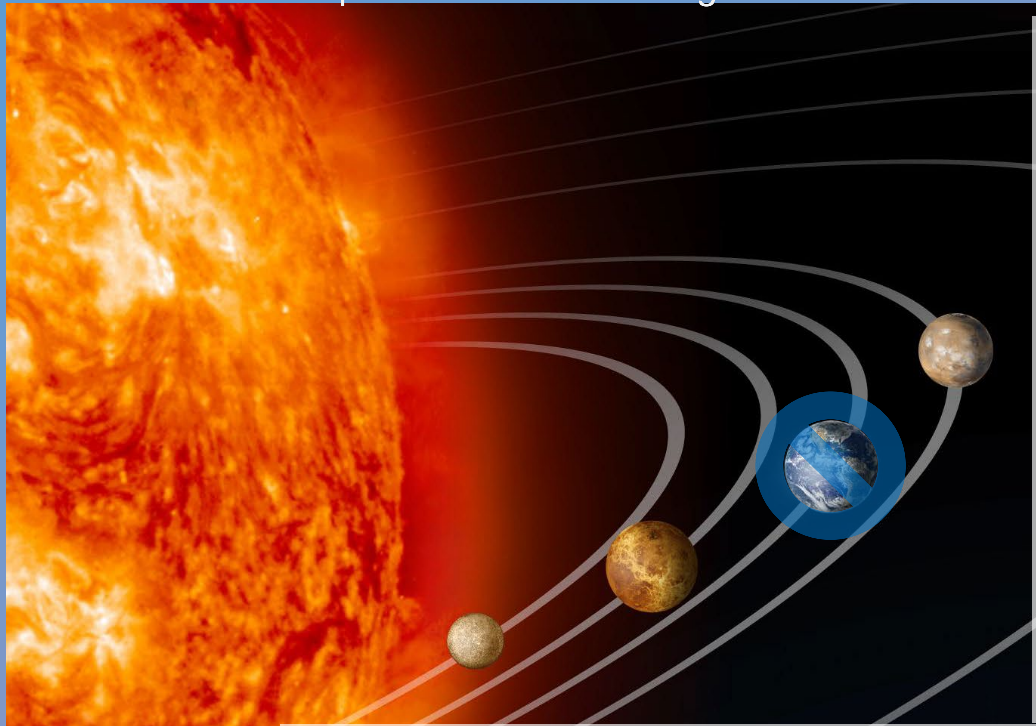
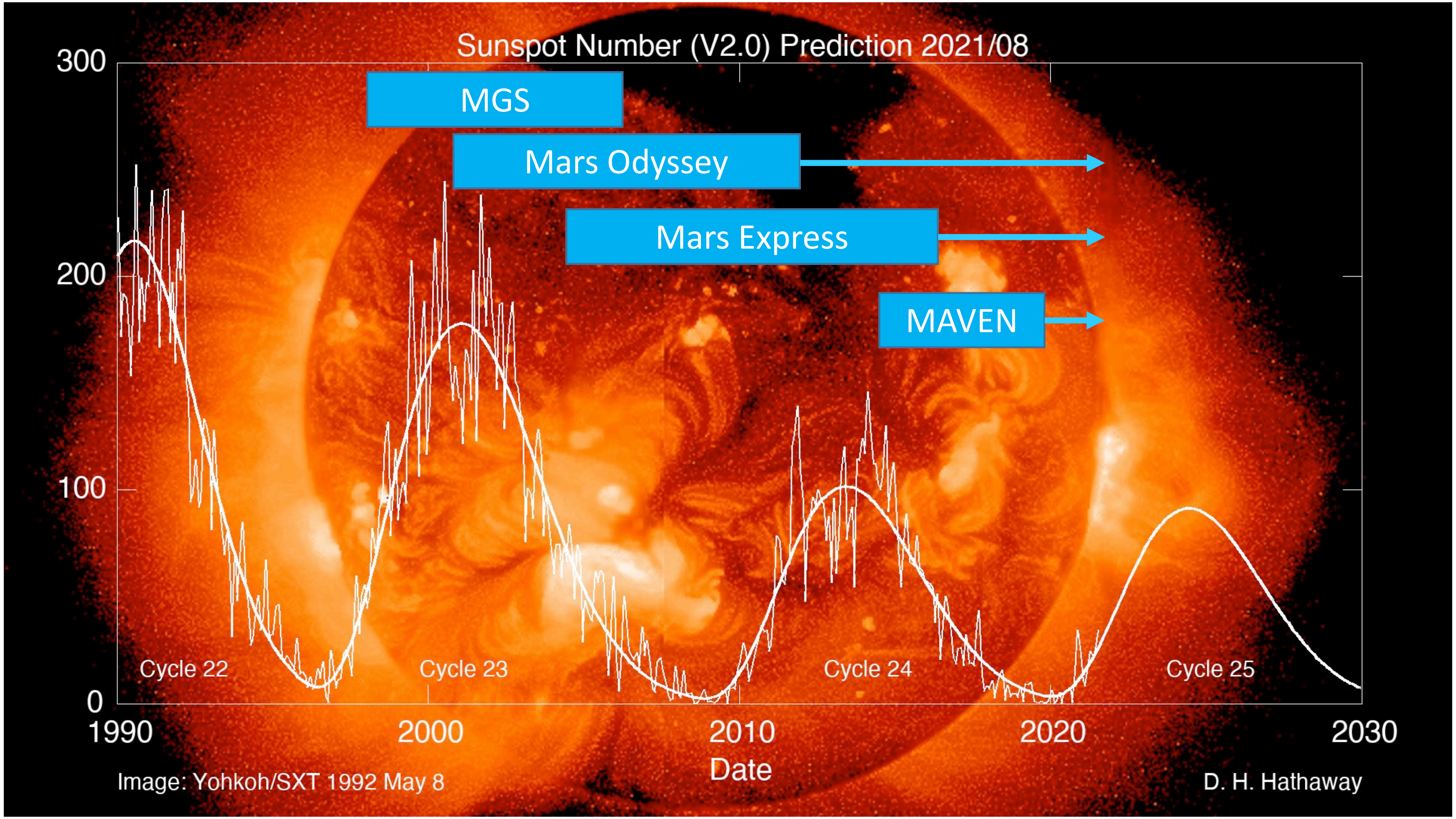


The ***PI*** part in ***WHPI***: Impacts and Effects of Solar Eruptive Events and Quiescent Solar Periods on Planets in the Inner Heliosphere: A *Very Quick* Overview

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

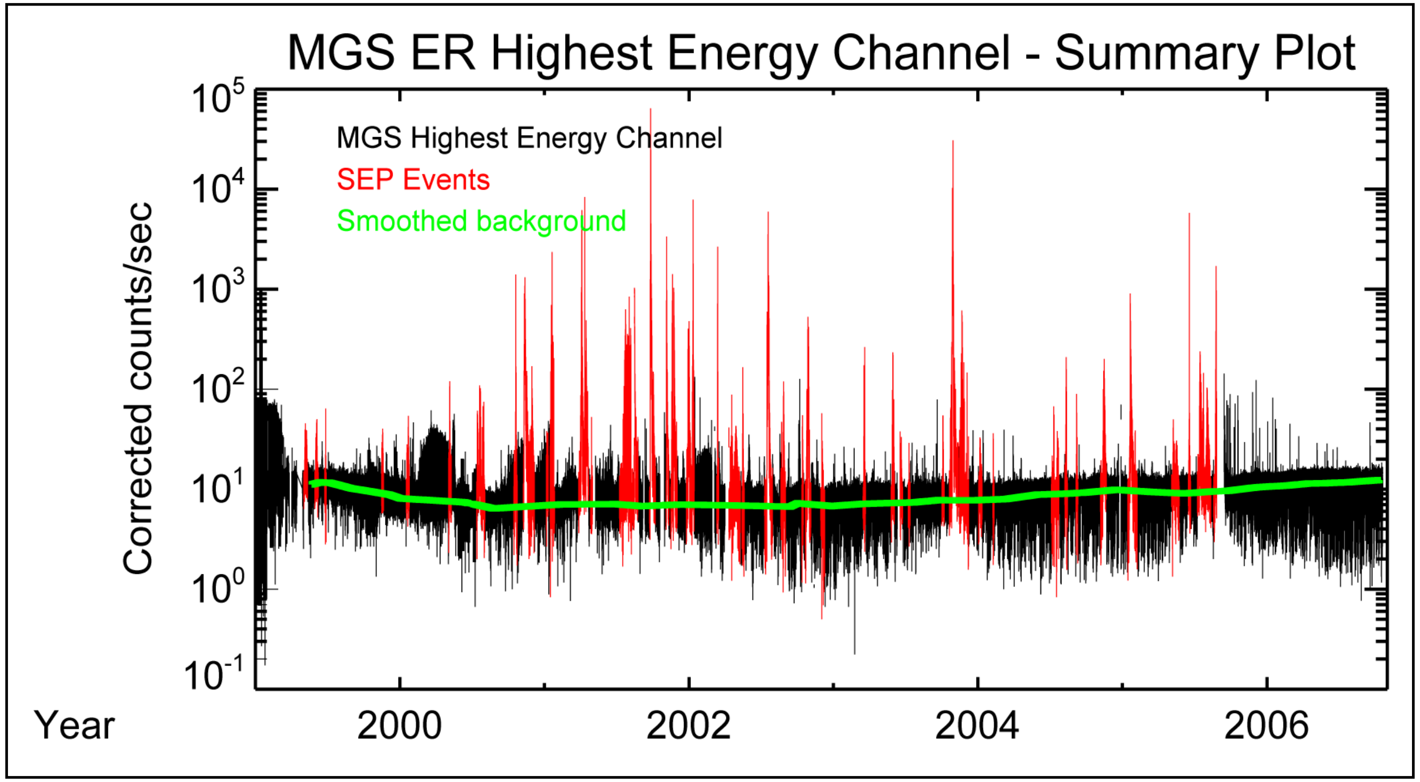
Gina DiBraccio, Réka Winslow, Janet Luhmann, Sarah Kovac, Dave Brain, Ed Thiemann, Phil Chamberlin, Frank Eparvier, Jasper Halekas, Jared Espley, Jacob Gruesbeck, Shaosui Xu, Shannon Curry, and Yingjuan Ma

Continuous observations of space weather conditions at Mars spans nearly two solar cycles.



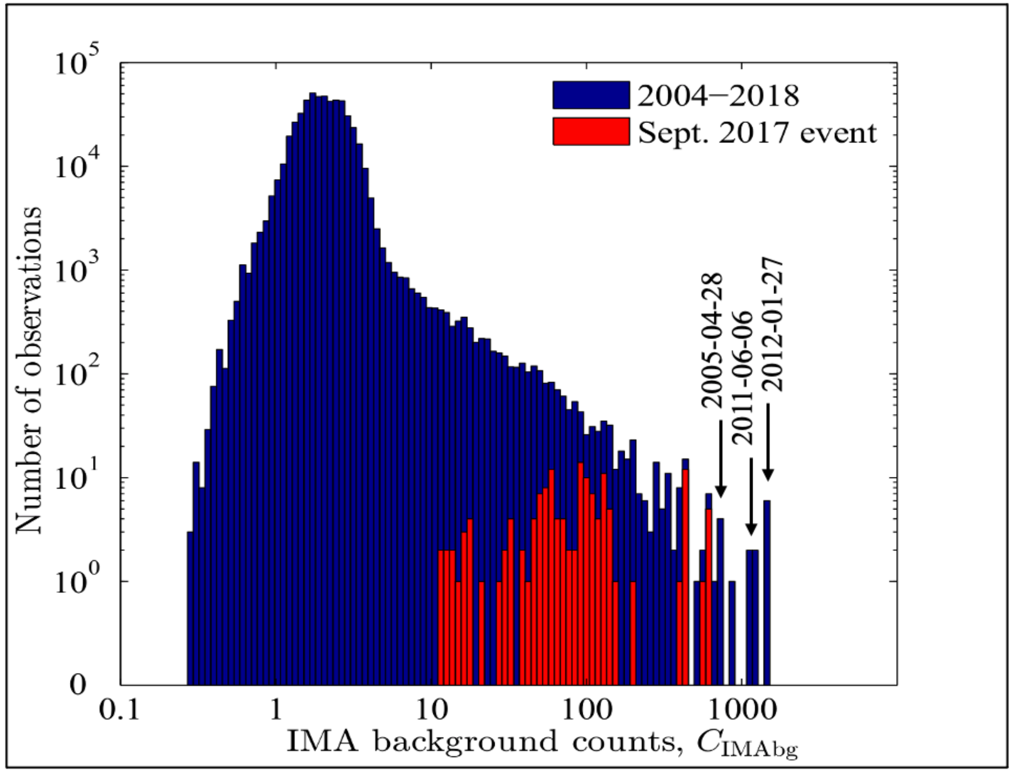
Solar Energetic Particles have been measured continuously at Mars since 1997.

