Space Weather at Mars

Christina O. Lee
Space Sciences Laboratory, UC Berkeley
clee@ssl.berkeley.edu

A Science Strategy for the Human Exploration of Mars:
NASEM Panel on Atmospheric Science and Space Physics

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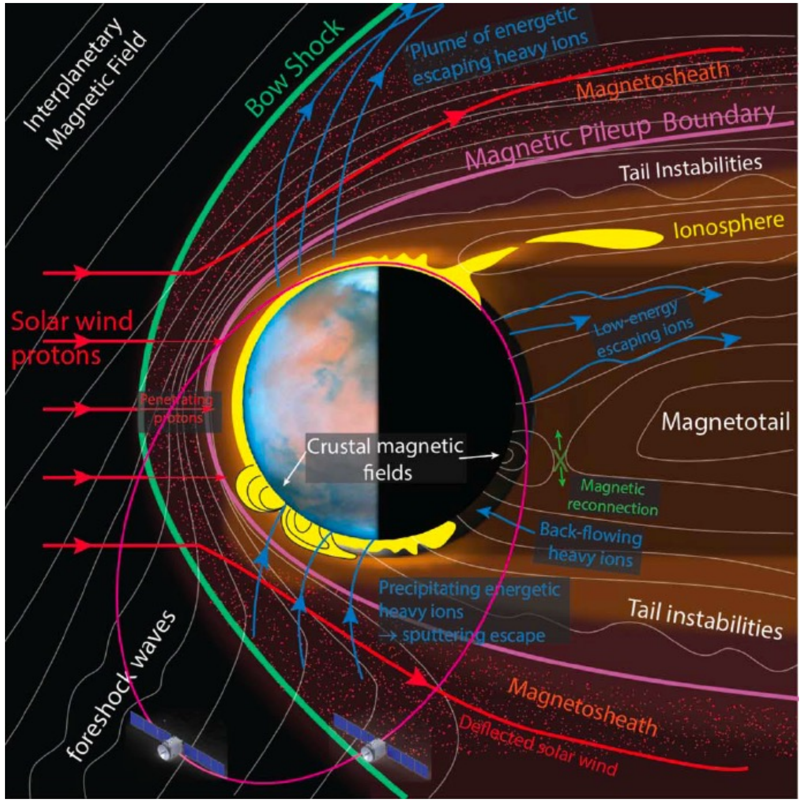
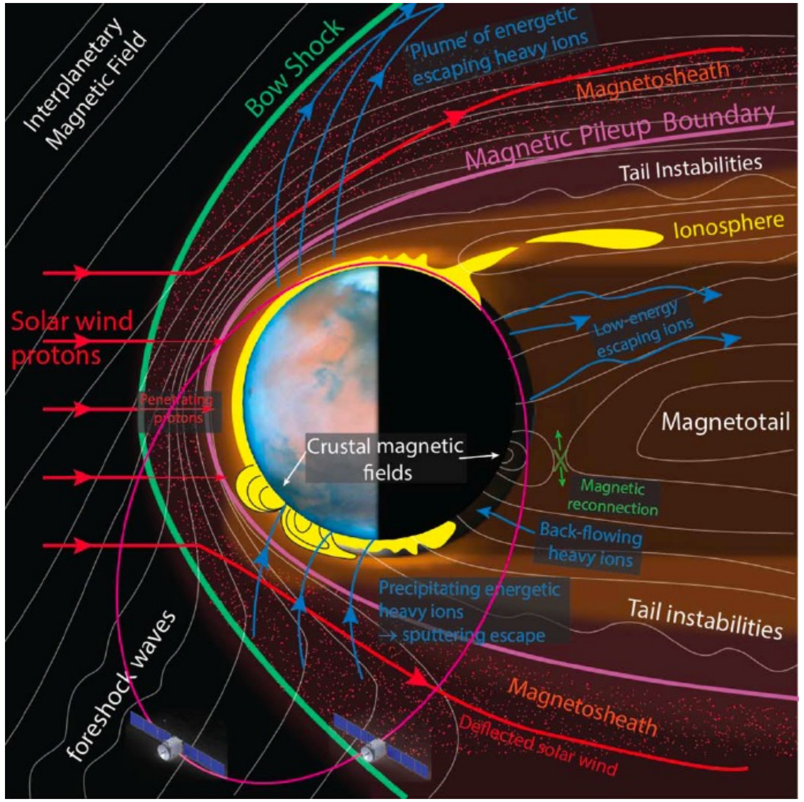
Mars has a thin atmosphere and a so-called "hybrid" magnetosphere, because it has properties of both an intrinsic magnetosphere like Earth (e.g., Mars' crustal magnetic fields) and an induced magnetosphere like Venus.



Lillis+
(Planetary Science, 2021)

Mars has a thin atmosphere and a so-called "hybrid" magnetosphere, because it has properties of both an intrinsic magnetosphere like Earth (e.g., Mars' crustal magnetic fields) and an induced magnetosphere like Venus.

Due to its weak magnetic shielding, the effects of space weather at Mars can extend all the way down to its surface.



Lillis+
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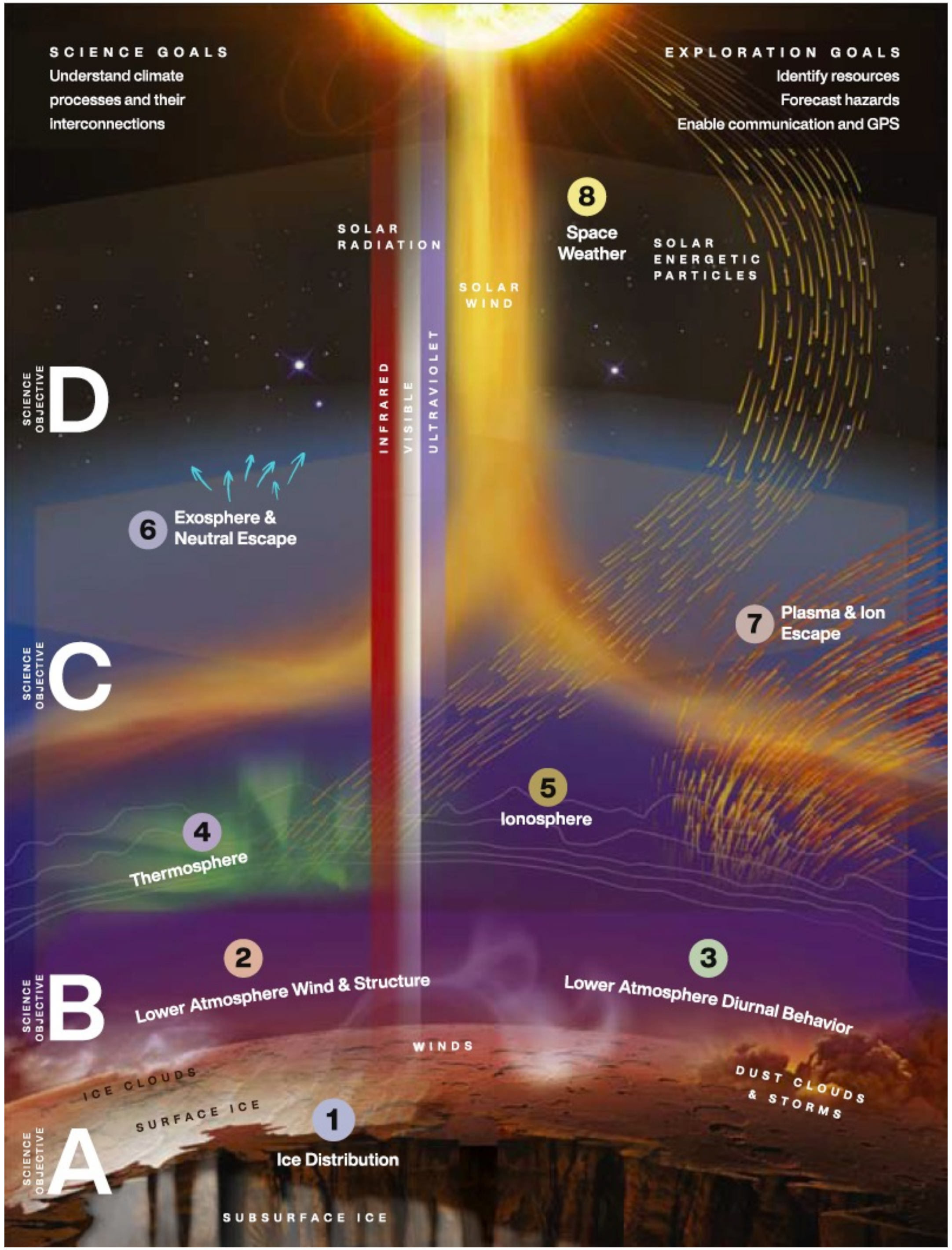


Measurements at Mars

Mars has a long history of space weather observations with continuous coverage starting in the late 1990s (Solar Cycle 23)

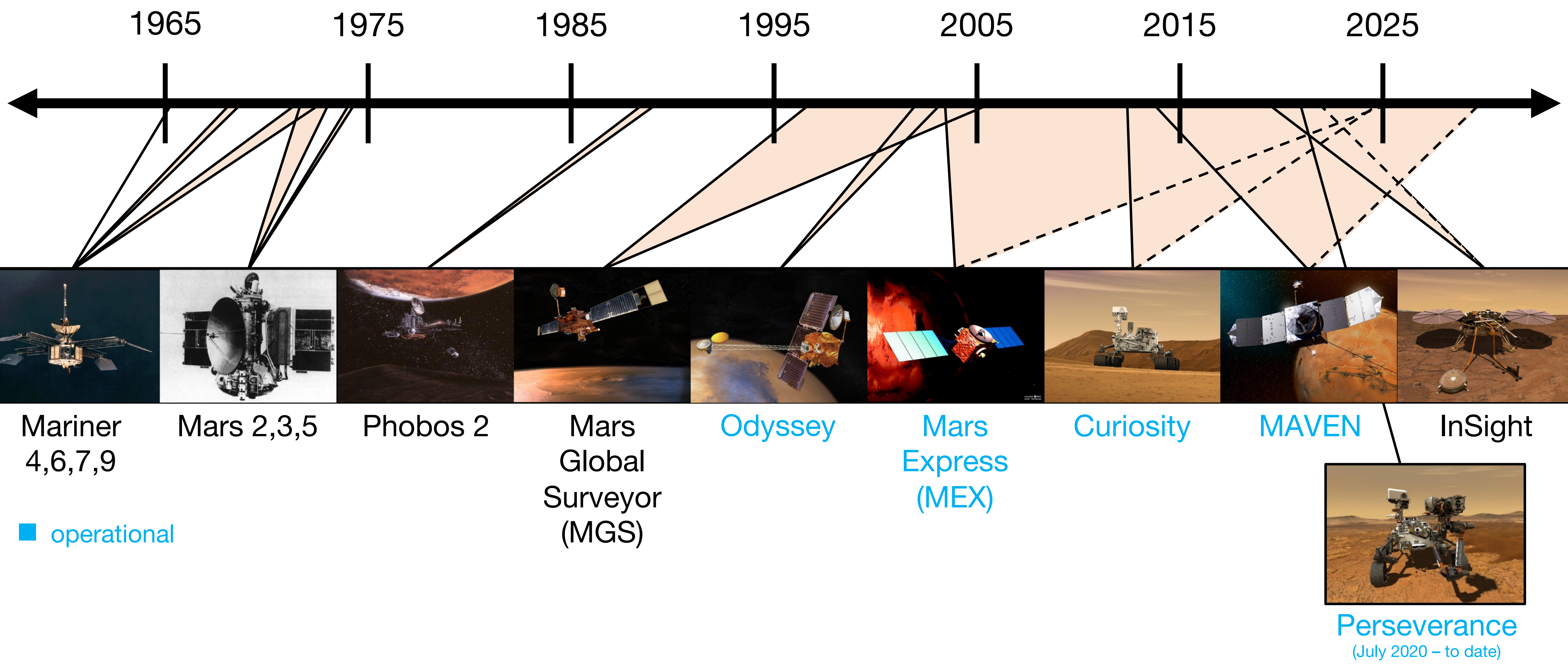
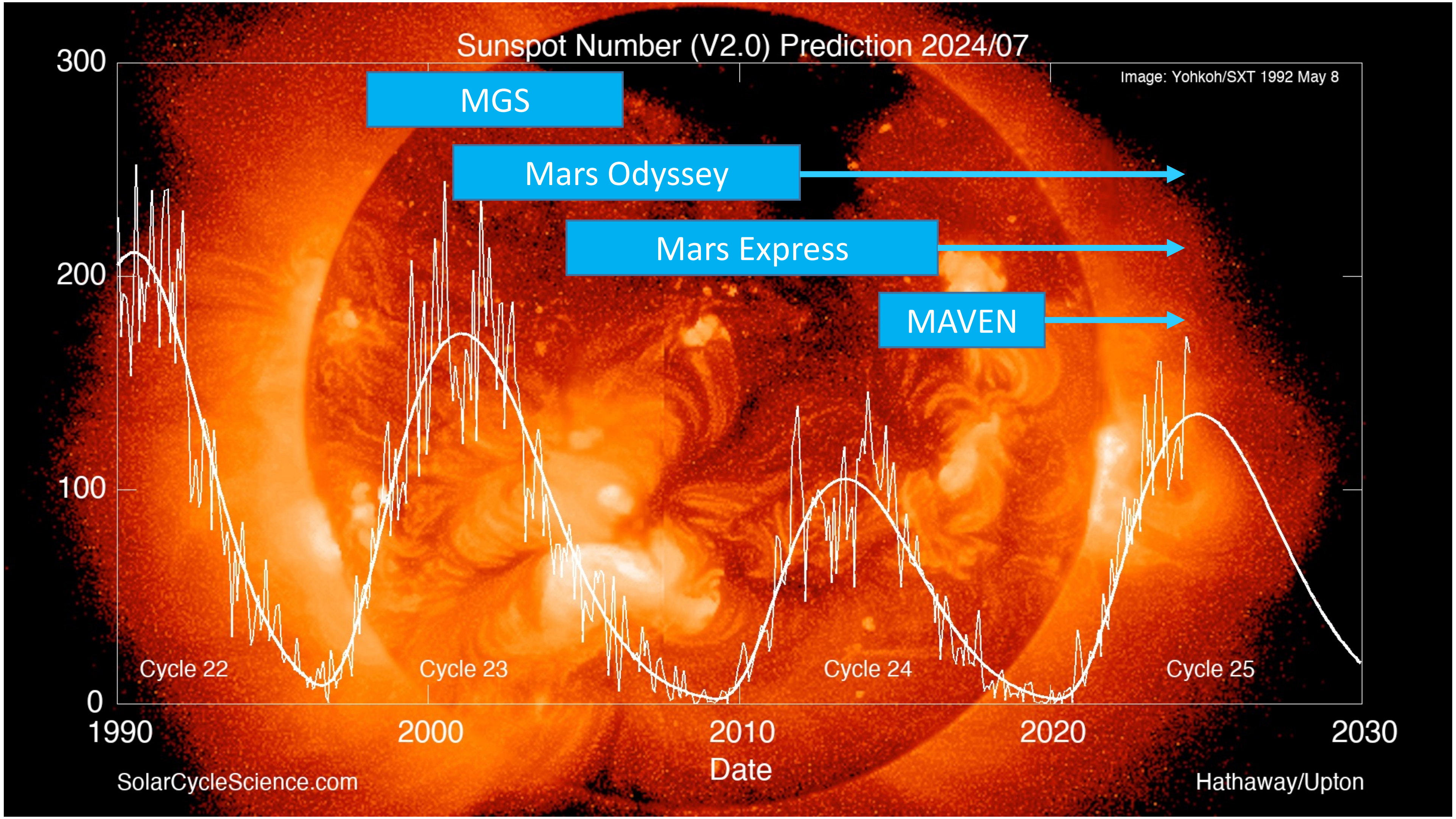
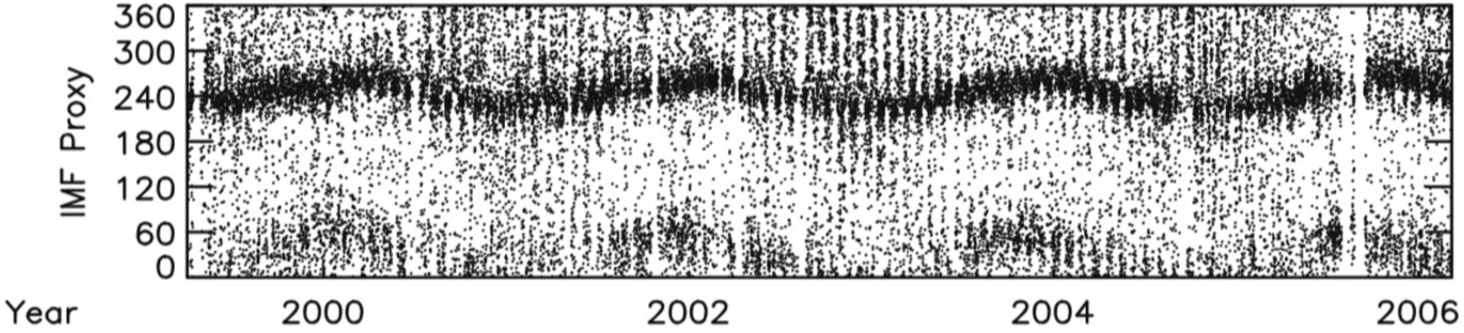


Figure adapted from *D. Brain/LASP* (WHPI seminar, 2020)

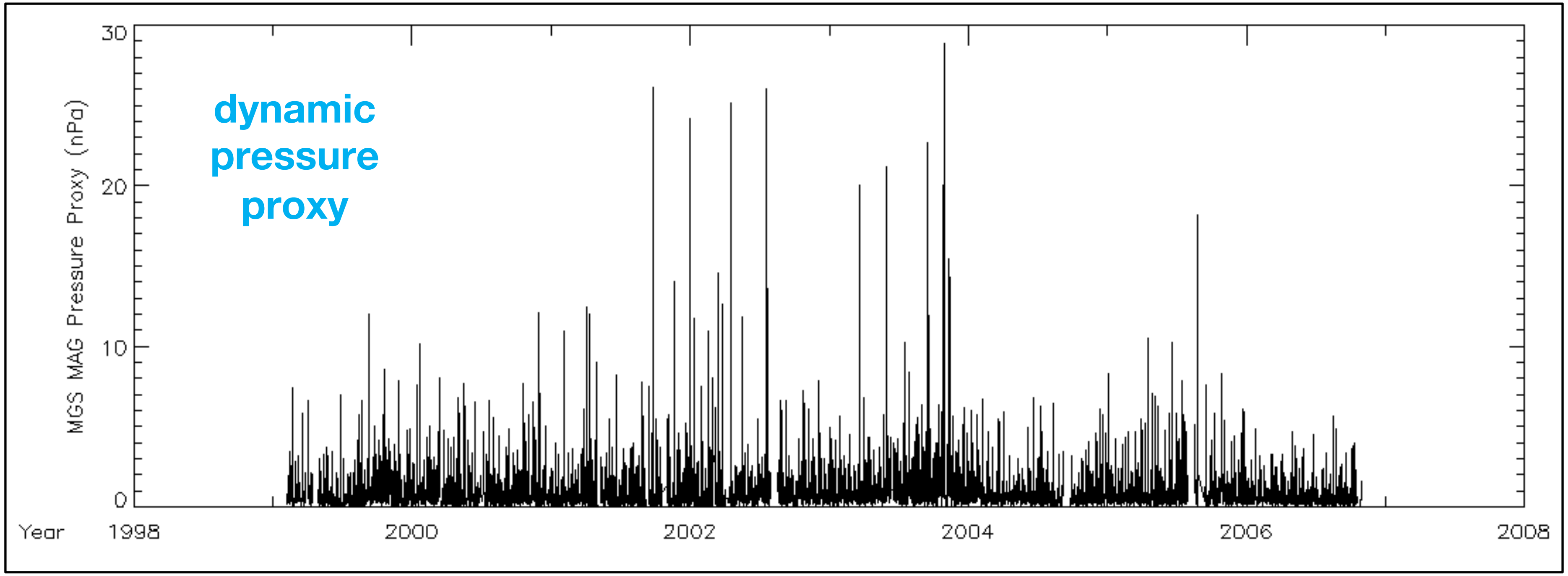
These observations spans two+ solar cycles



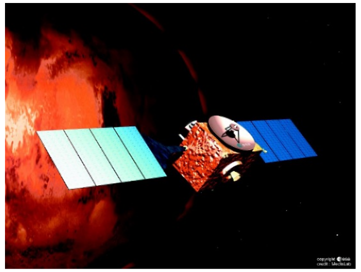
MGS “measured” the IMF direction and solar wind pressure upstream from the bowshock, even though its orbit did not go outside of the bowshock and it was not instrumented to measure ions



