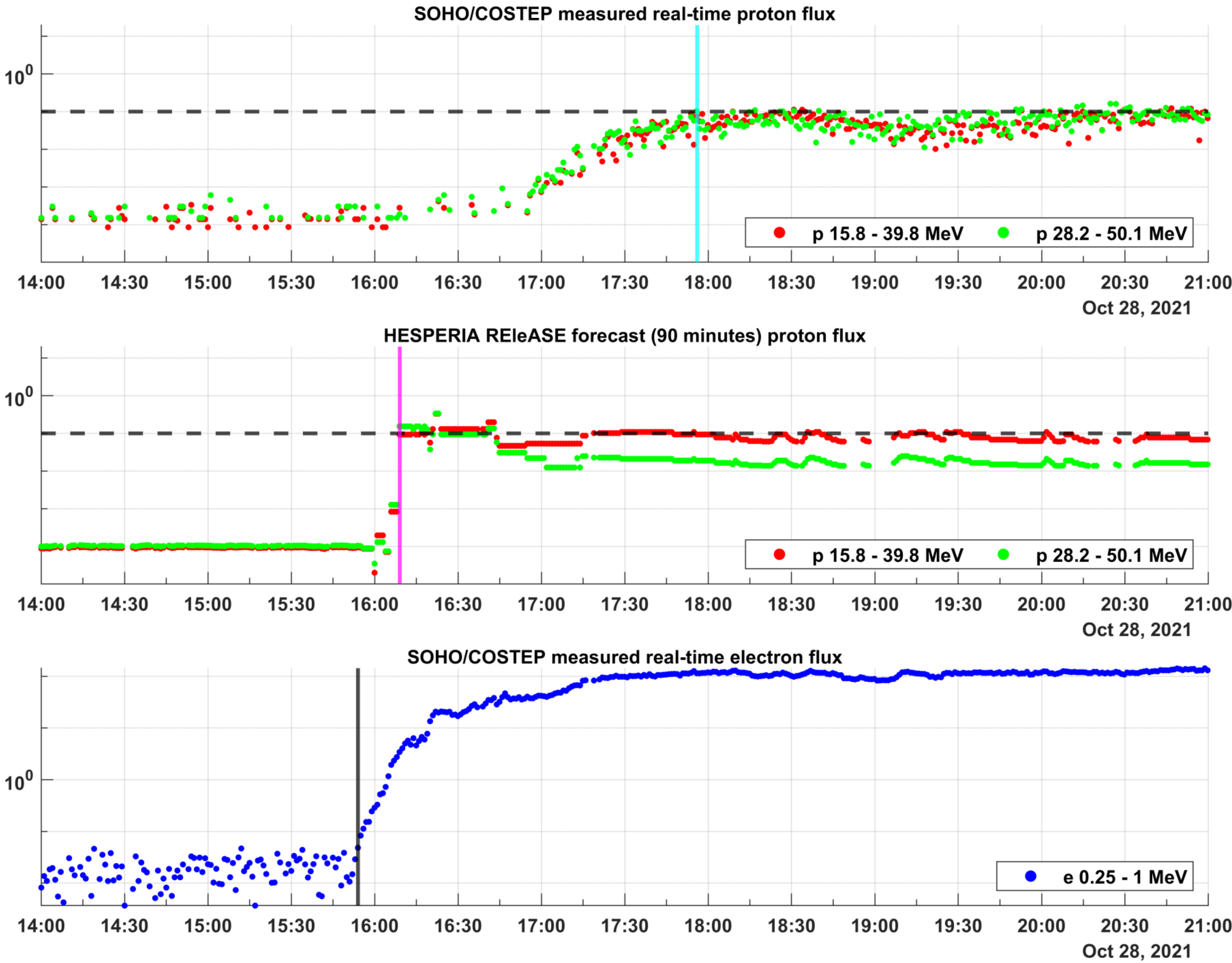
for September 2021 – December 2023 significant SPE events