Mars Global Surveyor



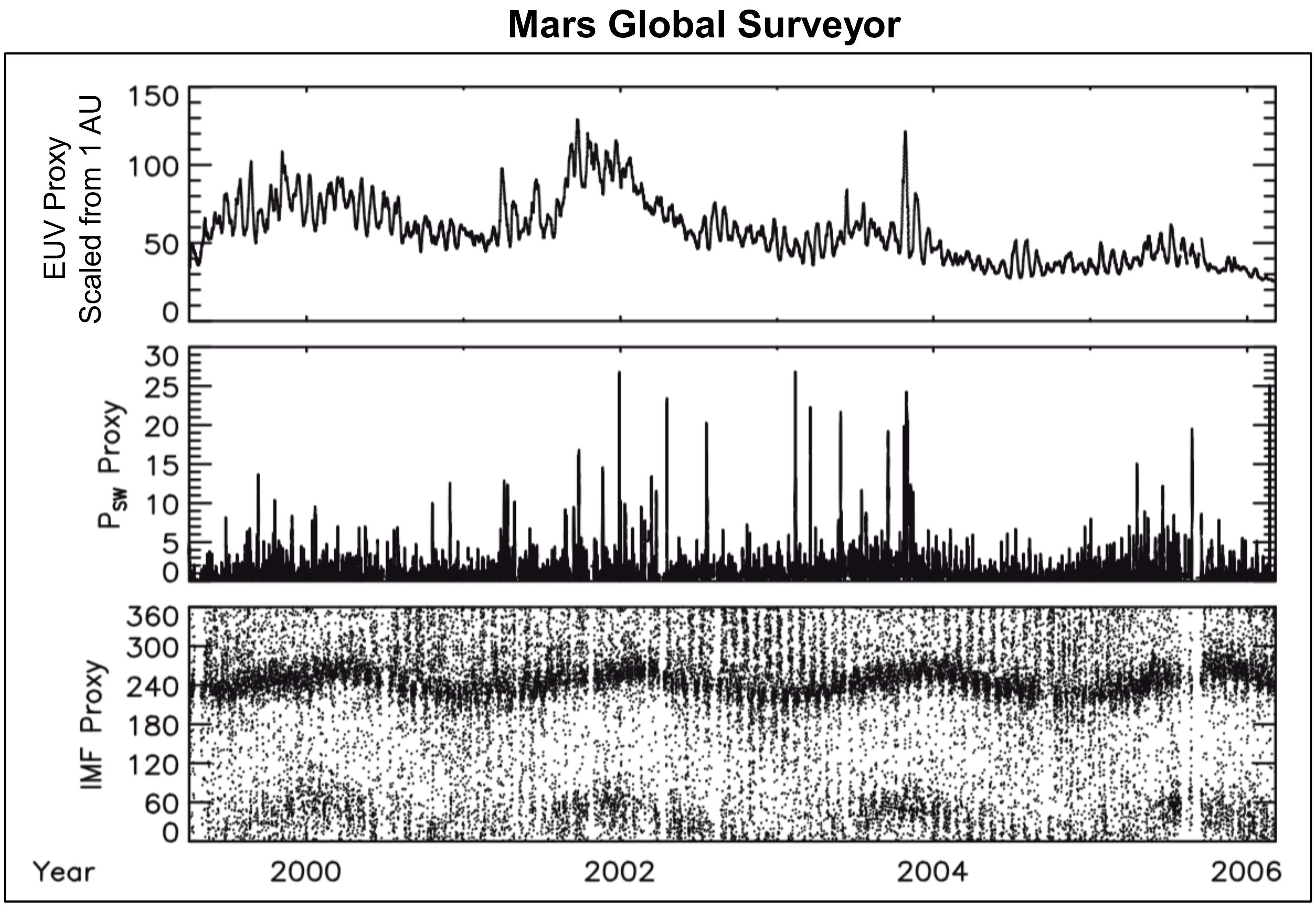
Brain et al. (2011)

Mars Express



Ramstad et al. (2018)

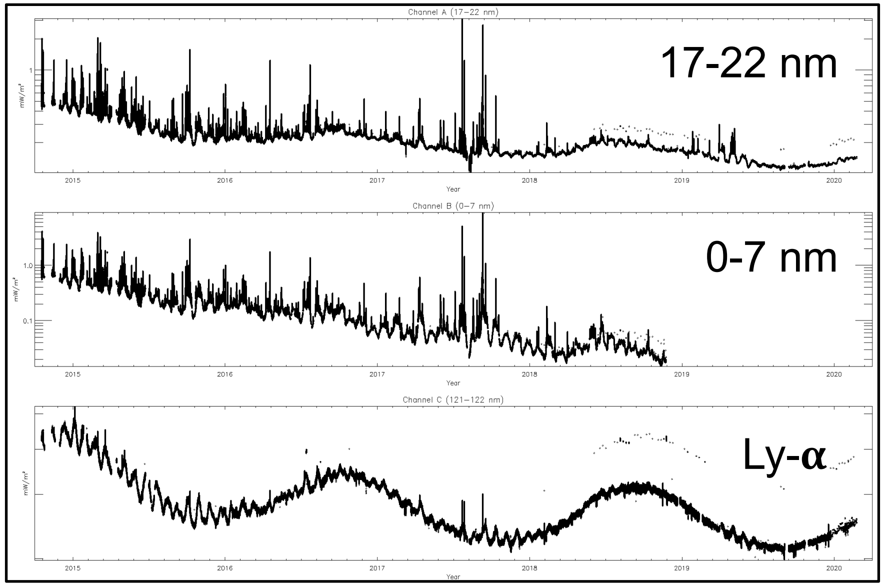
MGS "measured" solar wind pressure and IMF direction upstream from the bowshock, even though its orbit didn't go outside of the bowshock and it wasn't instrumented to measure ions.



From
D. Brain
(CU/LASP)

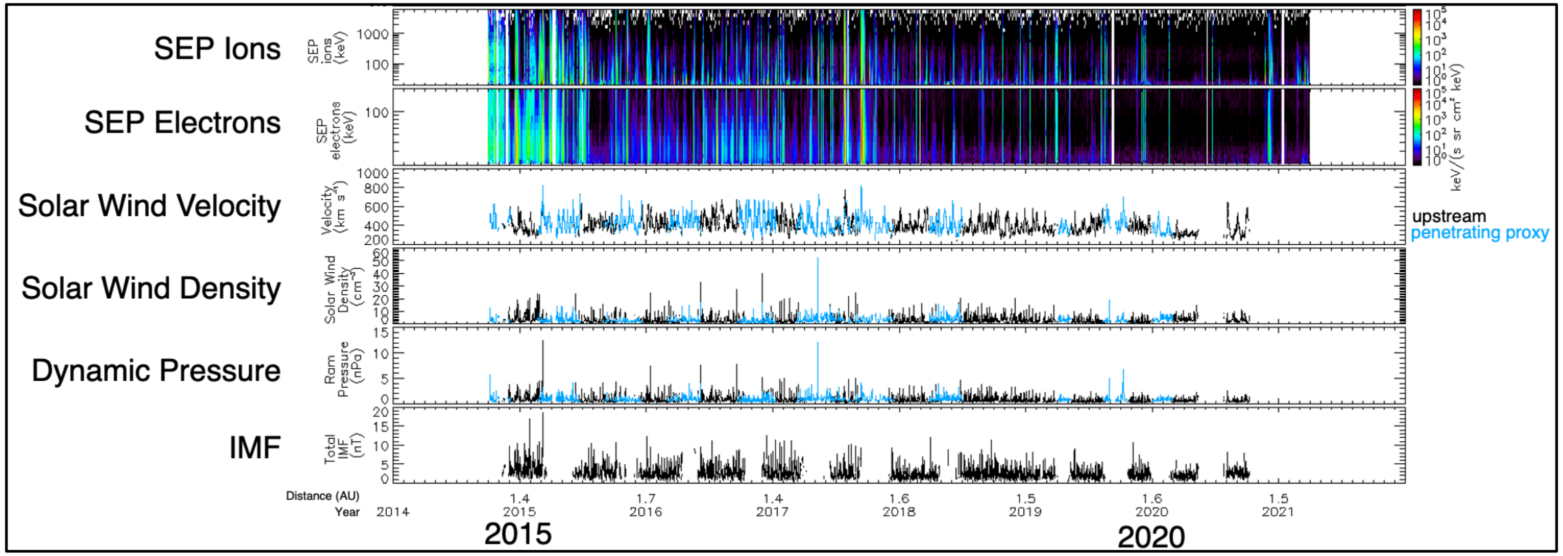
MAVEN have been making a full complement of space weather observations since the end of the maximum phase of Solar Cycle 24.

Solar EUV

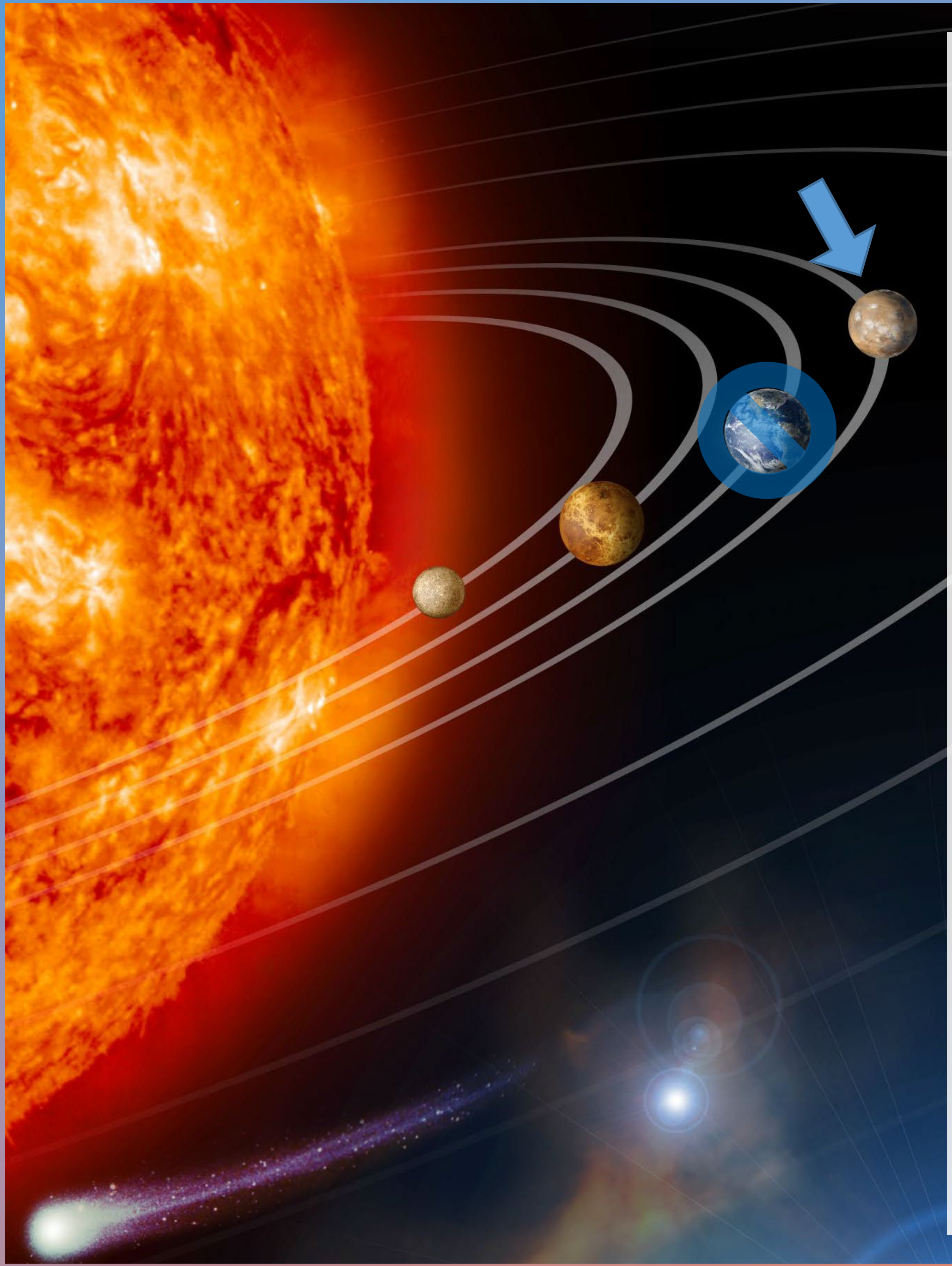


From F. Eparvier, P. Chamberlin, and E. Thiemann (LASP/CU)

Upstream solar wind, IMF, and SEPs

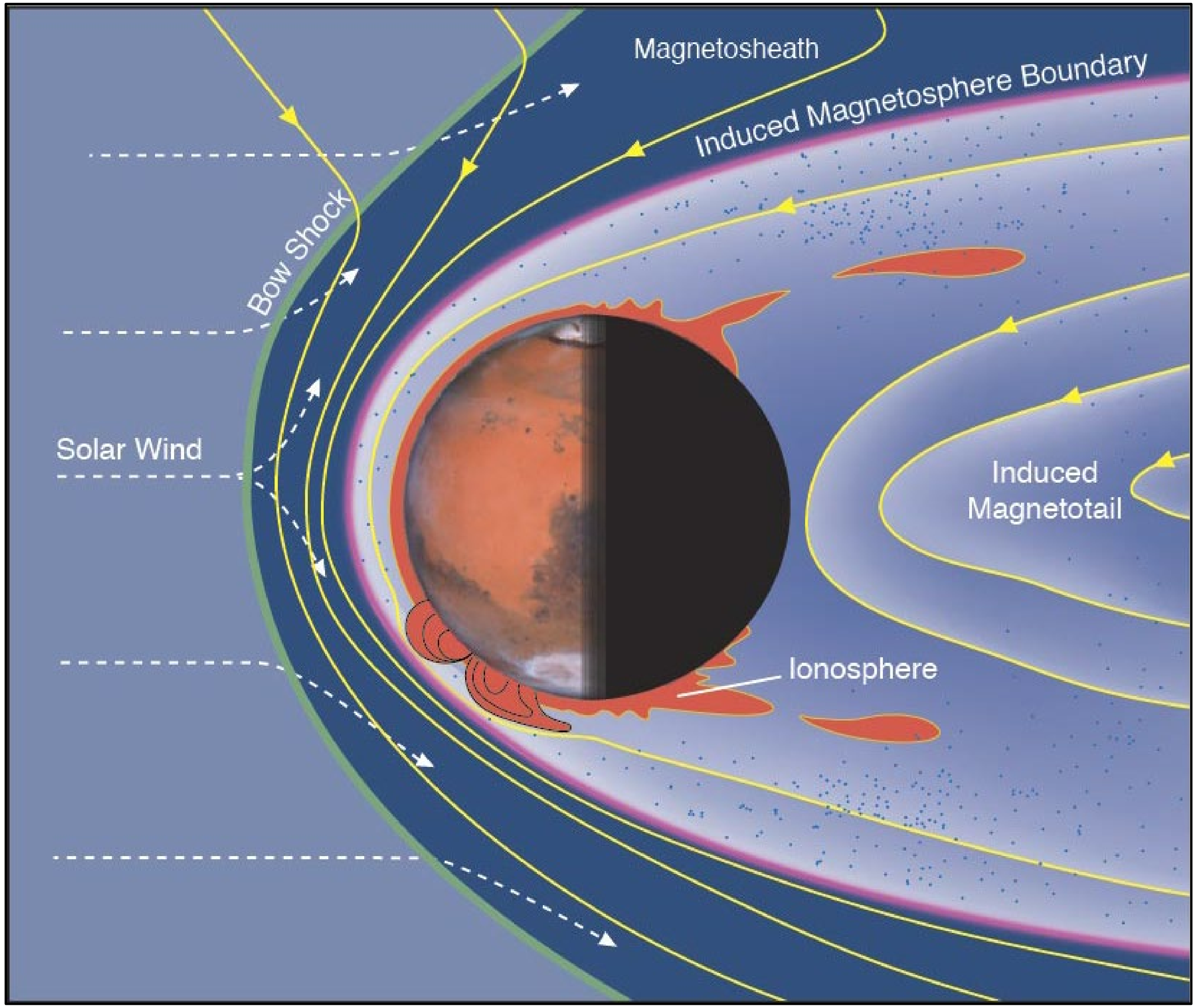


update to *Lee et al.* (2017)