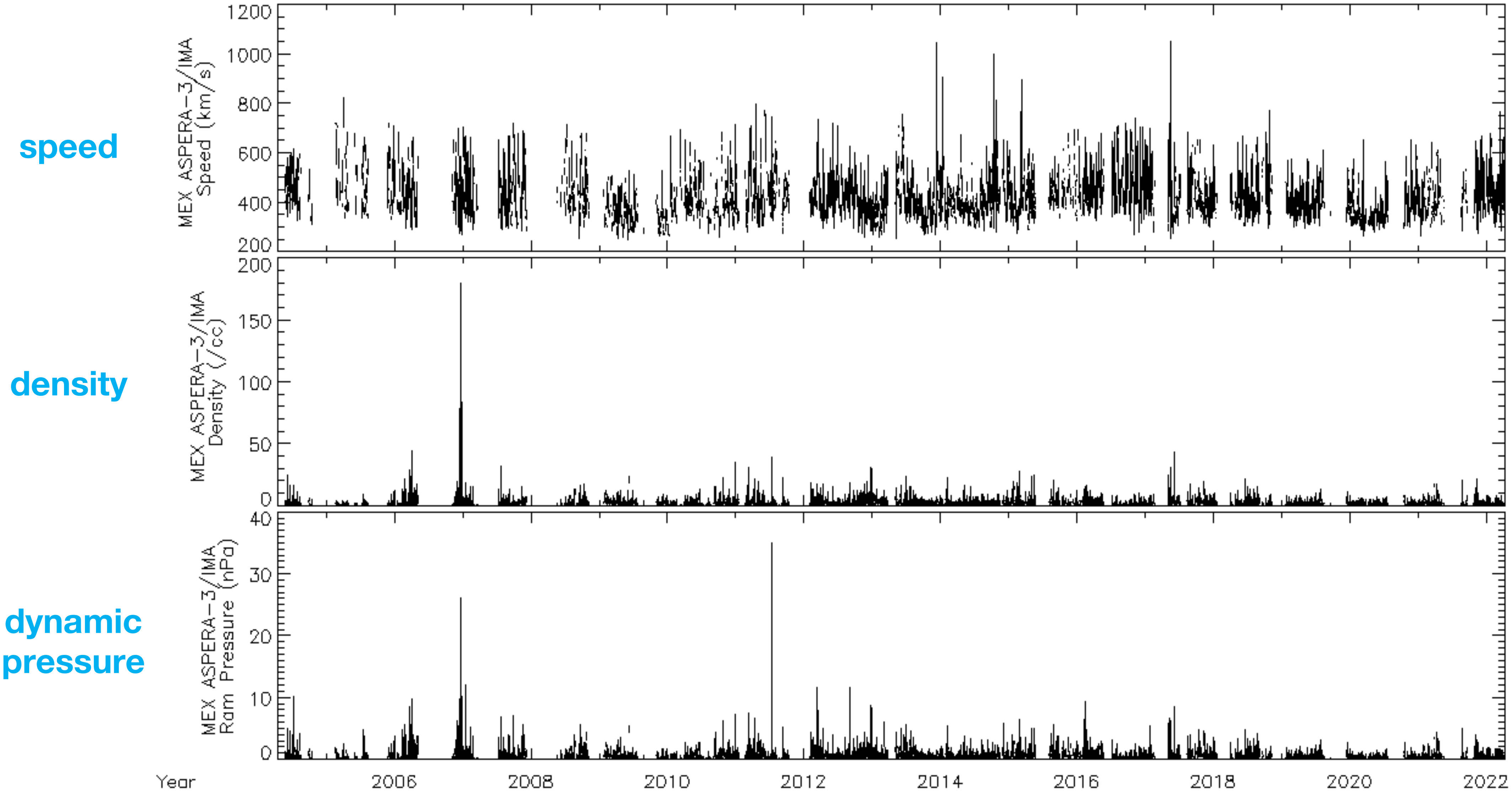
Brain+ (Icarus, 2006)
(see also Crider+, JGR, 2003)



Data courtesy of S. Xu (SSL/UCB)



More than 20 years of upstream solar wind observations have been made by the Mars Express ASPERA-3 Ion Mass Analyzer (MEX/IMA)



Data courtesy of R. Ramstad (CU/LASP)

MAVEN Observes Solar Inputs at Mars since late-2014

Solar Irradiance
Instrument: EUVM

GCR background
SEP

Energetic Ions
SEP

Energetic Electrons
SEP

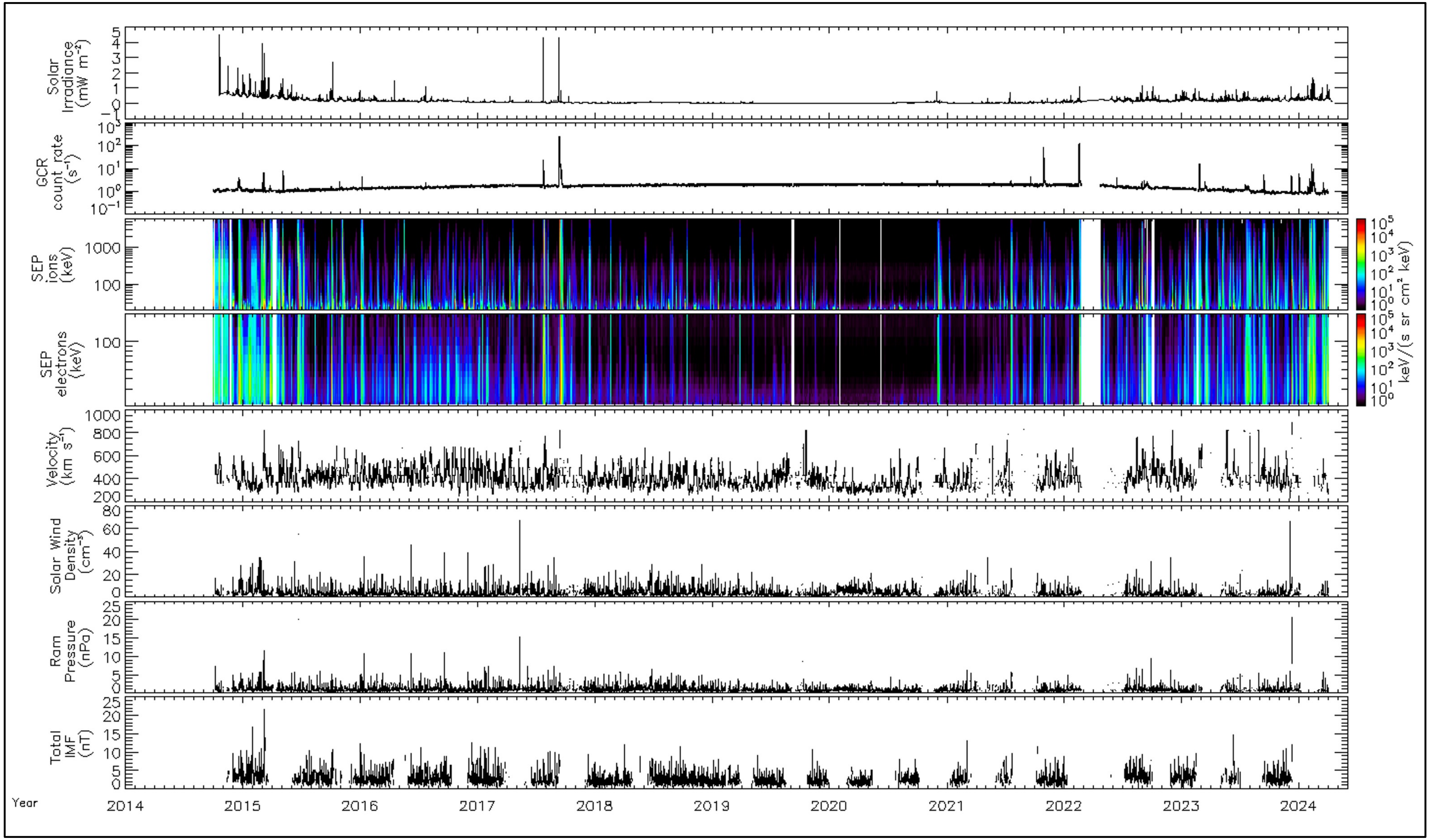
Solar Wind Velocity
SWIA

Solar Wind Density
SWIA

Solar Wind Pressure

IMF
MAG

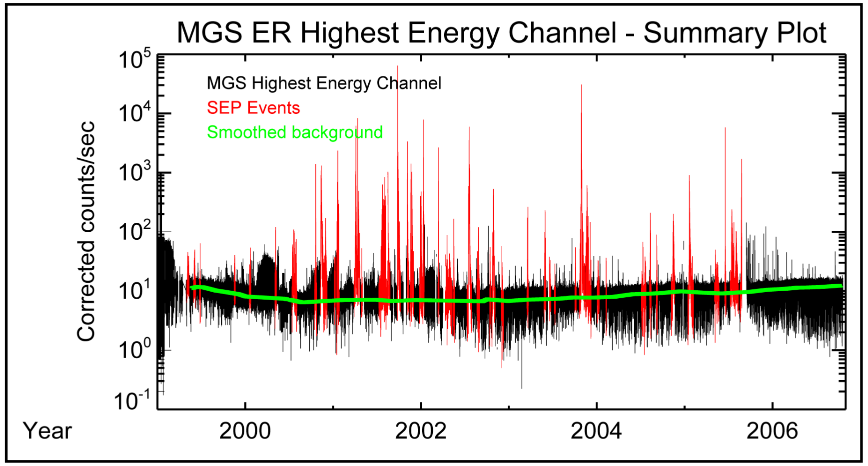
Adapted from Lee+(JGR, 2017)



2015

2020

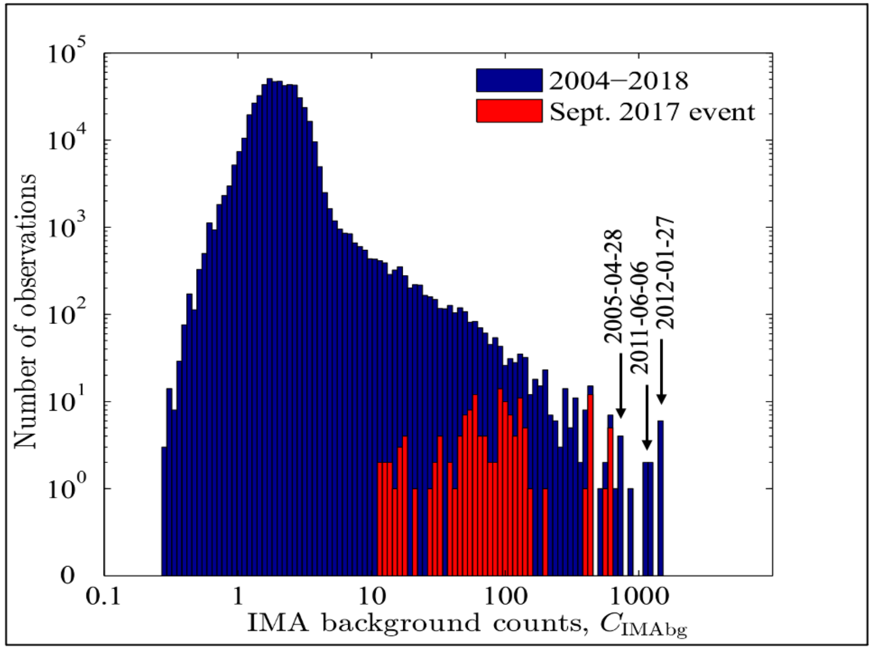
Solar Energetic Particles (SEPs) have been continuously measured *in orbit* at Mars since 1997



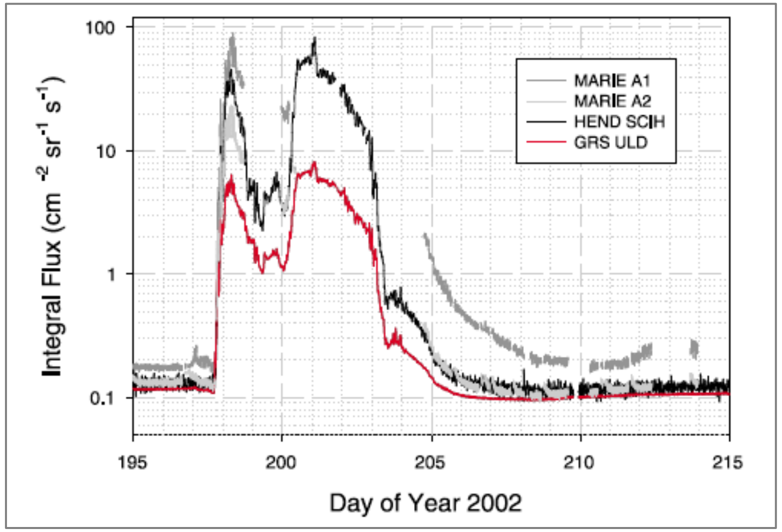
Mars Global Surveyor

D. Brain (adapted from Delory+, Space Weather 2012)

Mars Express



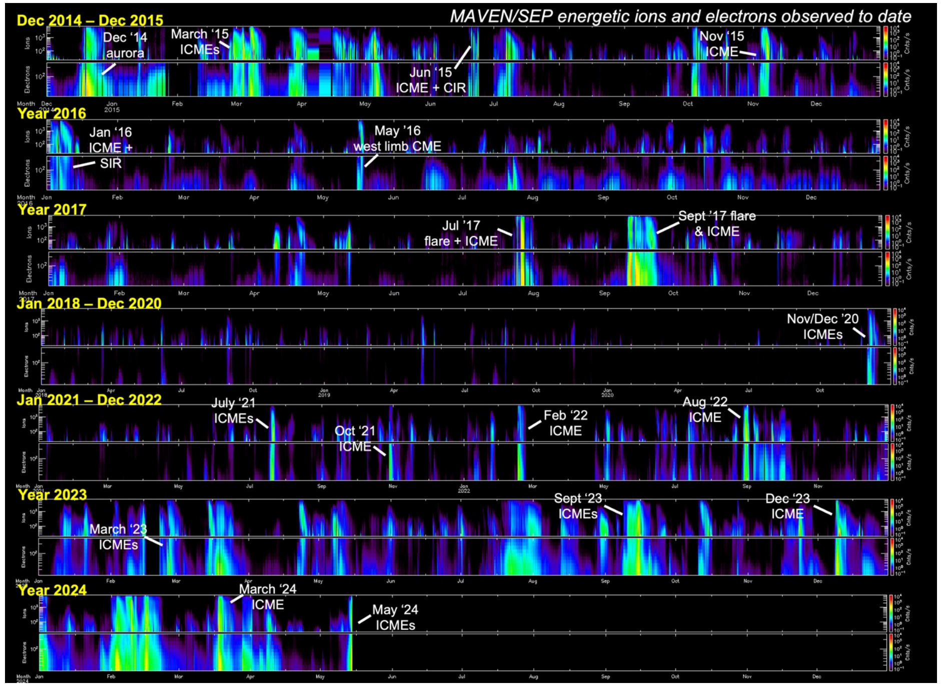
Ramstad+ (GRL 2018)



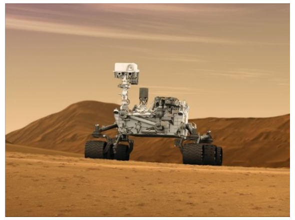
Mars Odyssey

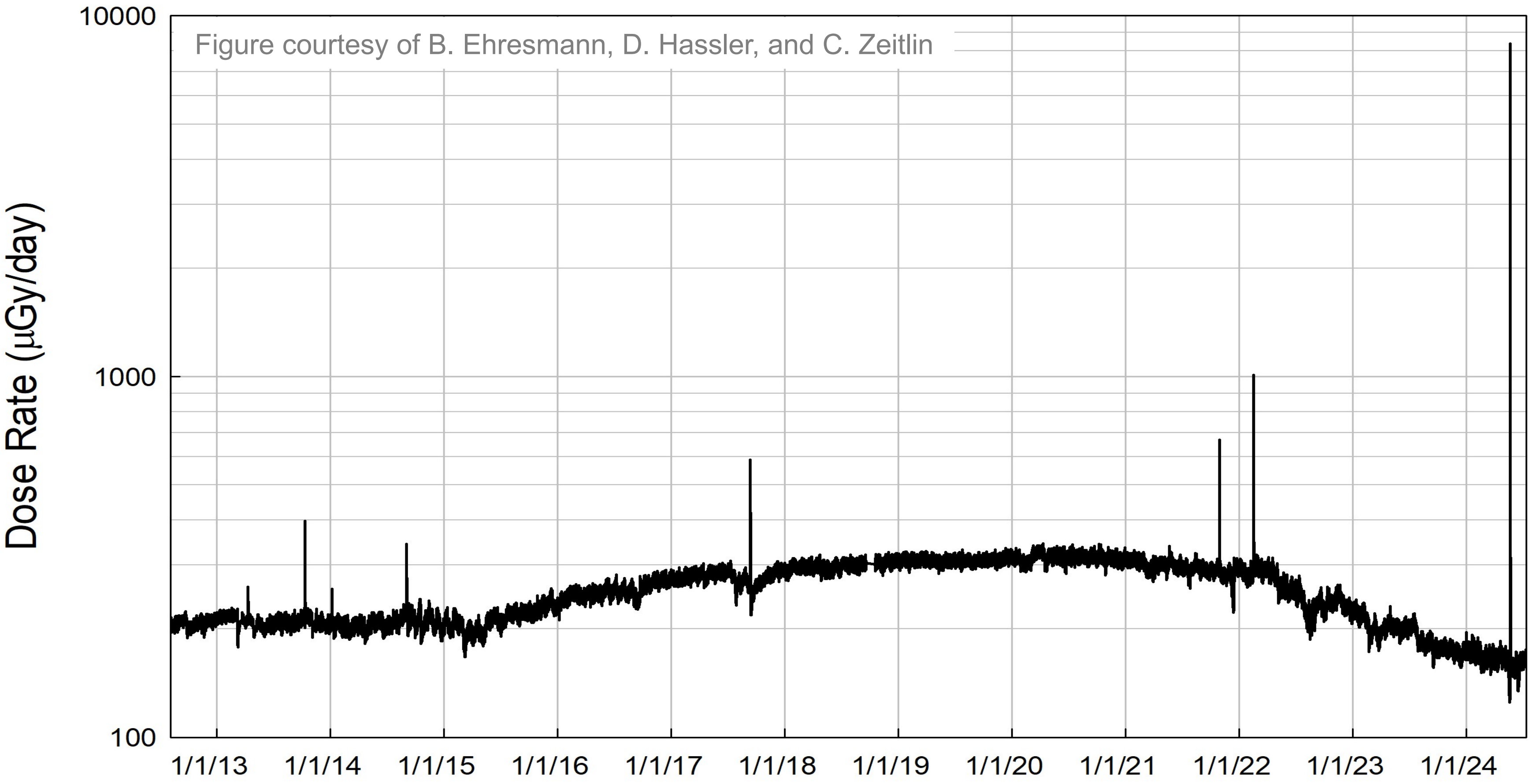
Zeitlin+ (JGR, 2010)

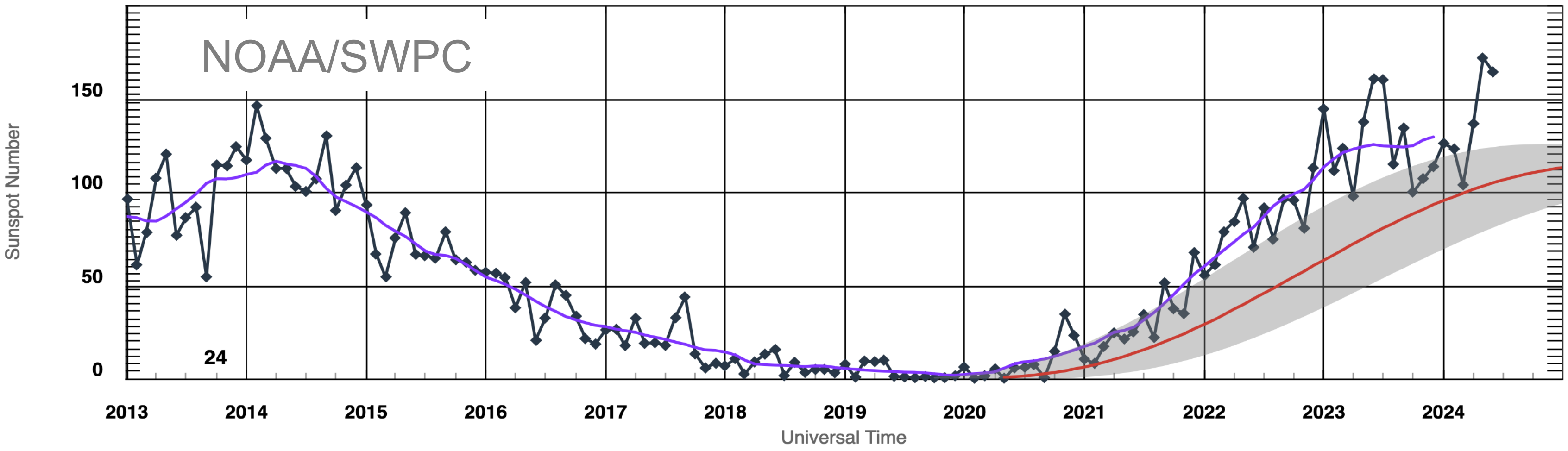
MAVEN



Since mid-2012, charged particle radiation from SEPs and GCRs have been directly measured at the surface by MSL/RAD



