MSL/RAD on Mars and Beyond...
Improving Space Weather Situational Awareness

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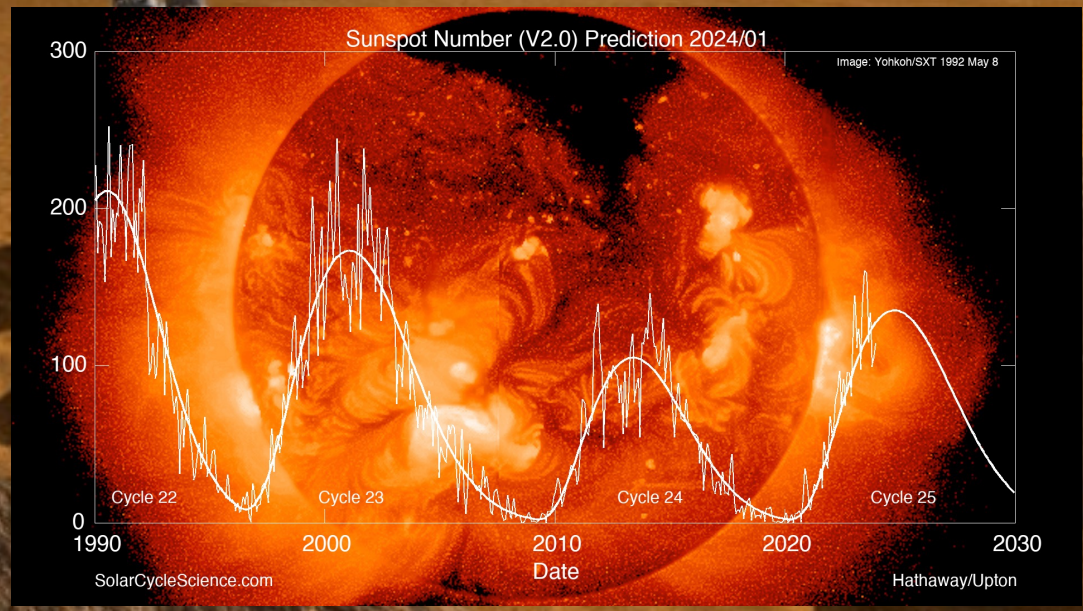
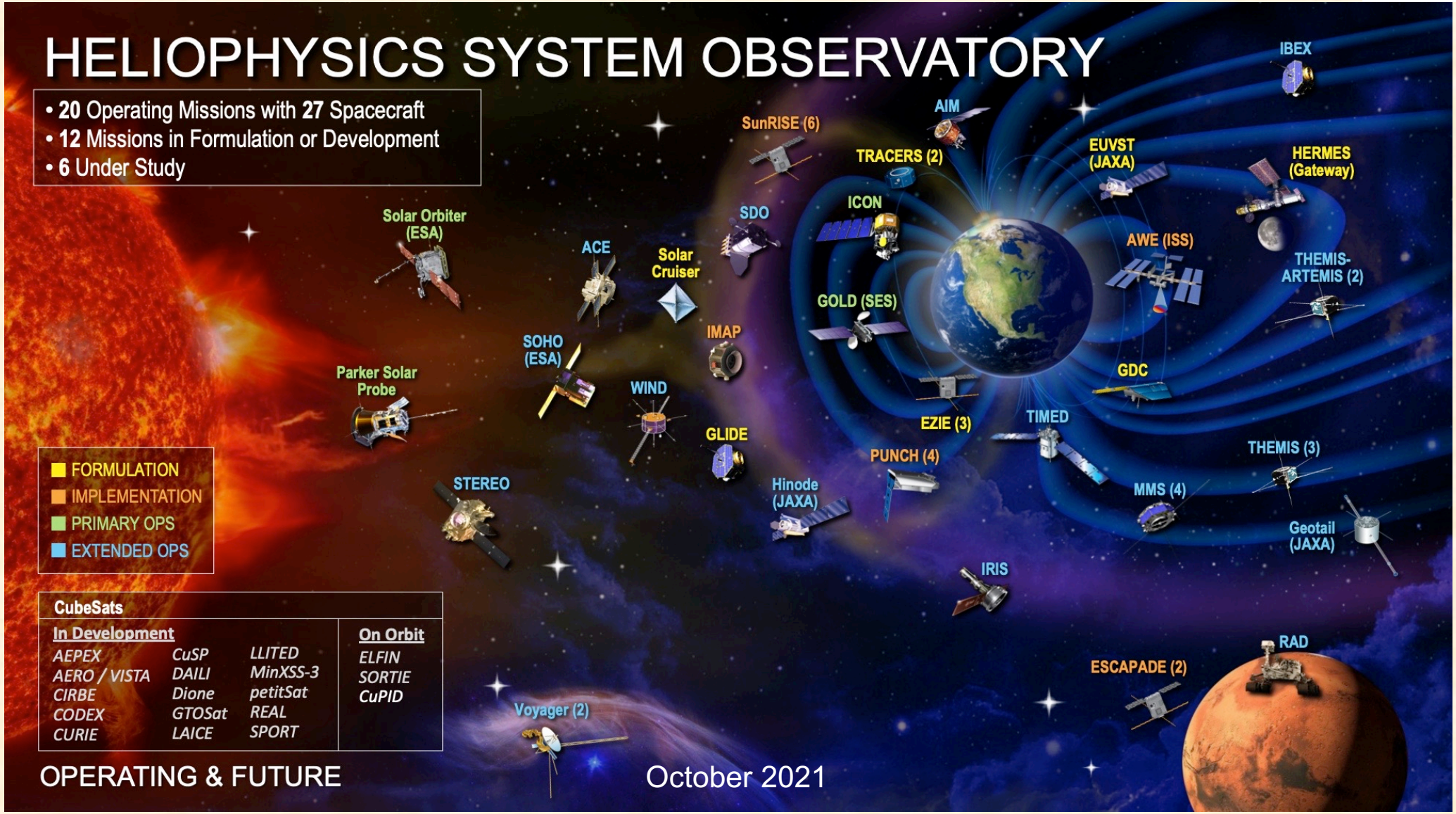


RAD on Mars: Part of NASA's Heliophysics System Observatory (HSO)

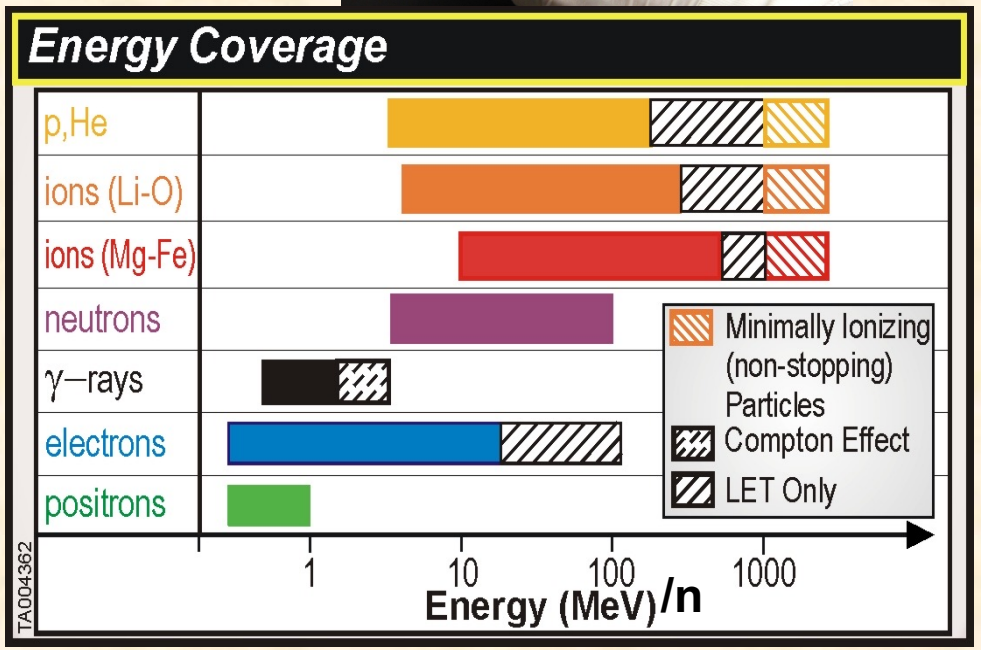
(RAD data available on the NASA SPDF and PDS)



Mars Science Laboratory (MSL)
RAD (Radiation Assessment Detector) Overview

RAD is a collaboration between NASA SMD (Heliophysics and Planetary Science Divisions), Human Exploration Mission Directorate, and internationally between the US (NASA) and Germany (DLR).

…RAD is serving as a ***space weather outpost*** on the surface of Mars ("Spaceship Mars"), characterizing the **radiation environment on Mars over the solar cycle**, due to Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs).



RAD is made of:

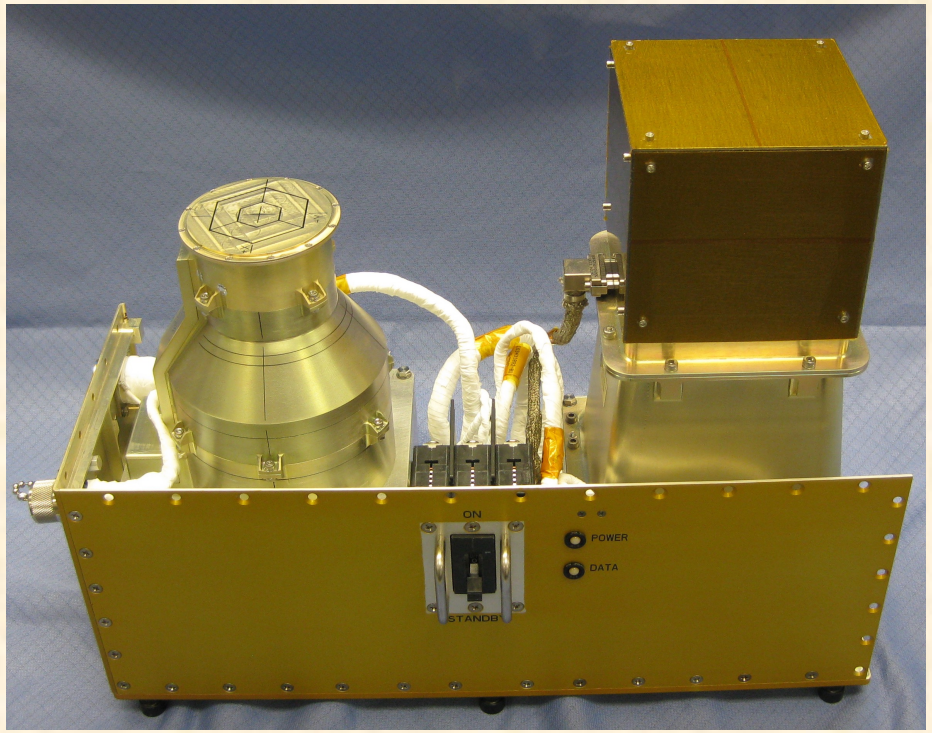
- Solid state detector telescope and CsI calorimeter with active coincidence logic to identify ***charged particles.***
- Separate scintillators w/ anti-coincidence logic to detect ***neutral particles (neutrons and γ-rays)***.

The RAD Family

Mars:
MSL/RAD

2012 - present

ISS:
ISS/RAD w/ FND

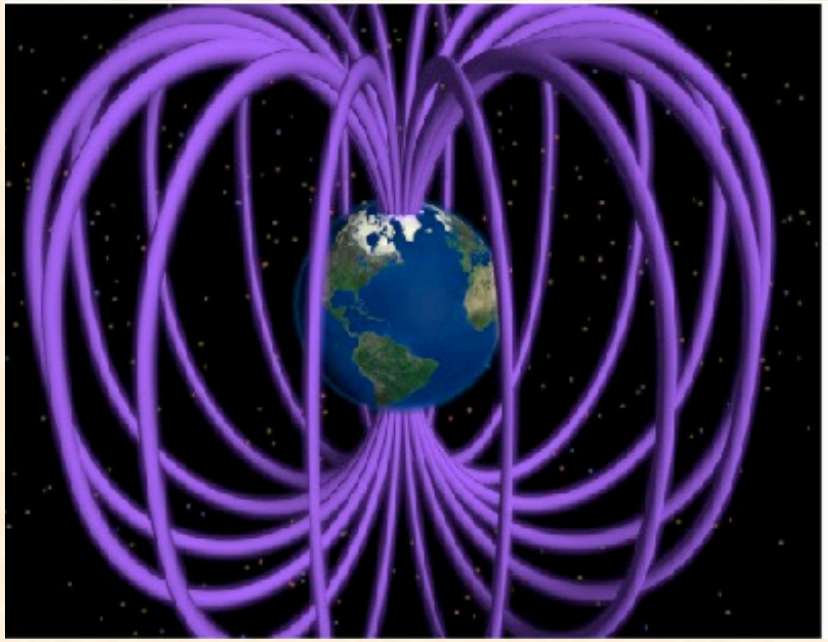


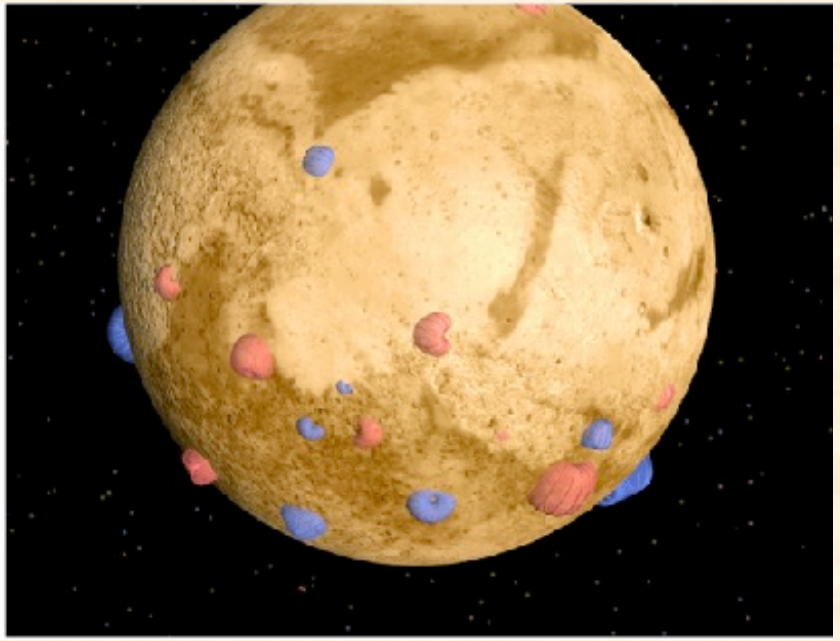
2016 - present

The Moon:
CLPS-22/Leia Mini-FND

launch: 2027

Unlike Earth, the Surface of Mars experiences DIRECTLY the effects of Space Weather...thus every event is a Ground Level Event (GLE)!