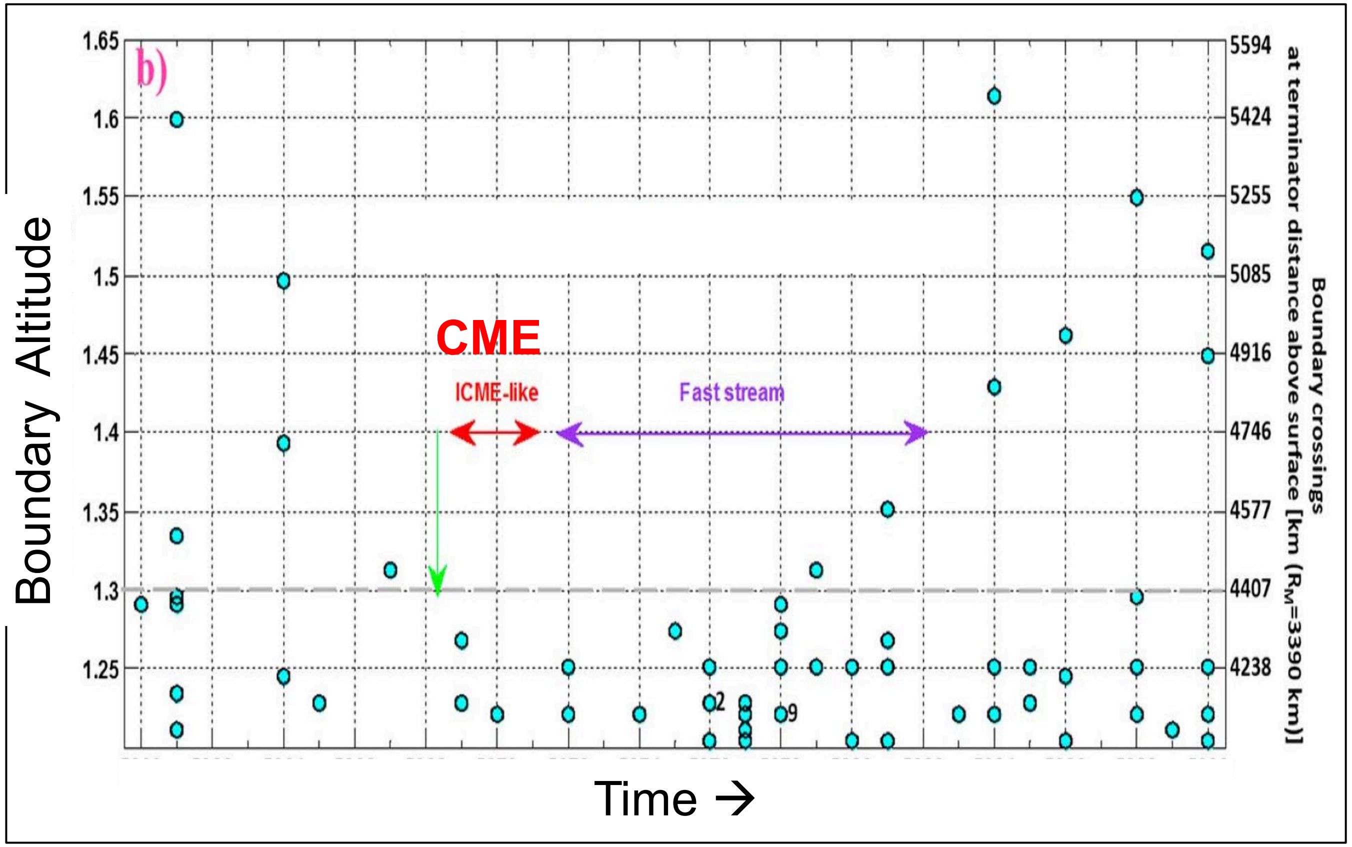
Impacts and Effects of the Space Environment at Mars

Mars has an induced magnetosphere perturbed by strong crustal magnetic fields and an ionospheric reservoir. The planet is only weakly shielded from impacts by solar and interplanetary disturbances.



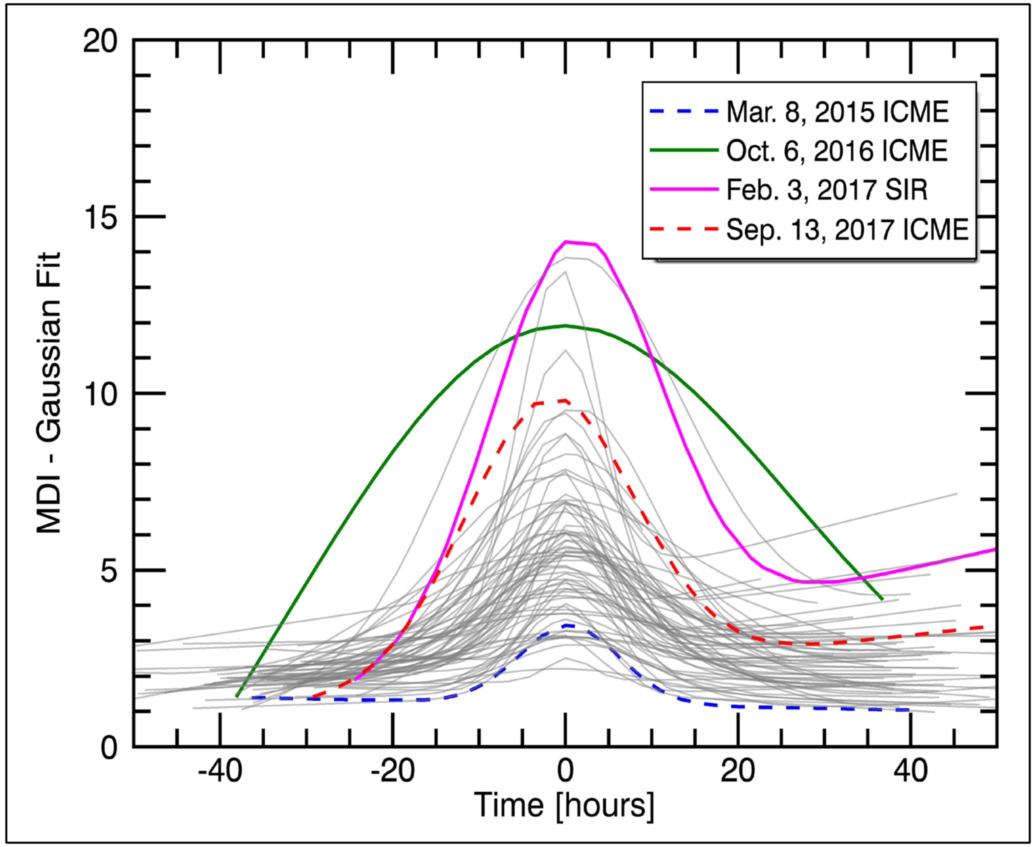
During CME and SIR/CIR events, the induced magnetosphere is compressed.

Mars Express



Sanchez-Cano et al. (2017)

MAVEN

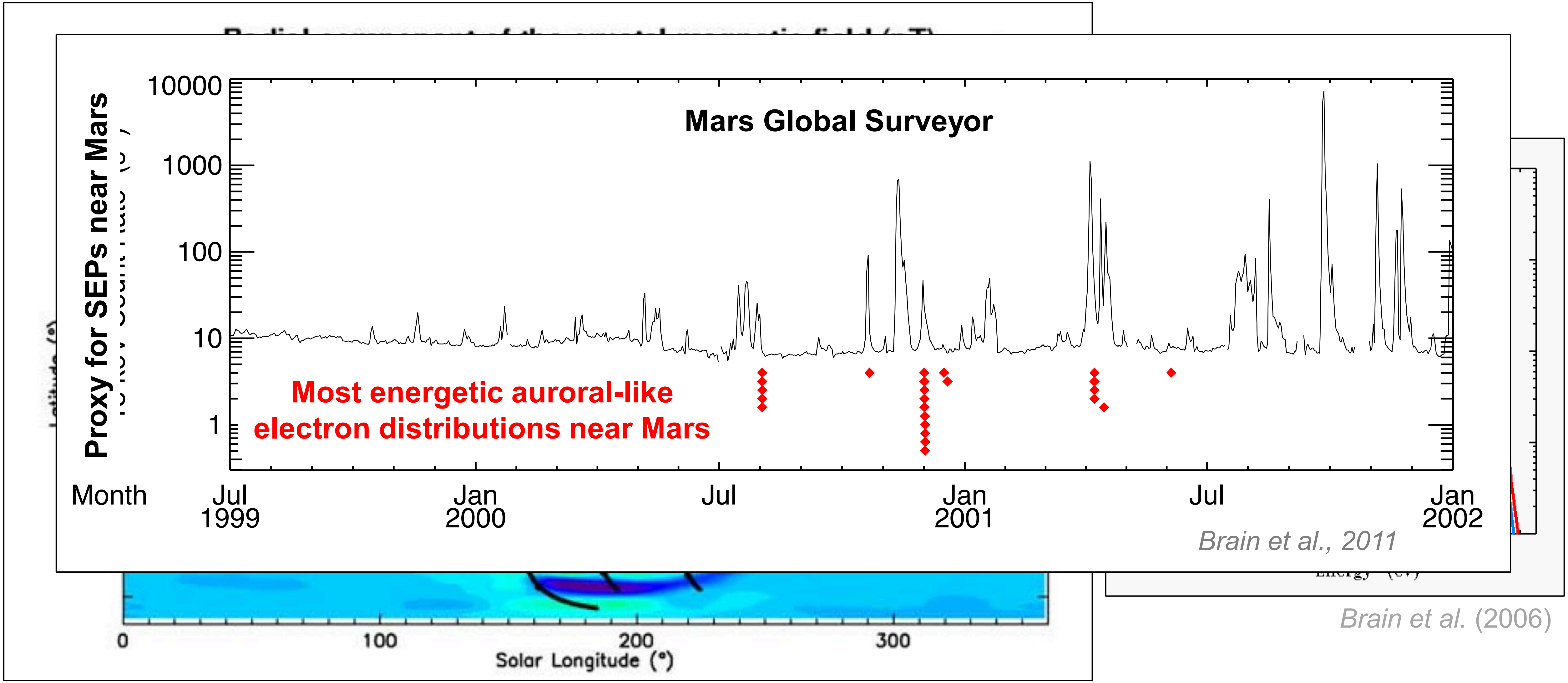


Gruesbeck et al. (2021, under review)

From D. Brain (CU/LASP)

Discrete aurora in Martian crustal magnetic fields appear to be more intense and more likely during SEP events.

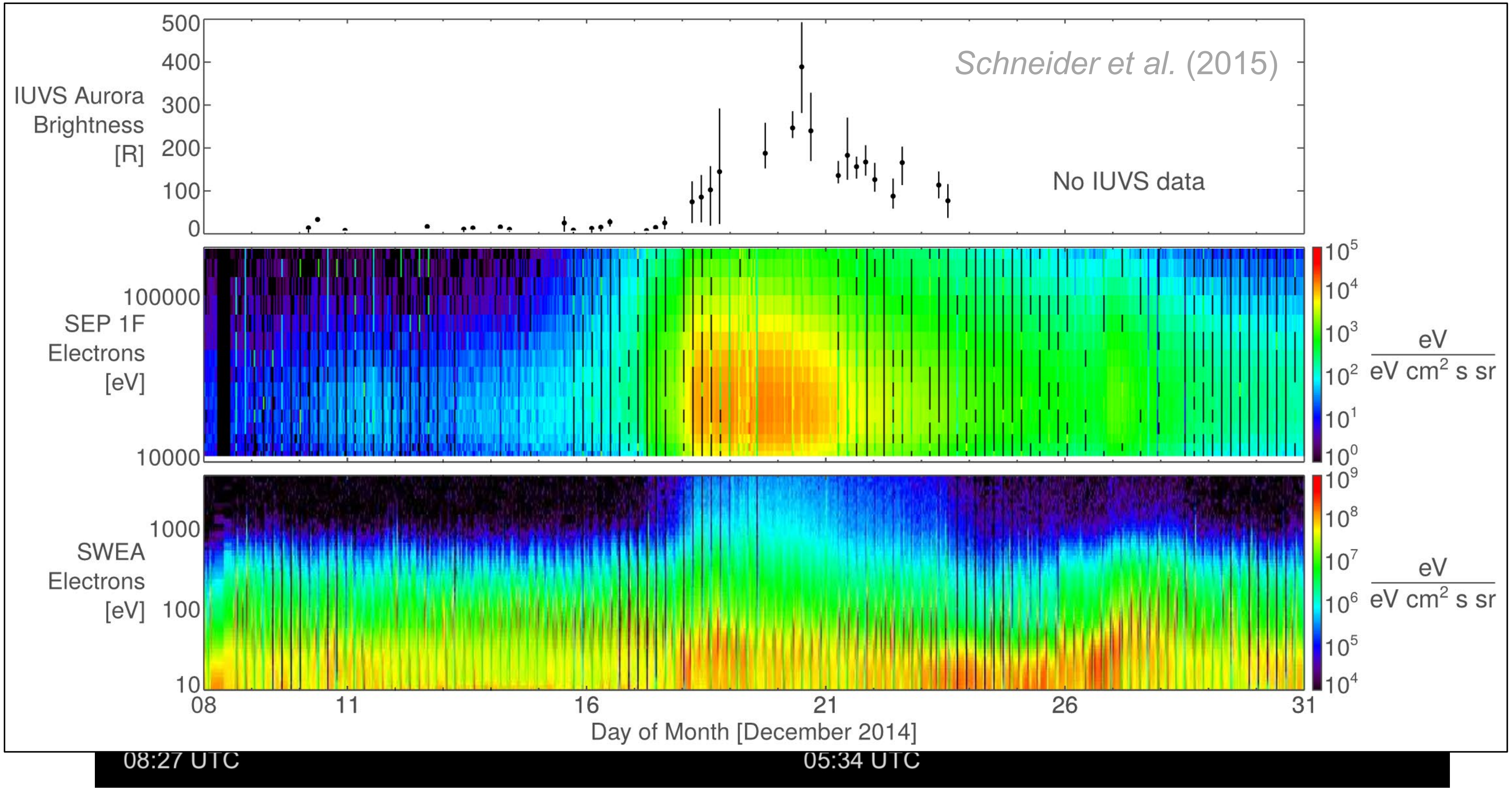
Mars Express



Brain et al. (2006)

Energetic electrons triggered global “diffuse aurora” around Mars during high-flux SEP event periods.