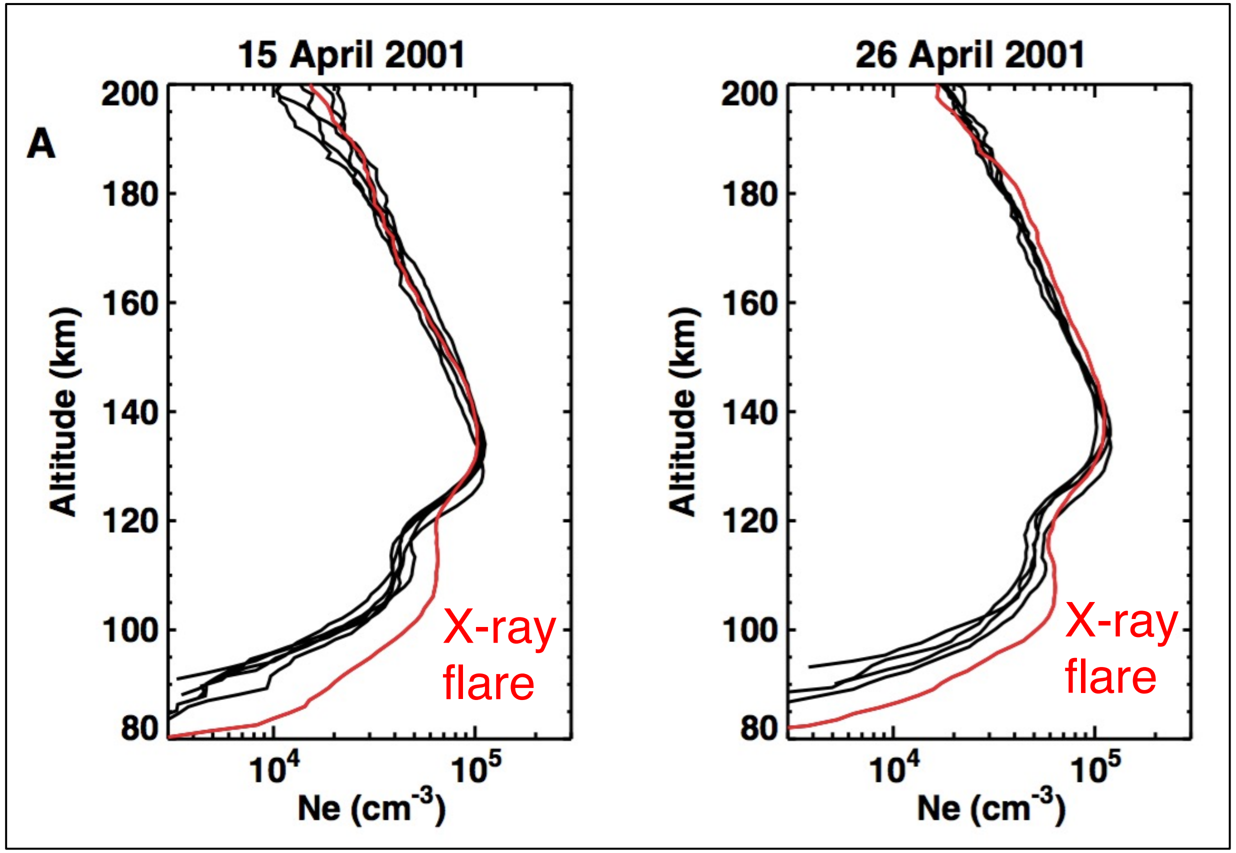




Impacts and Effects of Space Weather at Mars During Solar Cycles 23 and 24

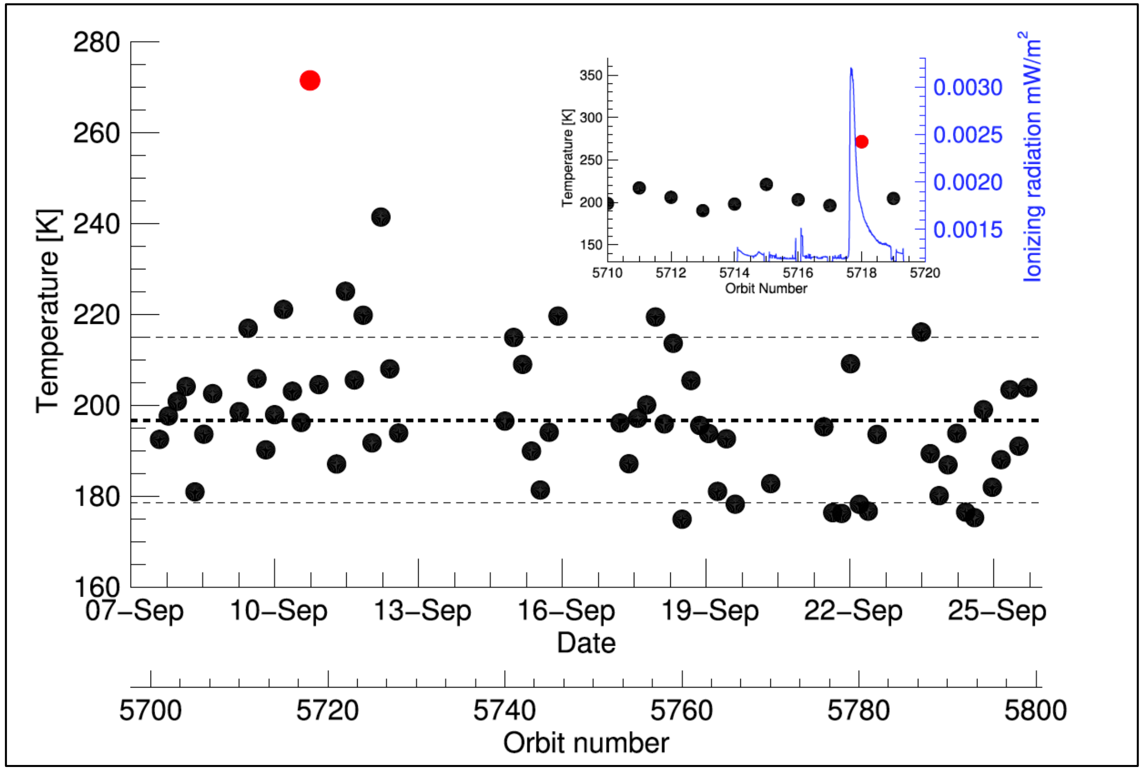
The Martian ionosphere and thermosphere respond to energetic photons from solar flare events

MGS: Ionospheric response to an X14.4 (left) and and M7.8 flare (right) during Cycle 23 maximum phase



Mendillo+ (2006)

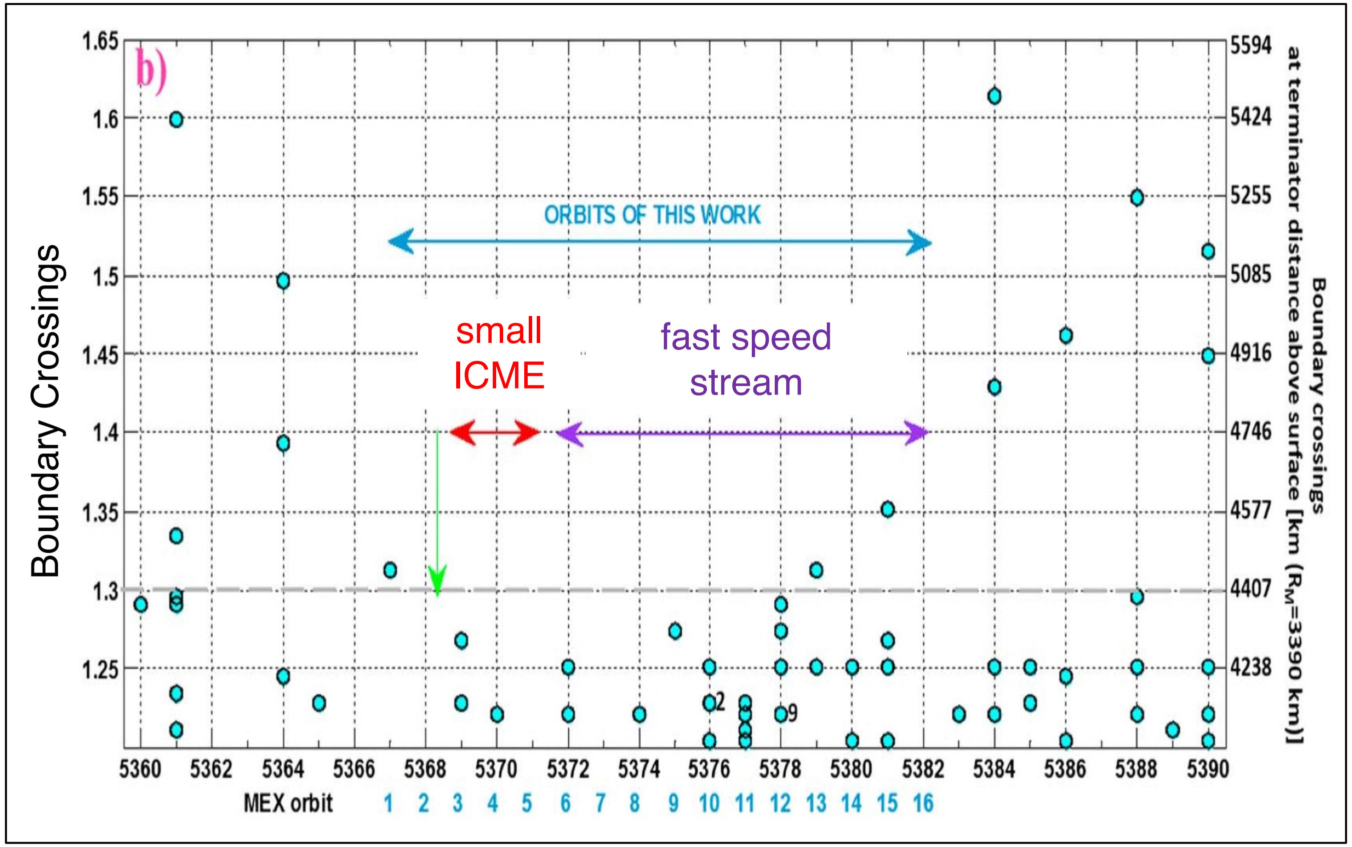
MAVEN: Thermospheric response to an X8.2 flare during Cycle 24 declining phase



Jain+ (GRL, 2018)

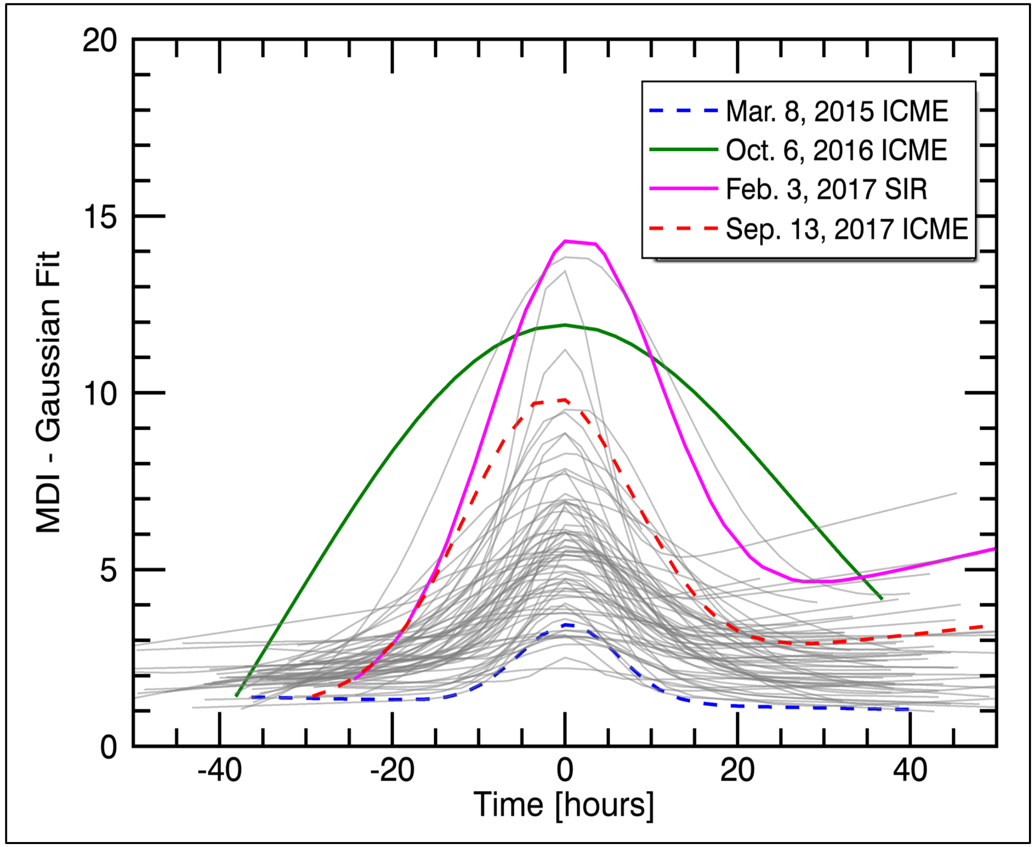
During CME and SIR/CIR events, the hybrid-magnetosphere of Mars gets compressed

MEX observations during Cycle 23/24 minimum phase



Sanchez-Cano+ (2017)

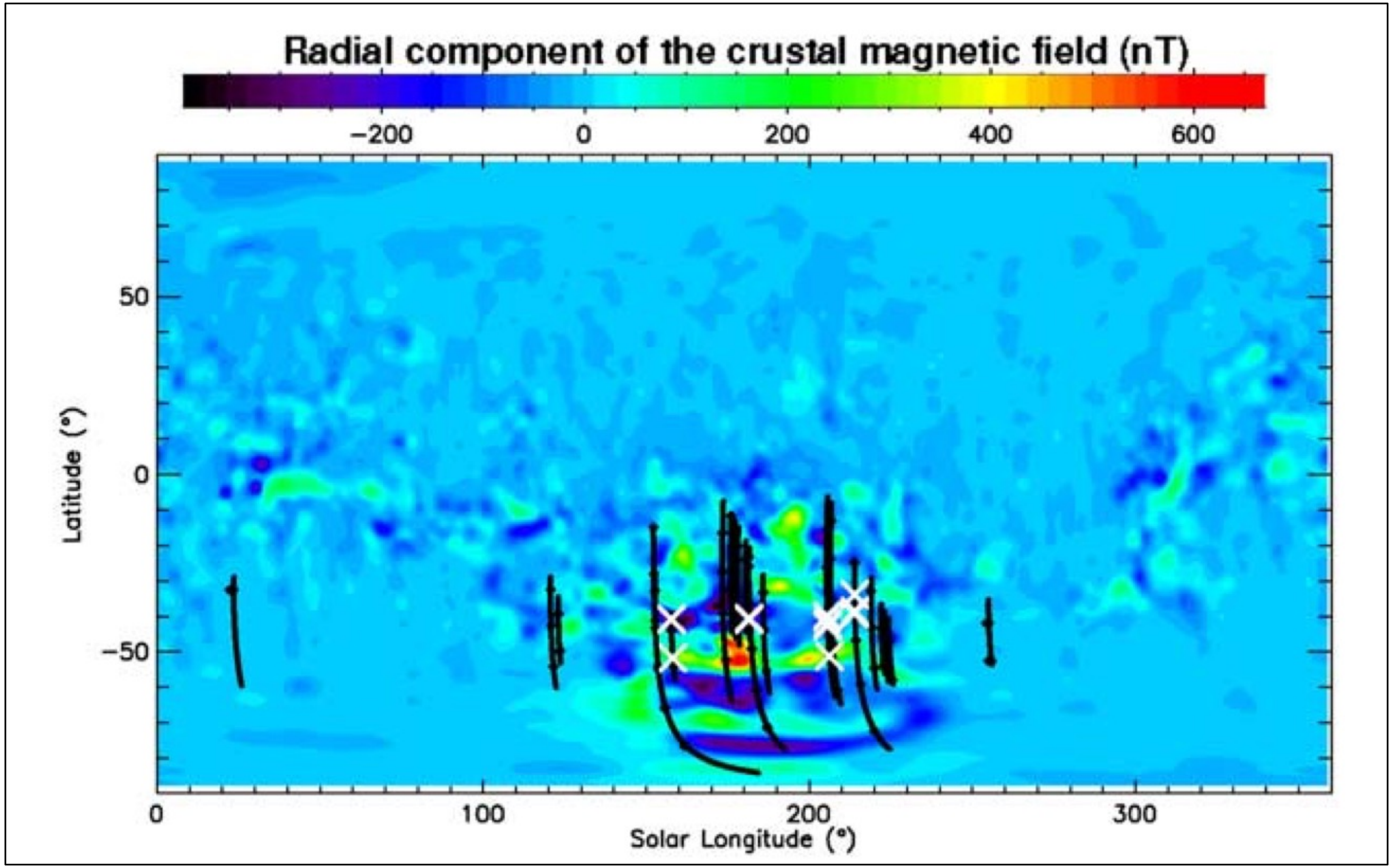
MAVEN observations during Cycle 24 late-maximum through declining phases



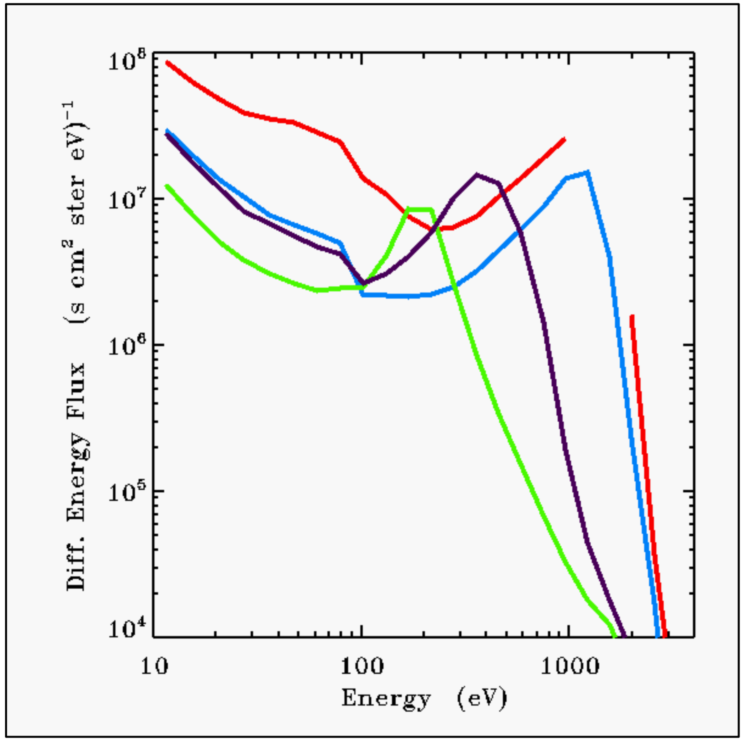
Gruesbeck+ (JGR, 2021)

MEX observed "discrete" aurora over Martian crustal magnetic fields

MEX UV observations (X) over crustal magnetic field

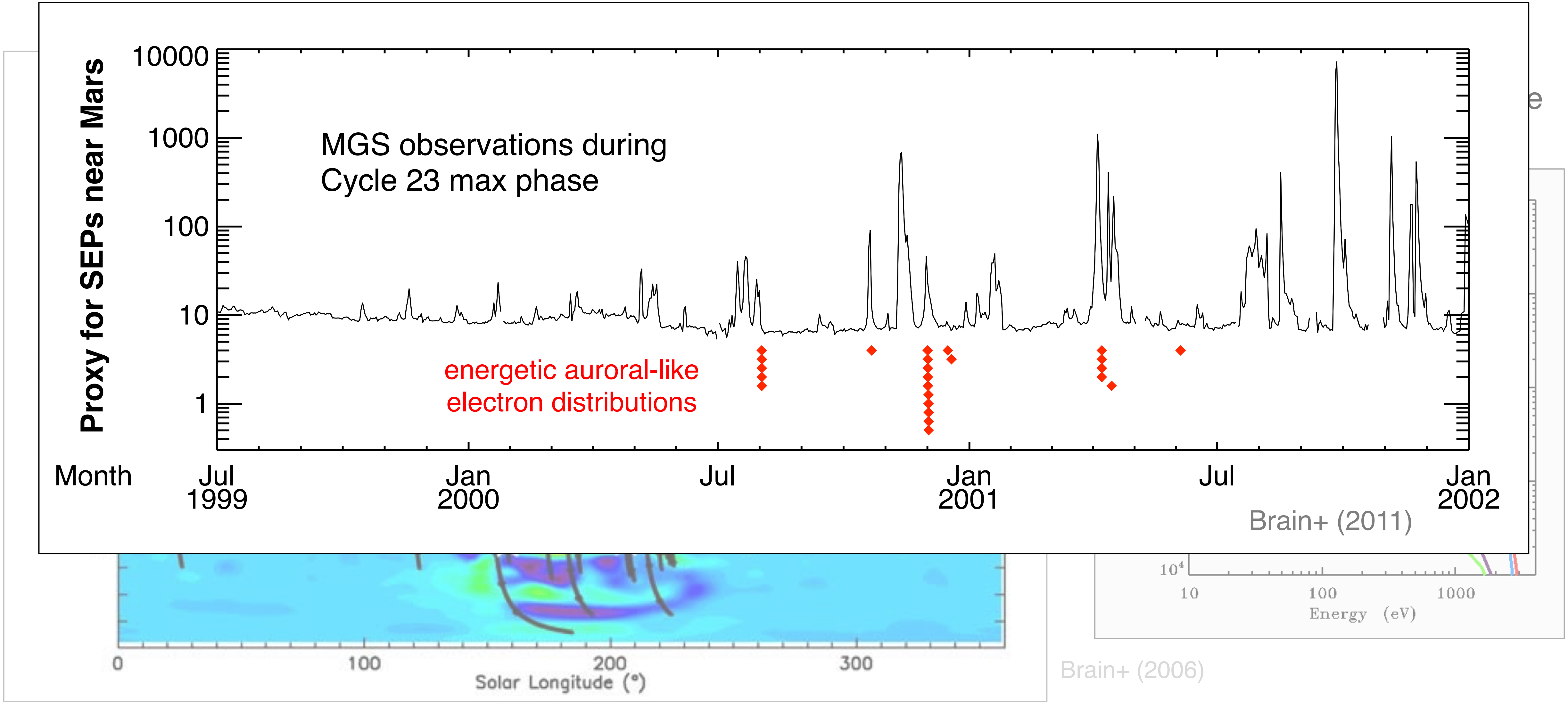


MGS observed accelerated electron distributions during the MEX observations



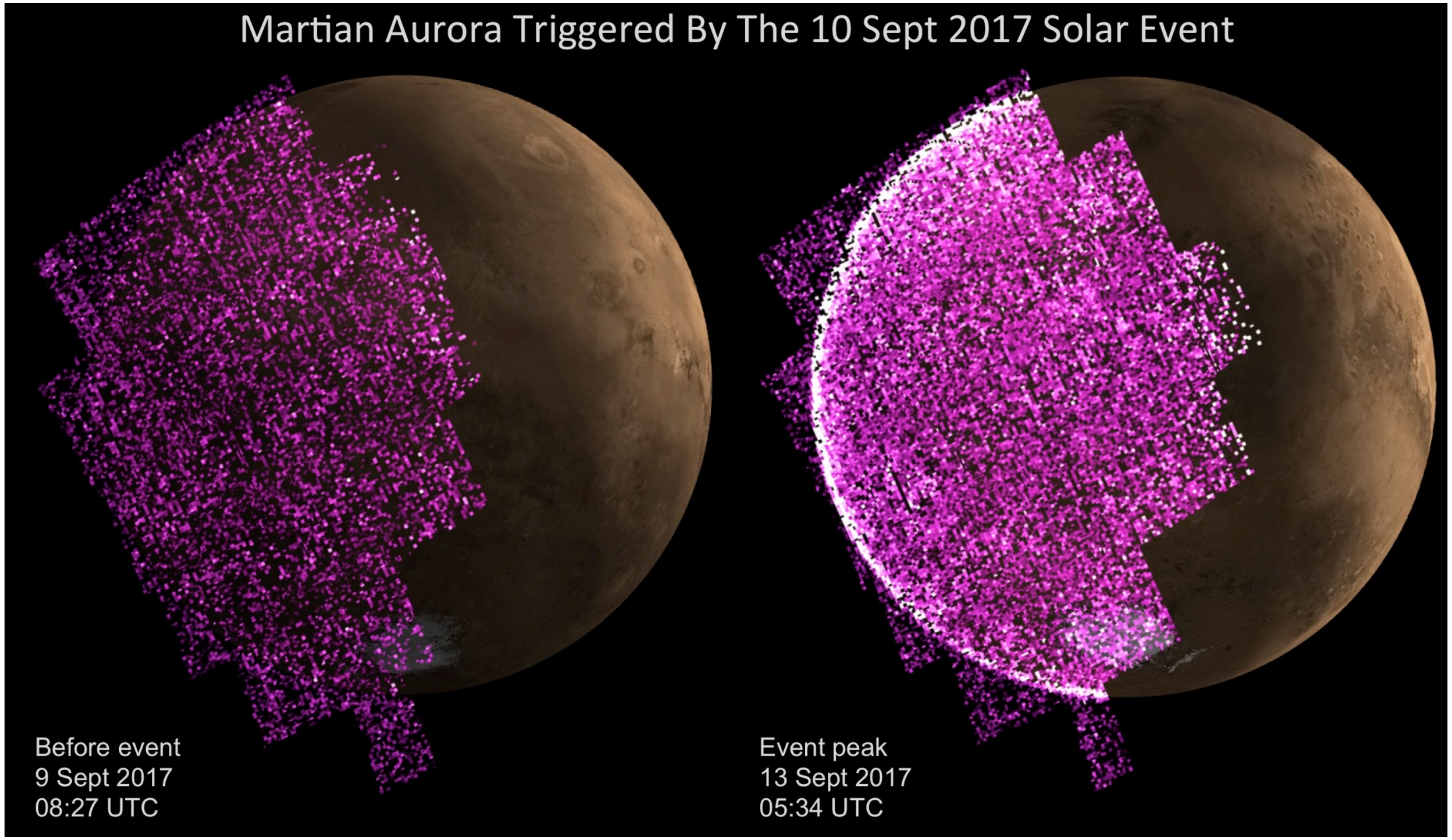
Brain+ (2006)