Mean AWT: ~ 70 min

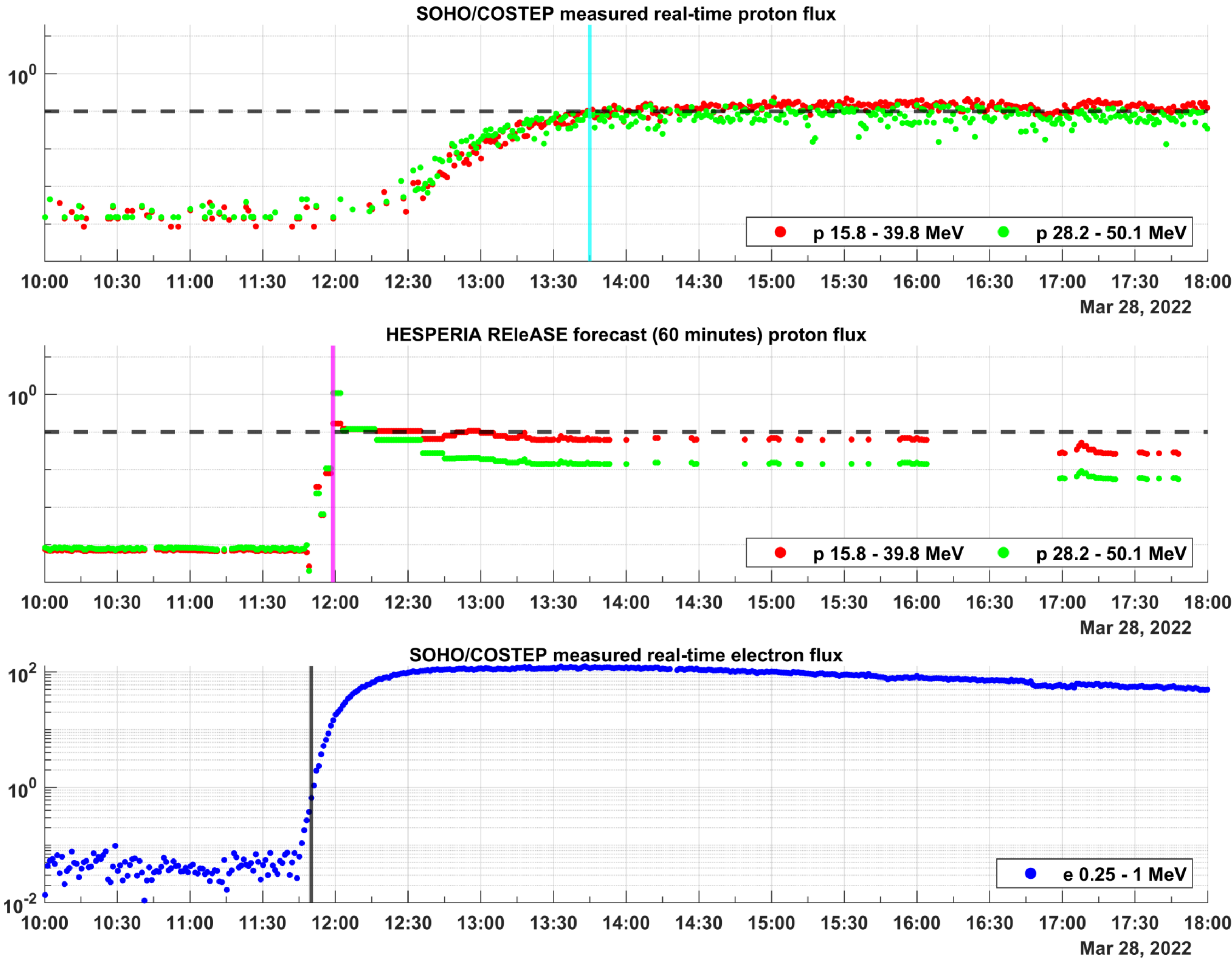
HESPERIA REleASE Hit: 28-Oct-2021

- **Electron event occurred at 28-Oct-2021 17:54**
- Proton Alert generated via the HESPERIA REleASE system at 28-Oct-2021 16:08
- SEP event occurred at 28-Oct-2021 17:55
- AWT: 107 minutes