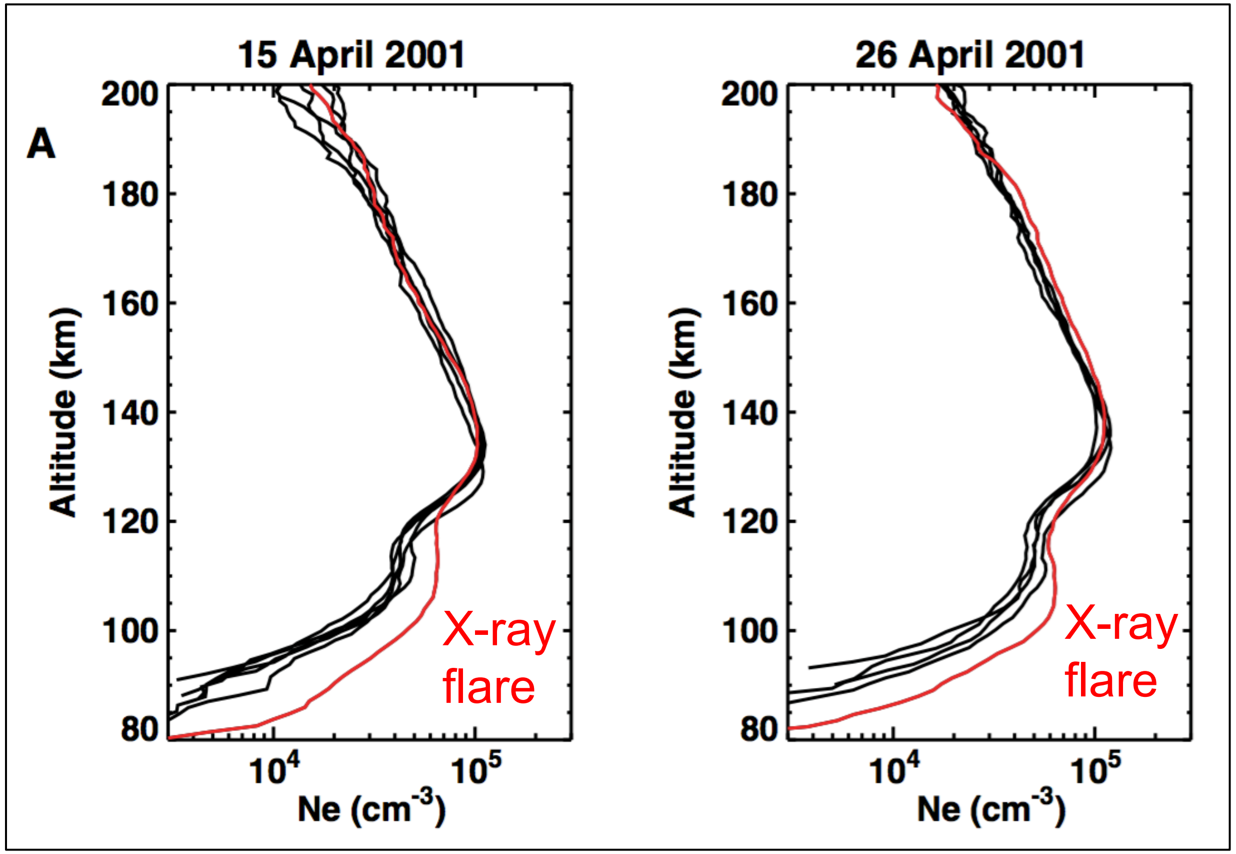
MAVEN



Schneider et al. (2018)

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

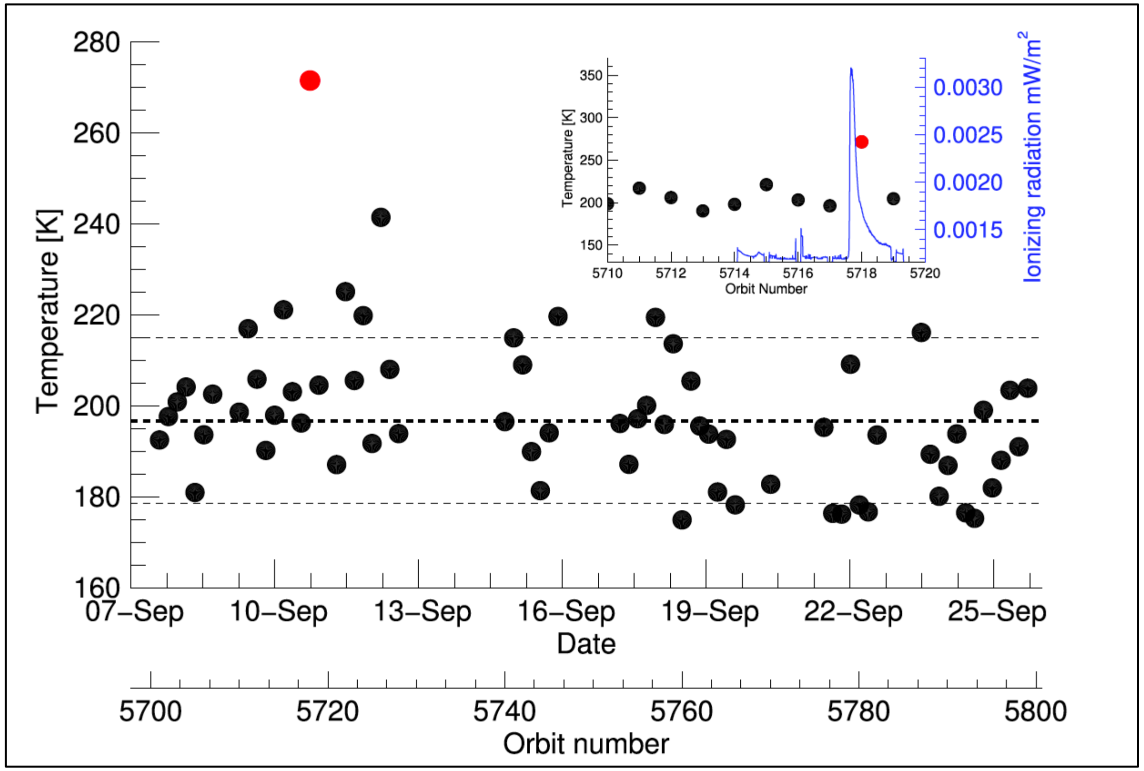
Ionosphere



Mars Global Surveyor

Mendillo et al. (2006)

Thermosphere



MAVEN

Jain et al. (2018)

From D. Brain (CU/LASP)

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

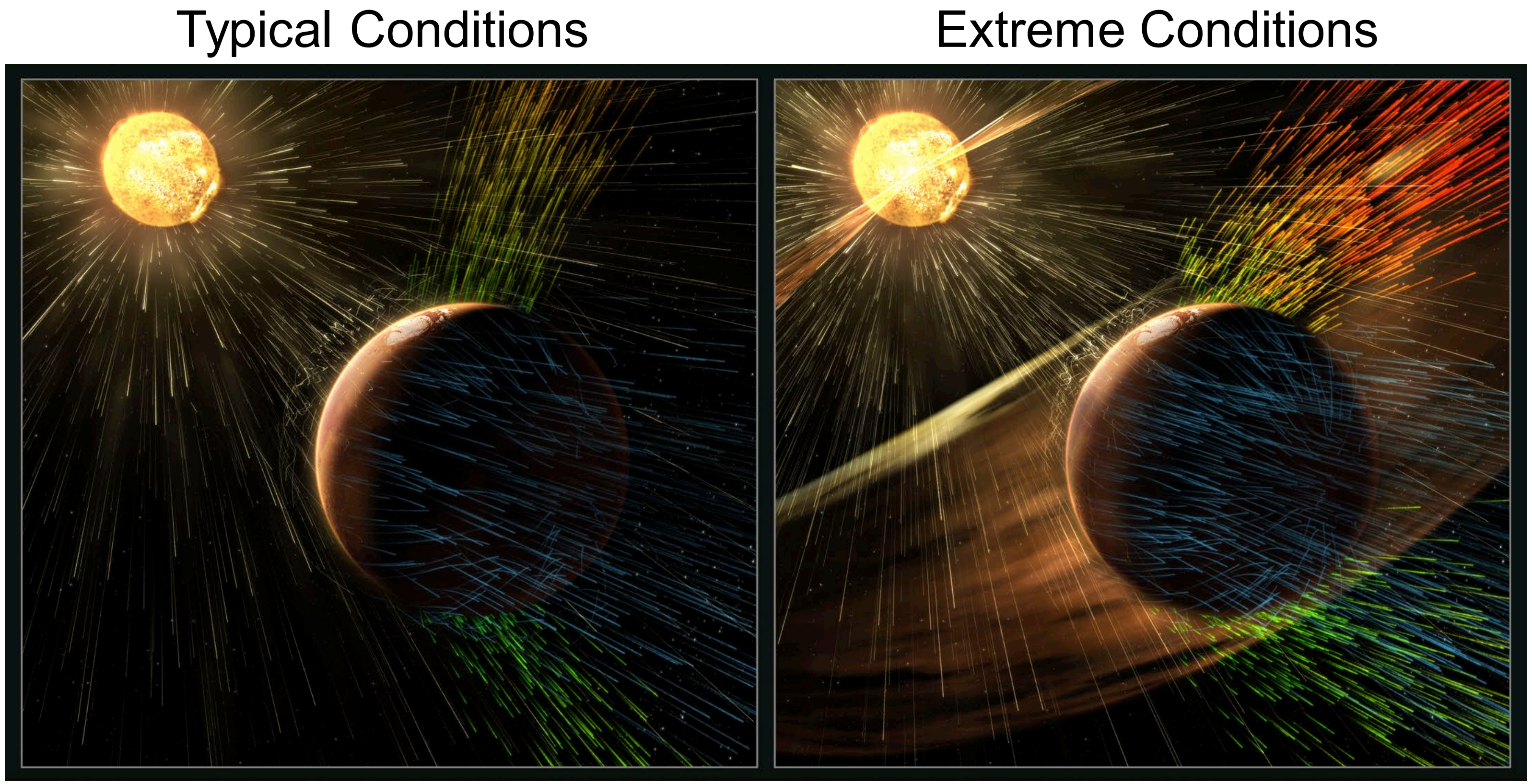
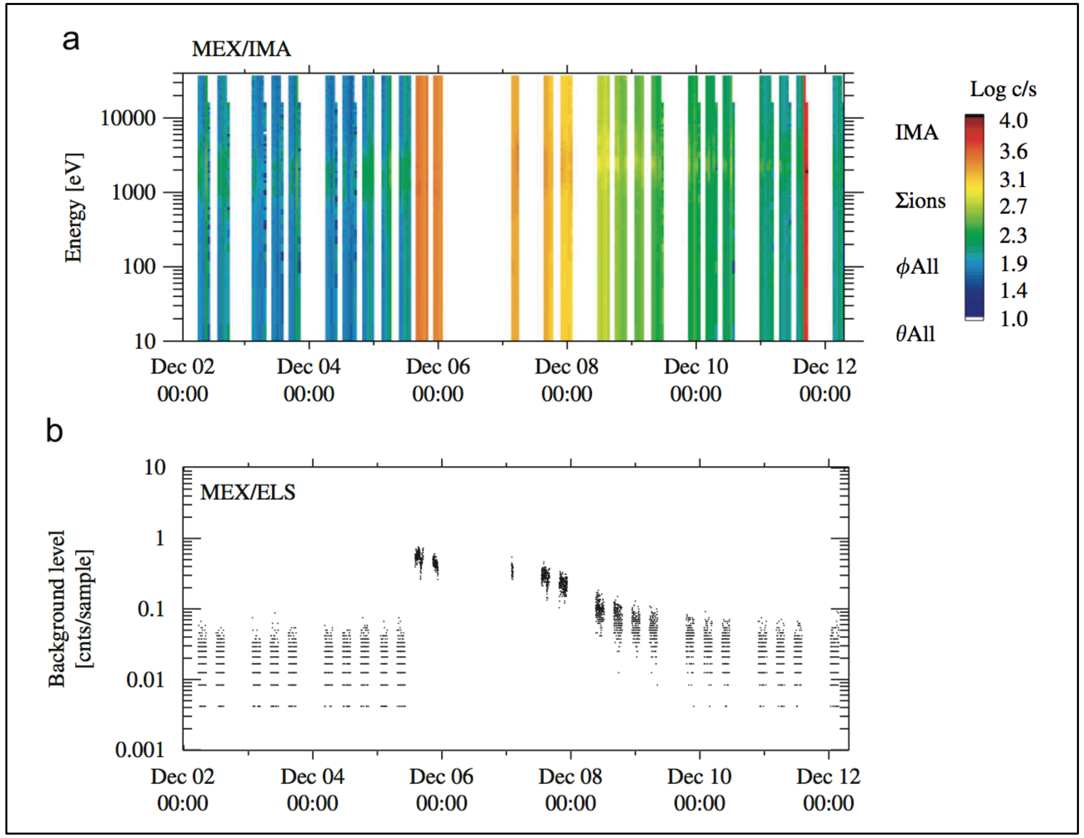


Image credit: (left) NASA and (right) *Jakosky et al.* (2015)

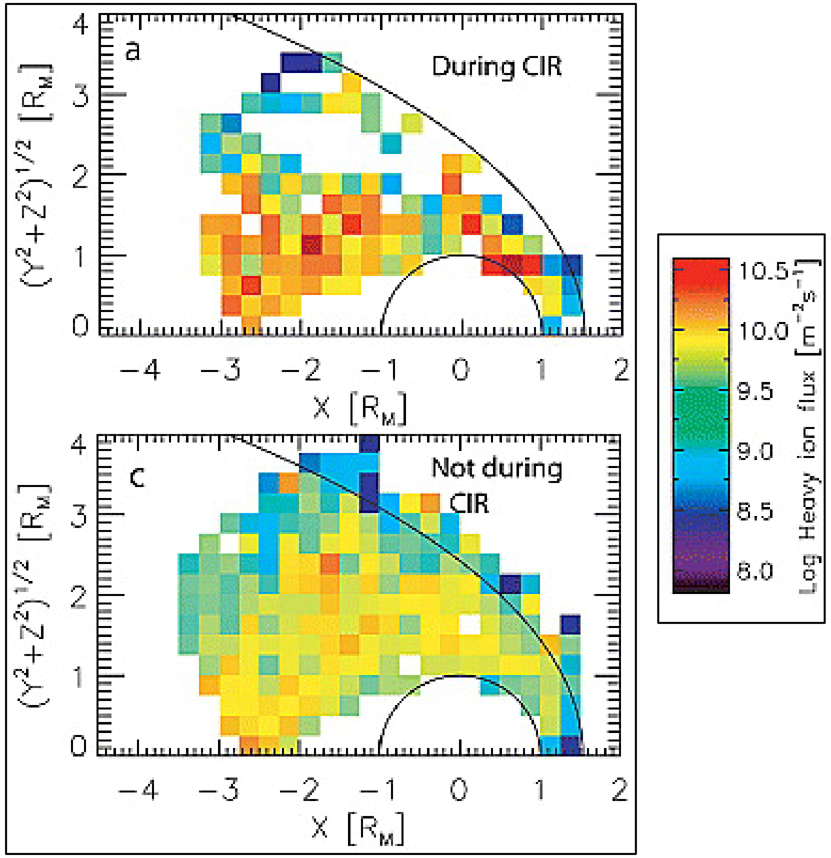
Mars Express observed increases in ion escape during CME and CIR/SIRs events.