MEX observed "discrete" aurora over Martian crustal magnetic fields, which coincided with observations of SEPs



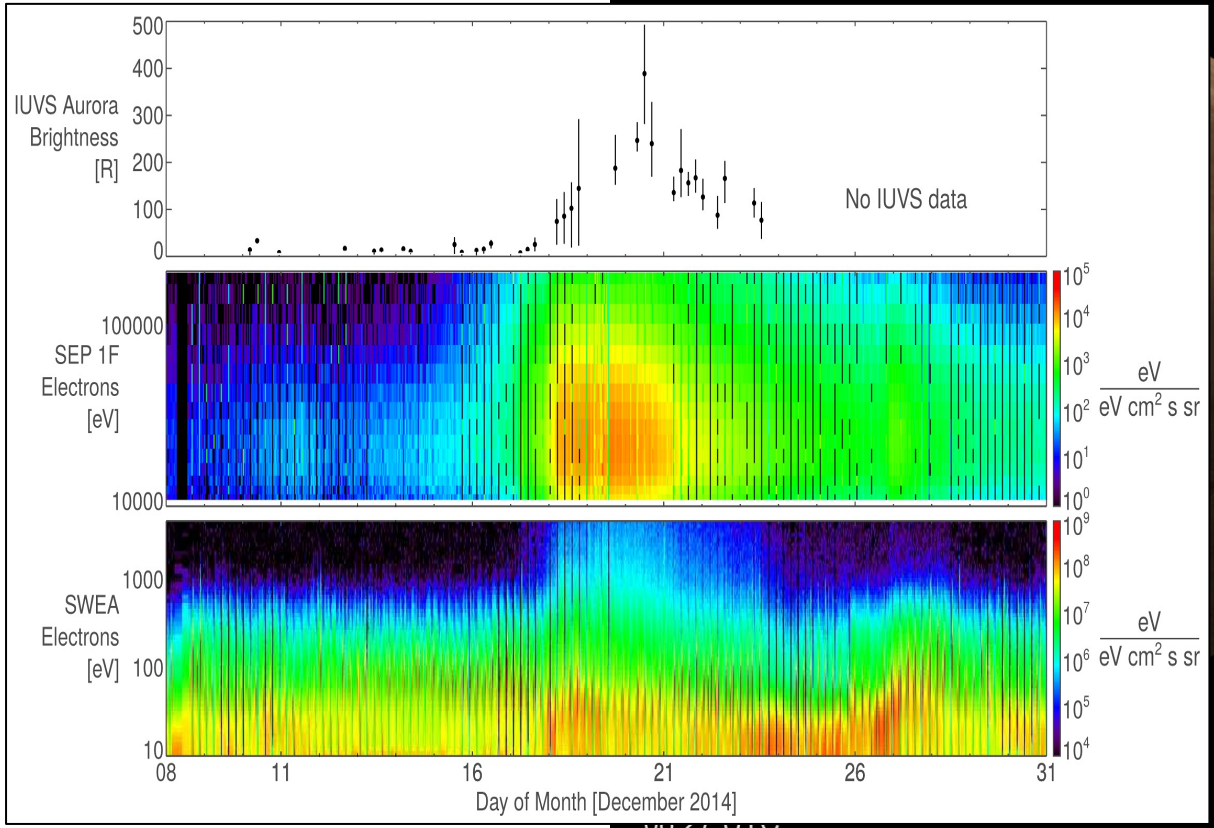
Brain+ (2006)

MAVEN observations of global “diffuse” aurora during SEP events of Cycle 24

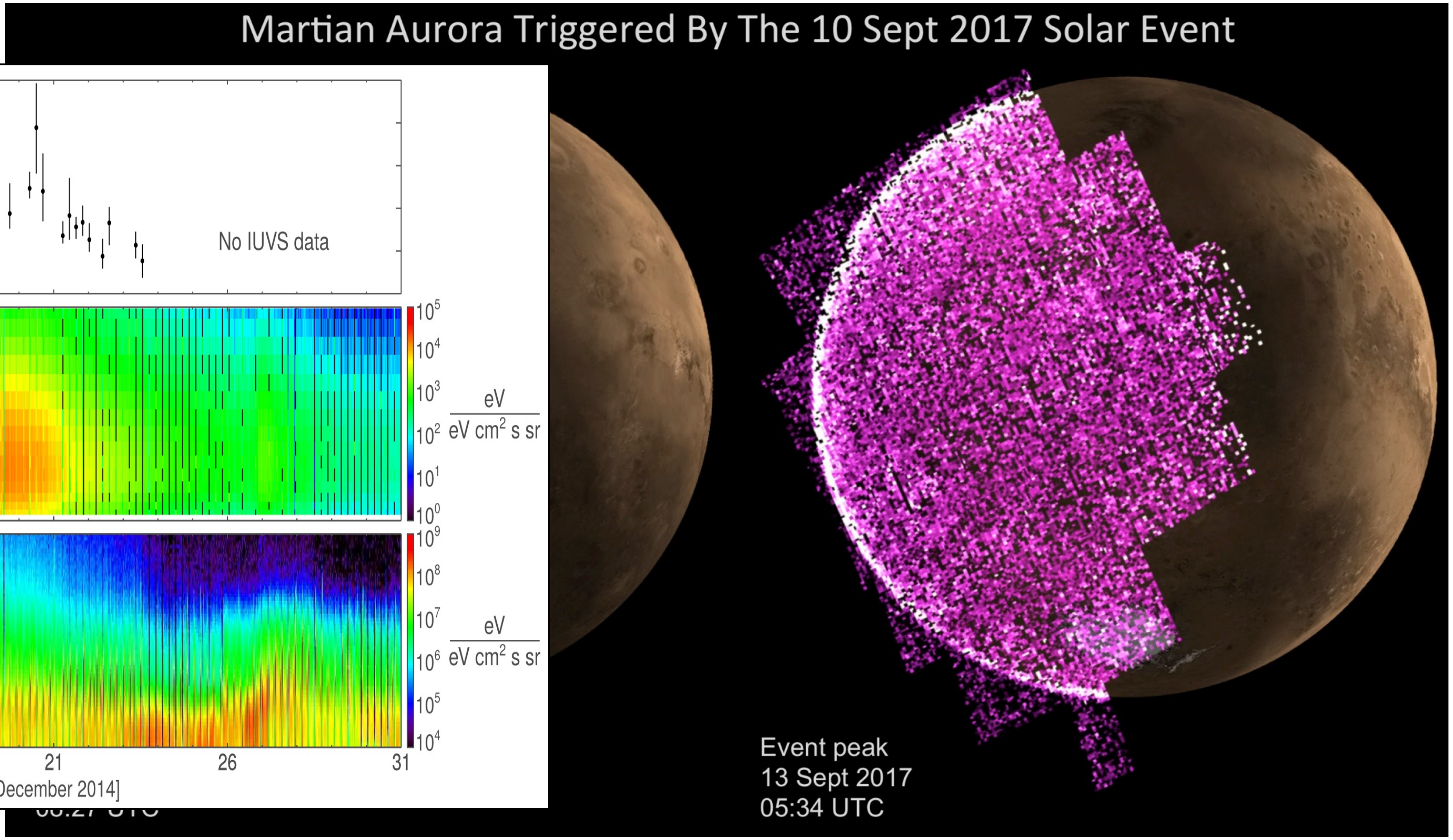


Schneider+ (GRL 2018)

MAVEN observations of global "diffuse" aurora during SEP events of Cycle 24



Schneider+ (2015)

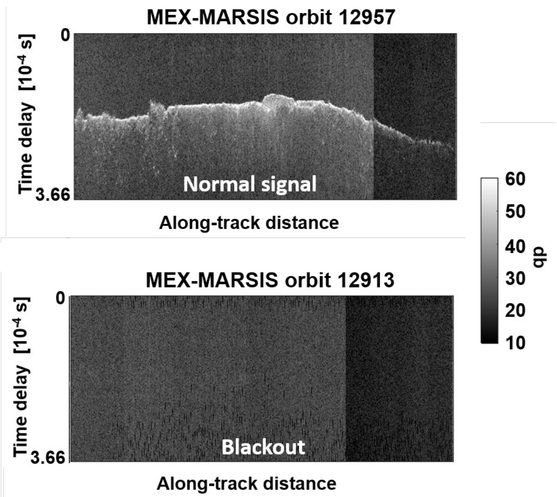


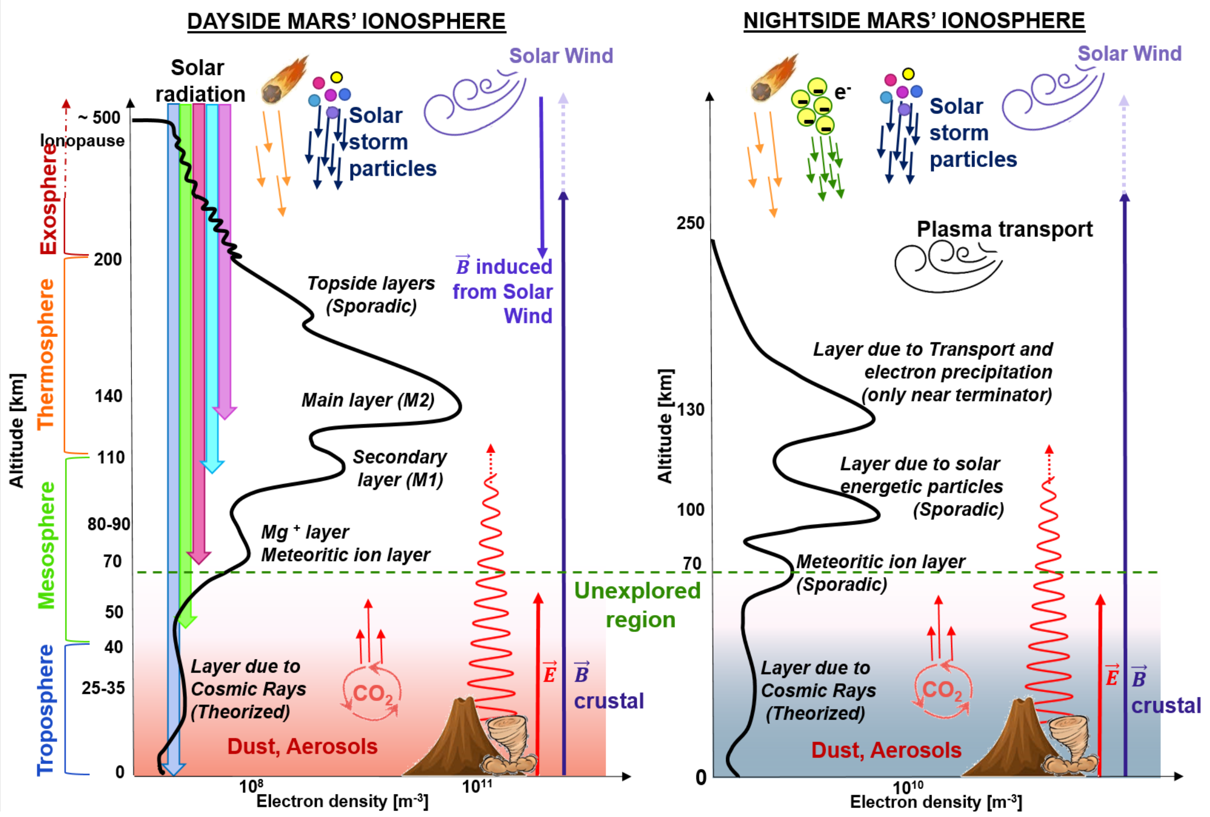
Schneider+ (GRL 2018)

The diffuse aurora was observed to correspond with SEP electron events, but recent modeling studies indicate that **SEP protons may play an important role** (Nakamura+, JGR 2021).

Radar blackout events during SEP activity

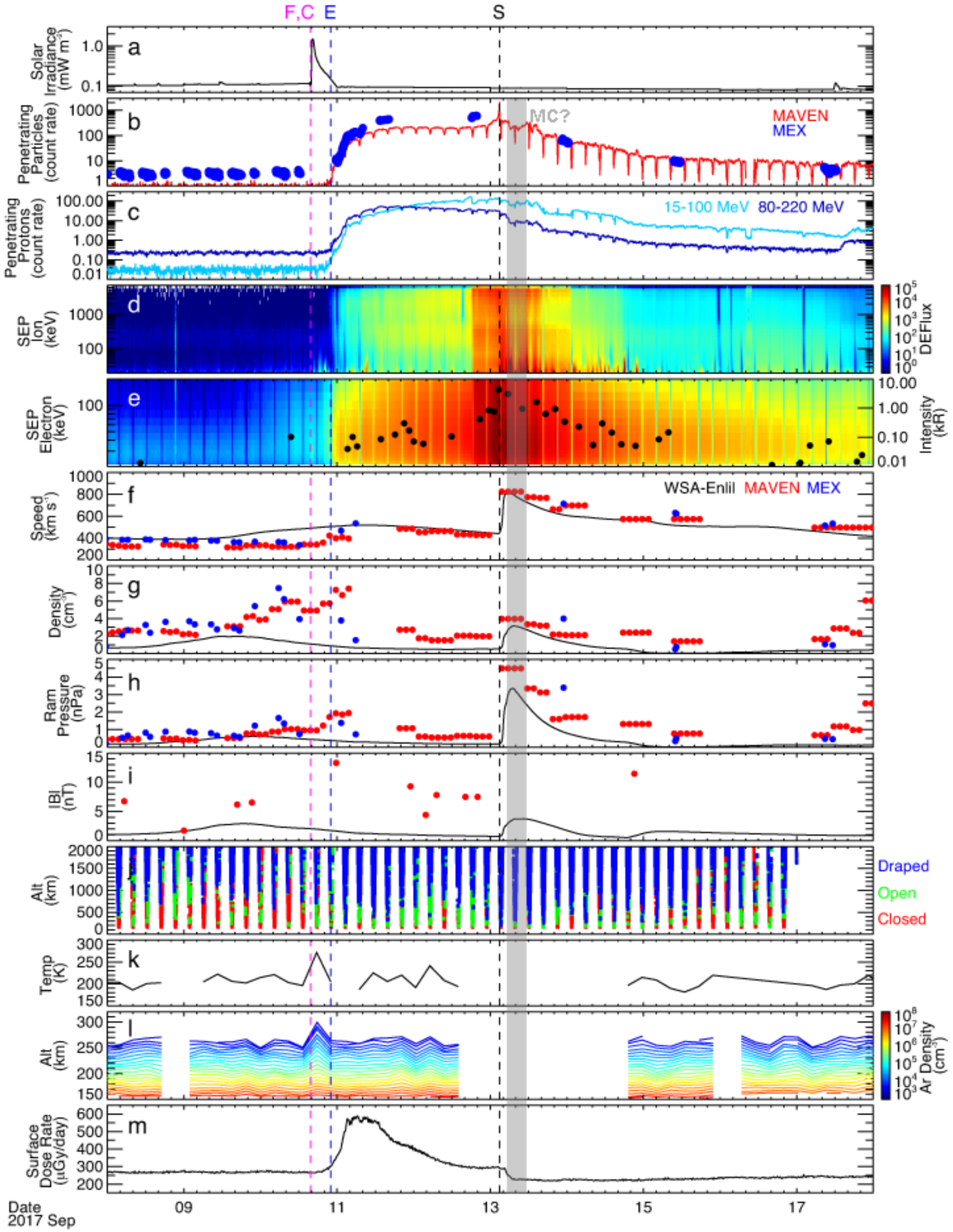
- SEPs are the most intense source of ionization at low altitudes.
- MEX MARSIS and MRO SHARAD conduct radar sounding of the Mars ionosphere.
- Observations show extended periods of **radar blackouts that lasted up to 10 days** during the Sept 2017 SEP activity (Sánchez-Cano+, JGR 2018).
- High-energy electrons created a dense, global layer of ions and electrons at ~90 km, which attenuated radar signals and thereby prevented MARSIS from receiving any surface signal.
- While SEP electrons are understood to be the source of the attenuations, **the importance of energetic protons remains unclear**.





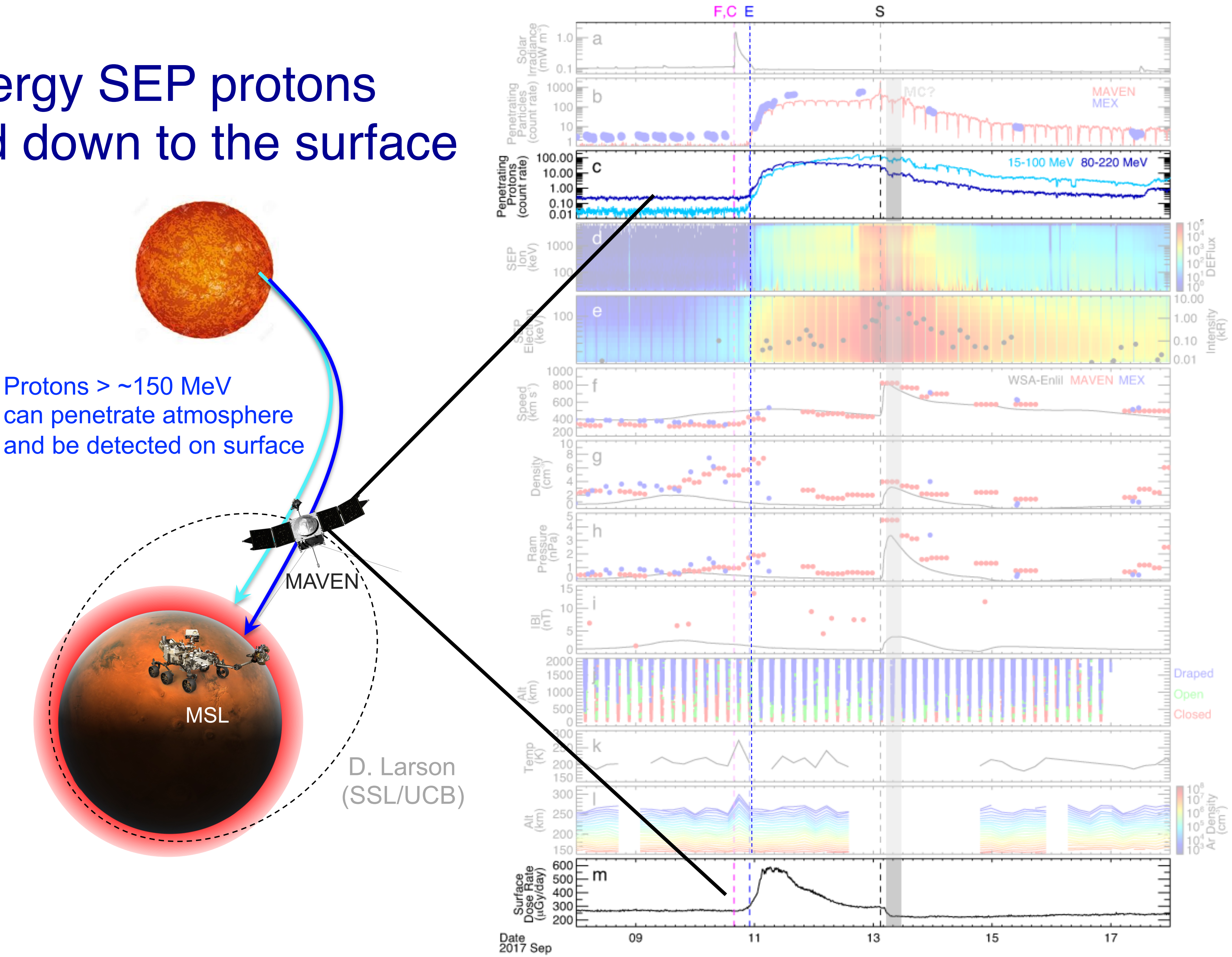
Sánchez-Cano+ (Exp Astron., 2022)

Cycle 24: Combined observations from MAVEN, MEX, and MSL together with solar wind modeling results provides context for understanding the impact and response at Mars.