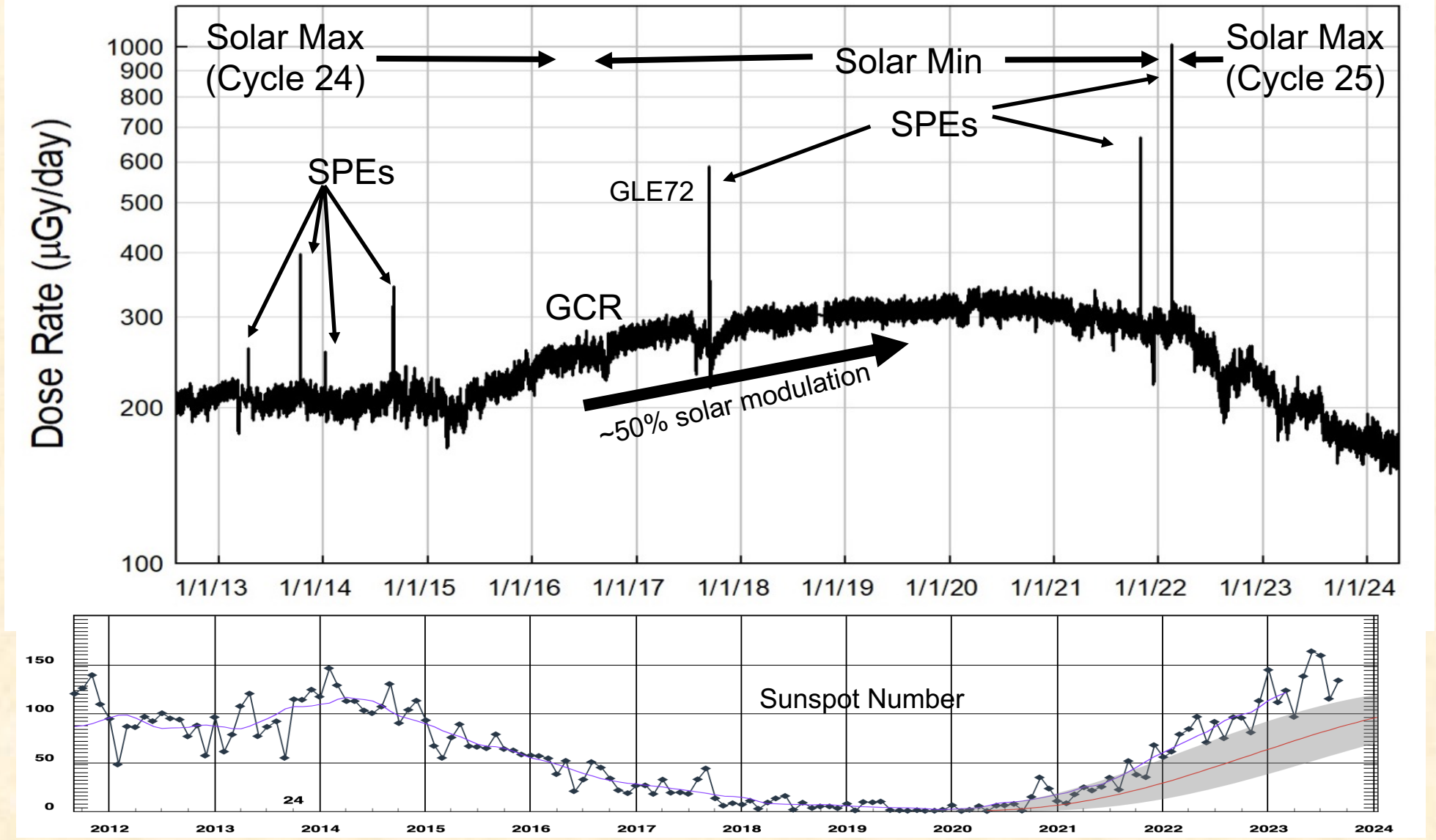


The surface of Mars is much more exposed to space radiation than the surface of Earth, for two reasons:

- Mars lacks a global planetary magnetic field (magnetosphere)
  - Only weak, local, remnant magnetic fields
- Mars atmosphere is much thinner
  - ~1% of thickness of Earth's atmosphere

RAD Observations over the Solar Cycle

(NOT including May 24 event...yet!)



The September 10, 2017 Event (GLE72) (Aurora on both Earth and Mars - @ Solar Min!)

The First GLE observed on Two Planets at Once!

Aurora seen on Mars from MAVEN

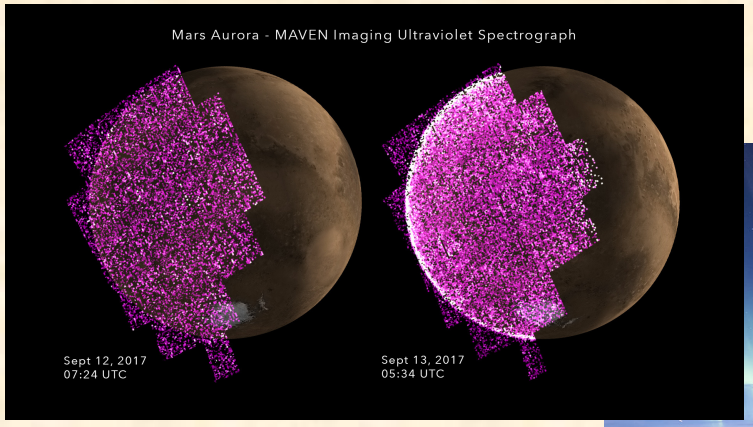


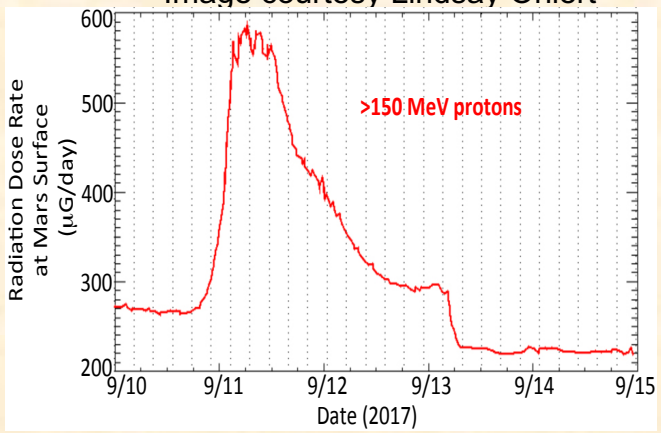
Image courtesy NASA/MAVEN

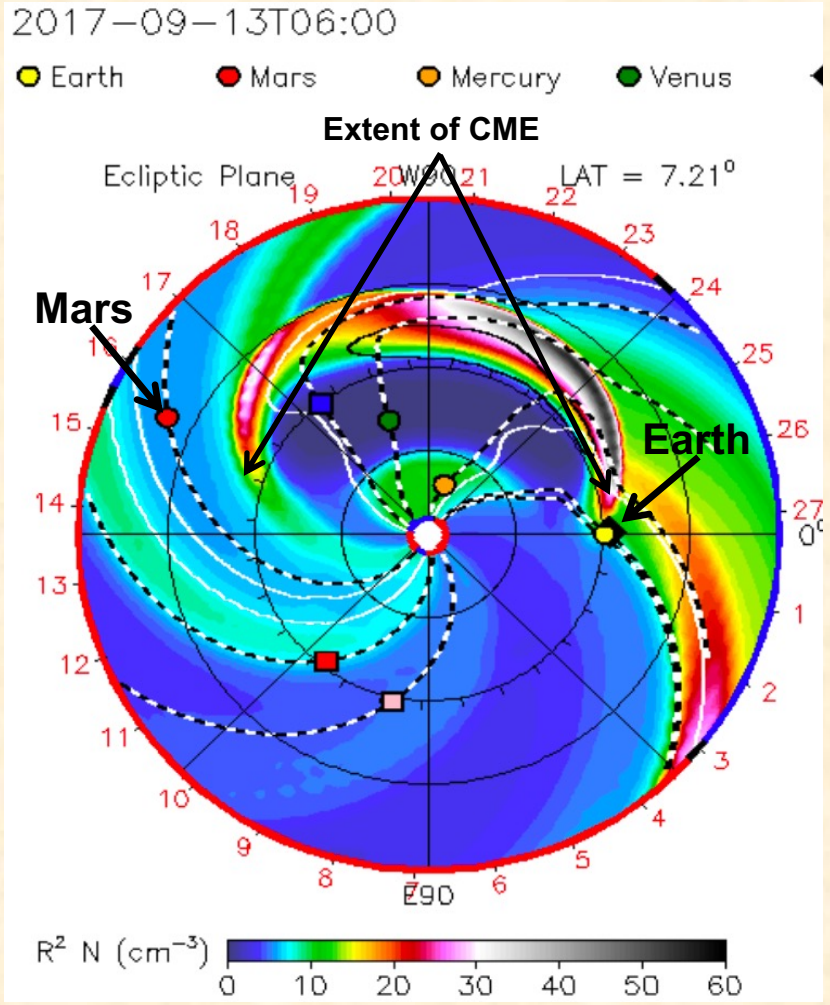
Aurora seen on Earth from Alaska

All together, this event was seen…

- On the surface of Mars by RAD
- In Mars orbit by MAVEN
- In Earth orbit by GOES & ISS/RAD
- On the ground here on Earth by several Neutron Monitors