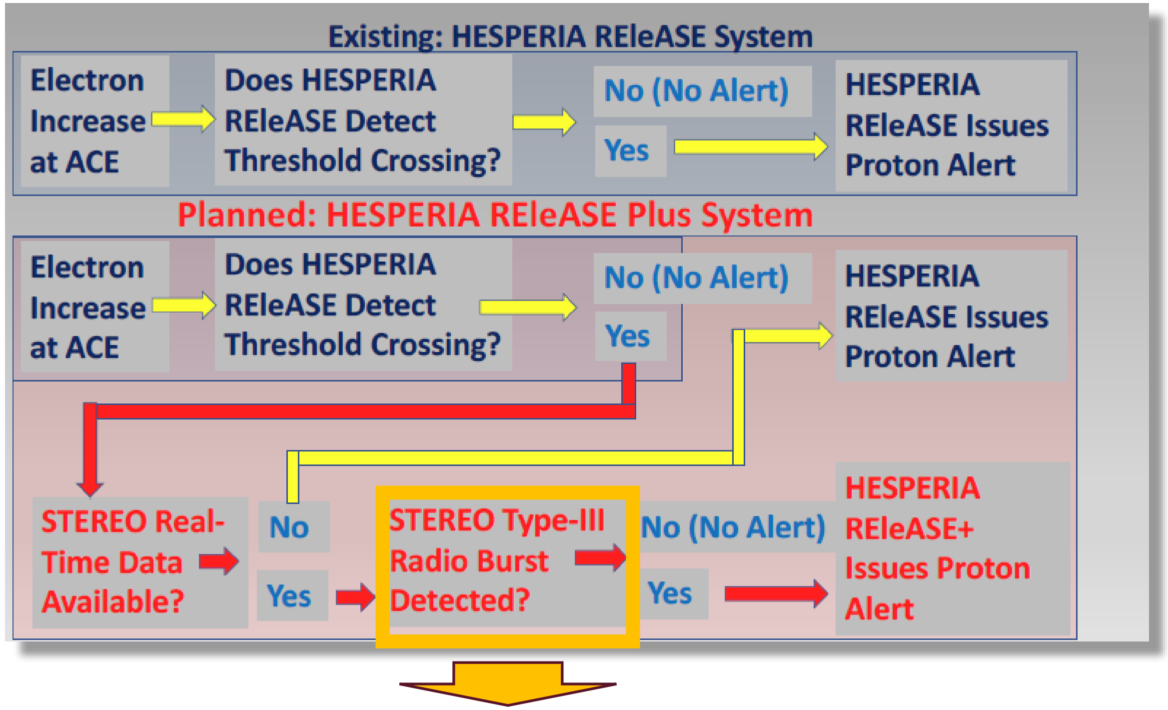


HESPERIA REleASE Hit: 28-Oct-2021

- **Electron event occurred at 28-Mar-2022 11:53**
- Proton Alert generated via the HESPERIA REleASE system at 28-Mar-2022 11:59
- SEP event occurred at 28-Oct-2021 13:44
- AWT: 105 minutes

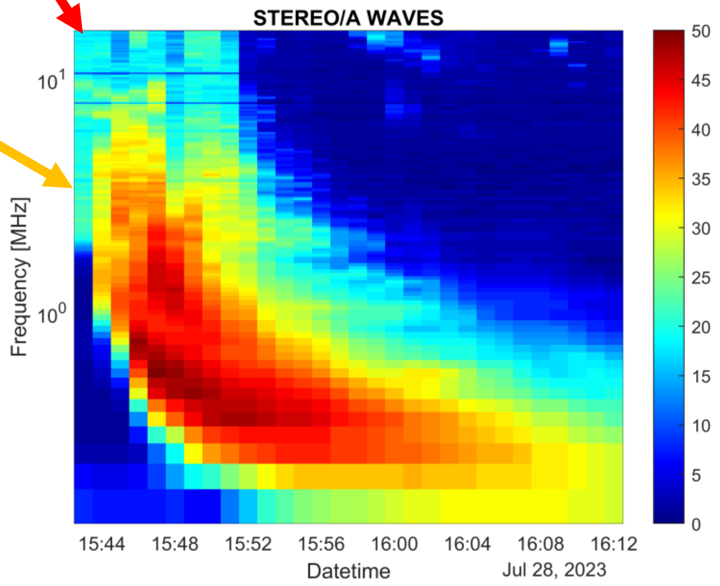


REleASE forecast improvement with evidence of particle escape from the Sun: HESPERIA REleASE+