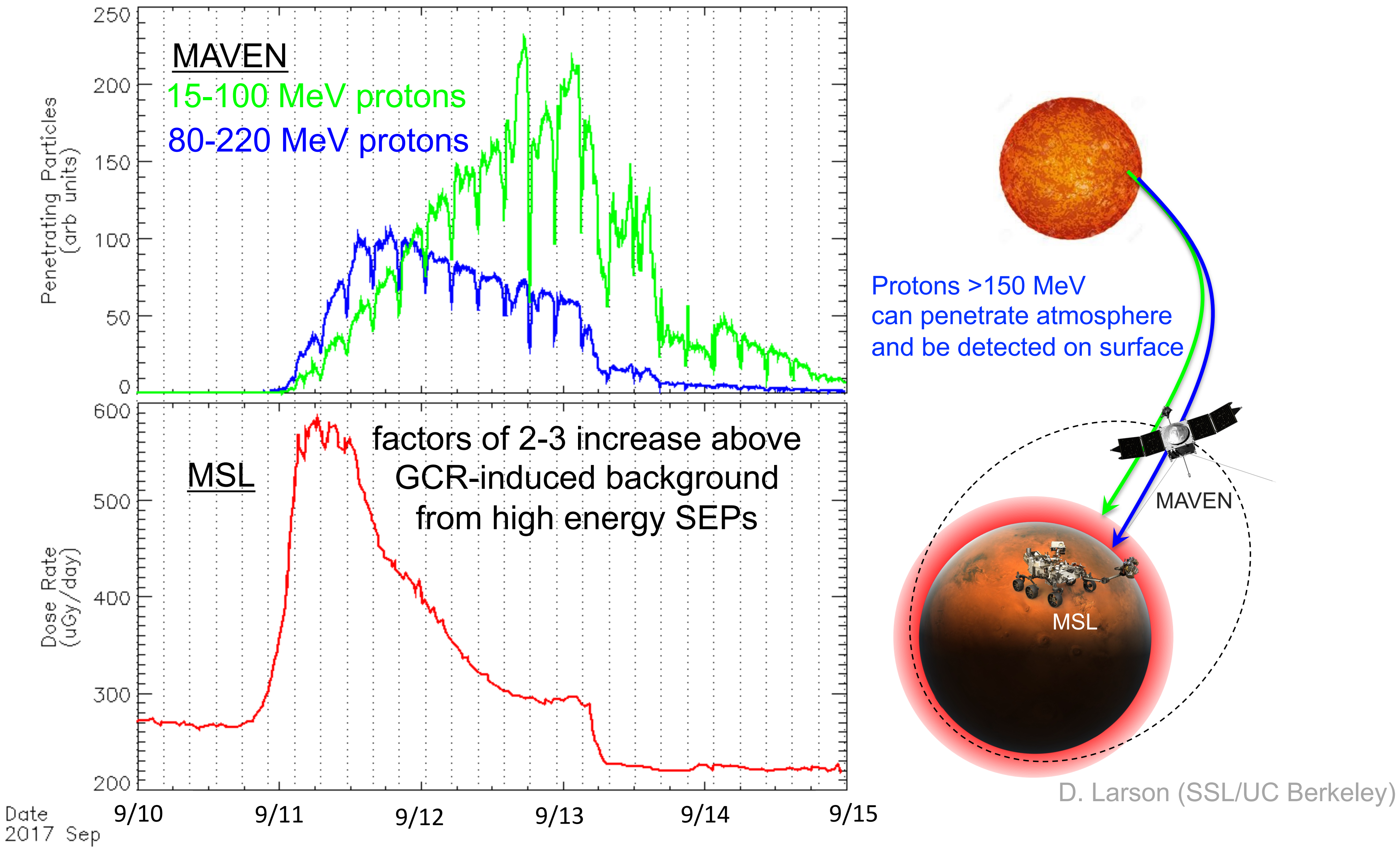


Lee+ (GRL 2018)

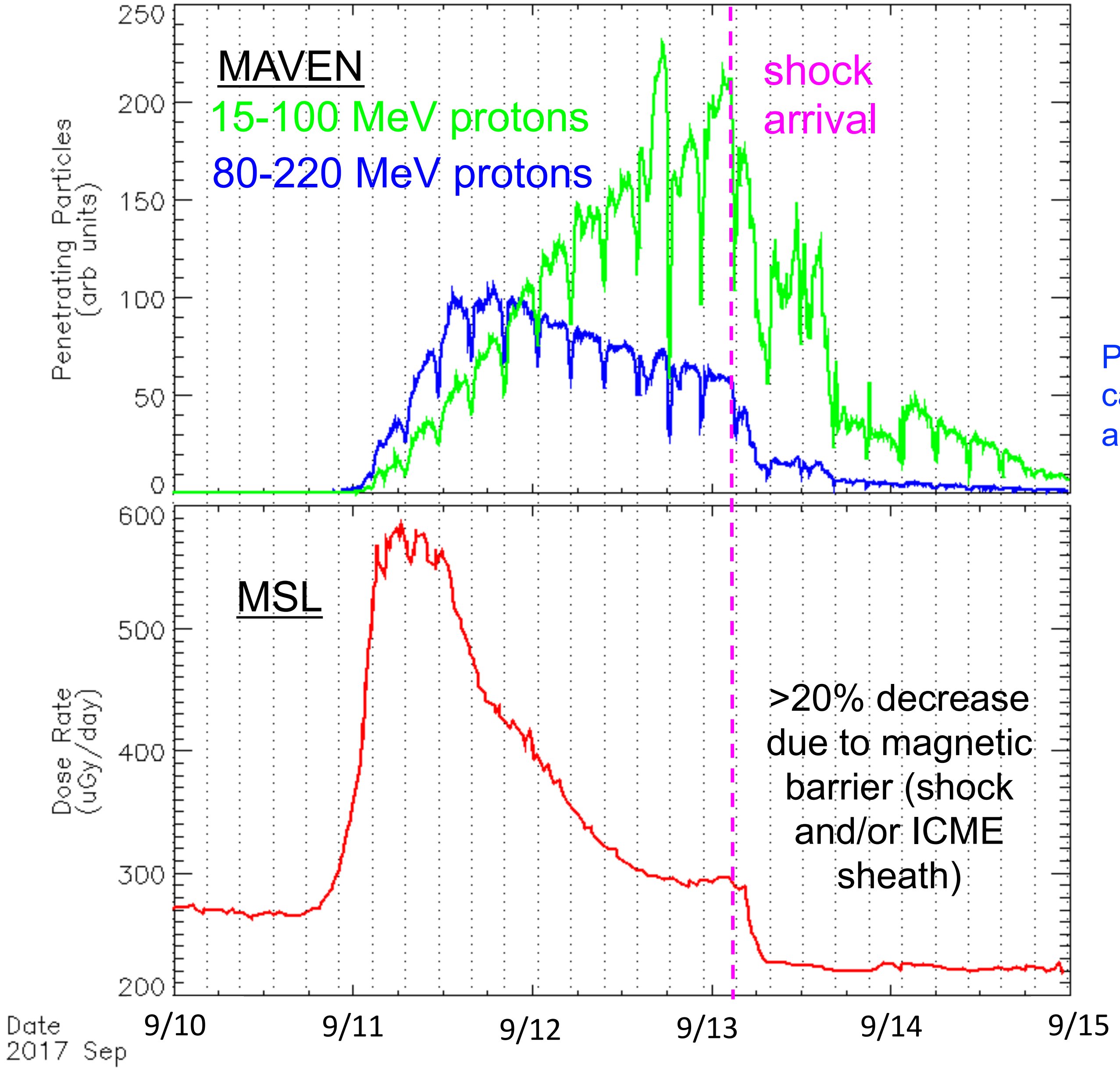
Higher energy SEP protons penetrated down to the surface

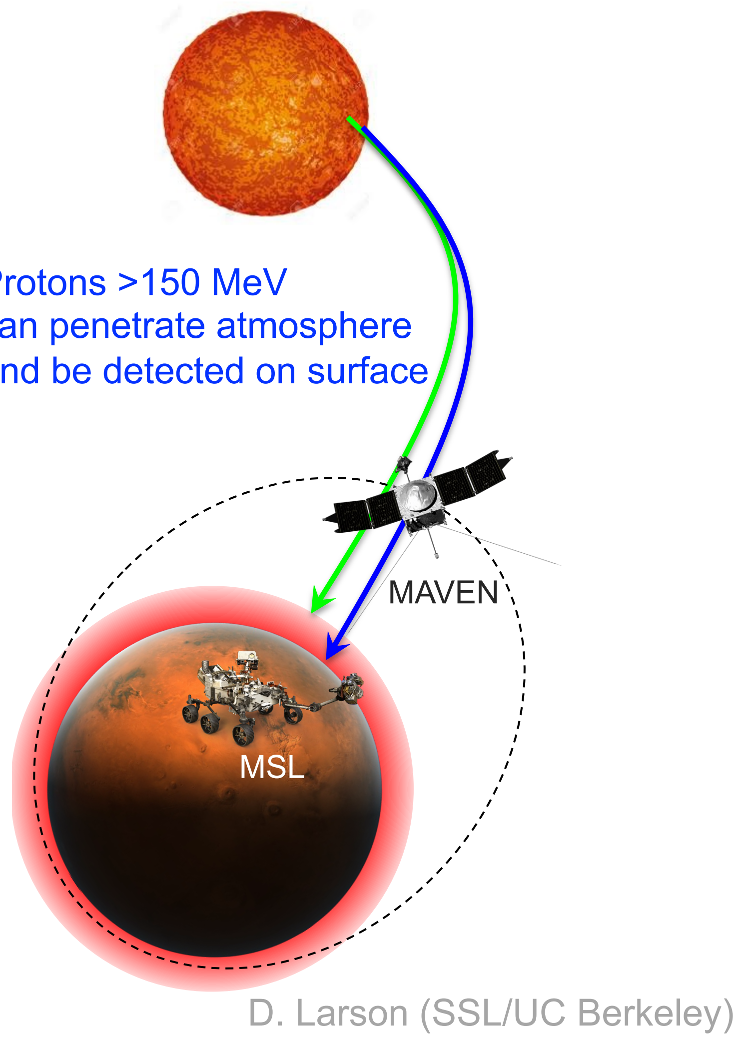


Lee+ (GRL 2018)



This was the largest surface enhancement observed by MSL/RAD during Cycle 24 since its arrival to Mars in 2012 (Ehresmann+; Zeitlin+ GRL 2018)





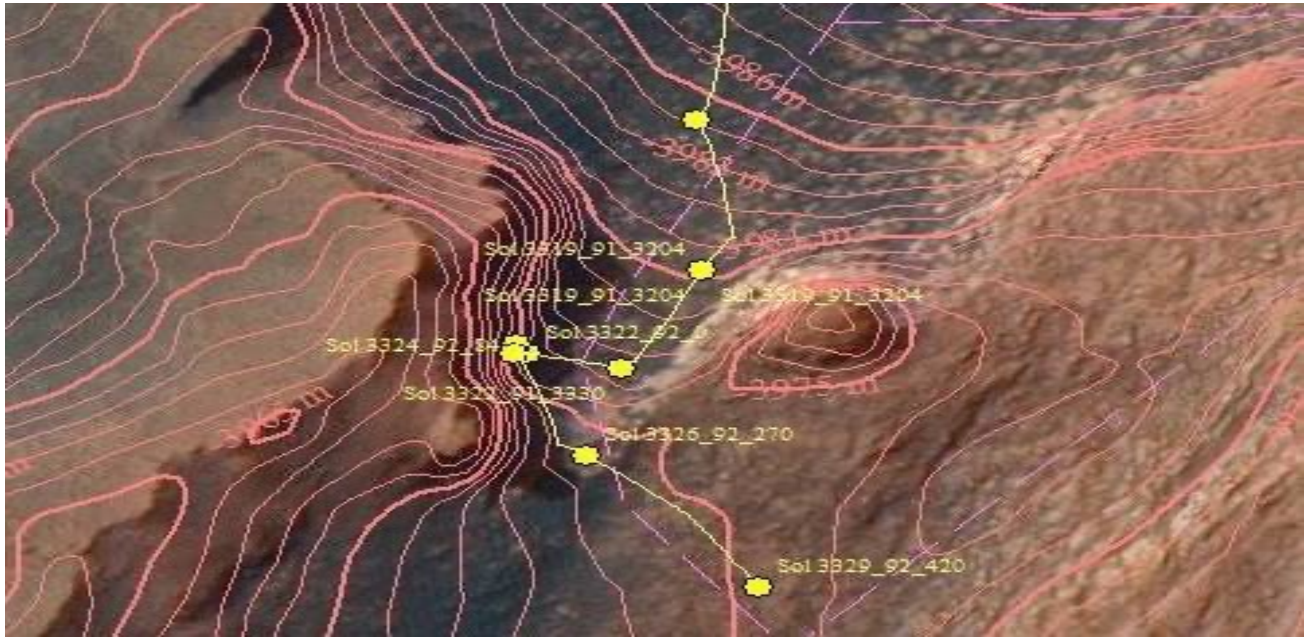
Enhancement was balanced out by a very deep Forbush-like decrease when the ICME impacted Mars (Guo+, Space Weather, 2018)

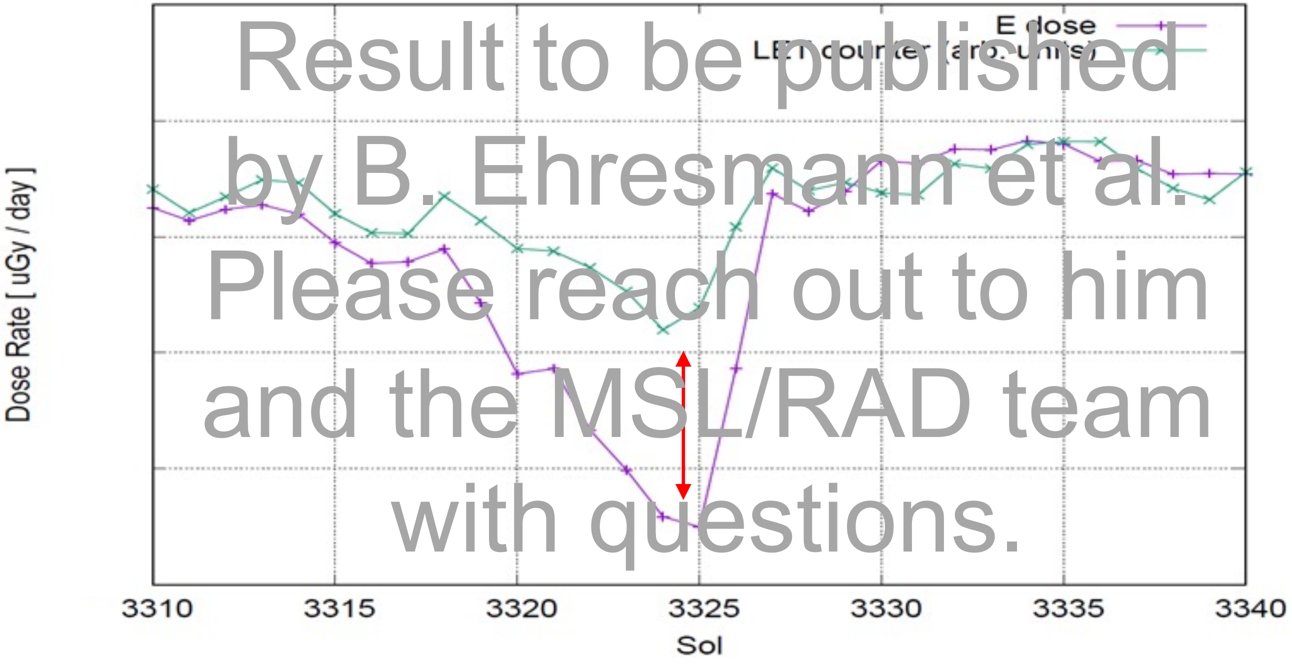
Radiation Shielding by Natural Terrain on Mars

- Whenever Curiosity drives close to a mountain, cliff side, or through a narrow pass, RAD can observe a ***decrease in radiation dose*** (Ehresmann+, JGR Planets, 2021).

- This is due to the rock features ***blocking out*** part of the sky and ***shadowing*** RAD from the incoming GCR radiation.

- RAD has observed ~10 instances of the shielding effect so far, and the observed dose ***decreases range from a few percent to ~15% depending on the amount of sky blocked*** (Ehresmann+, manuscript in preparation)





Slide content courtesy of B. Ehresmann (SwRI)

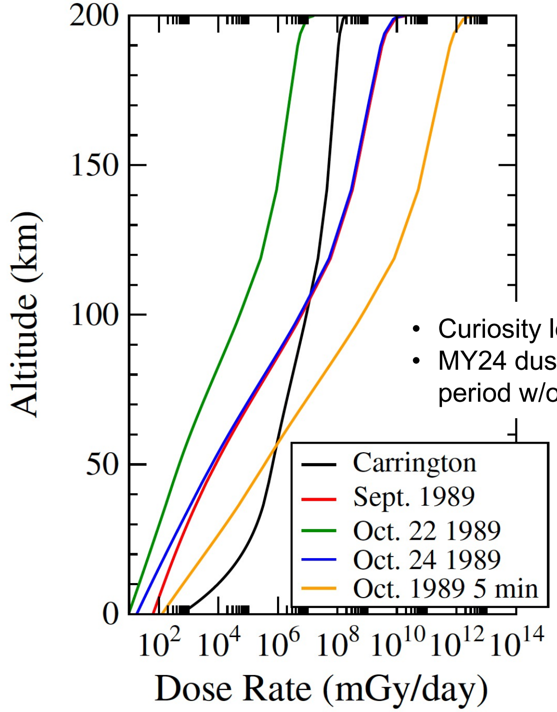
Effects of atmospheric dust loading on the radiation environment

- Modeling by Norman+ (JGR 2014) revealed:

  For the GCR environment
  - Dose rates (in tissue) as a function of altitude were found to be very flat, i.e., very little altitudinal variations
  - Variation in the surface dose rate was very small, < 0.1%

  For the SEP environment
  - Dose rates as a function of altitude were not flat
  - Effects were dependent on both the spectral hardness of the event and the integral fluence
  - Effects on surface dose rates were moderate for the 1989 events, with < 10% variation
  - Variation ranged from 8% to 26% (minimum atmospheric depth vs maximum depth) for the Carrington event, which had larger integral flux and softer spectrum compared to the 1989 events

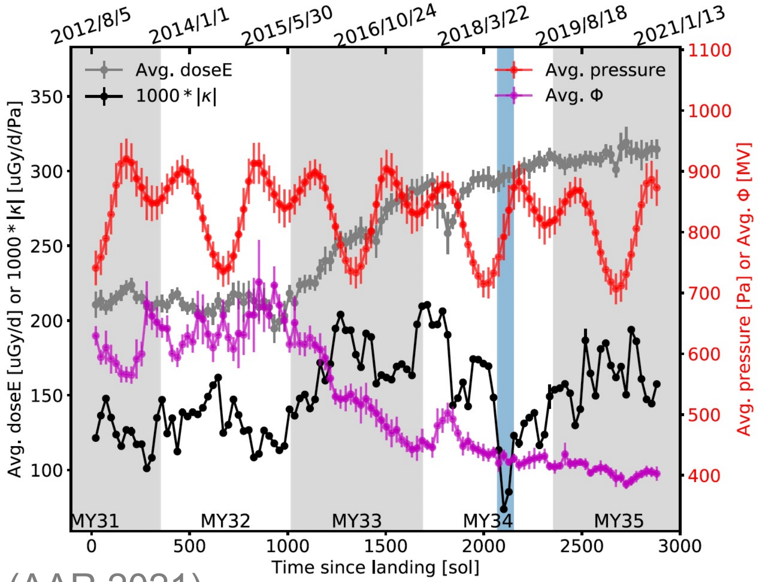
- MSL/RAD observations showed that the 2018 global dust storm had no notable effects on the surface dose rates (Guo+, Astron Astrophys Rev 2021)



Norman+ (JGR 2014)

- Curiosity location
- MY24 dust conditions (MGS period w/o global storm)

2018 global dust storm



Guo+ (AAR 2021)

Atmospheric escape rate at Mars can increase by an order of magnitude during extreme solar storm events