Image courtesy Lindsay Ohlert

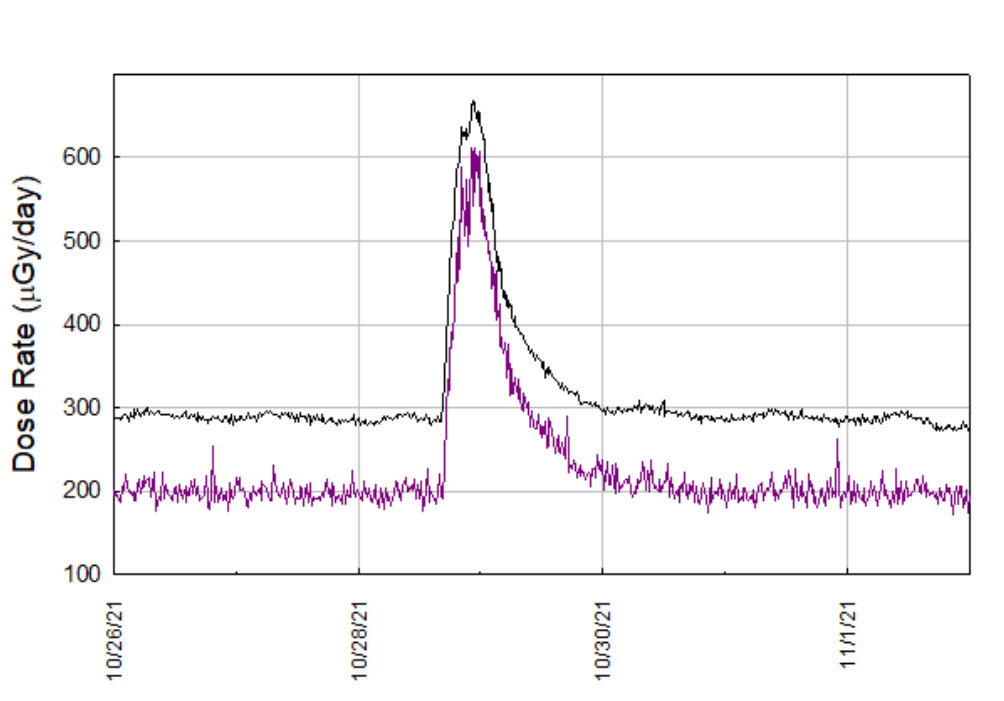




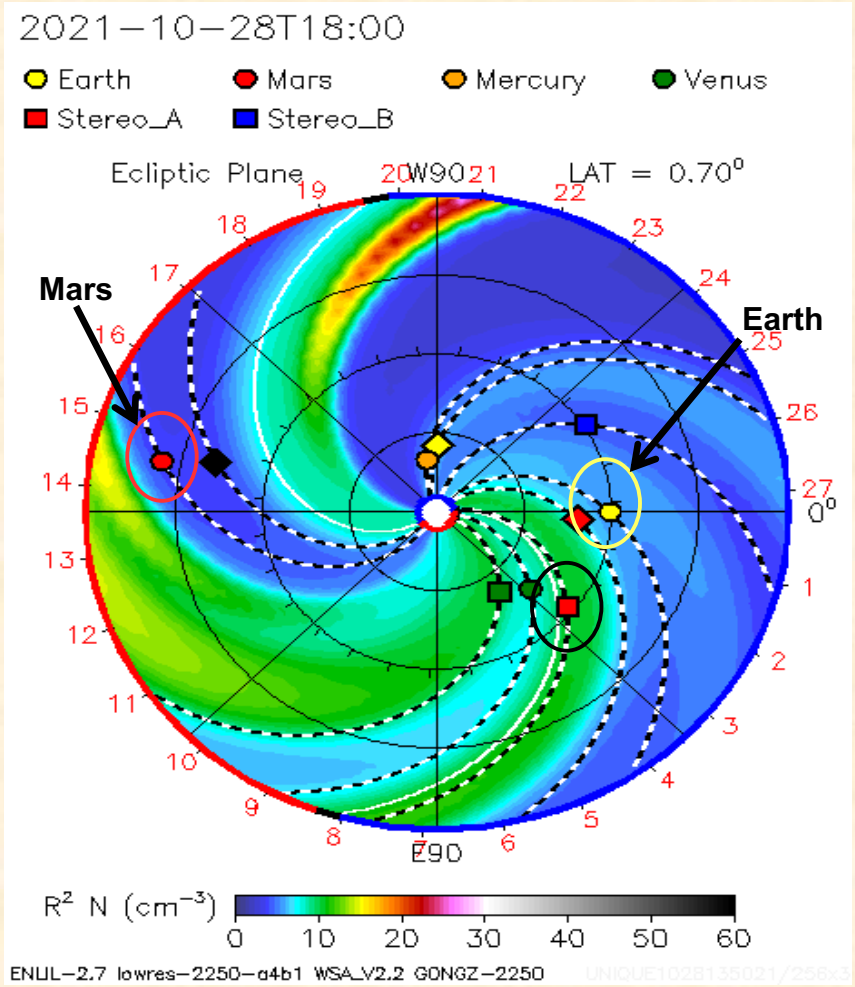
ENLIL Solar Wind Model showing propagation of the CME through the inner solar system.

The October 28, 2021 Event (GLE73): 1st X-class flare of new Solar Cycle

The Oct. 28, 2021 event corresponds with the ***first observed X-class flare of the new solar cycle!***



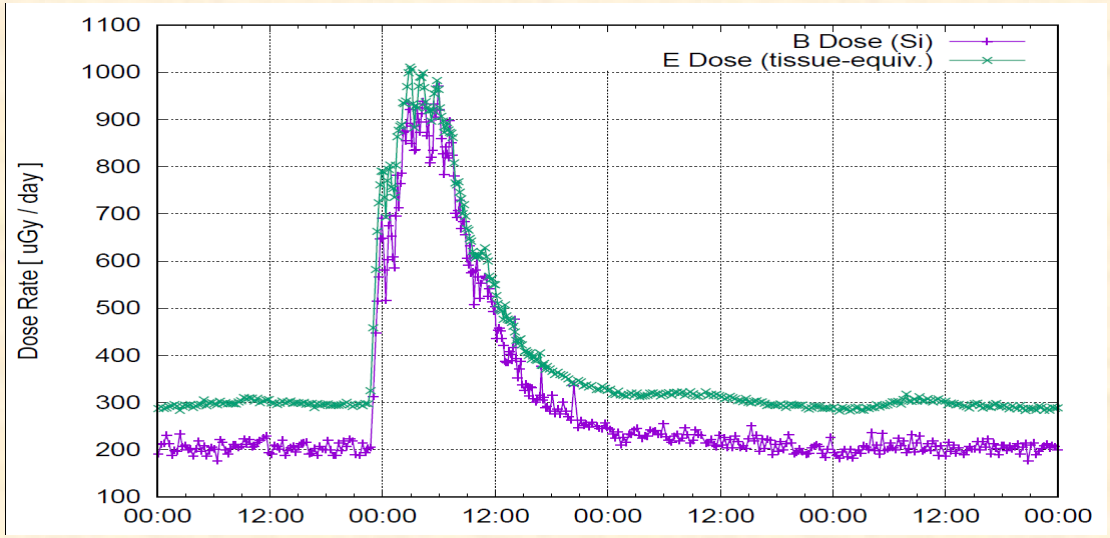
Mars & Earth were magnetically well separated at the time (~180°) … yet the event was still seen at both locations.



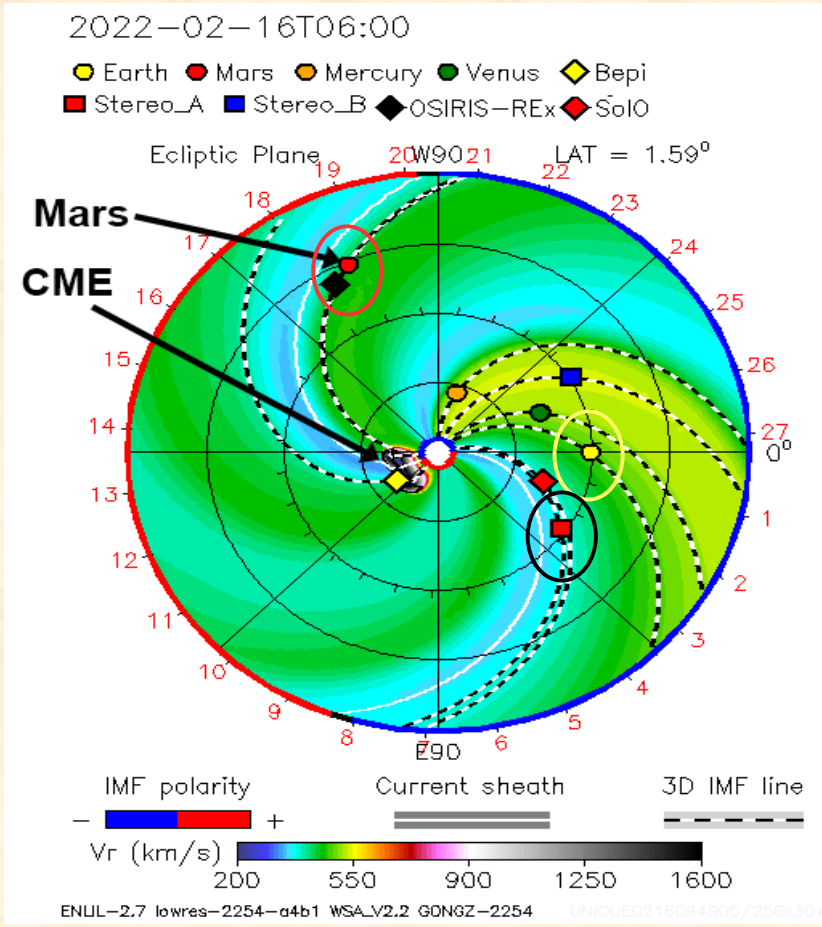
The February 16, 2022 SPE Event:
Seen at Mars but NOT at Earth!

The ***heliospheric longitudinal spread of SPEs*** is extremely important to understand for astronaut safety.

The ***largest event observed by RAD on the surface of Mars prior to Solar Max!***



If space agencies plan space station EVAs or off-base Lunar or Martian "sorties", they need to understand ***if there are any active regions on the far side of the sun that could develop into solar storms that might still reach the astronaut on the near side.***

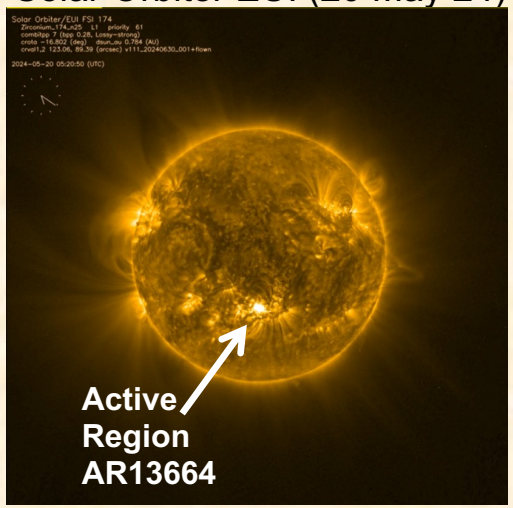


ENLIL plot for Feb 16

...Finally, the May 2024 Solar Storms: the largest in more than a Solar Cycle!

- May 2024 saw prolonged solar activity from AR 13664
- Earth-Mars separation ~ 95 deg

Solar Orbiter EUI (20 May 24)



Aurora seen from my backyard in Colorado!

Images courtesy Kim Hempstead

Aurora seen on Mars (MAVEN)

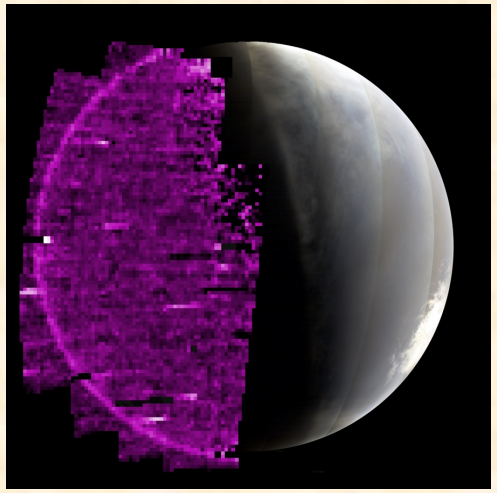
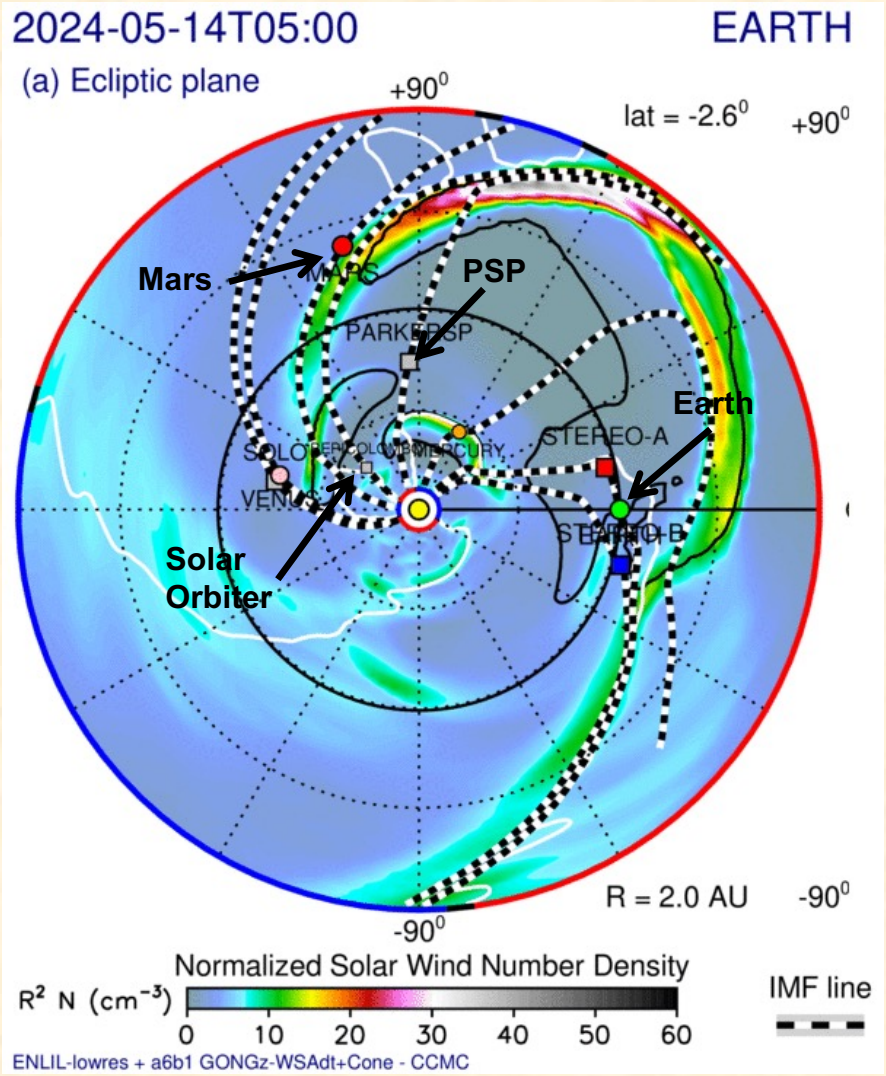