Electron beams accelerated in solar eruptive events travelling outward through the corona along open magnetic flux tubes

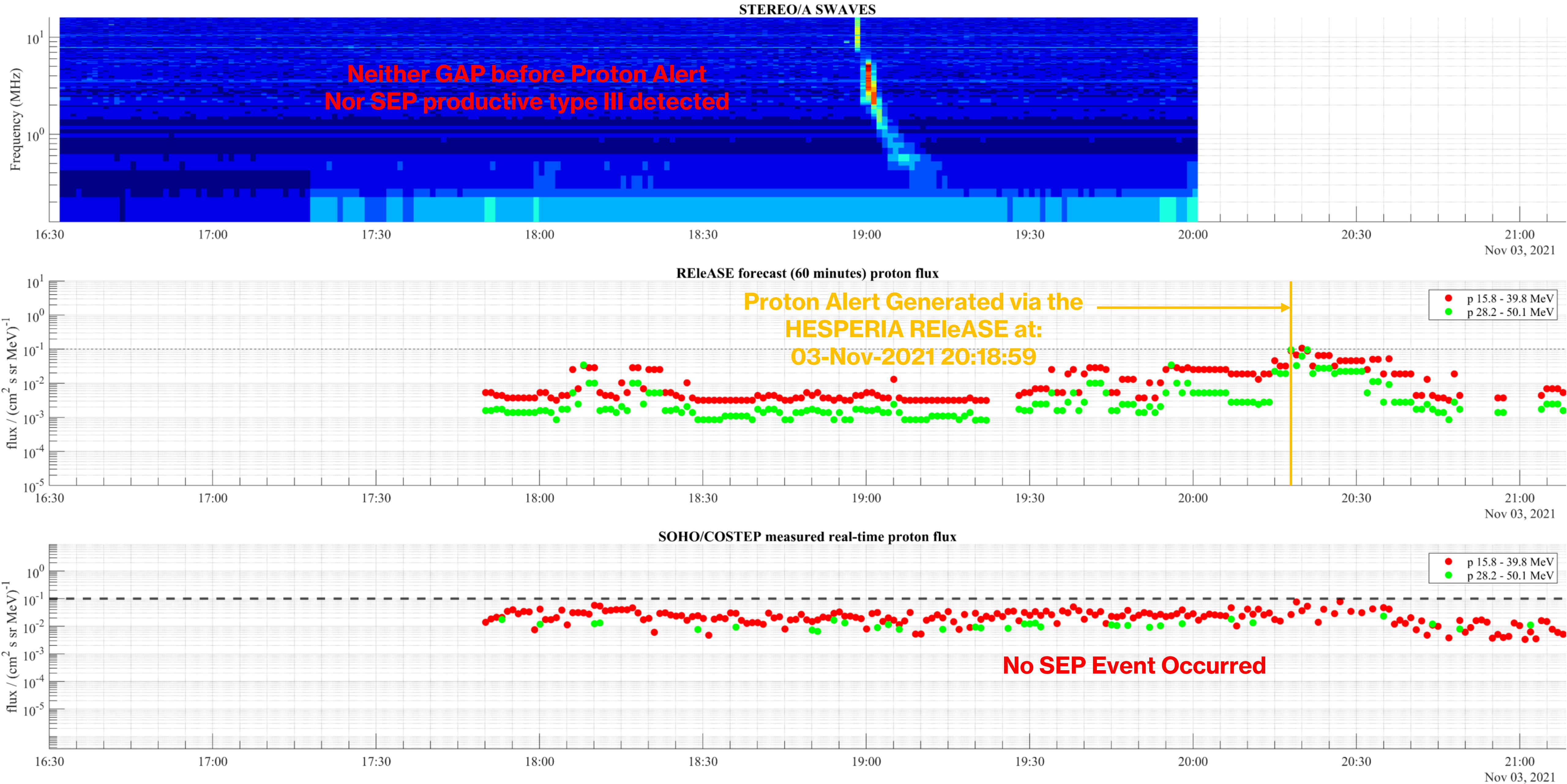
The emission is observed to drift to lower frequencies as the energetic electrons travel away from the Sun in the solar corona and the interplanetary medium (Lin et al., 1990; Lin, 2006)