Typical Conditions | Extreme Conditions

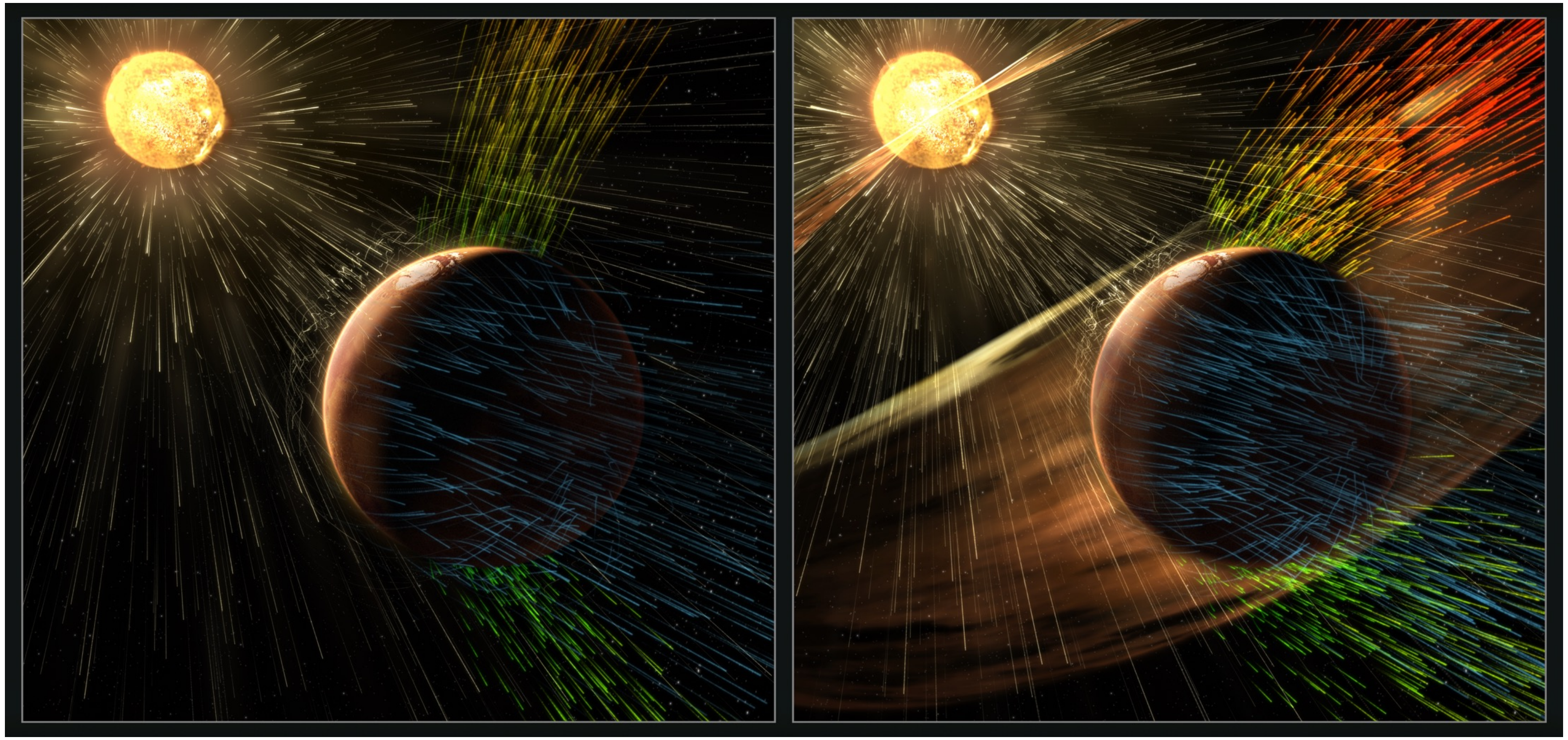
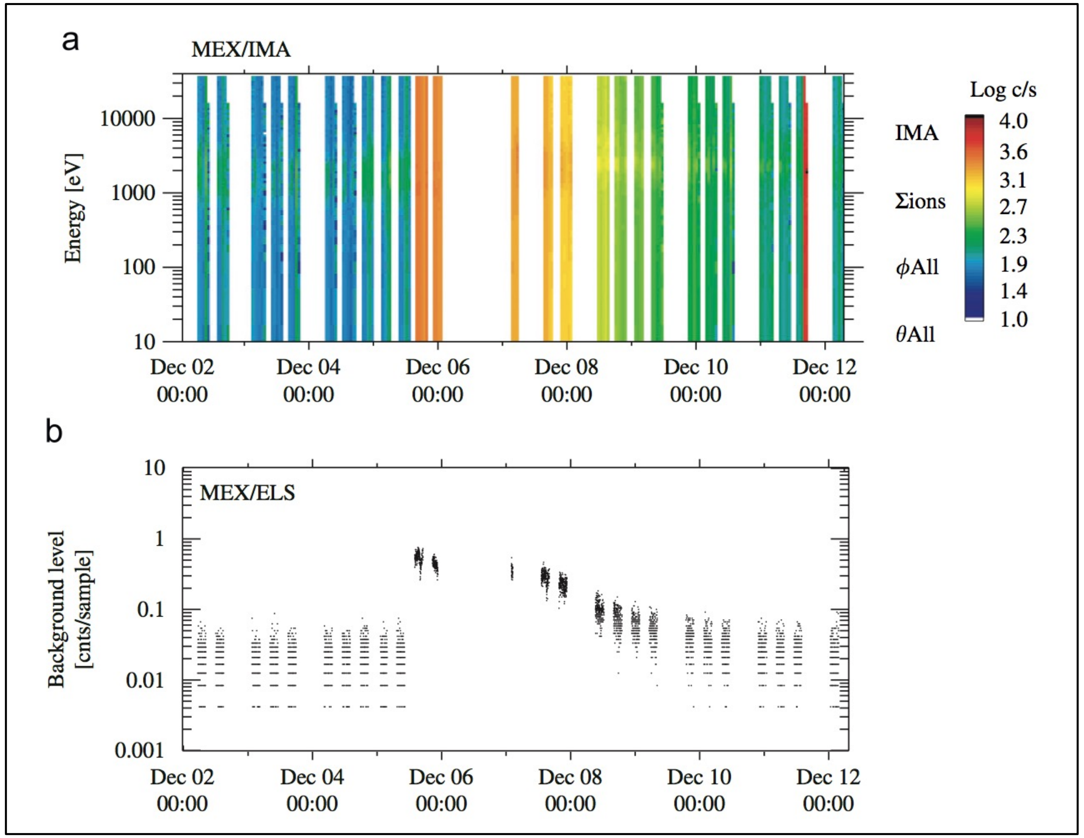


Image credit: (left) NASA and (right) Jakosky et al. (2015)

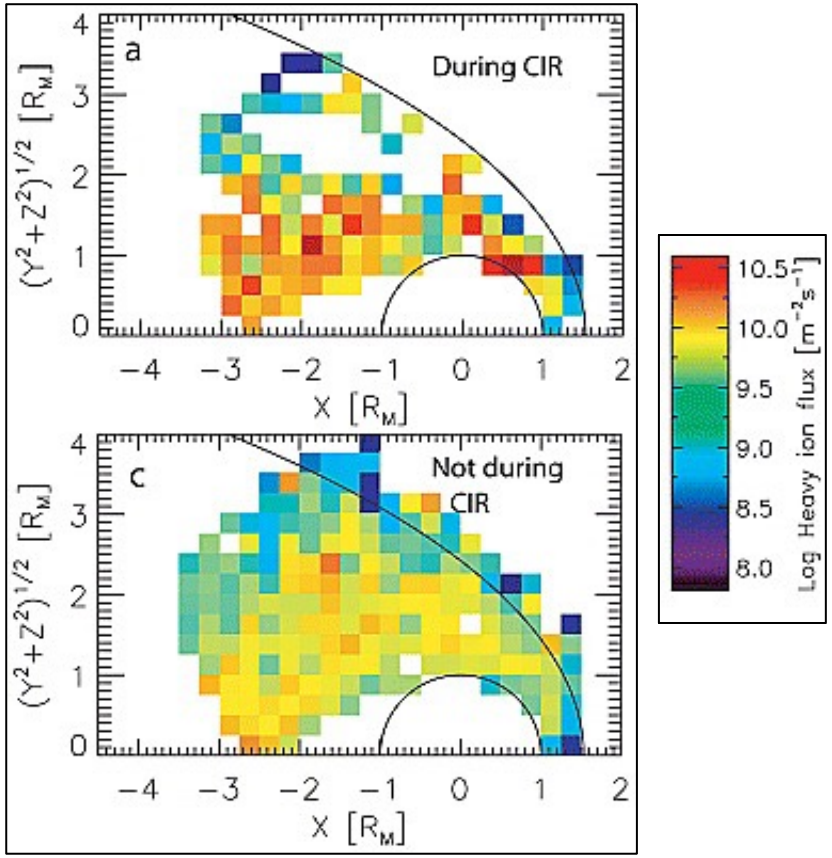
MEX observed increases in ion escape during CME and CIR/SIRs events

During an ICME event of Cycle 23



Futaana+ (2008)

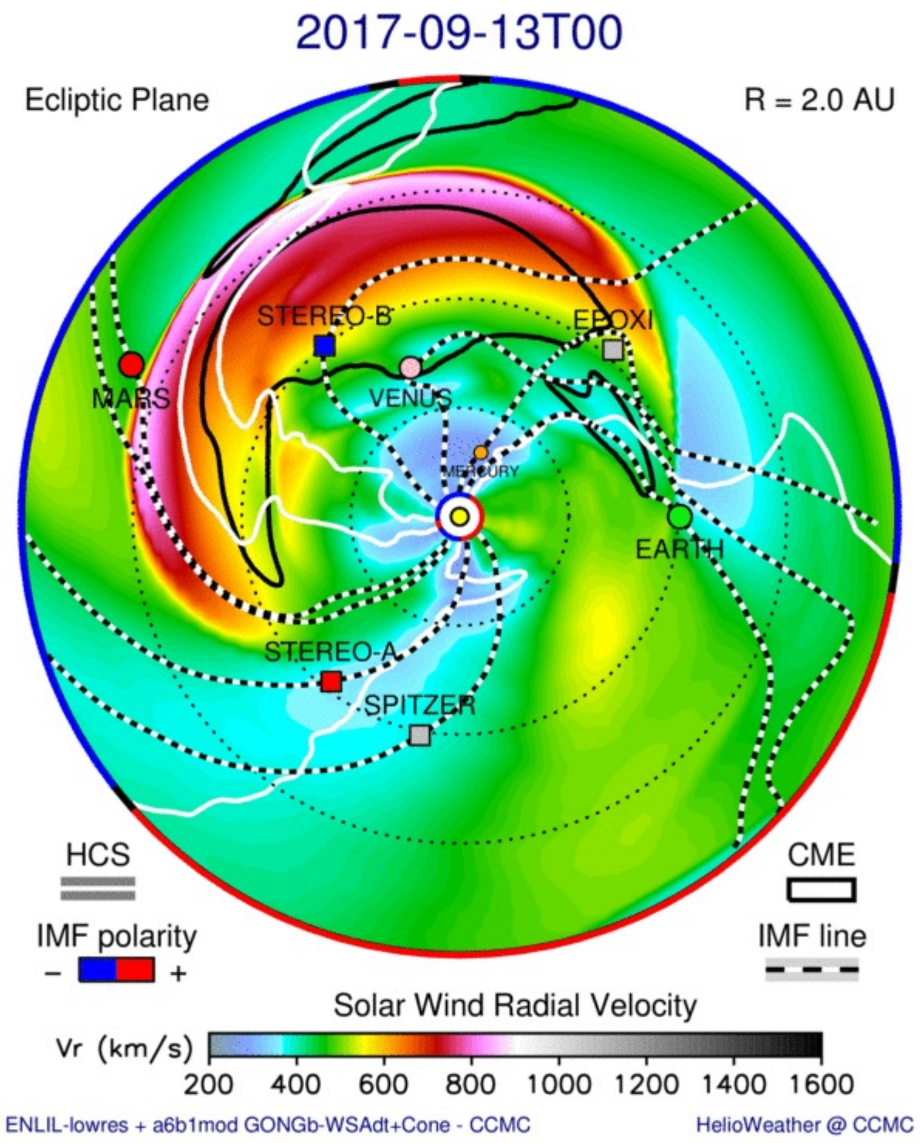
During CIR/SIR event periods in Cycle 23/24 minimum phase



Edberg+ (2010)

From D. Brain (CU/LASP)

MAVEN observed increases in the ion and neutral escape rates during a CME event



WSA/Enlil simulation from M. L. Mays (NASA/CCMC)

MAVEN

Neutral Hydrogen

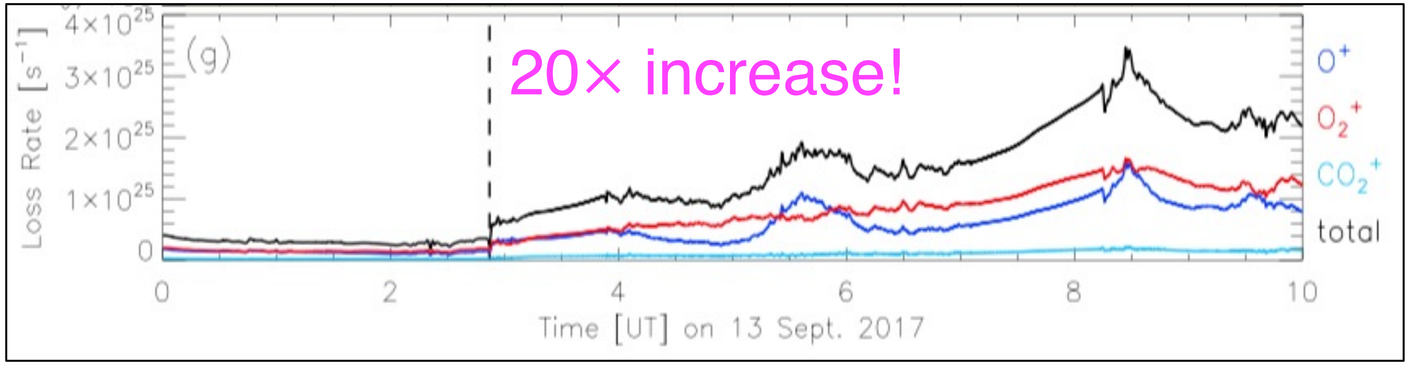
Table 2. Variability of dayside H escape flux during the September 2017 solar storm.

Date in 2017	MAVEN Orbit, echelle segment	T_n (K) at exobase	H Density (cm^{-3}) at exobase	H Escape Flux (atoms cm^{-2} s^{-1})
Dayside				
Aug 31st	5660, inbound disk	200	$1.2 \pm 0.1 \times 10^5$	$3.9 \pm 0.4 \times 10^7$
Sep 8th	5706, inbound disk	230	$1.1 \pm 0.1 \times 10^5$	$8.2 \pm 0.7 \times 10^7$
Sep 11th	5722, inbound disk	280	$0.9 \pm 0.2 \times 10^5$	$20 \pm 0.4 \times 10^7$

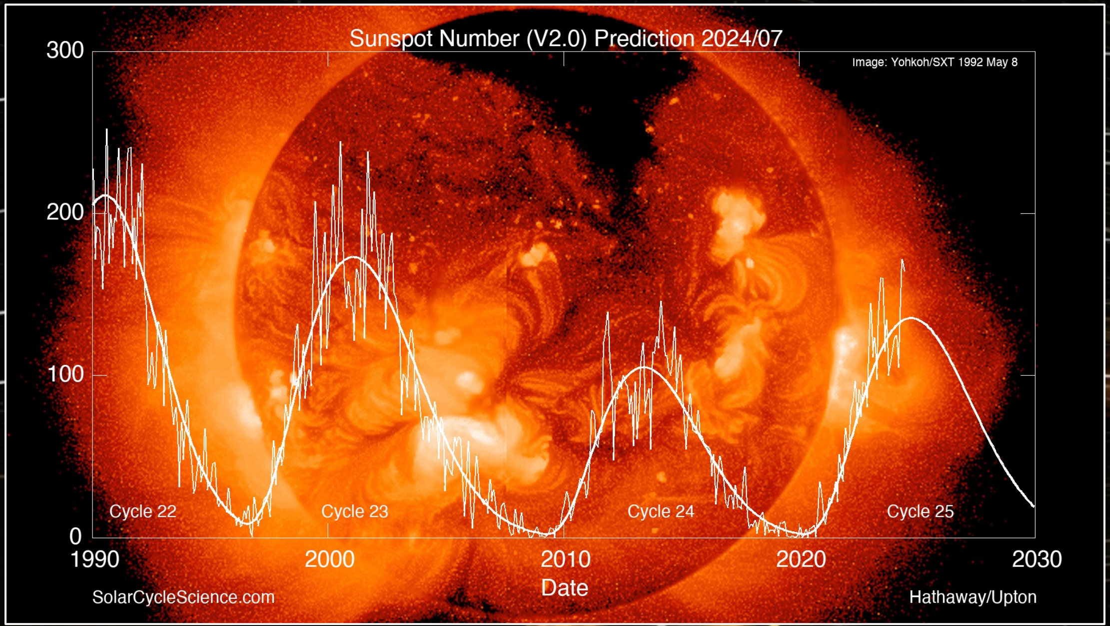
Mayassi+ (2018)

5× increase!

Ions: O^+, O_2^+, CO_2^+



Ma+ (2018)



How has Mars been responding to Cycle 25 activity?

This is an exciting time for studying space weather at Mars, **especially since solar max is happening concurrently with the Mars dust storm season.**

Cycle 25 will provide opportunities to further study and analyze space weather impacts and effects observed by multiple Mars missions, in orbit and at the surface, current and future.

Dust storm season occurs during southern spring-summer

Today: $L_S = 324°$

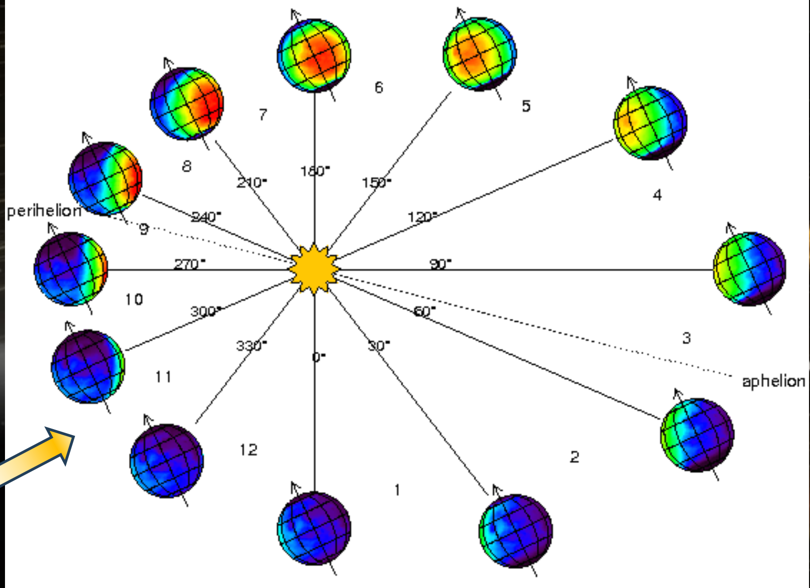
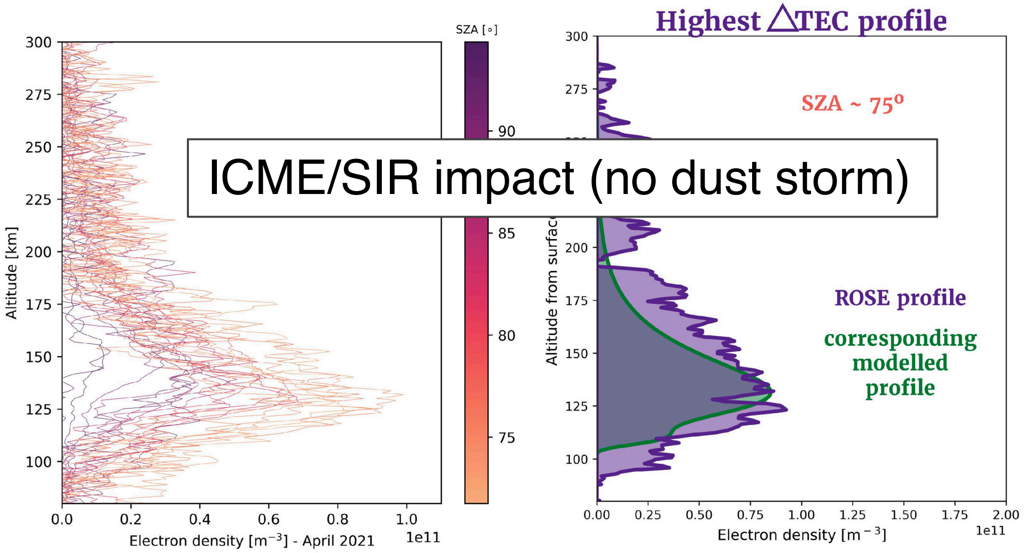
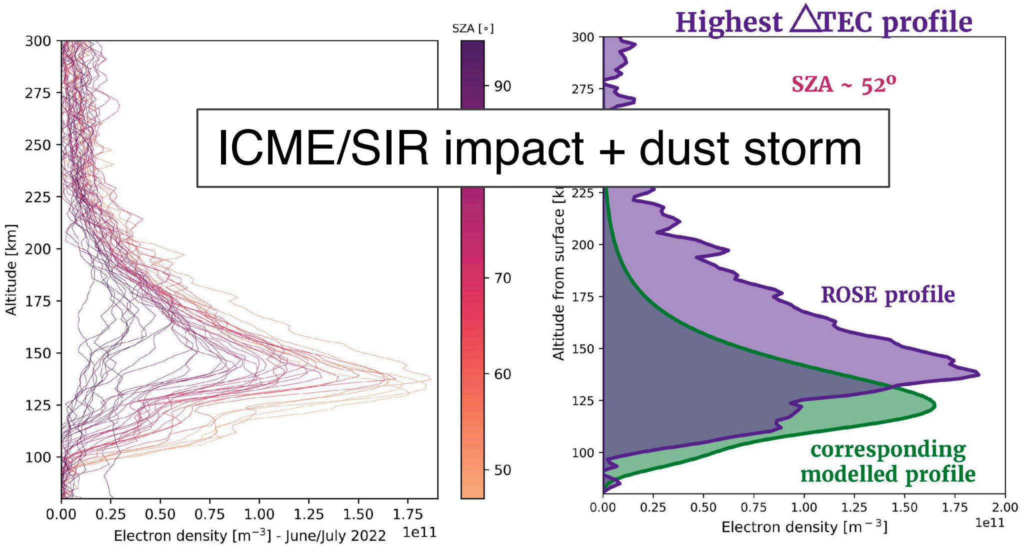


Image credit: Mars Climate Database Project

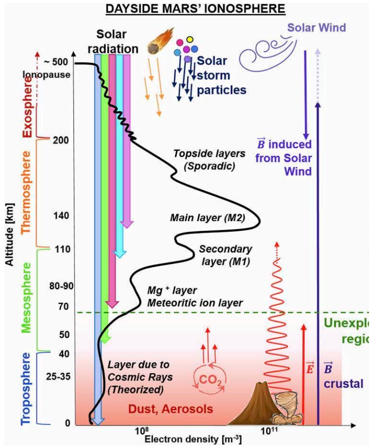
Total electron content (TEC) observations at the dayside ionosphere (80-300 km) during ICME/SIR events + dust storm activity

- MAVEN Radio Occultation Science Experiment (ROSE) observations were used to examined the response of the Martian ionosphere to ICMEs and SIRs during dust storms (M. Felici+, Icarus 2024)
- Increase in TEC **up to 2.5×10^{15} m^{-2}** in the ionosphere **following an ICME/SIR impact**, indicating higher ionization of the neutral atmosphere
- Increase in TEC is higher, **up to 5×10^{15} m^{-2}** when a **dust storm** was happening concurrently
- The peak altitudes of the M1 and M2 ionospheric layers loft together, suggesting that the thermosphere might loft as a unit by the dust storm underneath





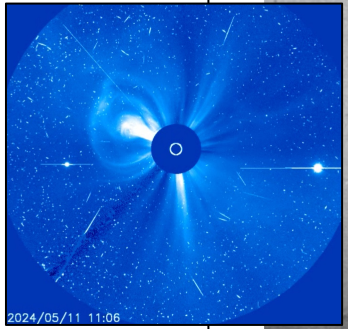
(left) ROSE electron density profiles and *(right)* ROSE profiles of the highest increase in TEC (purple) compared to the baseline (photochemically produced ionosphere) profiles (green). Adapted from Felici+ (2024).