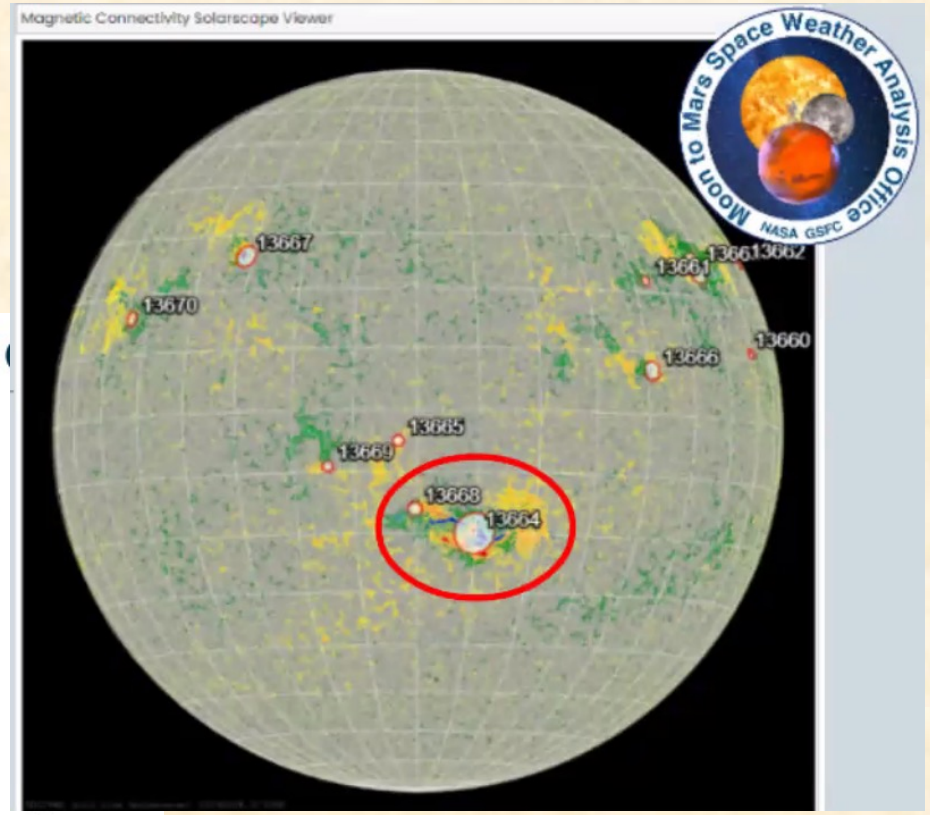
Image courtesy NASA/MAVEN

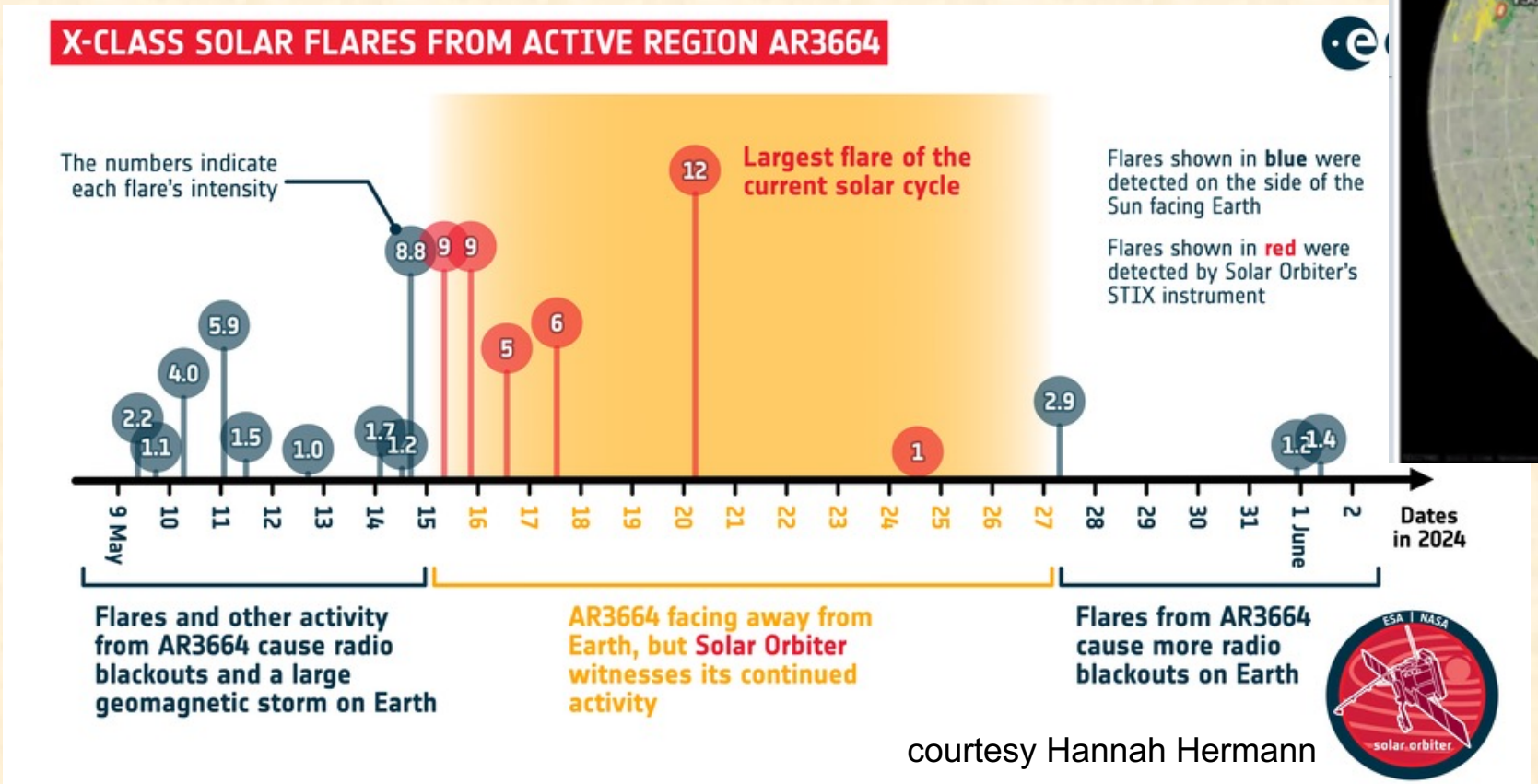


ENLIL Solar Wind Model showing propagation of the CME through the inner solar system.

The Show begins May 8...

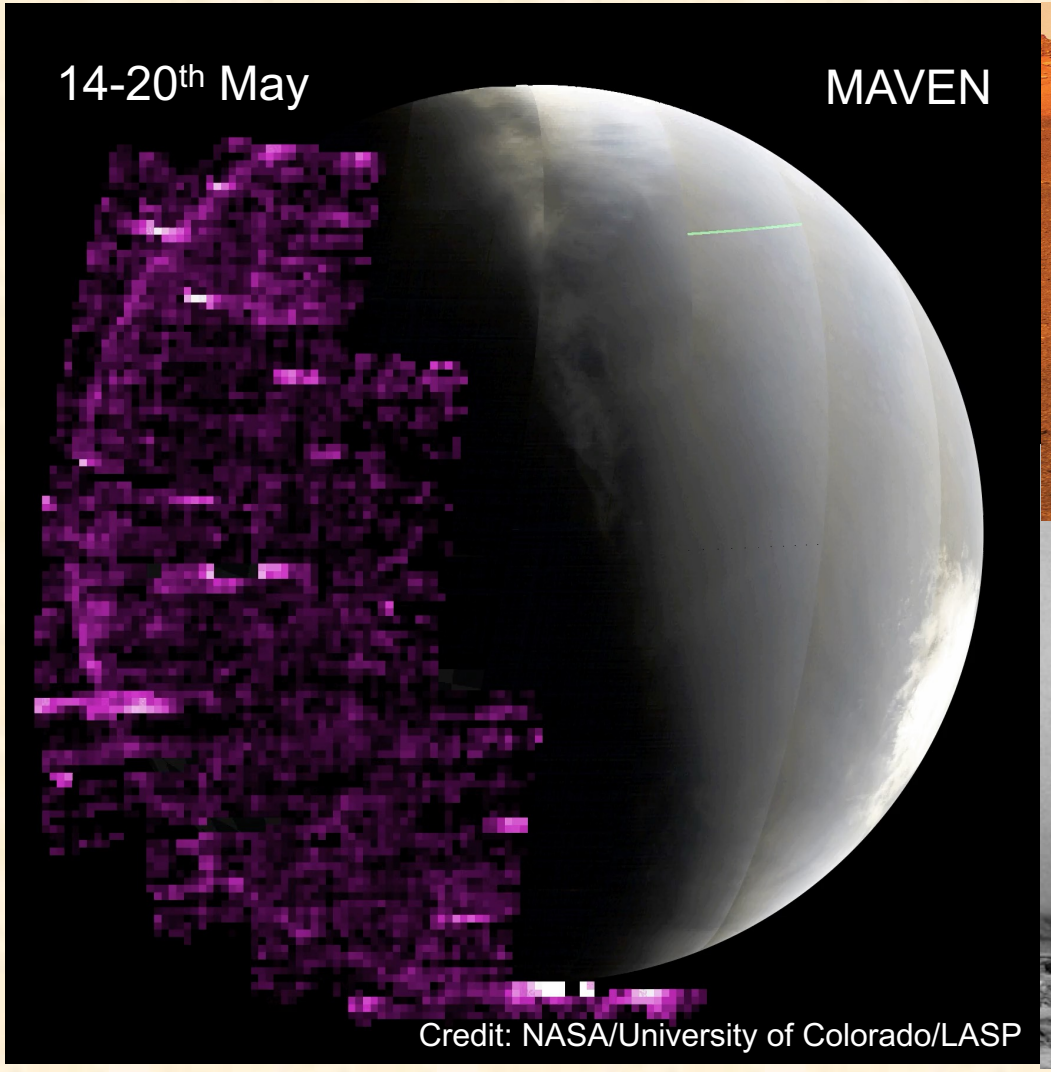
- AR 13664 wakes up with the 1st X-class flare and a large CME
- Numerous flares & CMEs follow in quick succession in the following days
- No one CME was “spectacular” on its own, until...

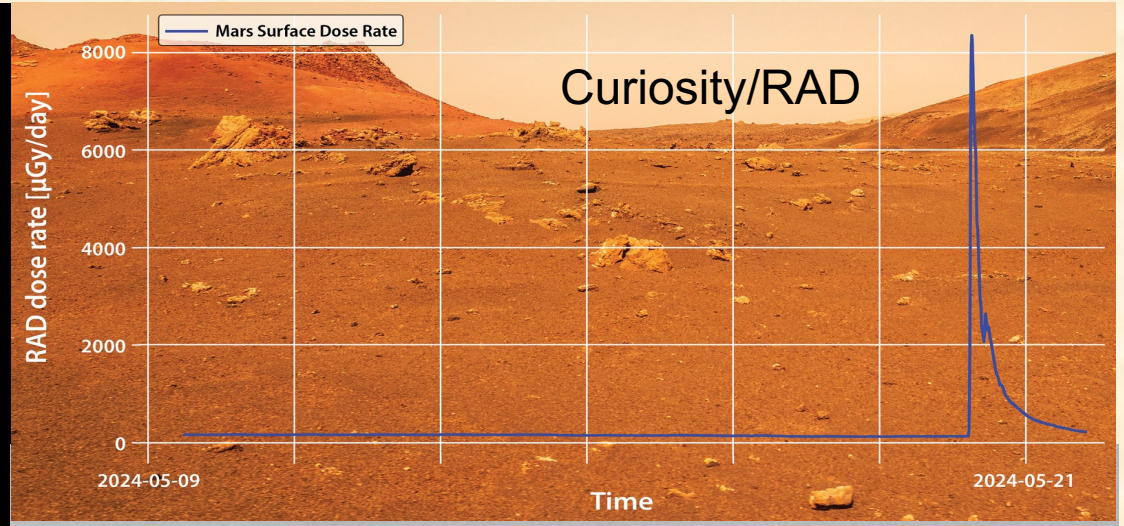


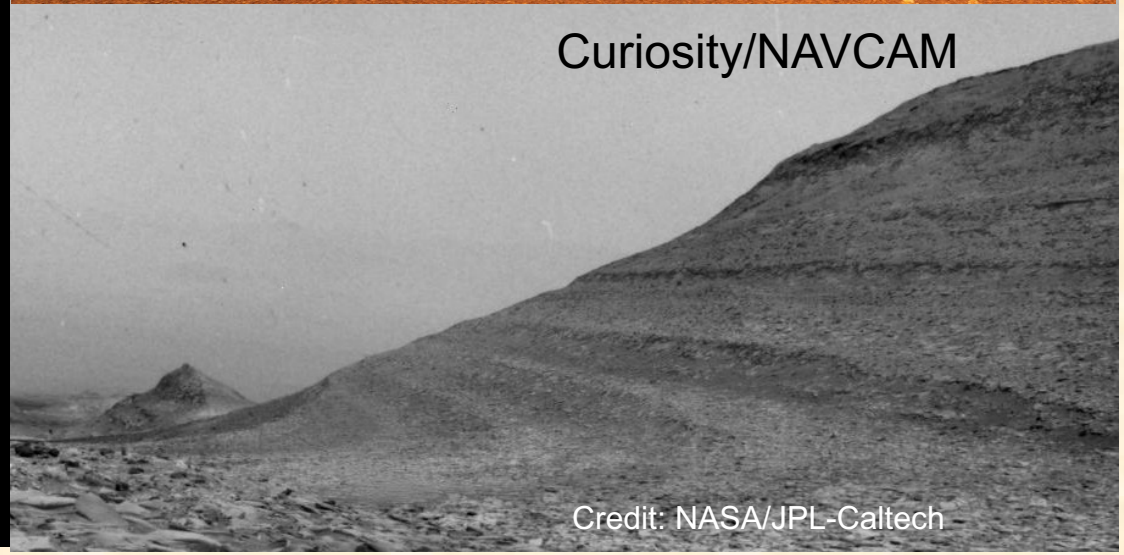


courtesy Hannah Hermann

and then...May 20, 2024 at Mars!