Interplanerary type III radio bursts are a timely and reliable proxy of particle escape from the Sun onto open field lines

For the first time, we paired REleASE with evidence of particle escape from the Sun which substantially eliminates false alarms

HESPERIA REleASE+ False Alarm Elimination

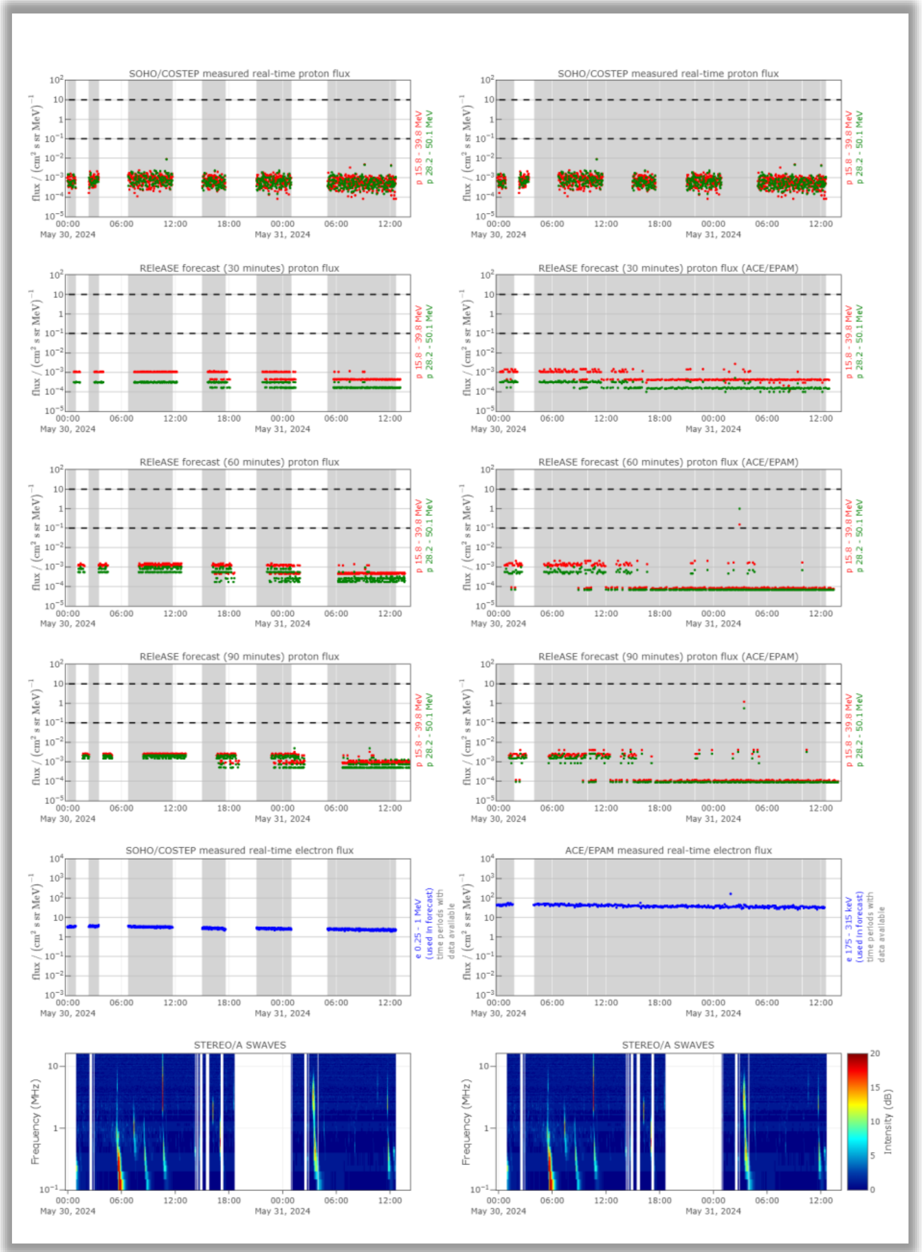


HESPERIA REleASE+ status

Relevant paper Submitted to Space Weather Journal (AGU)