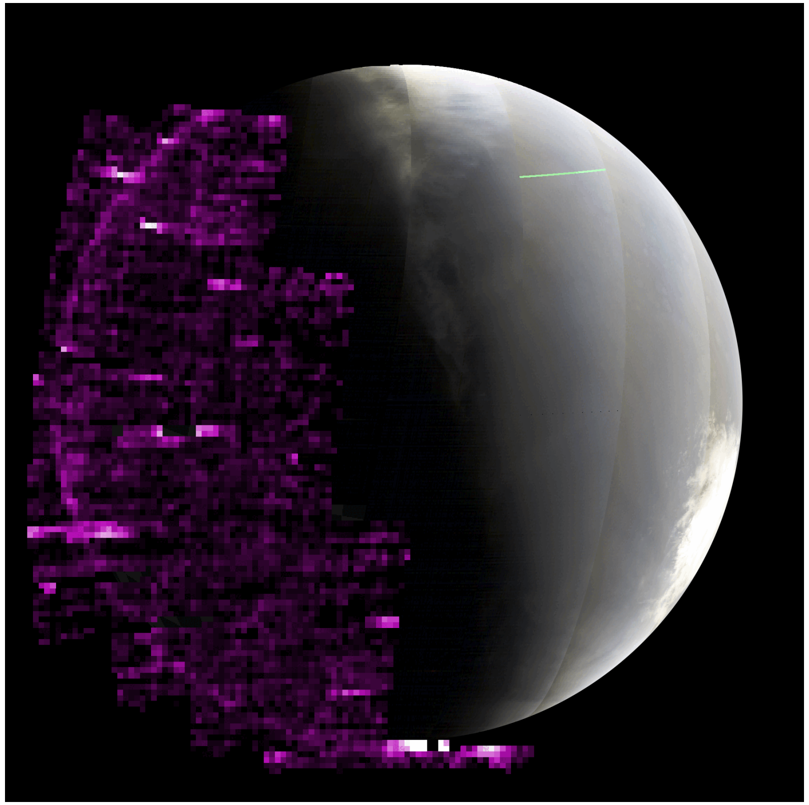
Sánchez-Cano+ (Exp Astron., 2022)

Mars experienced some of the most exciting space weather activity during May 2024

NASA Watches Mars Light Up During Epic Solar Storm



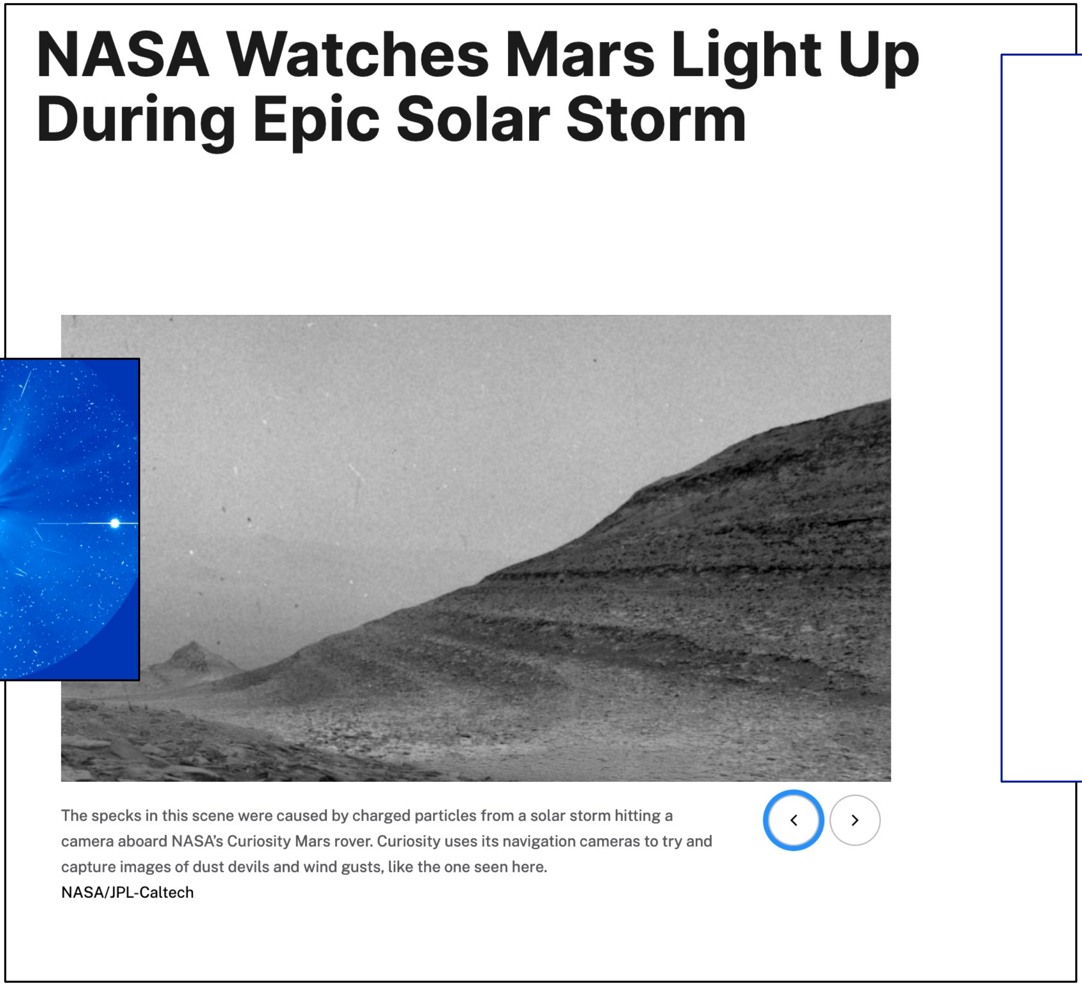
The specks in this scene were caused by charged particles from a solar storm hitting a camera aboard NASA's Curiosity Mars rover. Curiosity uses its navigation cameras to try and capture images of dust devils and wind gusts, like the one seen here.
NASA/JPL-Caltech

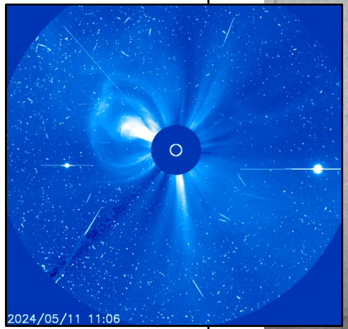


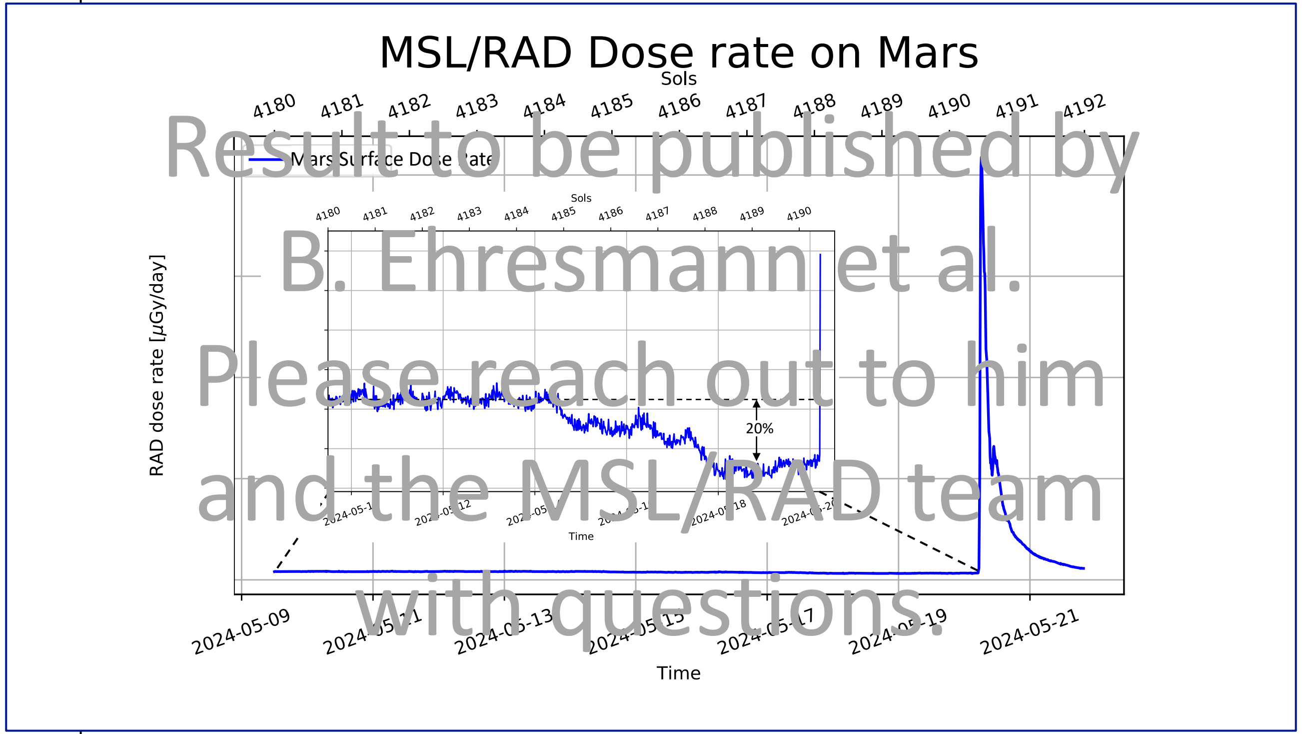
The purple color in this video shows auroras on Mars' nightside as detected by the ultraviolet instrument aboard NASA's MAVEN orbiter between May 14 and 20, 2024. The brighter the purple, the more auroras that were present.

see https://www.nasa.gov/solar-system/planets/mars/nasa-watches-mars-light-up-during-epic-solar-storm/

Mars experienced some of the most exciting space weather activity during May 2024



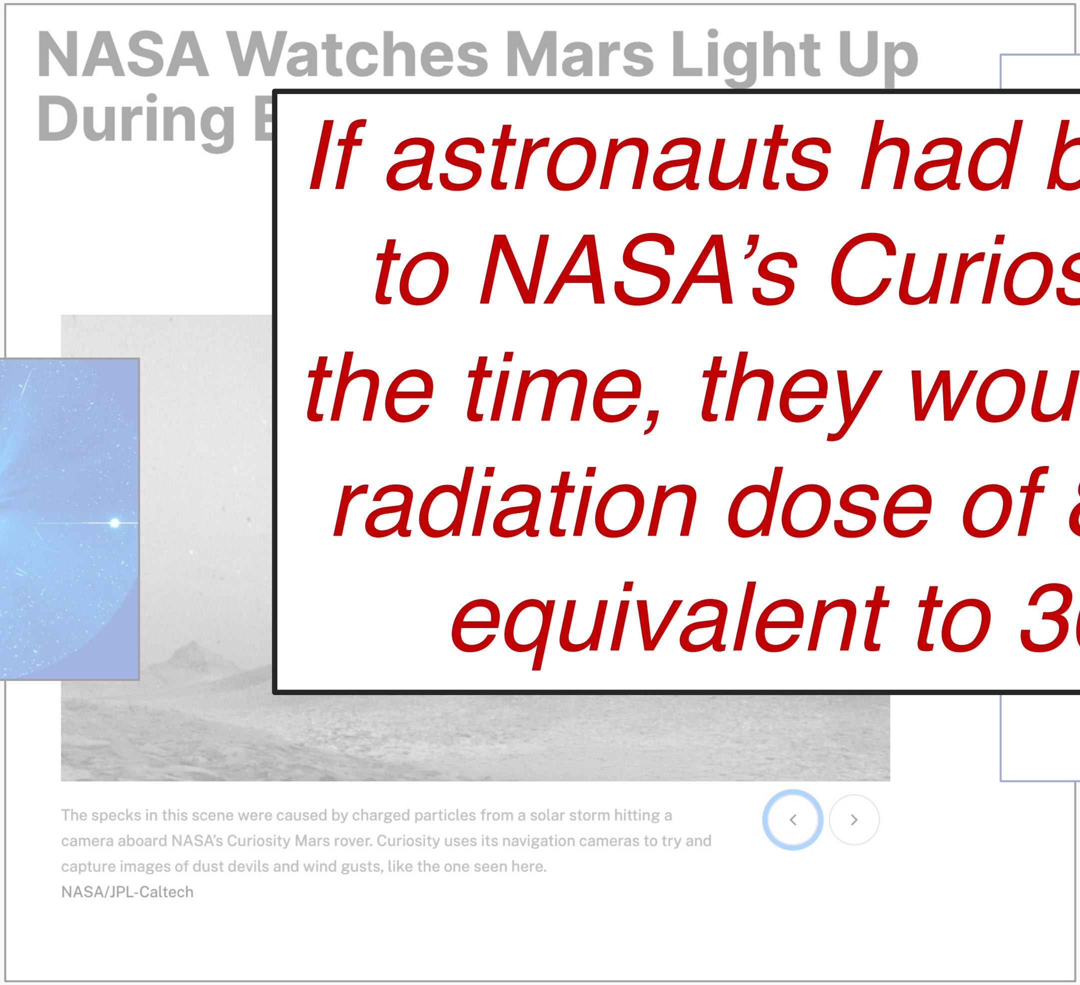


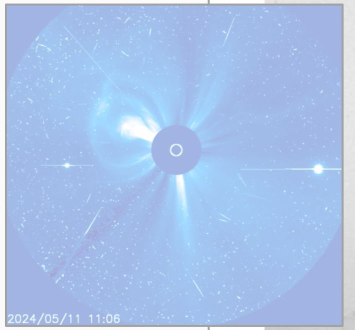


Largest dose rate enhancement was observed starting on May 20th, associated with the X-class flare and CME activity that occurred on the solar farside. Figure courtesy of B. Ehresmann and D. Hassler (SwRI).

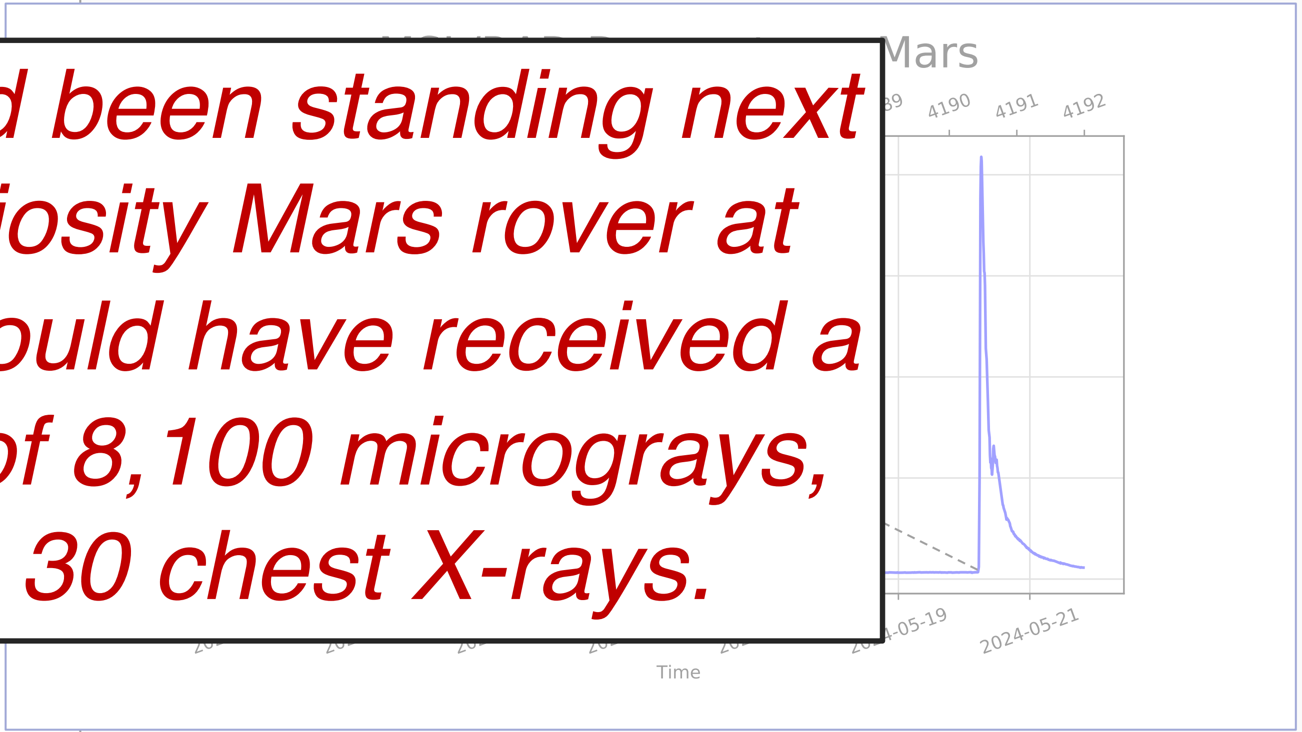
see https://www.nasa.gov/solar-system/planets/mars/nasa-watches-mars-light-up-during-epic-solar-storm/

Mars experienced some of the most exciting space weather activity during May 2024!





If astronauts had been standing next to NASA's Curiosity Mars rover at the time, they would have received a radiation dose of 8,100 micrograys, equivalent to 30 chest X-rays.