CME event



Futaana et al. (2008)

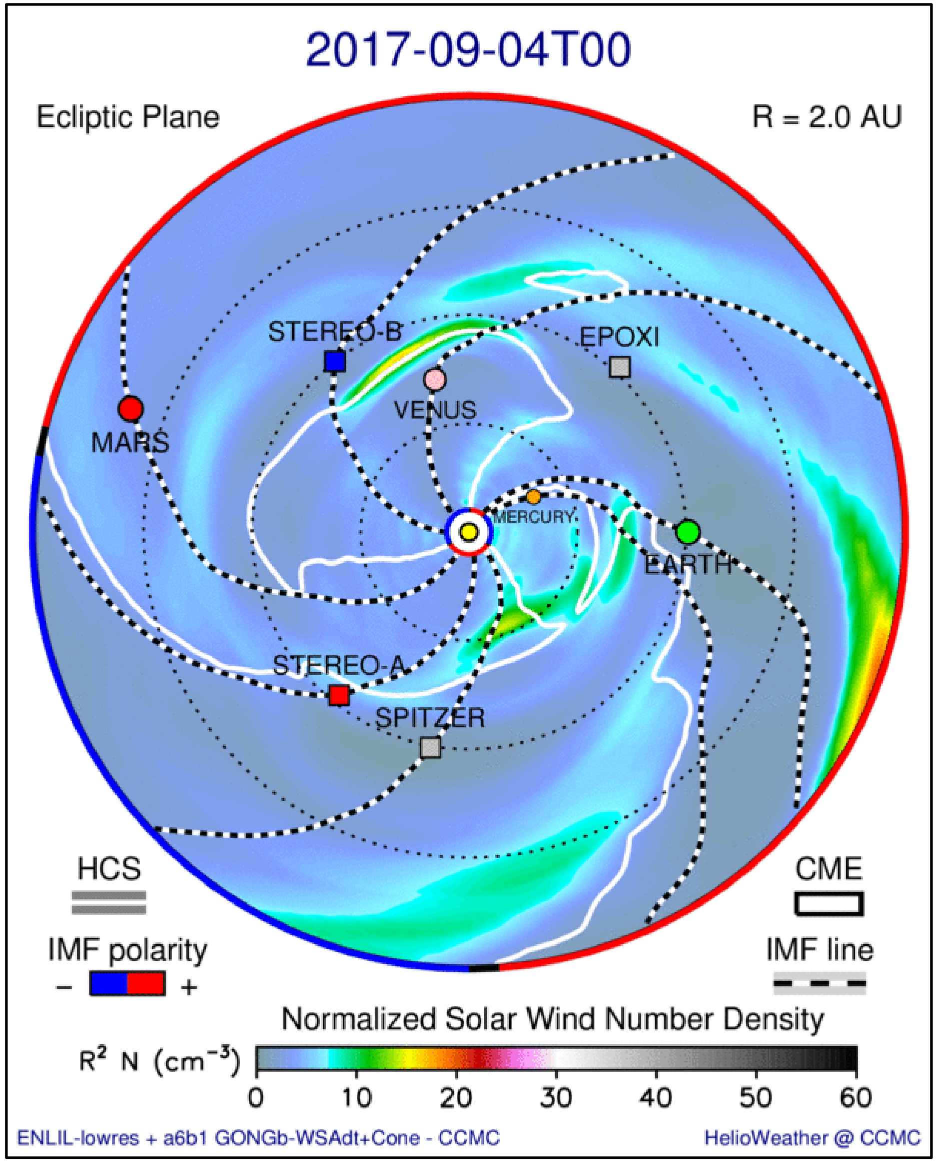
CIR/SIR event



Edberg et al. (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

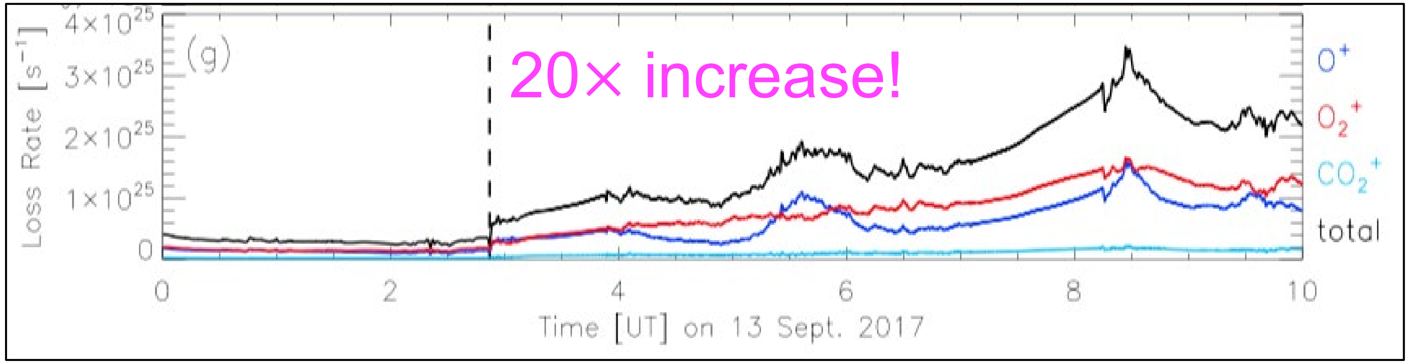
Table 2. Variability of dayside H escape flux during the September 2017 solar storm.

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	$0.9 \pm 0.2 \times 10^5$	$20 \pm 0.4 \times 10^7$

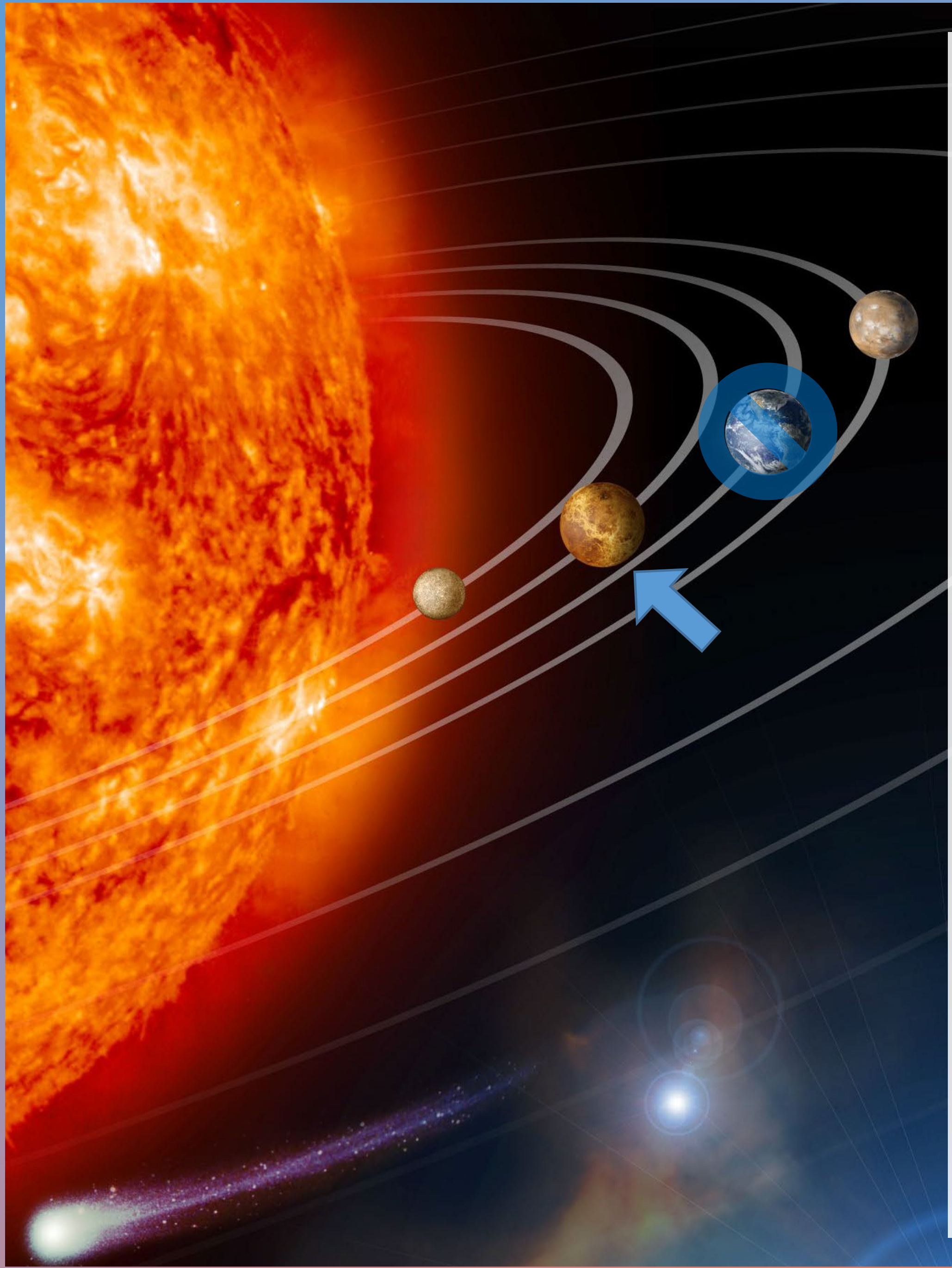
Mayassi et al. (2018)

5× increase!

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

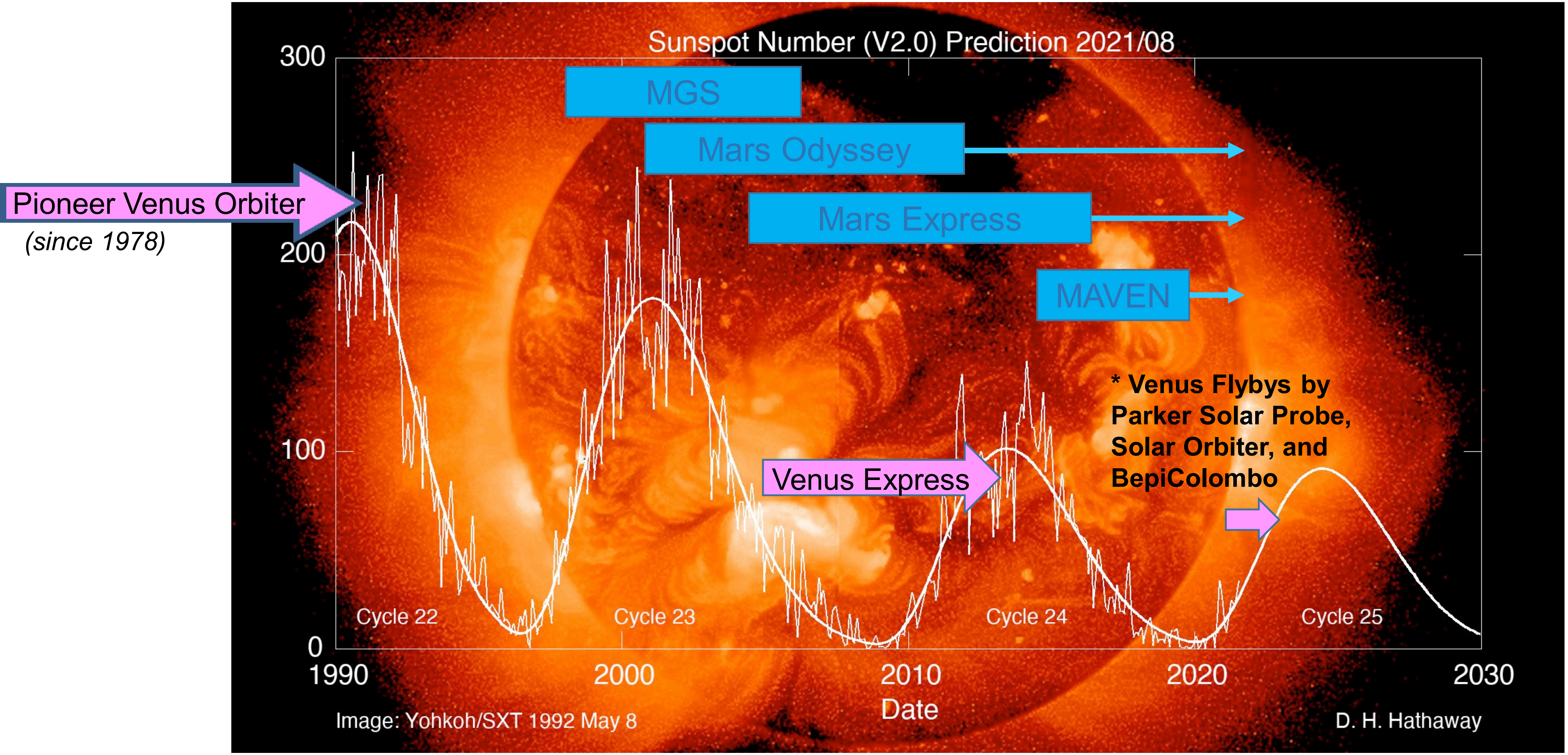


Ma et al. (2018)



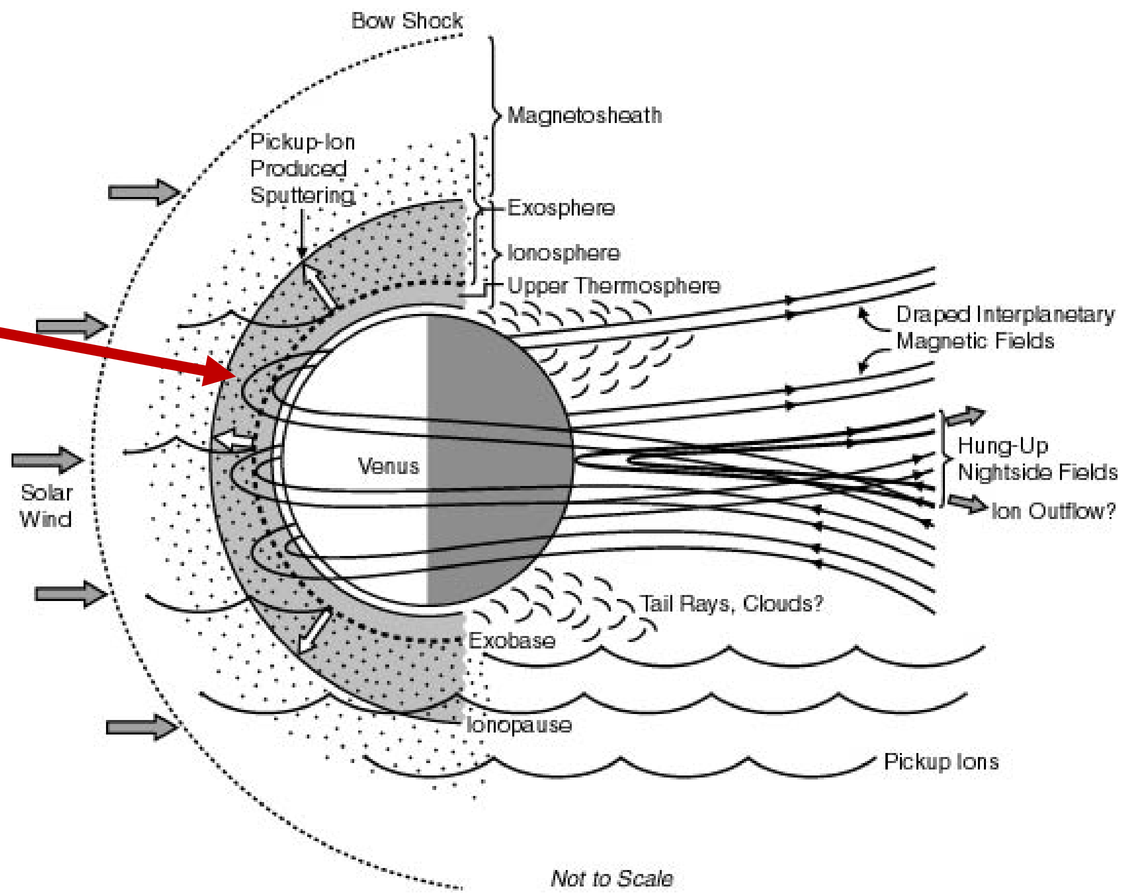
Impacts and Effects of the Space Environment at Venus

There have been fewer observations of the space environment around Venus, but recent mission flybys* are providing opportunities to update and expand our knowledge on this topic.