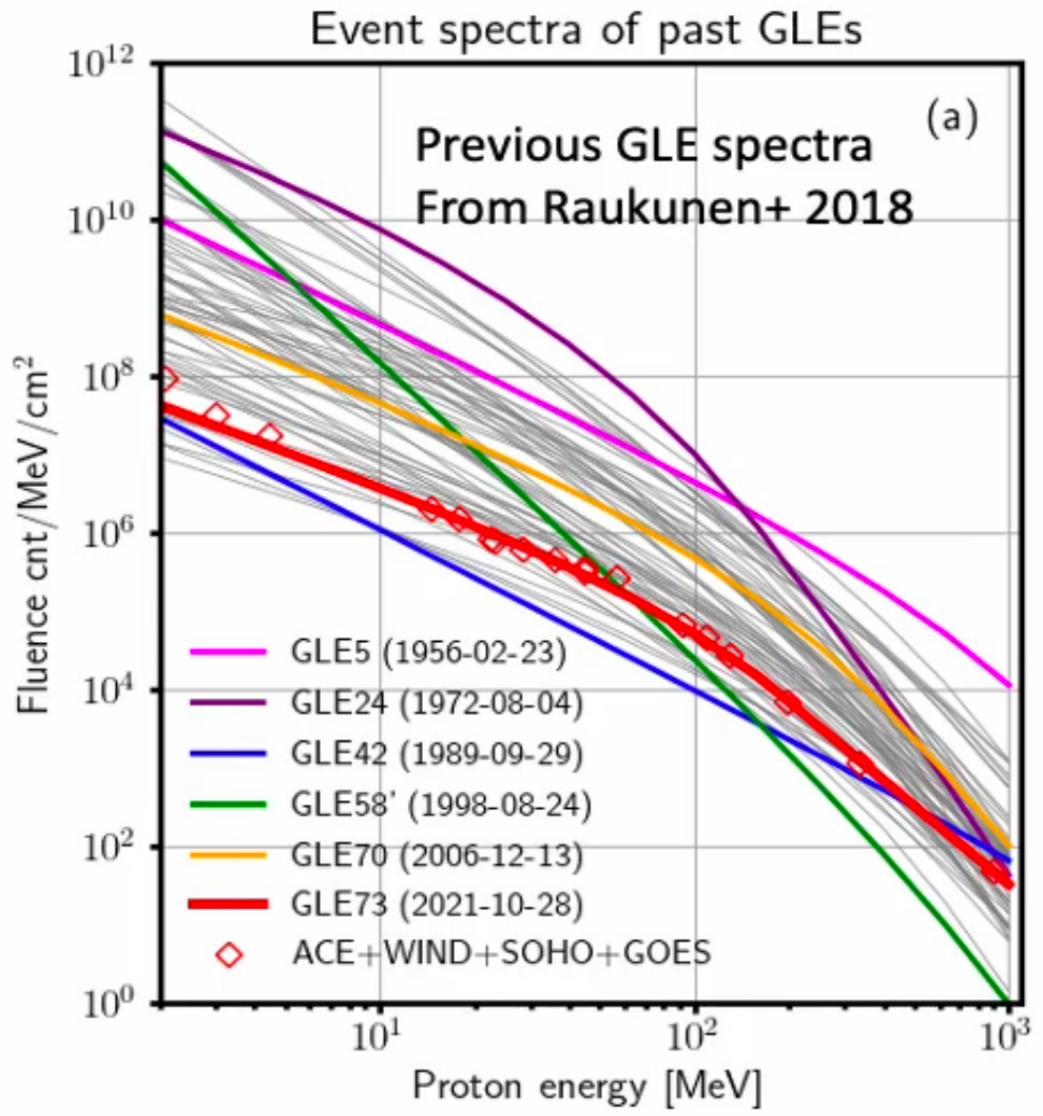






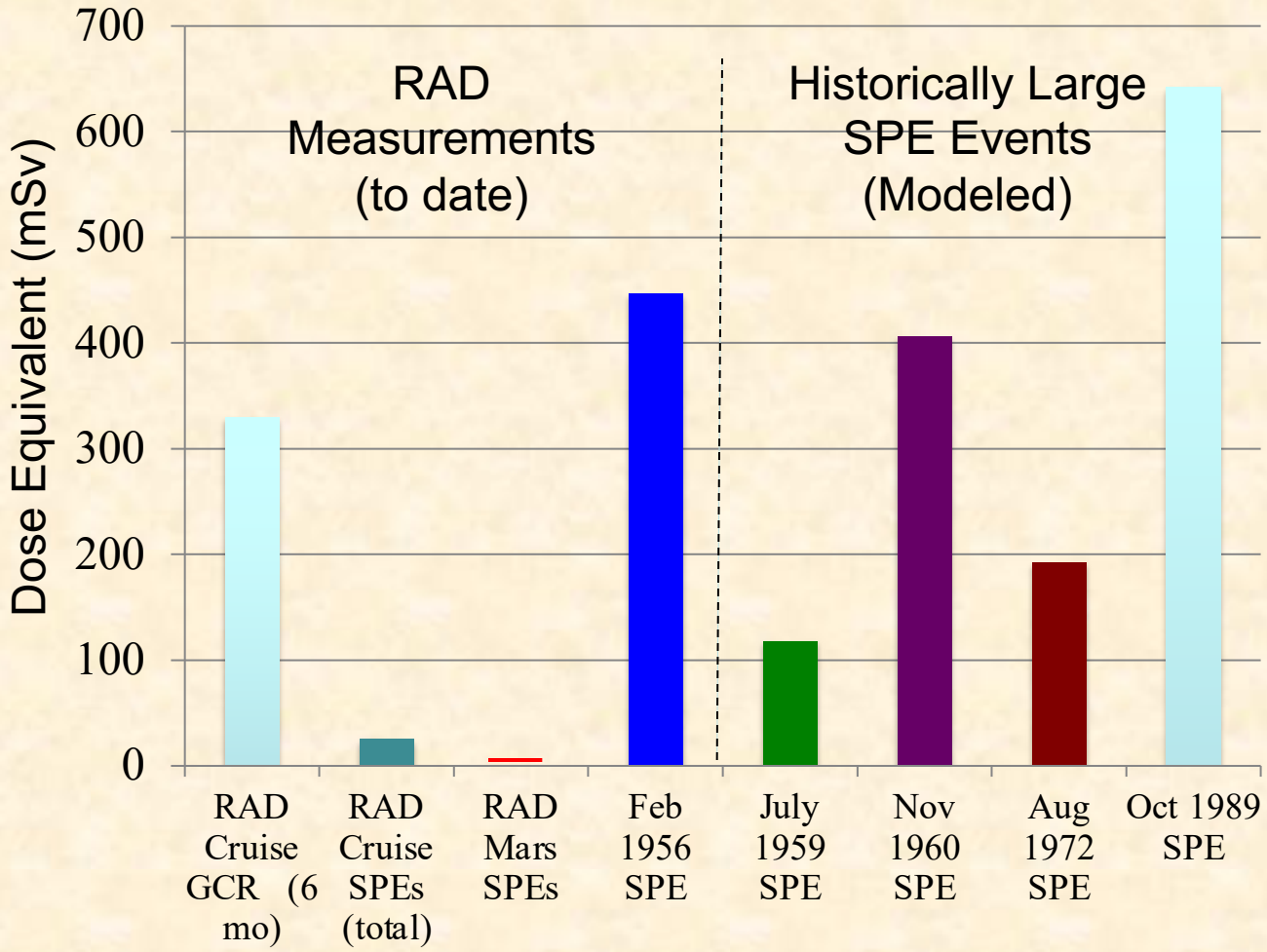
Comparison of the October 28, 2021 SPE (GLE73) to "historically large" events seen since the beginning of the Space Age

Comparison of ***Ground Level Event (GLE) 73 (Oct. 28, 2021)*** observed by several assets (ACE, WIND, SOHO & GOES) in the Heliophysics System Observatory (HSO) to other "historically large" events seen since the beginning of the space age.



How do the events observed by RAD compare with other "historically large" Solar particle events?

What might we expect from a Carrington Event or Super-Storm?

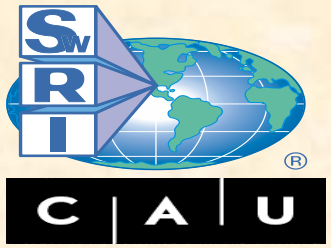


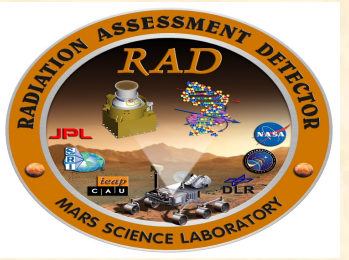
*SPE Dose Equivalent values modeled behind 5 g/cm^2 Aluminum by M.-H. Kim, F. Cucinotta, et al. (AGU, 2012).

RAD cruise measurements from Jan-July 2012.

Nov. 1960 SPE includes contributions from 2 events.

Oct. 1989 SPE includes contributions from 5 events over 1 month.



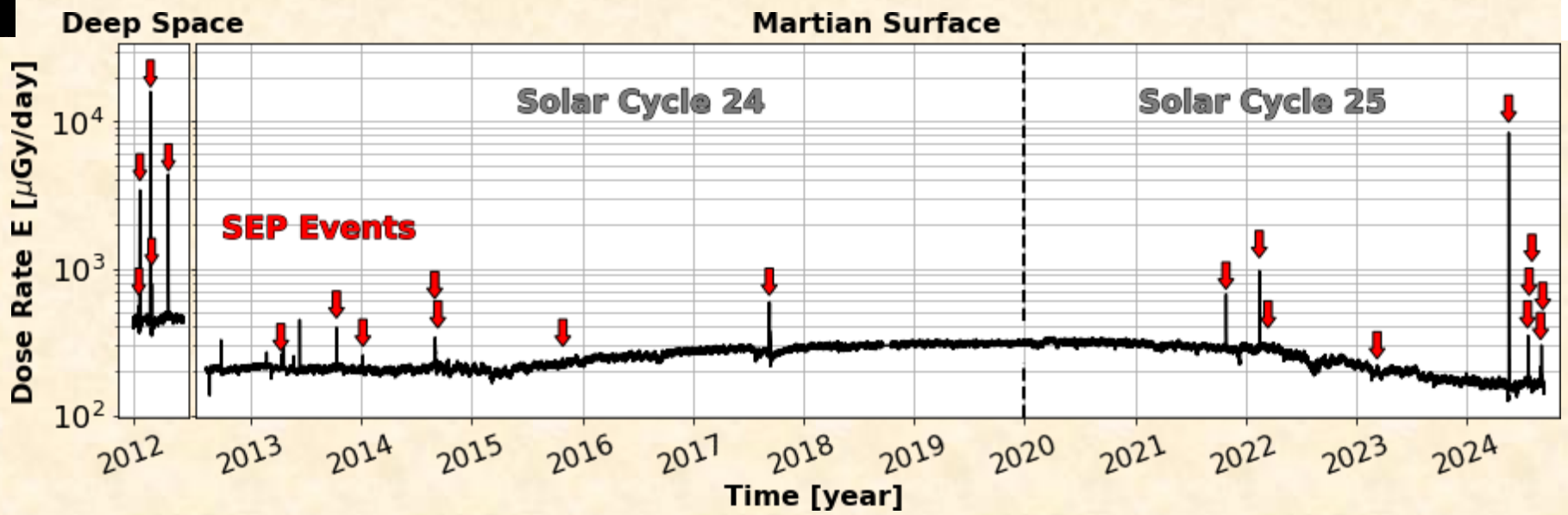


Nowcasting Solar Energetic Particle Events for Mars Missions

Jan Leo Löwe, R.F. Wimmer-Schweingruber, S. Khaksarighiri, D.M. Hassler, B. Ehresmann, J.Guo, T. Berger, D. Matthiä, C. Zeitlin, S. Löffler, G. Reitz