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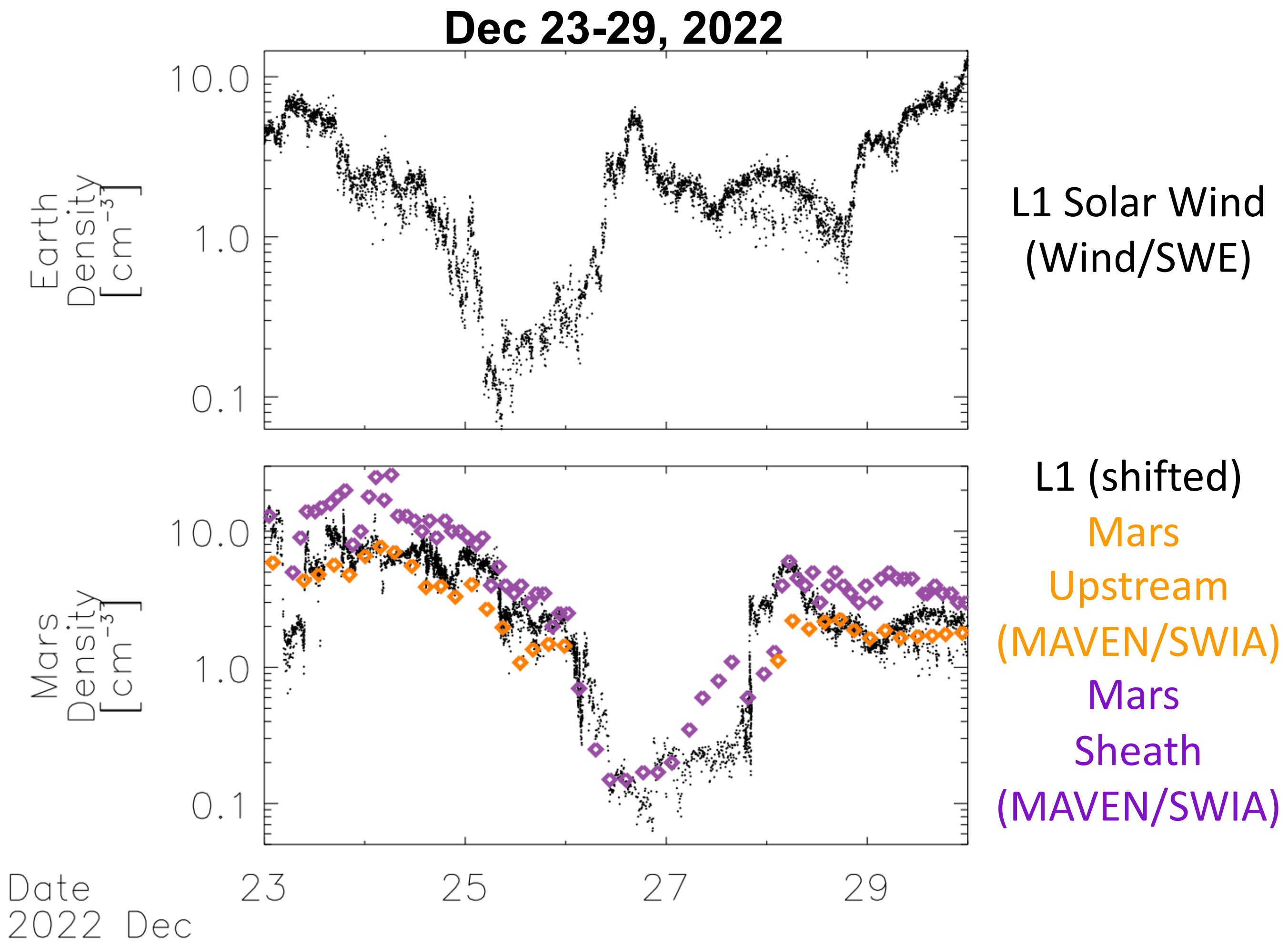
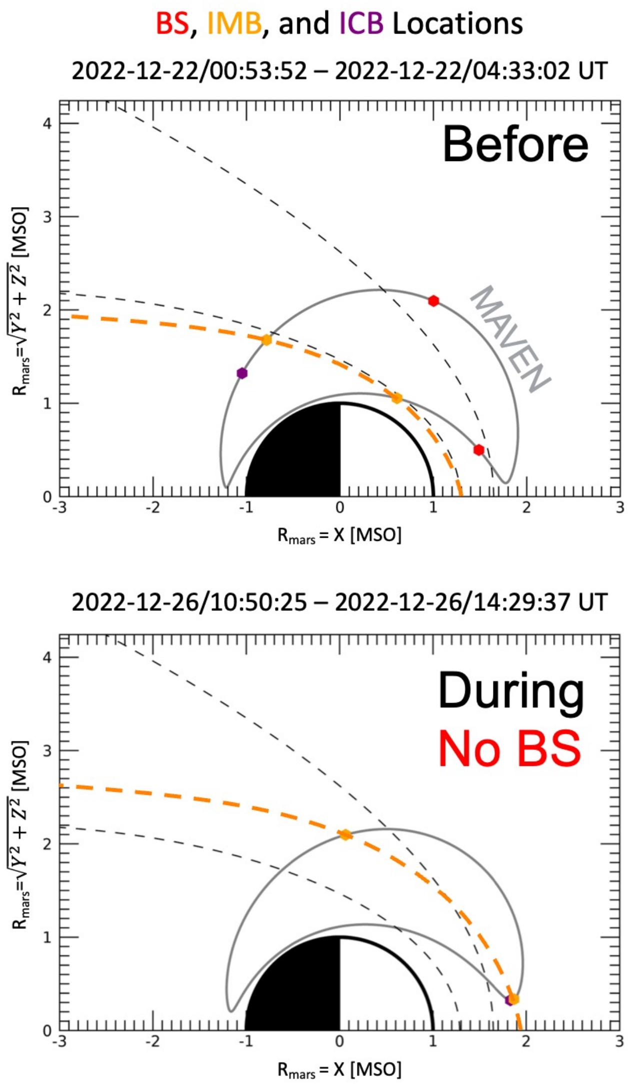
Disappearing Solar Wind Event at Mars

- Solar wind proton densities drop below 0.1 particles/cm^3, lasting ~1 day
- Dayside ionosphere was observed outside the typical bowshock location

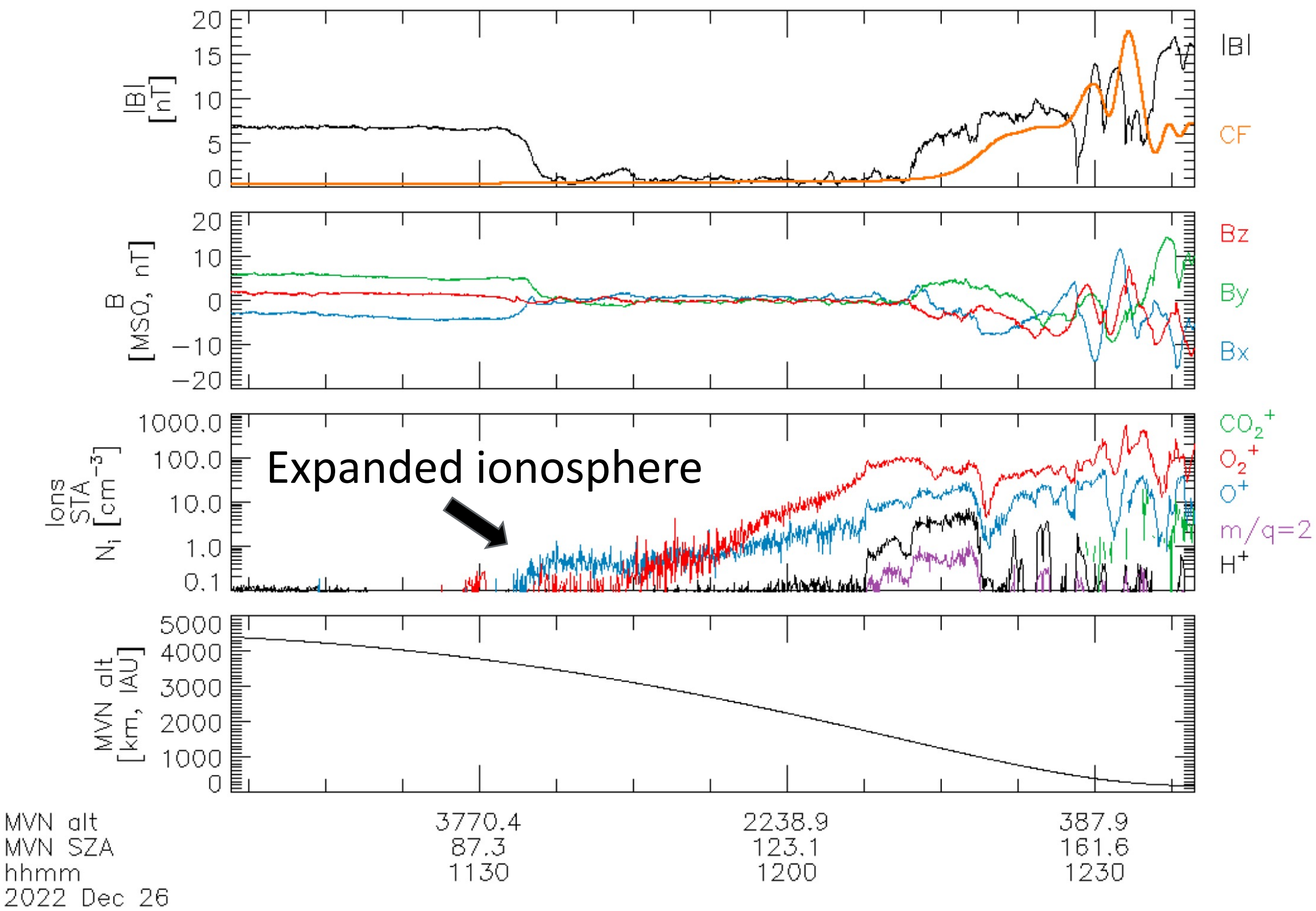
Halekas+ (JGR, 2023)



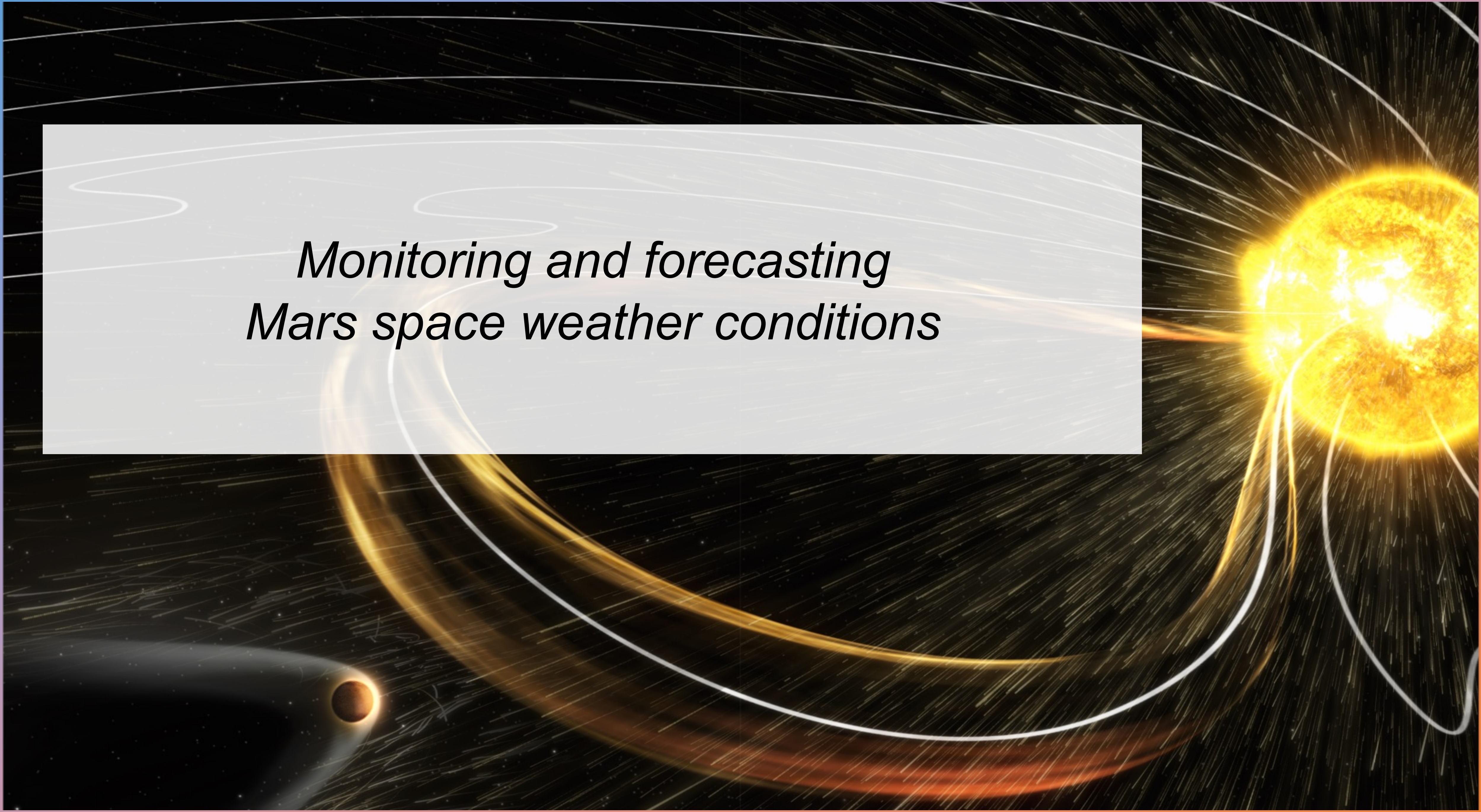


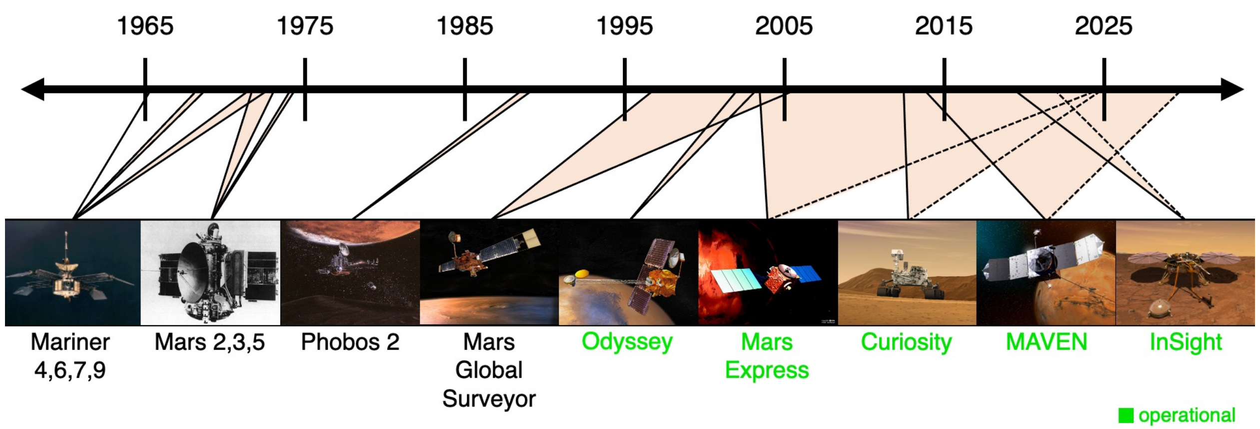
Drastic changes in the upstream solar wind conditions changed the state of the solar wind-Mars interaction on timescales of less than 4.5 hours (one MAVEN orbit) (Fowler+, JGR 2024).

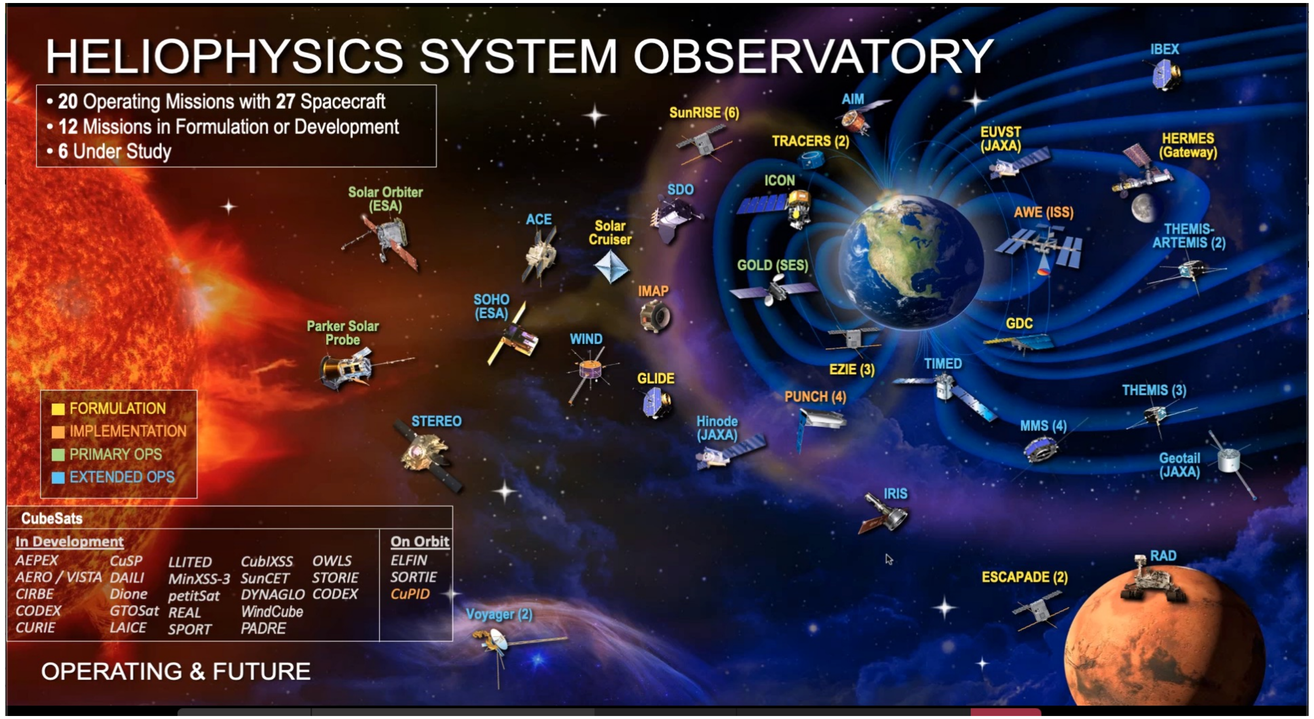
- MAVEN observations showed that the ionosphere "pushed out" against the solar wind, **expanding thousands of kilometers above it's typical extent**.
- The ionospheric thermal pressure was able to drive this expansion because the solar wind density (and associated dynamic pressure) was so low.
- The system returned "to normal" in tandem as the solar wind density recovered.



Monitoring and forecasting Mars space weather conditions







To anticipate/understand potential impacts of solar activity on Mars' environment, we have been utilizing

- upstream observations from Mars missions (not continuous; depends on spacecraft pointing and orbit geometry)
- solar/heliospheric observations from NASA HSO missions (not necessarily located near Mars when an event occurs)
- together with numerical modeling of solar wind conditions (input solar boundary conditions might be out of date)

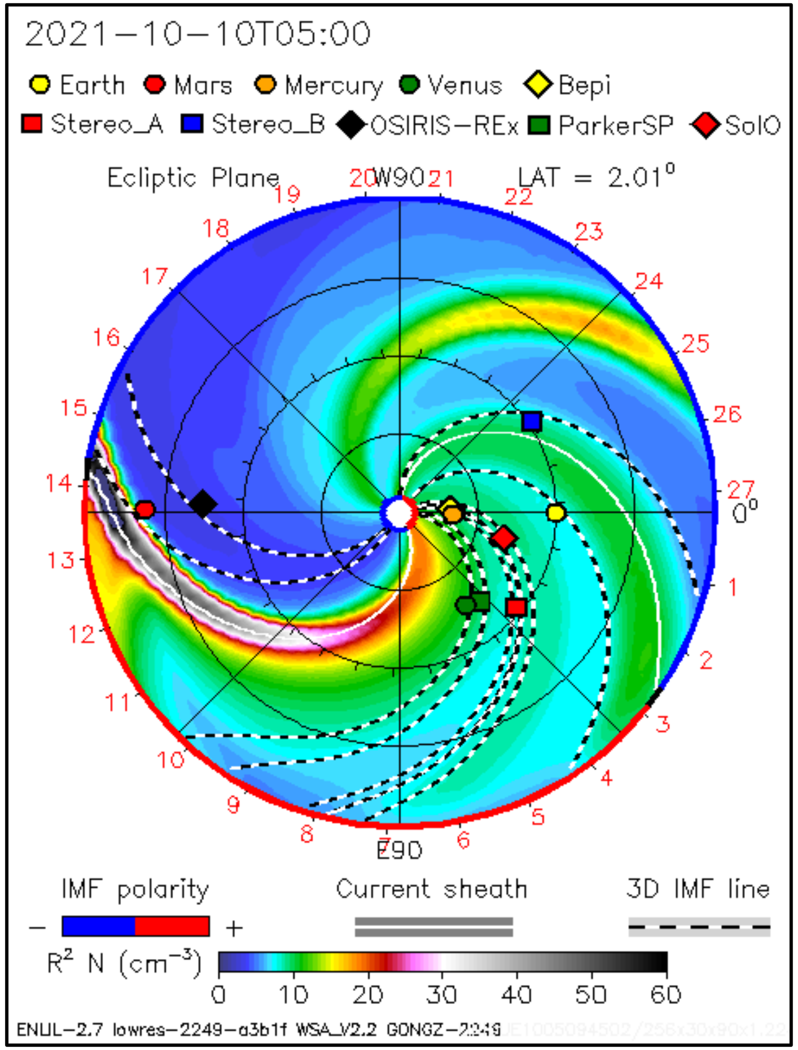
Future operational needs in support of human exploration and infrastructure at Mars

- Current ‘forecasting’* for Mars missions operations relies heavily on real-time/beacon information from Earth (ACE, SDO, SOHO) and STEREO-A

  *Mars SWx Alert Email Notification (MAVEN mission activity)

- <u>Mars in solar conjunction:</u> If a strong Mars-directed space weather event occurs, assets near Earth or at STEREO-A might not observe the activity (in time, or, if at all). Also, direct communication between Earth and Mars is not possible until Mars exits conjunction.

- Setting up a Mars L1 monitor will be an integral part of a space weather hazard forecasting and mitigation system. The monitor can be a relay that serves as the backbone to the Earth communication infrastructure.



(above): WSA-Enlil simulation snapshot from NASA/CCMC/M2M for a recent period when Mars was in solar conjunction, i.e., eclipsed by the Sun from the Earth vantage point.

Mars Space Weather Collaboration

A close partnership to develop near-real time analysis tools for Mars Space Weather (in support of Earth-Independent Operations)

POCs: Phil Chamberlin (and Gina DiBraccio)

Community Coordinated Modeling Center (CCMC)

Models

Space Radiation Analysis Group (SRAG)

Human Spaceflight Operations

Moon to Mars Space Weather Analysis Office (M2M)

Near real-time forecasting

MAVEN, MSL/RAD

In situ data

Establishing the collaboration

Goal: Bring community together to create Mars space weather resources and tools that are crucial for human and robotic exploration

- Created a working group with key personnel from MAVEN/M2M/CCMC in mid-2021
- Currently adding relevant and interested teams as we grow (SRAG, MSL/RAD, etc)

MAVEN observations inform CCMC models and M2M near-real time forecasts

- Confirm whether forecasted events have impacted Mars
- Validate arrival times of observed events (CMEs, SEPs, etc)

M2M & CCMC provide support for understanding Mars-direct events observed by MAVEN

- Simulations and forecasts help to understand timeline of events and provide global context
- M2M notifications provide alerts to Mars missions for potentially-impacting events

Creating valuable resources for the Mars space weather community

- Mars Space Weather Dashboard has been established on CCMC's iSWA
- CCMC is directly pulling relevant MAVEN data products
  - This is a test case for other potential users (e.g., SRAG , SWPC)

Mars Space Weather Dashboard

MAVEN data are available on CCMC's integrated Space Weather Analysis System (iSWA)

Mars tab now available