Pioneer Venus Orbiter and Venus Express succeeded in measuring many basic properties of an induced magnetosphere, and the effects of the interplanetary conditions on Venus' ionosphere and atmosphere escape.

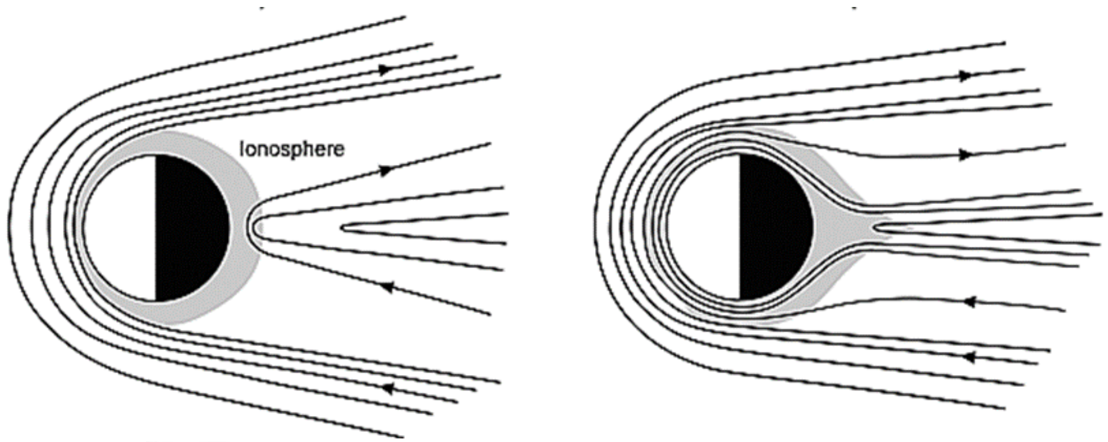
Pressure balance between incident solar wind and ionosphere.



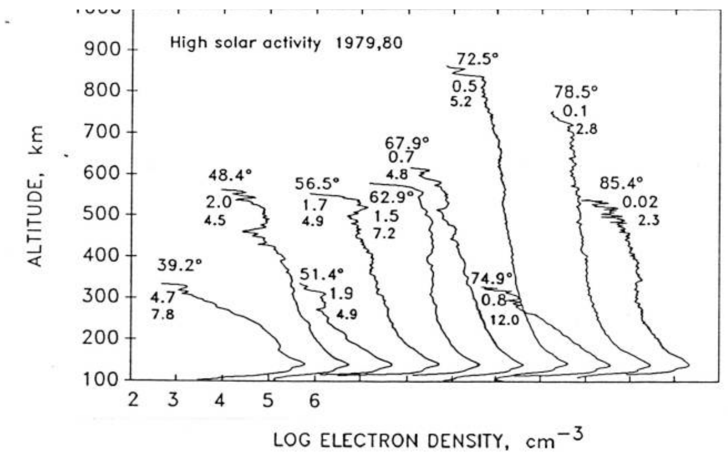
Ion mass loading by passing solar wind, and atmospheric escape by ion outflows, pickup processes, and possibly 'bulk' removal.

From J. Luhmann (SSL/UCB)

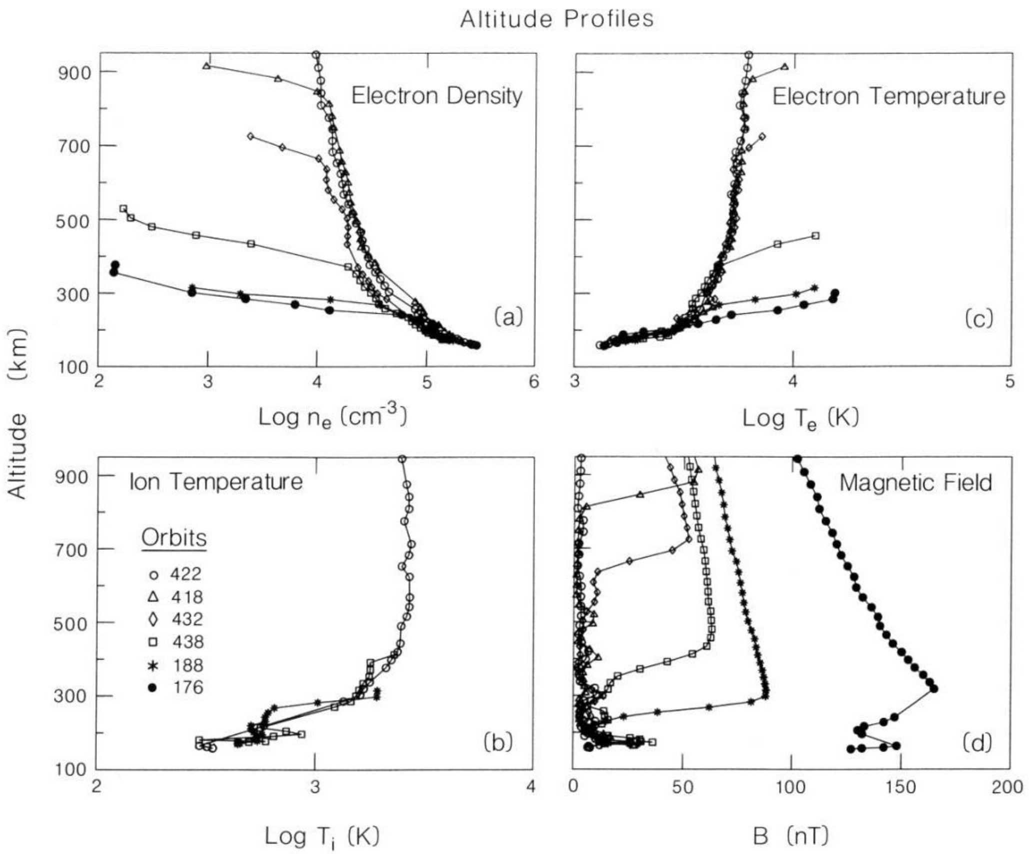
Pioneer Venus Orbiter radio occultation and in-situ measurements showed the ionosphere's response to increasing solar wind pressure – the lowering of the ionopause and ionosphere magnetization. Venus Express ionospheric measurements also exhibited these responses.



Pioneer Venus Orbiter



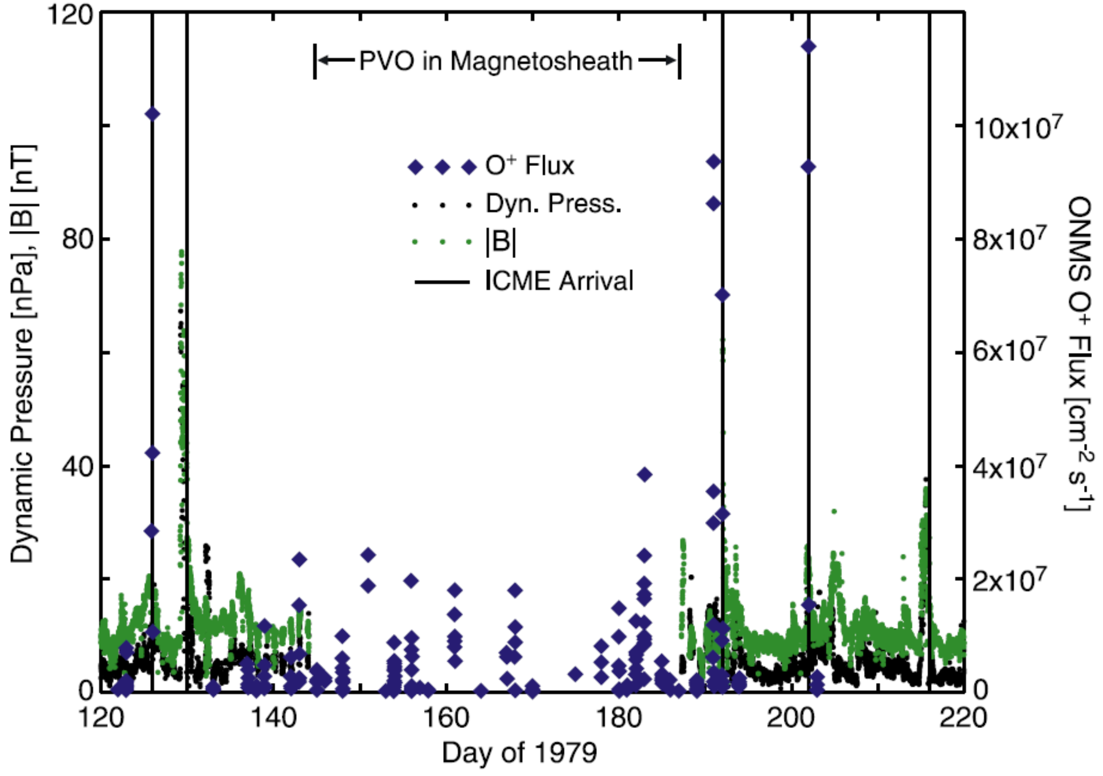
Venus Express



Figures from *Kliore et al.* (JGR) and *Luhmann et al.* (JGR)

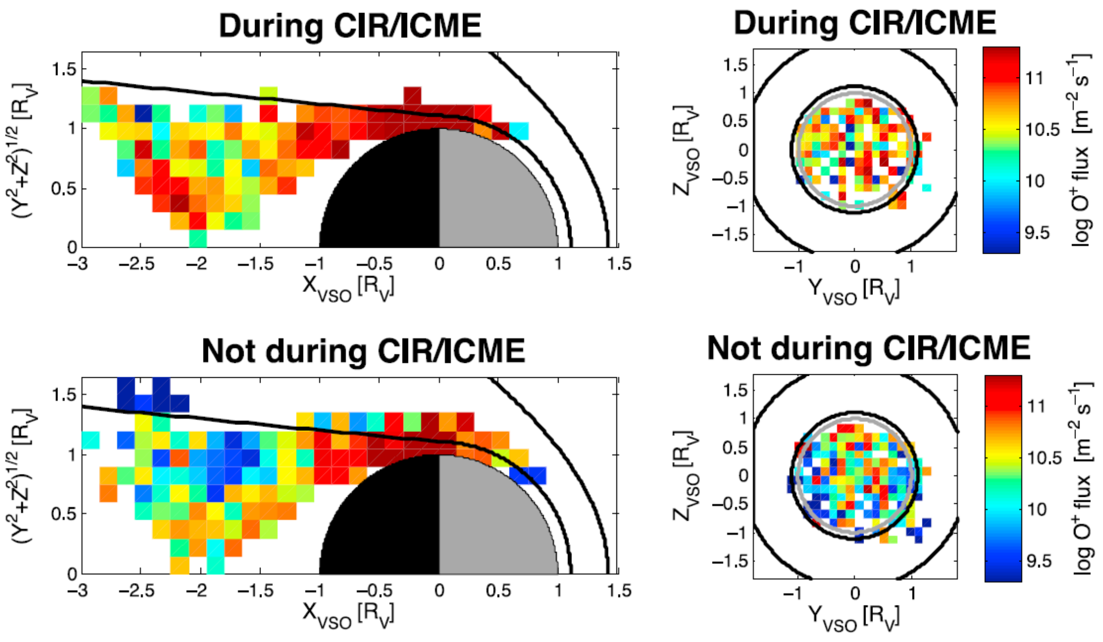
Pioneer Venus Orbiter suprathermal energy ion observations first suggested dynamic pressure enhancements from CMEs significantly increased escape fluxes of O+. Venus Express made similar observations of escaping fluxes during high dynamic pressure event periods.

Pioneer Venus Orbiter



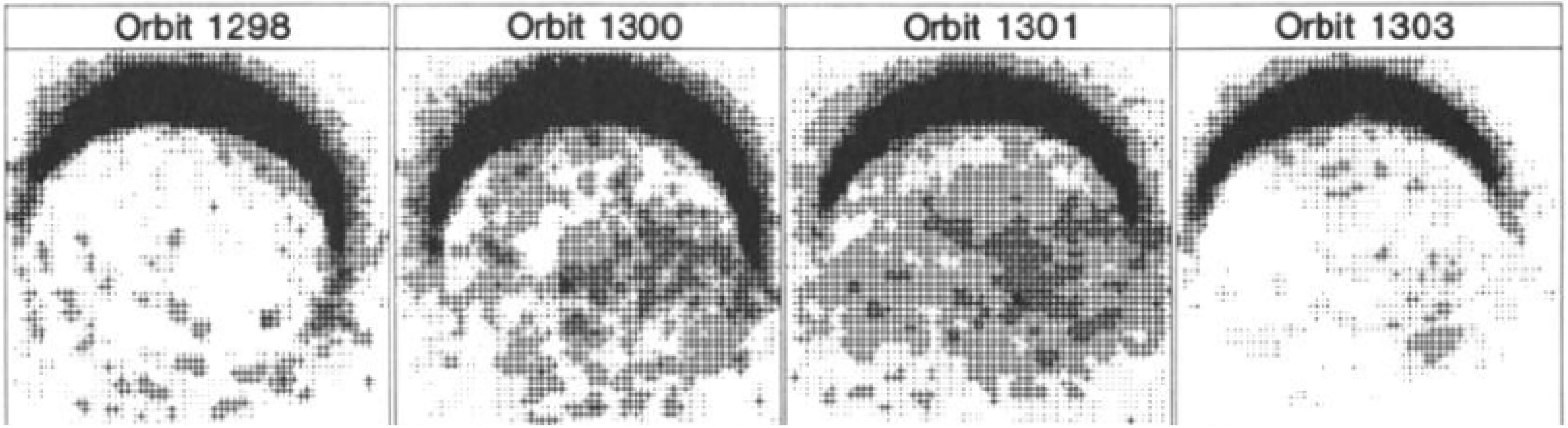
Luhmann et al. (2007)

Venus Express



Edberg et al. (2010)
see also Luhmann et al. (2008)

A high solar wind dynamic pressure-related "diffuse" nightside UV aurora was detected by Pioneer Venus Orbiter. The UV aurora is produced by electron precipitation (*Fox and Stewart*, 1991).