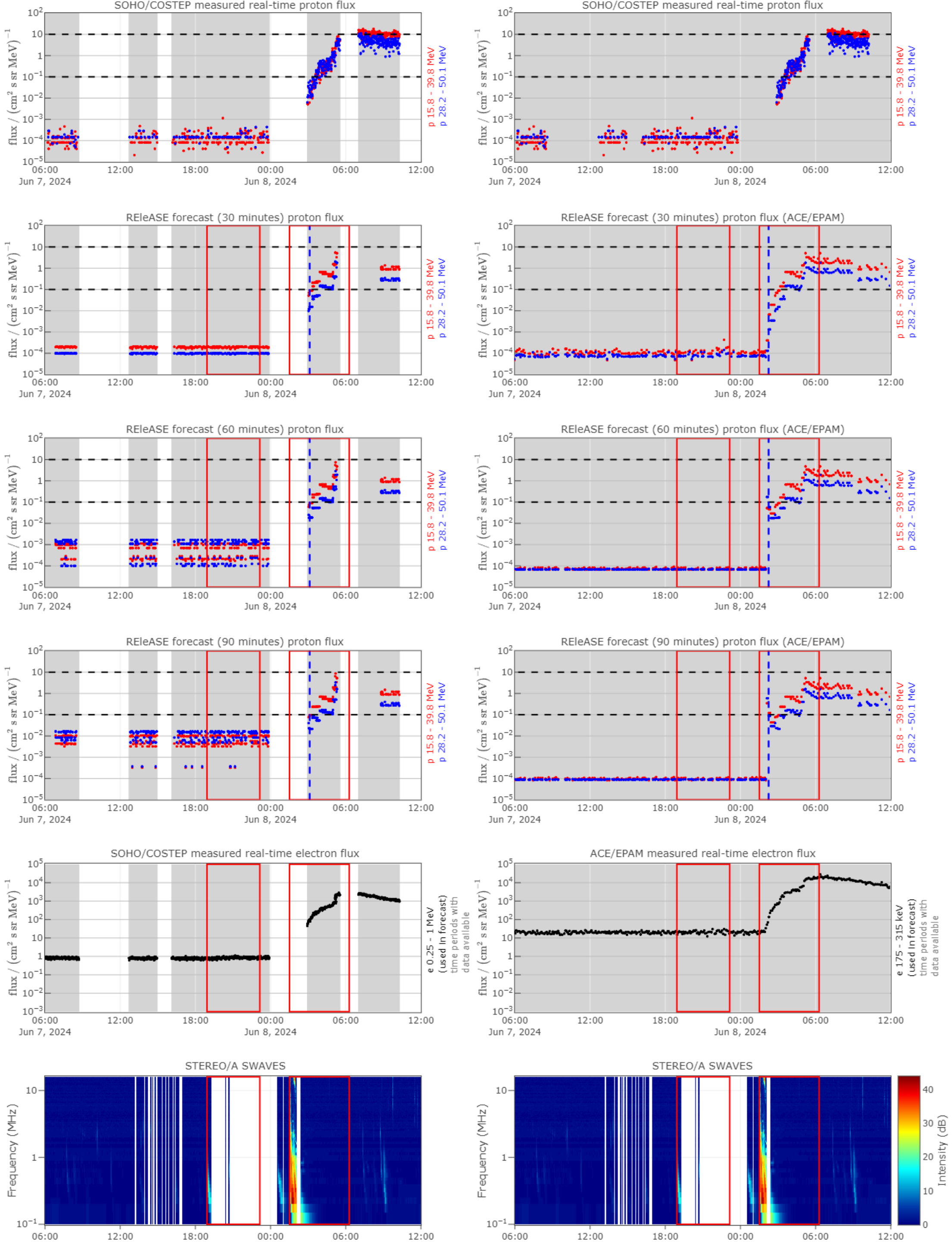
HESPERIA REleASE+ system publicly available on NOA premises soon

Stay Tuned!



HESPERIA REleASE+

Hit: 8 June 2024



New REleASE products

STEREO REleASE

Space weather instrumentation (ISWI instruments and other instruments)

POSTER 5 Application of the Relativistic Electron Alert System (REleASE) to instruments on board of STEREO-A, *Henrik DRÖGE, Germany*

STEREO REleASE+ based on the experience of the developed HESPERIA REleASE+