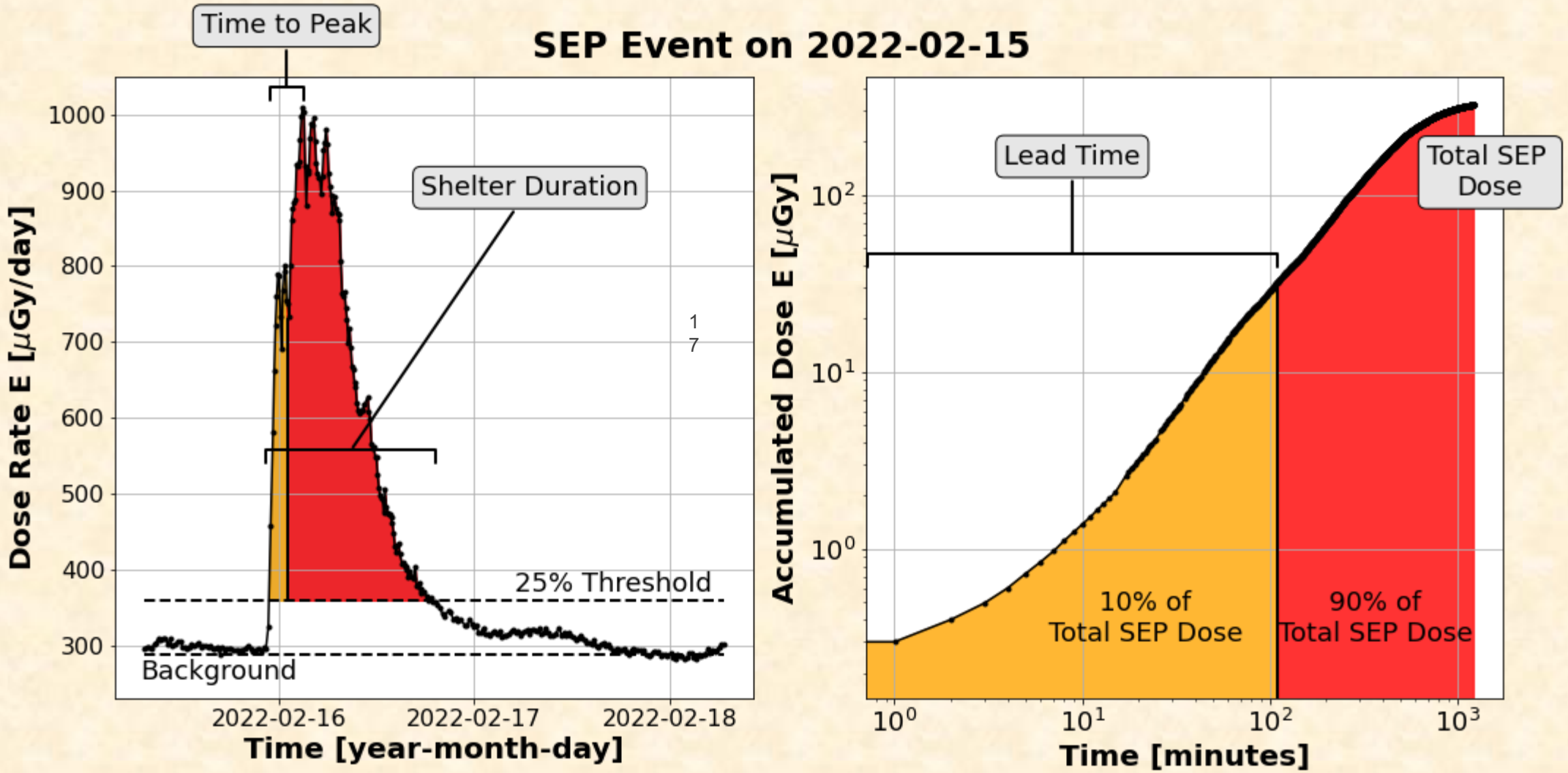
CAU Kiel: Extraterrestrial Physics

Nowcasting SEP Events for Mars Missions



1. When should an astronaut seek shelter?
2. When is it safe for an astronaut to leave the shelter?
3. How long would an astronaut need to stay in the shelter?
4. How much radiation exposure could have been avoided?
5. Can the nowcasting system still provide an astronaut with enough time to take shelter?
6. Can the nowcasting system reliably detect SEP events?

Nowcasting SEP Events for Mars Missions



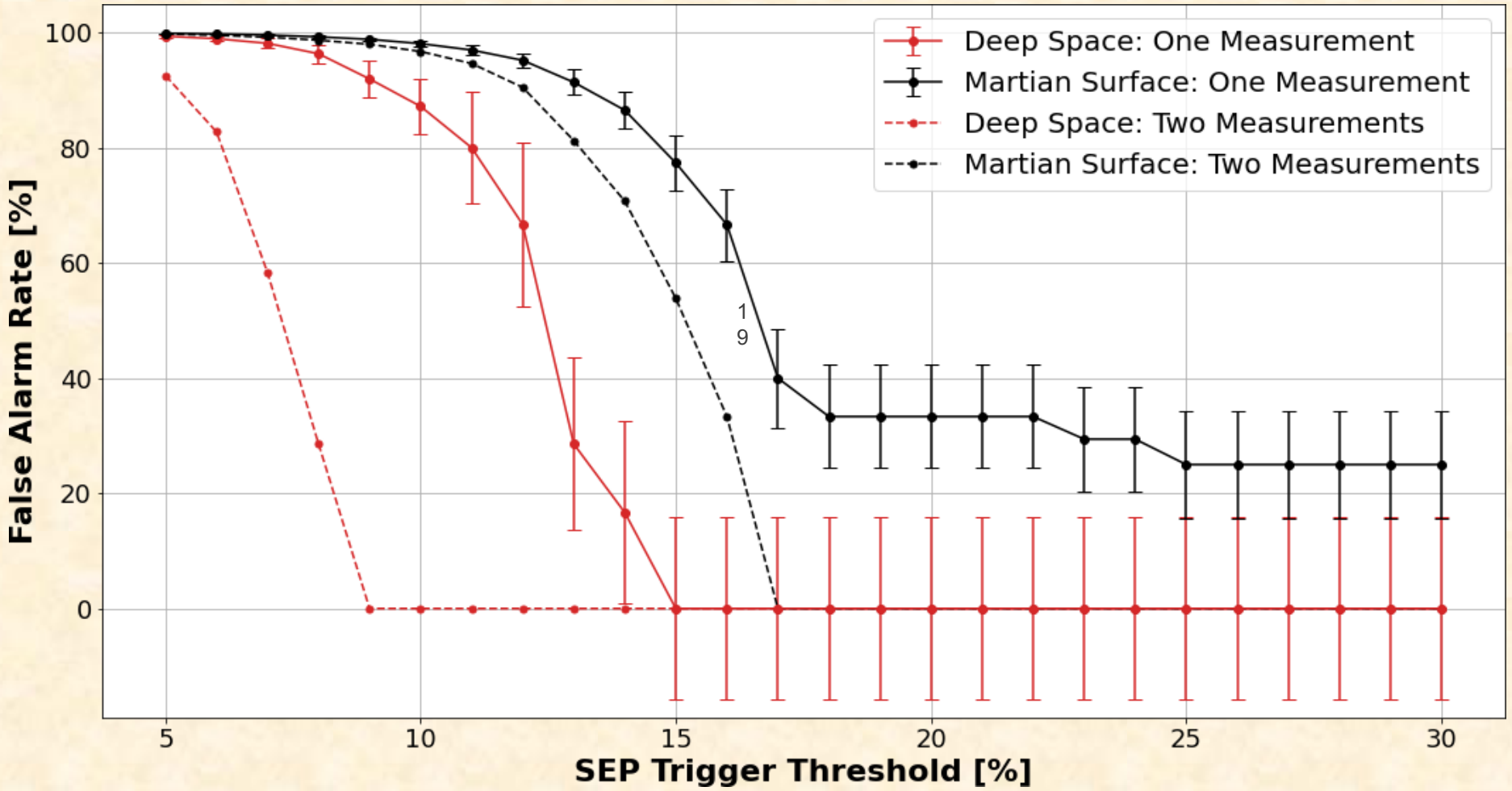
Nowcasting SEP Events for Mars Missions

	SEP Event [year-month-day]	Shelter Duration [day hour:minute]	Time to Peak [day hour:minute]	Lead Time [day hour:minute]	Total SEP Dose [μGy]	
DEEP SPACE	2012-01-23	00d 03h:09m	00d 02h:09m	00d 00h:17m	12.71	
	2012-01-27	02d 05h:54m	00d 02h:52m	00d 02h:11m	1466.30	
	2012-03-07	03d 07h:33m	01d 12h:34m	00d 16h:43m	9901.40	≈10× ICRP Limit*
	2012-03-13	00d 10h:16m	00d 00h:36m	00d 00h:35m	86.05	
	2012-05-17	01d 00h:43m	00d 01h:25m	00d 00h:51m	1170.20	
MARTIAN SURFACE	2013-04-11	00d 05h:33m	00d 01h:28m	00d 01h:28m	9.22	
	2013-10-11	00d 11h:15m	00d 02h:07m	00d 01h:07m	32.32	
	2014-01-06					
	2014-09-01	01d 14h:17m	00d 09h:01m	00d 02h:47m	125.93	
	2014-09-10	00d 01h:41m	00d 01h:02m	00d 00h:02m	2.09	
	2015-10-29					
	2017-09-10	01d 08h:01m	00d 06h:49m	00d 03h:44m	261.79	
	2021-10-28	00d 17h:47m	00d 05h:12m	00d 02h:01m	161.44	
	2022-02-15	00d 20h:31m	00d 03h:55m	00d 01h:50m	323.75	
	2022-03-14					
	2023-03-13	00d 01h:23m	00d 01h:08m	00d 00h:05m	1.22	
	2024-05-20	01d 17h:55m	00d 00h:53m	00d 00h:57m	1730.55	≈1.7× ICRP Limit*
	2024-07-22	00d 13h:16m	00d 02h:16m	00d 01h:20m	57.98	
	2024-07-26					
	2024-08-05					
	2024-09-03	00d 01h:25m	00d 00h:34m	00d 00h:08m	2.89	
	2024-09-05	00d 08h:35m	00d 00h:33m	00d 00h:33m	25.52	

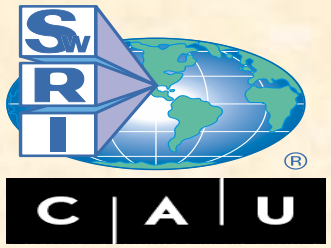
Time to Hide forAstronauts: ≳30 Minutes

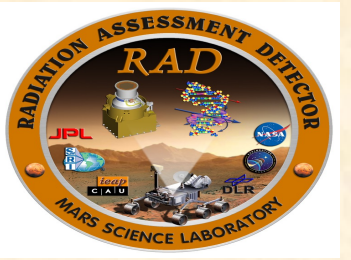
*ICRP (2007) recommended annual limit for **public exposure** = 1 mSv (radiation workers - 20 mSv, astronauts - 0.4 Sv)

Nowcasting SEP Events for Mars Missions



- Key Takeaways:
  - ”Nowcasting Solar Energetic Particle Events for Mars Missions” could serve as a last-resort warning system
  - Nowcasting with dose rates can be integrated into space missions as a backup if forecasting is unavailable

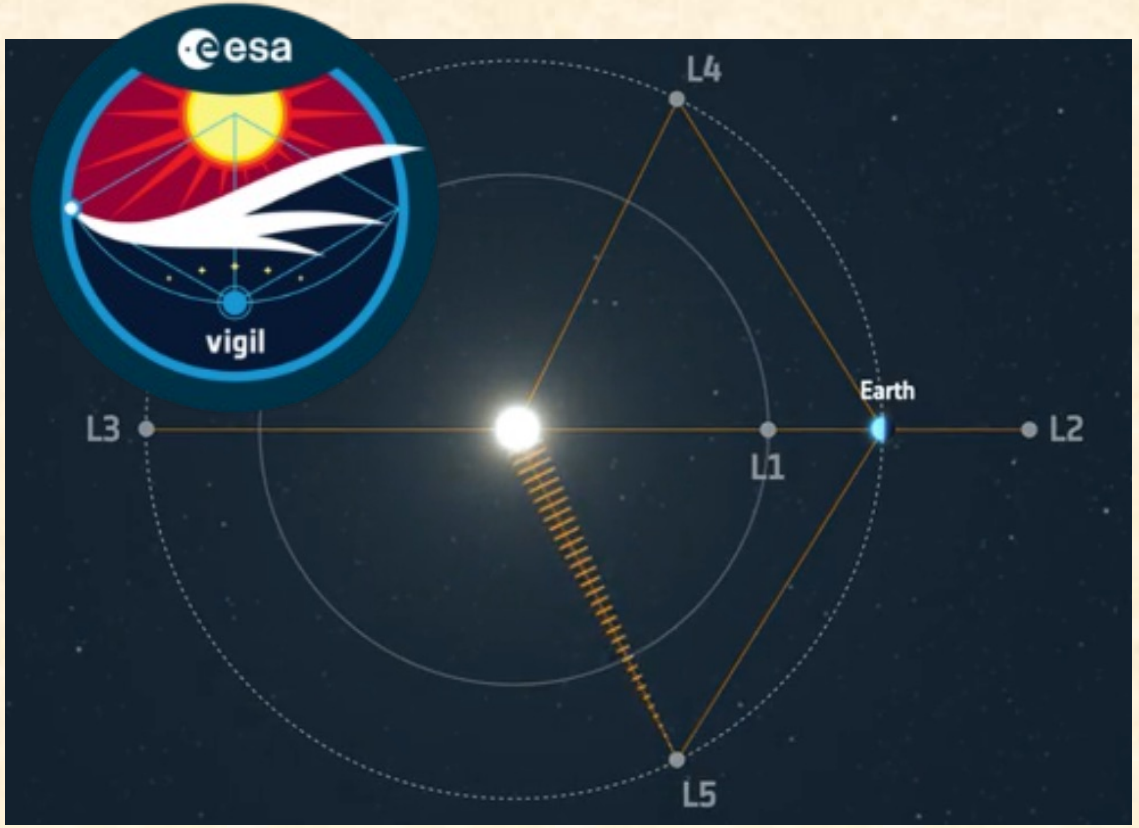




Improving our Space Weather Situational Awareness

The Vigil Mission at L5

- The ***Vigil Mission*** (formerly known as Lagrange) shall ensure a continuous provision of space weather measurements away from Sun-Earth line, to enhance the space weather services to ***protect critical infrastructure on Earth and in space***.
  - ***Early warning*** of emerging hazardous solar weather conditions.
  - Space Weather ***Forecasts up to 4-5 days.***
  - More ***accurate CME time and location impact predictions*** on Earth.
  - ***Operational 24/7***, including during severe space weather events (e.g. Carrington Events)
  - ***Low latency*** data to the Space Weather Network.
  - ***First Space Weather mission to L5.***