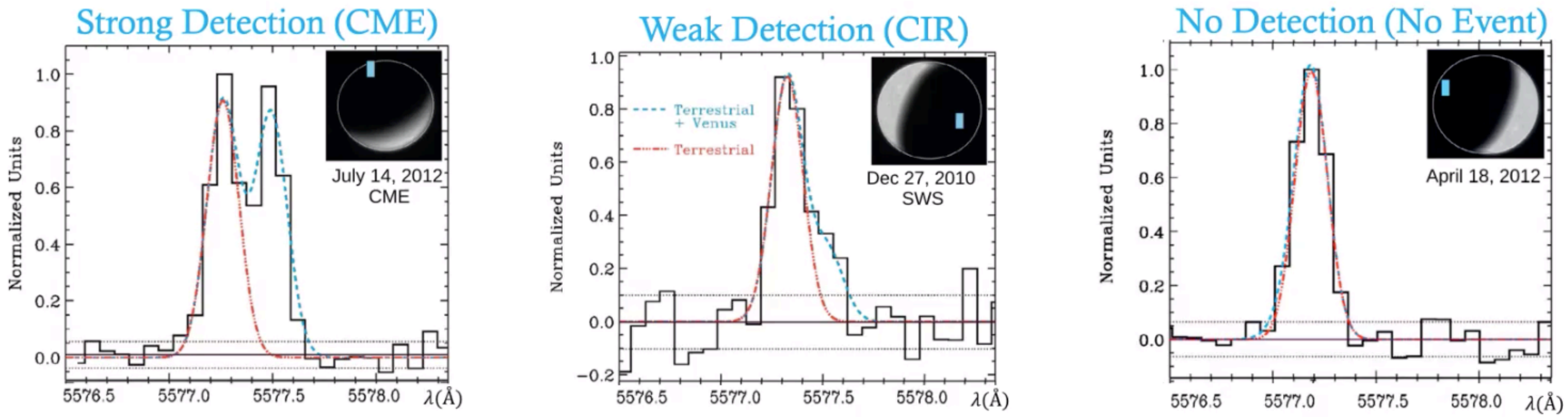


Nightside views of the Venus 130.4 nm aurora observed by the PVO UVS instrument showed a brightness response to a solar wind enhancement.
(Dayside seen as dark crescent in these images.)

From J. Luhmann (SSL/UCB) / Figure from *Phillips et al.* (1986)

Venus auroral green line emissions have also been detected from terrestrial ground-based observations and are associated with solar eruptive events (flares, CMEs). Weaker emissions have also been detected, associated with more quiescent solar wind conditions.

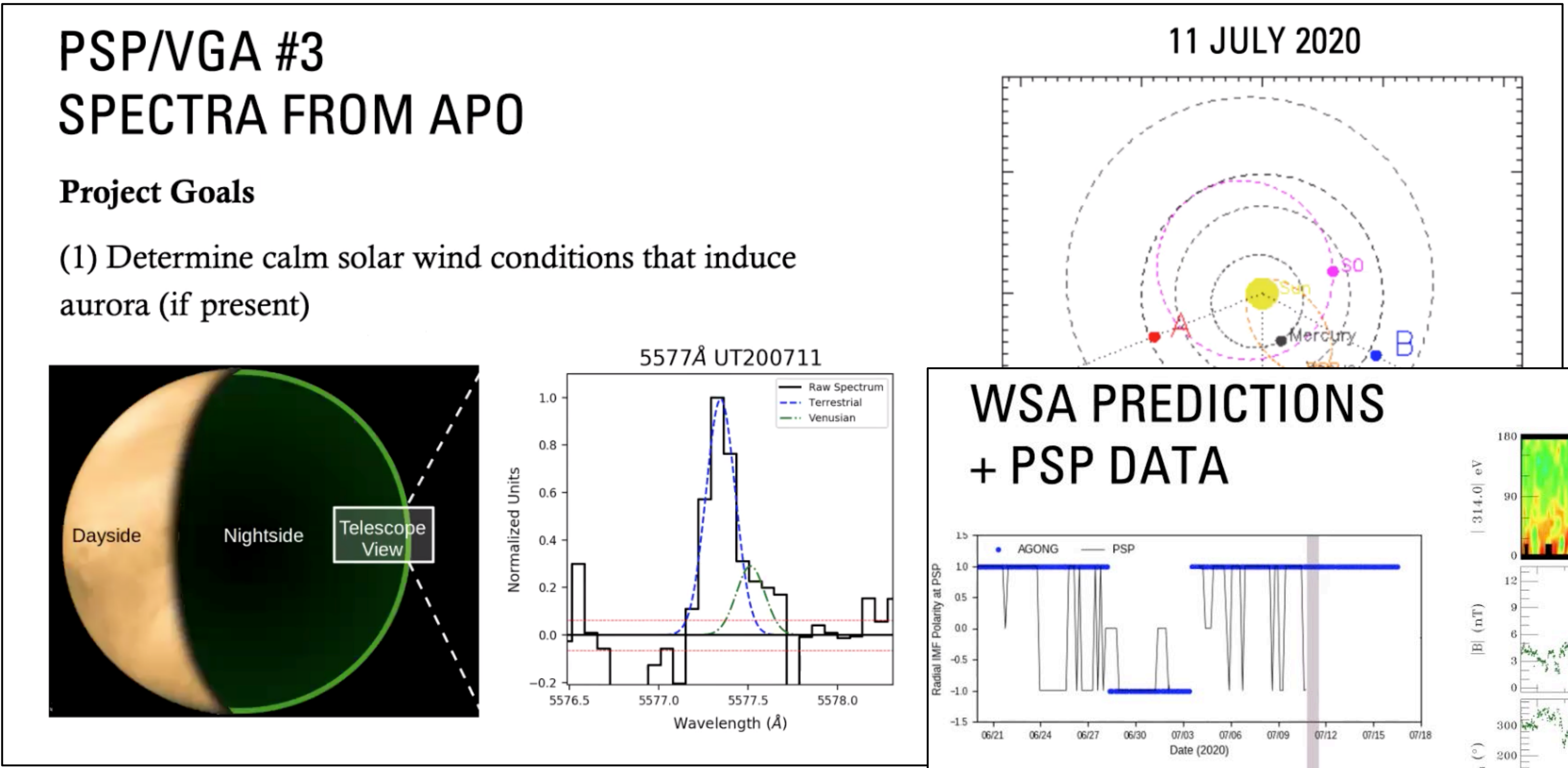
VENUSIAN AURORA OXYGEN GREEN LINE EMISSION (5577Å)



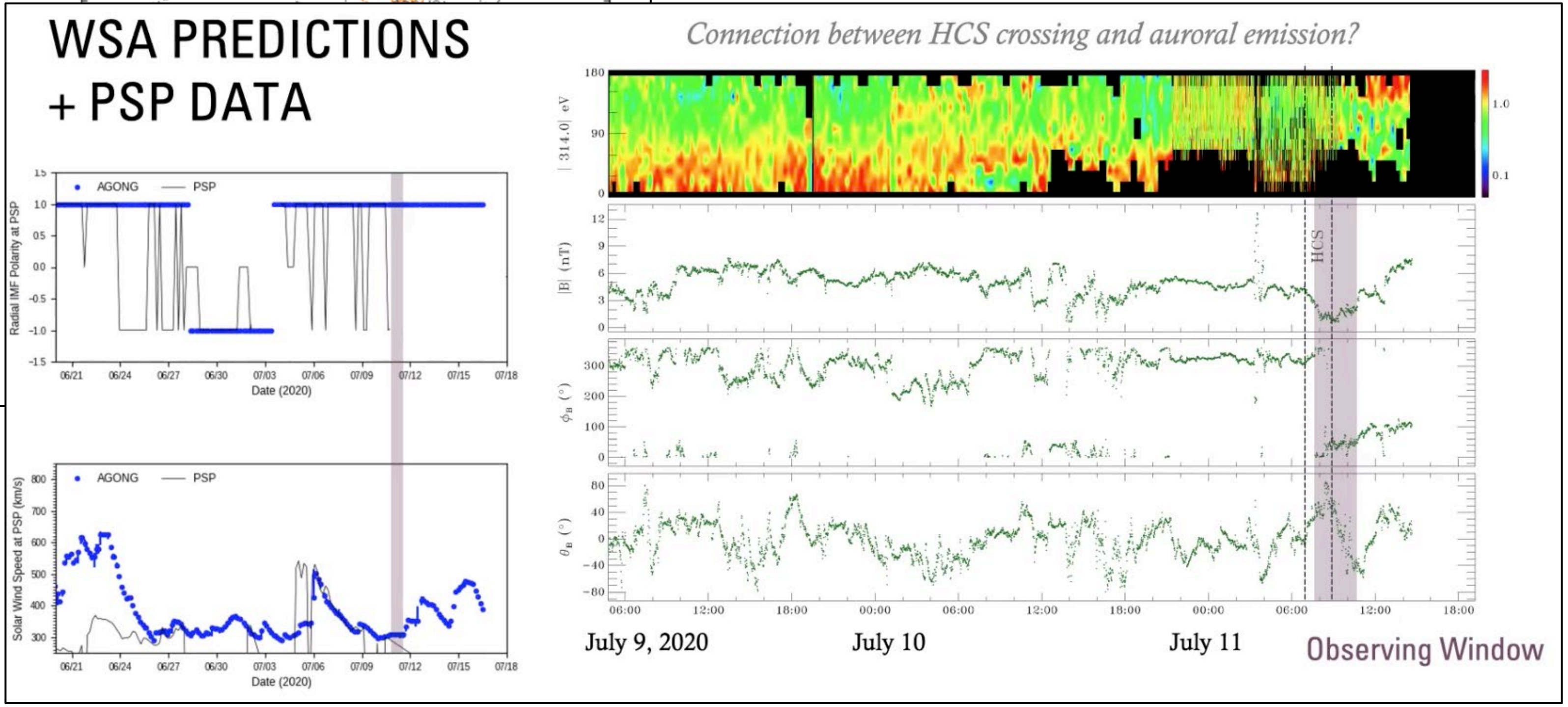
- Discovered in 1999, observations during target of opportunity solar storms
- Auroral emission detected during flares and CMEs; rare observations during calm conditions
- Process of emission is unknown, particularly the cause in ambient solar wind conditions

From S. Kovac (NMSU) / Figures adapted from *Gray et al.* (2014)

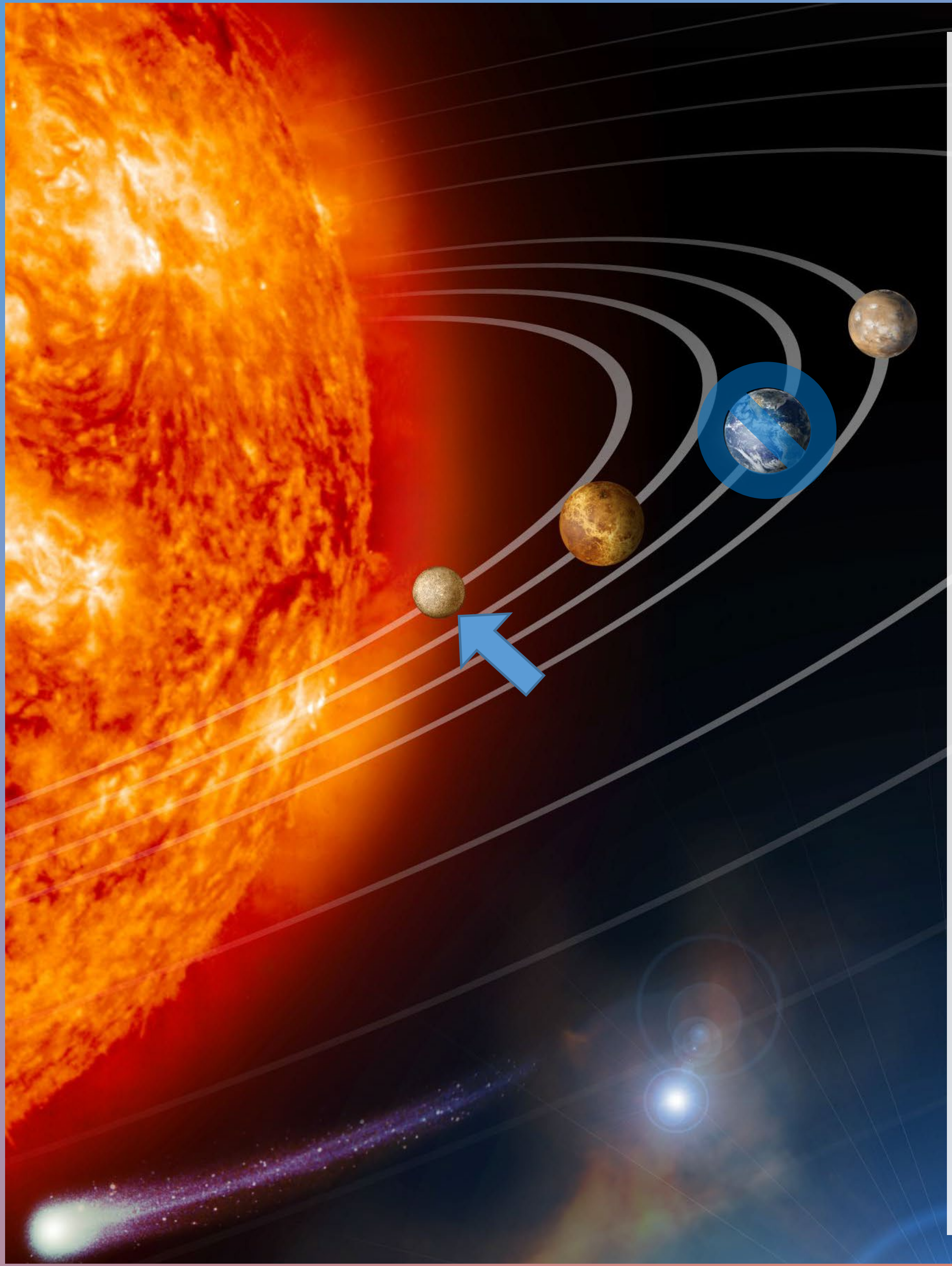
Work is ongoing by Kovac et al.* to investigate the cause(s) of emissions during calm solar wind periods at Venus, taking advantage of the Parker Solar Probe Venus Flyby observations together with WSA solar wind modeling results.