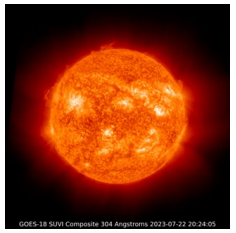
Vigil Payload Overview

Instrument	Inst. Prime	Observation	Utilisation
Photospheric Magnetic field Imager (PMI)	MPS/IAA	Vector magnetic field mapping of the solar photosphere	Evolving magnetic complexity: input into solar wind modelling and activity forecast
Compact Coronagraph (CCOR)	NOAA/NRL	Solar coronagraphy	Evolution and propagation of CMEs- Overlapping observation close to the SUN from 4 deg between CCOR and HI
Heliospheric Imager (HI)	Leonardo SpA	Heliospheric imagery	
Plasma Analyser (PLA)	MSSL	Solar wind particle densities, temperatures and velocity	Solar wind monitoring, detection and characterisation of high-speed solar wind streams
Magnetometer (MAG)	IPL/IWF	Interplanetary Magnetic Field vector-magnetic field	
JEDI	NASA/SWRI	Extreme Ultraviolet Images	Complementary to existing instruments for the forecasting service

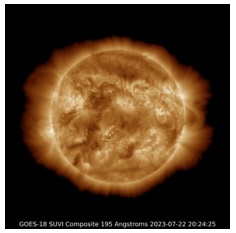
JEDI (Joint EUV Imaging of the Coronal Environment)

SWOC (Space Weather Operational Coronal Imager):

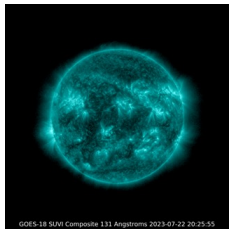
(3 Channels - Full disk images out to 3 R⊙)



He II/Fe XVI 30.4/33.5 nm
8 x 10^4/6 x 10^6 K



Fe XII/XXIV 19.3/19.5 nm
1.5 x 10^6 / 2 x 10^7 K

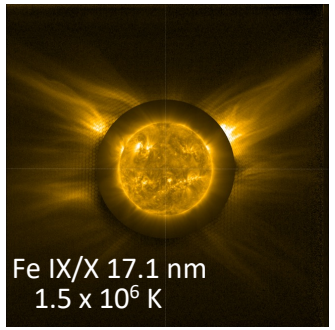


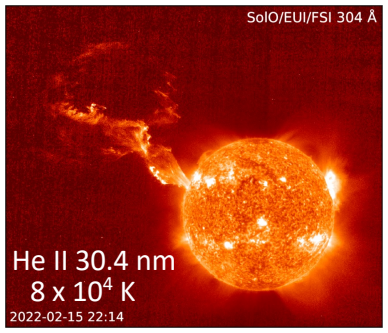
Fe VIII/XX 13.3 nm
1 x 10^6/1 x 10^7 K

SWOC provides high resolution EUV disk imaging in multiple passbands.

EWOC (Enhanced Wide-angle Coronal Imager):

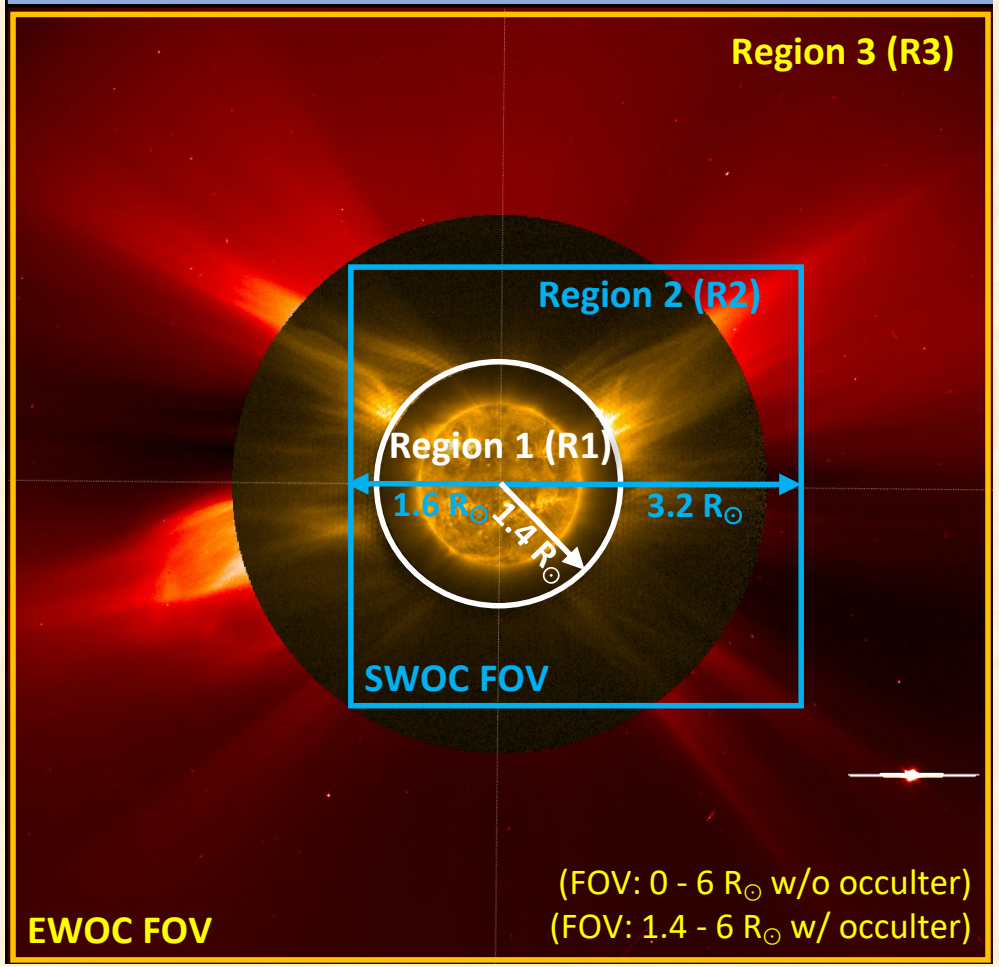
(2 Channels – Full disk & Occulted coronal images out to 6 R⊙)





EWOC images solar wind structures through the elusive Middle Corona.

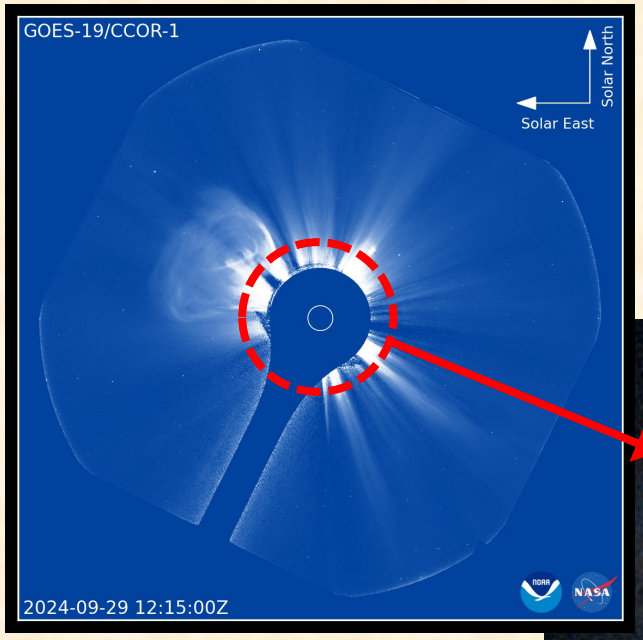
JEDI Instrument Fields-of-View



JEDI is as a Class D Contributed "Instrument of Opportunity" – the sole NASA contribution to Vigil

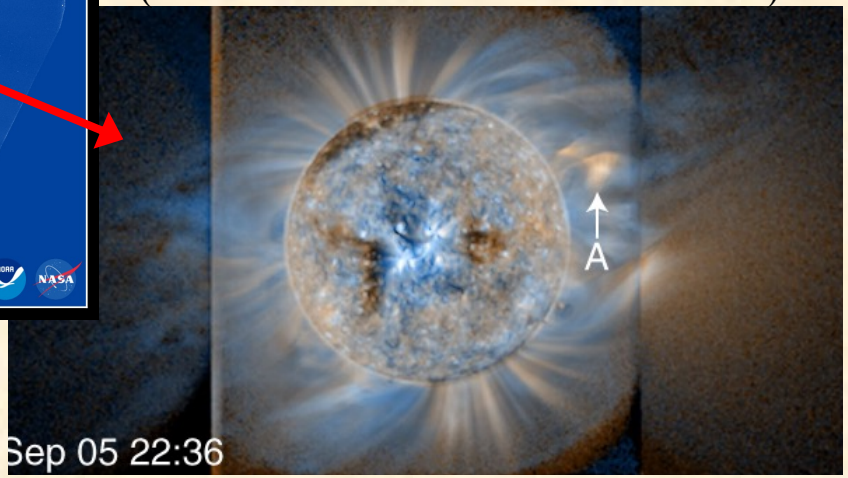
JEDI's Role on Vigil

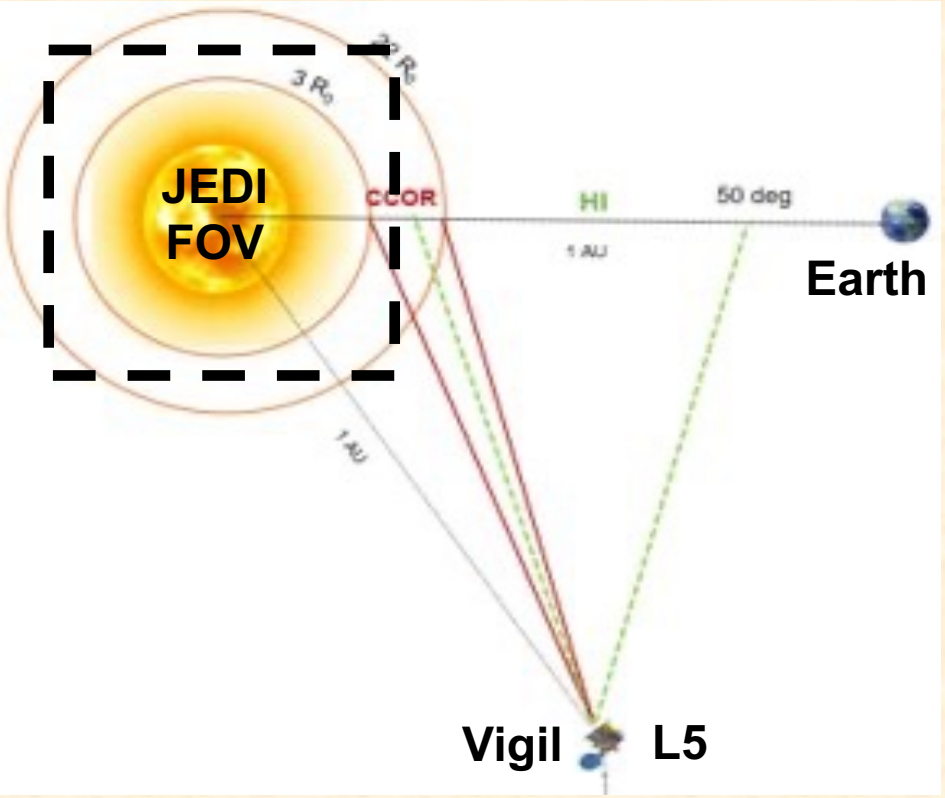
***JEDI fills the gap**, revealing source regions and hidden structures under the CCOR occulter, and connecting them to CMEs and other features observed in the corona and solar wind.*



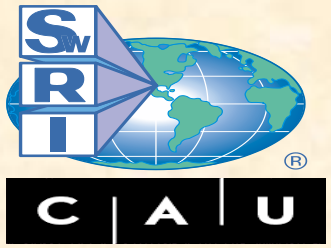
CCOR-1 First Light Image
(identical to **Vigil/CCOR**)

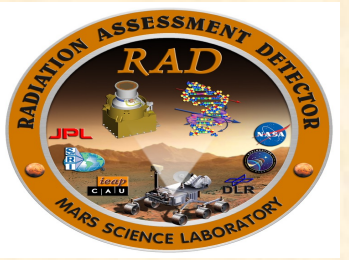
Vigil/JEDI Composite Image
(derived from Solar Orbiter EUI/FSI)





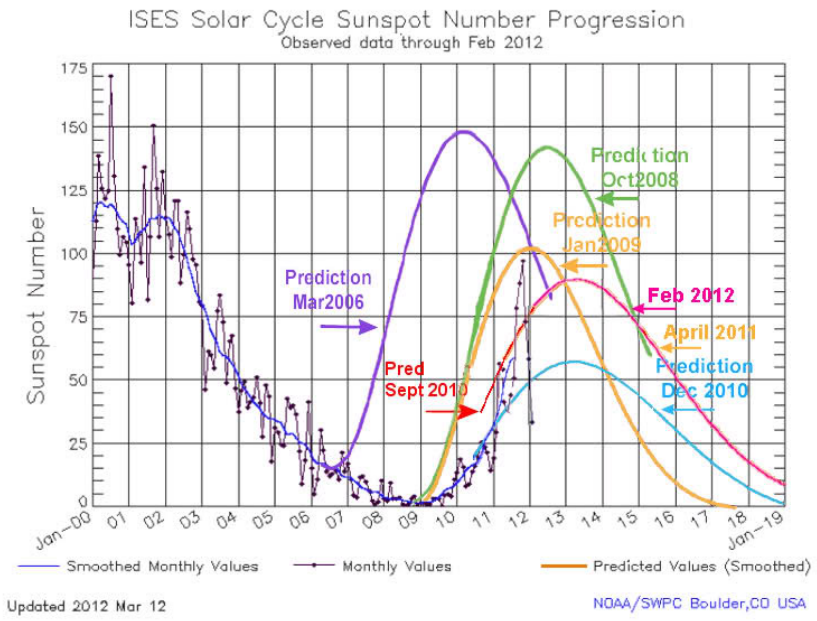
***JEDI will capture all Earth-directed space weather events**, connecting CMEs to their solar source regions and signatures in the corona.*

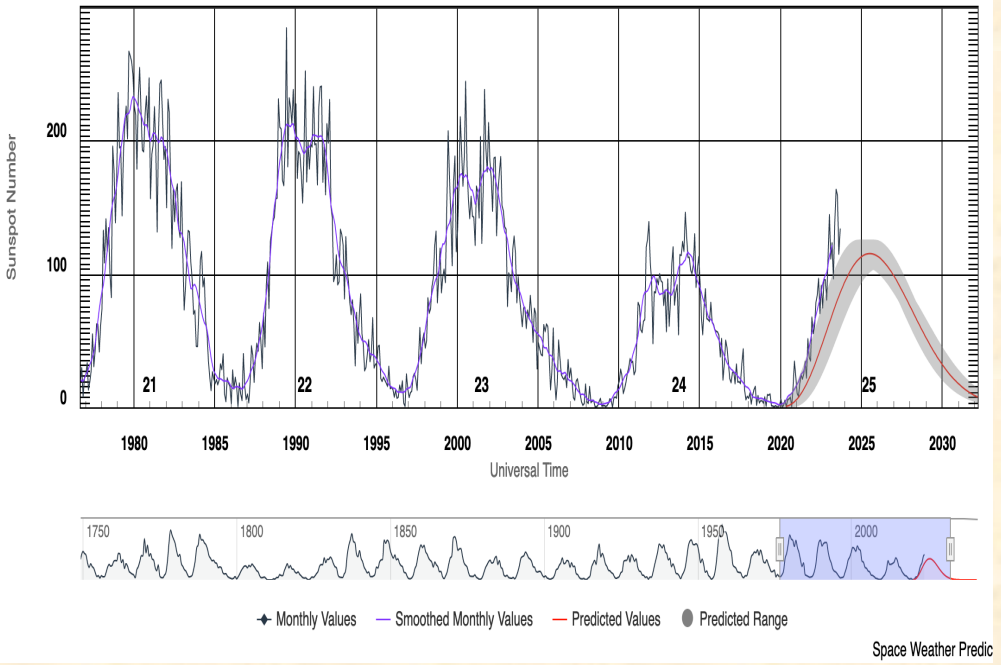


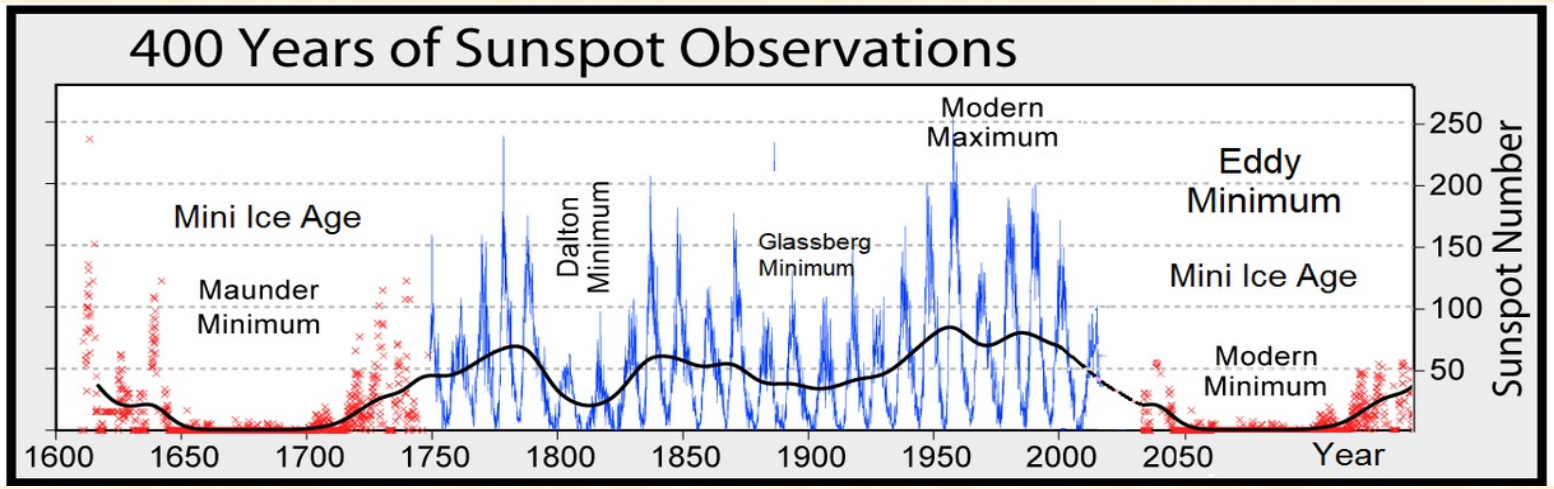


Prospects for the Next Solar Cycle

Predicting the Solar Cycle… is difficult!







Space Weather Effects Occur at All Phases of the Solar Cycle

(From Guhathakurta, 2015)

Solar La Niña (Minimum) (low sunspot number)

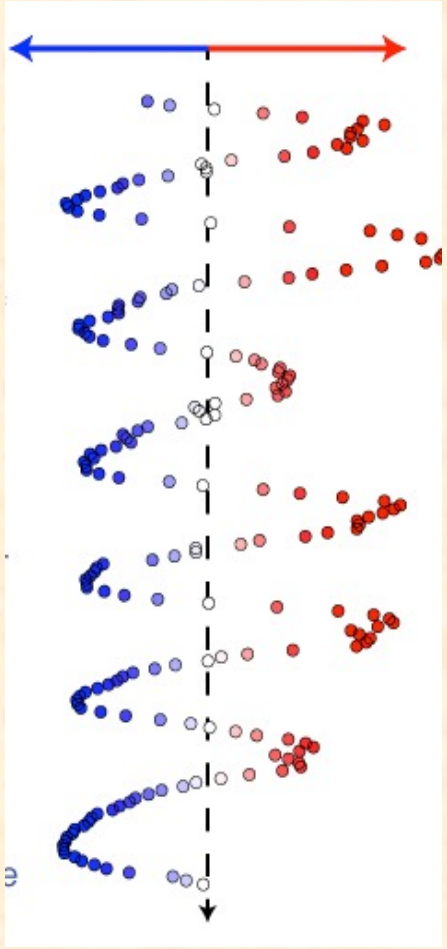
- Increased galactic cosmic rays

- Total solar irradiance changes

- Contraction of the heliosphere

- Collapse of the upper atmosphere

- Increased lifetime of space debris



Solar El Niño (Maximum) (high sunspot number)

- Decreased galactic cosmic rays

- Solar flares and coronal mass ejections

- Solar "cosmic rays" (energetic particles)

- Radio blackouts

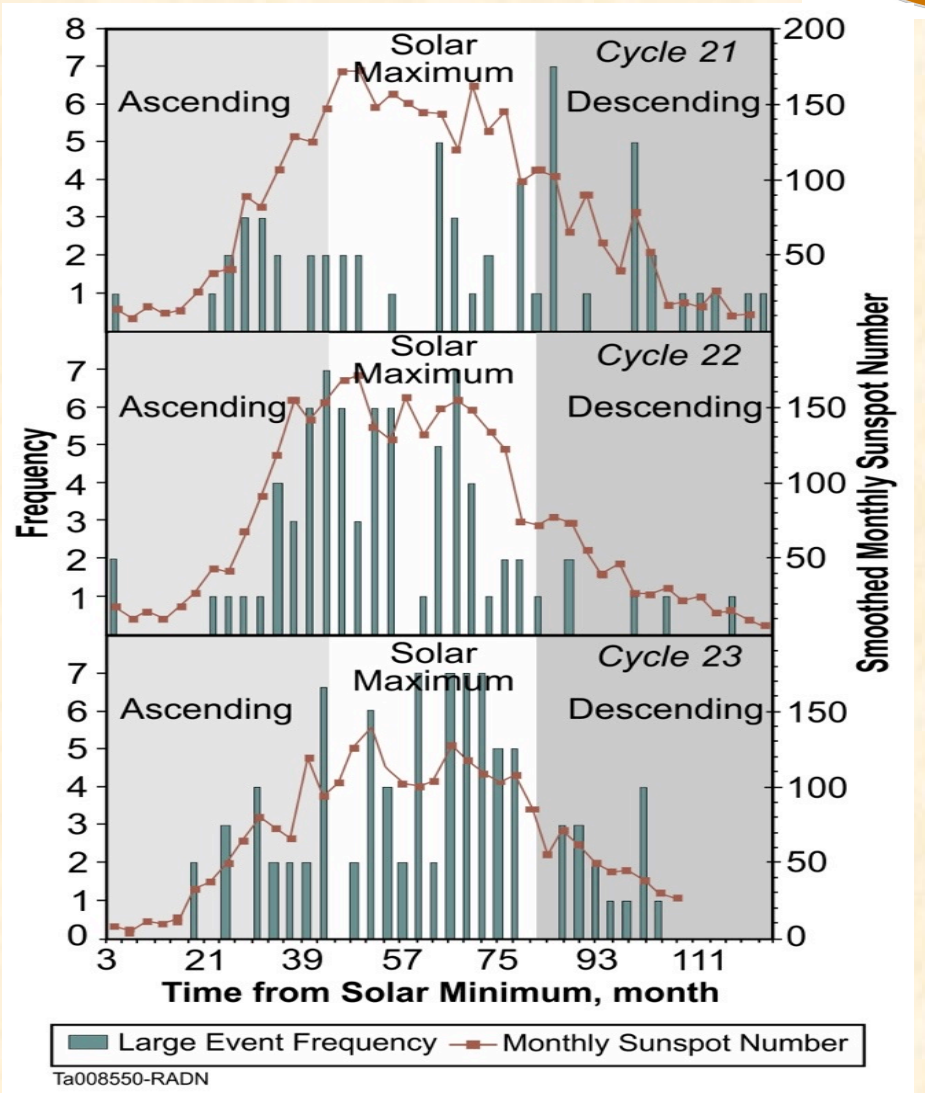
- Geomagnetic storms

- Disrupted power grid transformers = power blackouts

- Solar wind streams hit Earth

Large Solar Particle Events (SPEs) are seen throughout the Solar Cycle

- The ***3 largest SPEs of this past cycle*** were during ***Solar Min*** or the early rising phase of the next solar max. (NOT Solar Max…maybe the next big one is coming?)
- These SPEs also had very ***wide longitudinal extent***…~180 deg!
- Improved understanding of the ***structure and propagation*** of these solar storms will ***improve space weather prediction*** *at earth, Mars, and throughout the heliosphere*!



Histogram of large SPEs vs time

Take-Away Points...

- Understanding and predicting the longitudinal extent of CME and SPE propagation is important for Space Weather Prediction and All-Clear Forecasts
- Even events occurring on the far side of the Sun can have significant impact on EVAs and other Operational Space Activities
- The Heliophysics and Space Weather community is just beginning to take full advantage of the heliospheric network of spacecraft assembled (HSO, Vigil at L5, Korean Mission at L4, etc.)..
- MSL/RAD and Mars assets (Maven, Escapade, etc.) are a key part of this...!
- Extreme variations in the past 2 solar cycles have shown that current models ***clearly lack sufficient predictive capability***.
- Multi-spacecraft observations help us characterize these extreme events (and extreme conditions), even when they aren't directed at Earth...
- Ultimately, to ***support human exploration to Mars and beyond***, we will need to provide ***heliosphere-wide space weather monitoring***, prediction & early warning for these missions!

Thank you!

- RAD is supported by NASA (SMD/Heliophysics) under JPL subcontract #1273039 to SwRI.
- ...and by DLR in Germany under contract with Christian-Albrechts-Universitat (CAU).

RAD data is available to the community via SPDF and PDS.