Kovac et al. (2021)

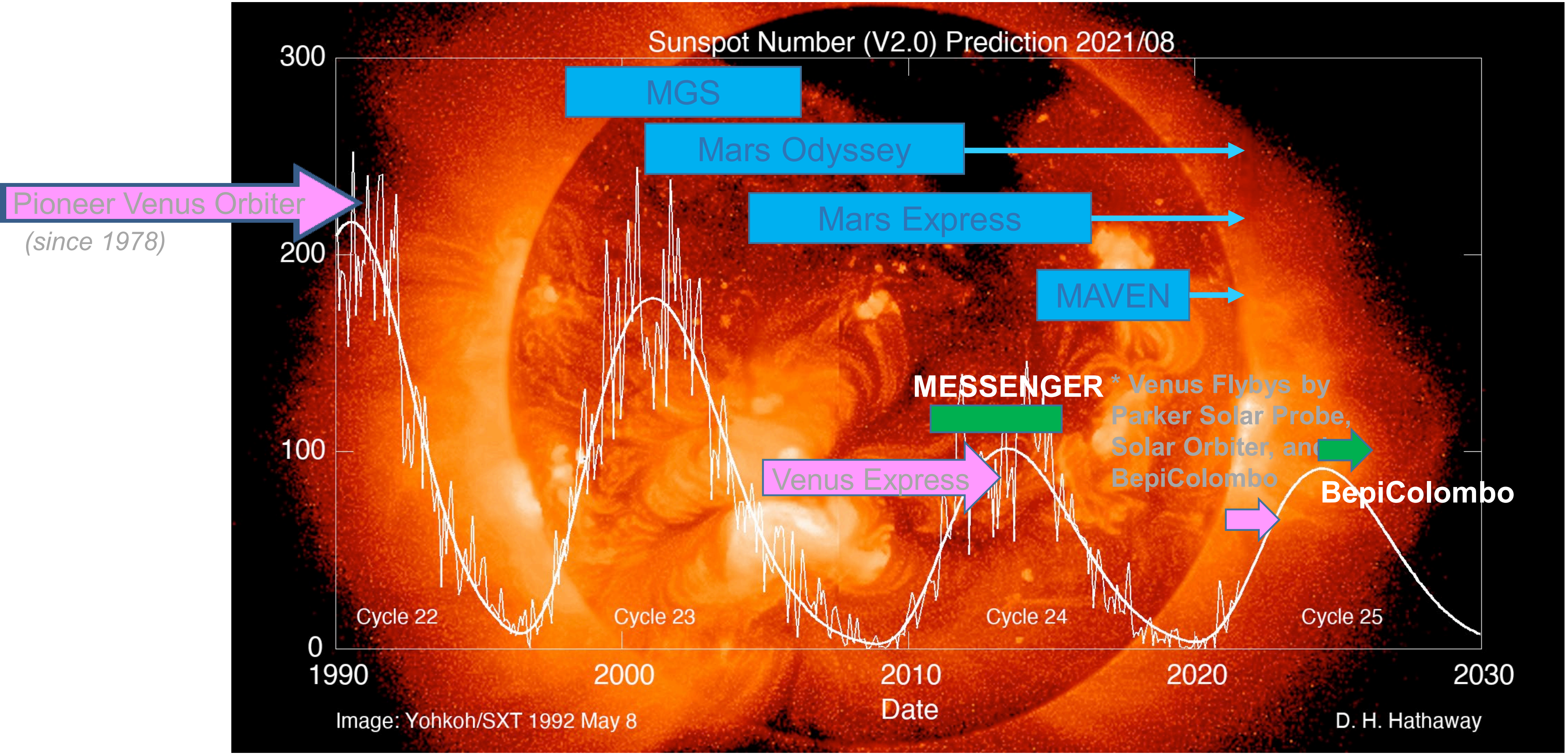


* In collaboration with Candace Gray, C. Nick Arge, James McAteer, Nancy Chanover, Chris Churchhill, Adam Szabo, and Matthew Hill

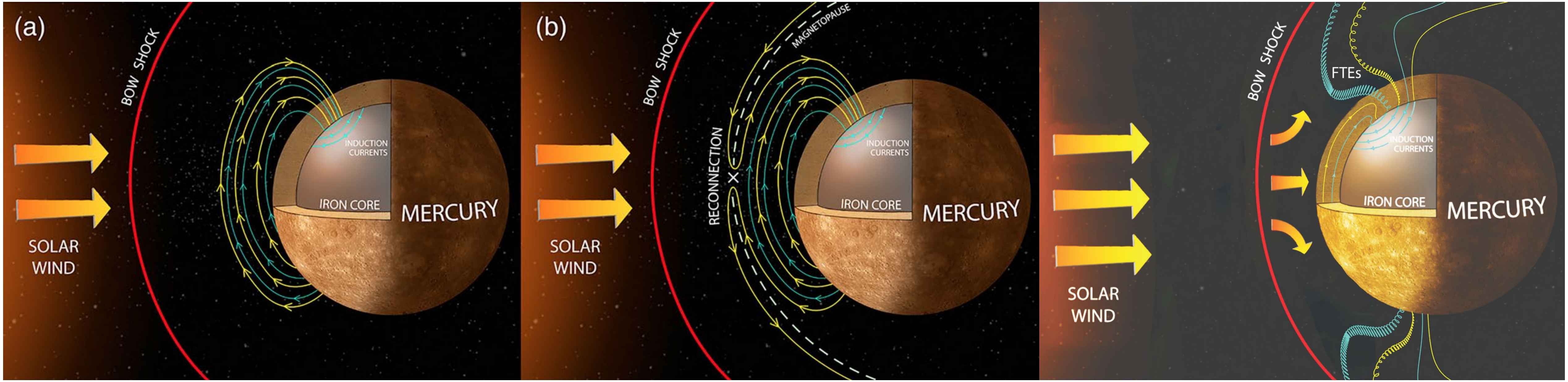


Impacts and Effects of the Space Environment at Mercury

There have been even fewer observations around Mercury – mainly from the MESSENGER mission, but BepiColombo will provide opportunities to comprehensively study the space environment around this planet.



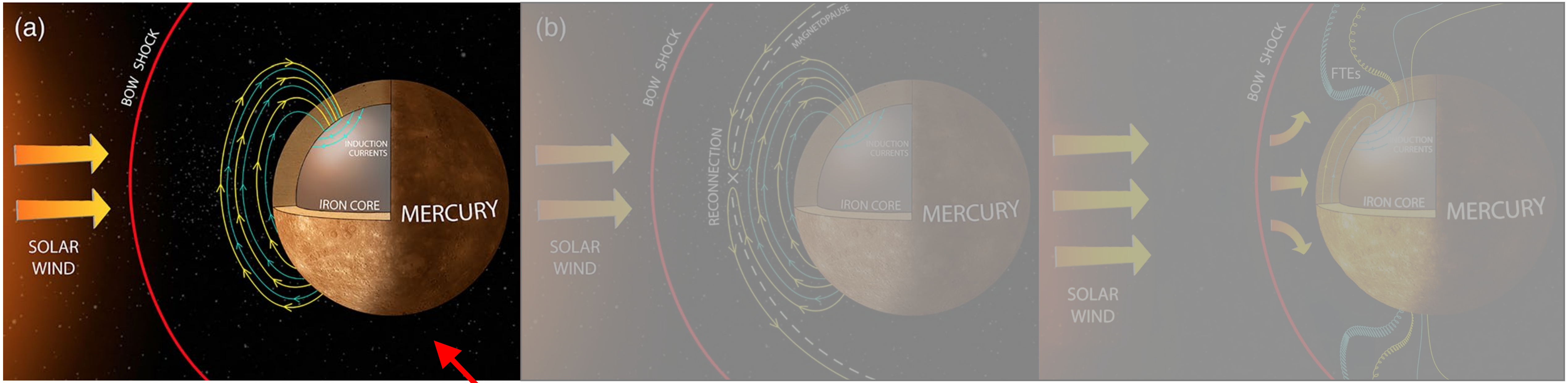
Intrinsic magnetosphere experiences extreme solar wind forcing due to Mercury's proximity to the Sun.



Slavin et al. (2019)

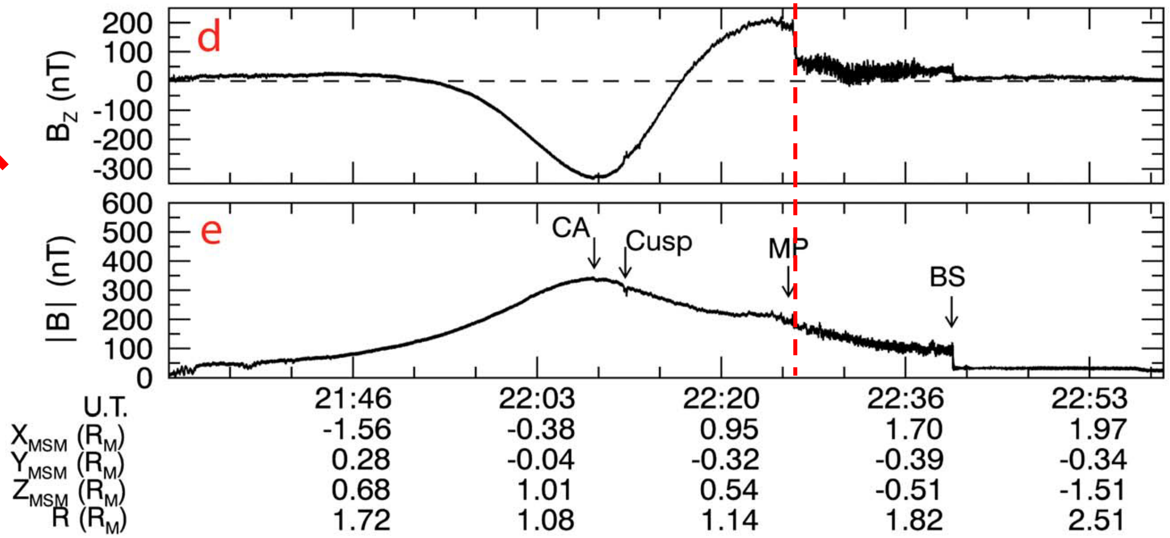
From G. DiBraccio (NASA/GSFC)

Induction currents can increase Mercury's total magnetic moment by up to ~25%.



Slavin et al. (2019)

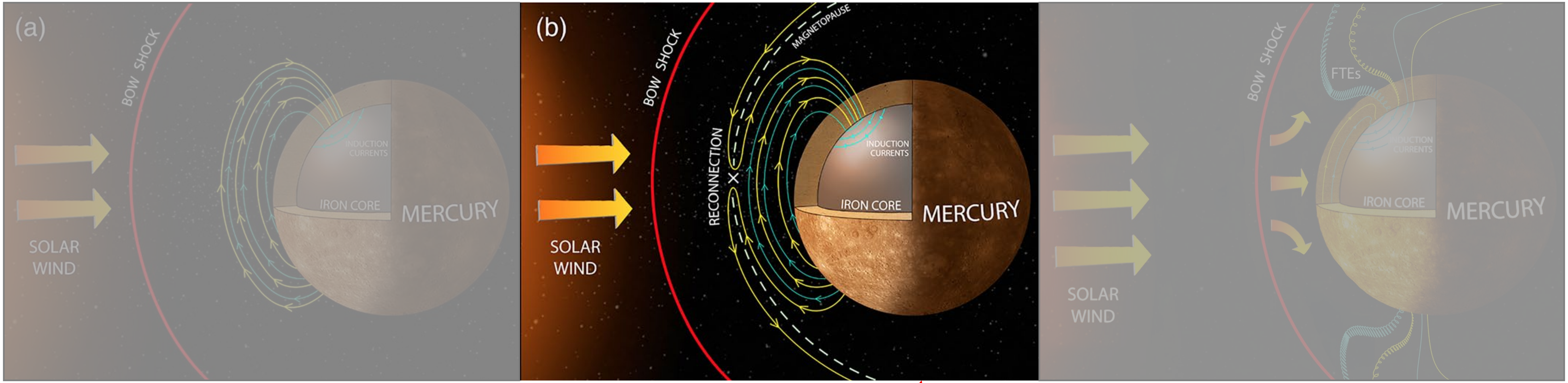
- Quiet and smooth magnetic field within the magnetosphere
- $+B_Z$ prior to magnetopause crossing indicates dayside magnetosphere



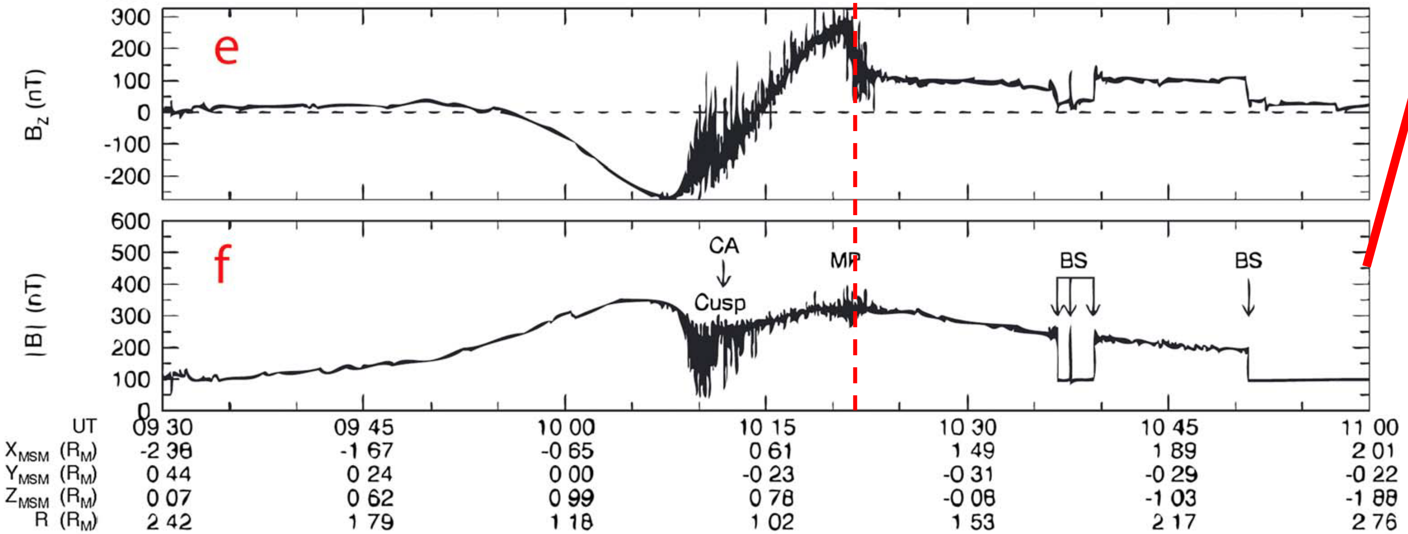
From G. DiBraccio (NASA/GSFC)

Magnetopause reconnection occurs at high rates to erode the dayside magnetosphere of Mercury.

Slavin et al. (2019)



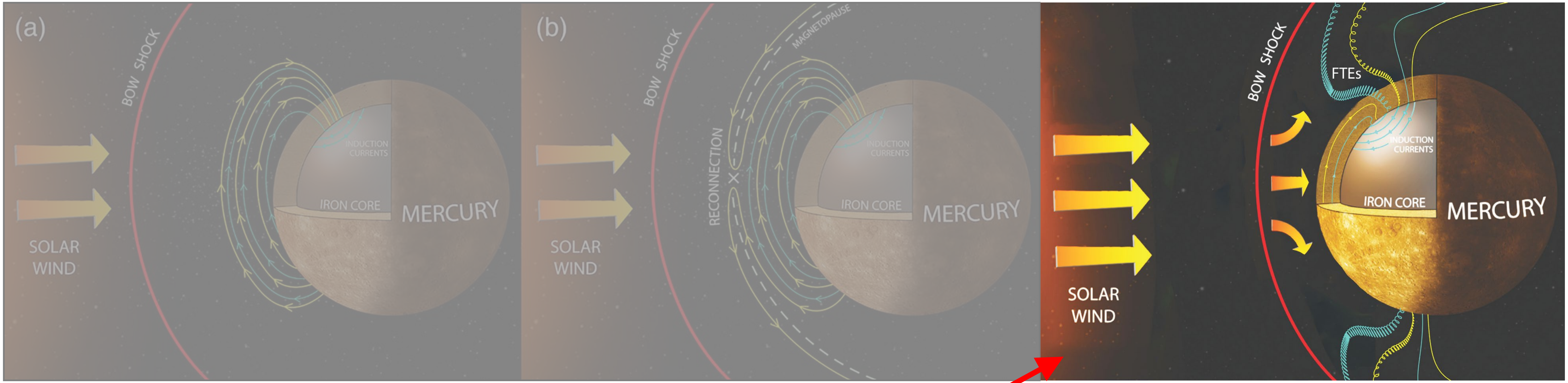
Slavin et al. (2019)



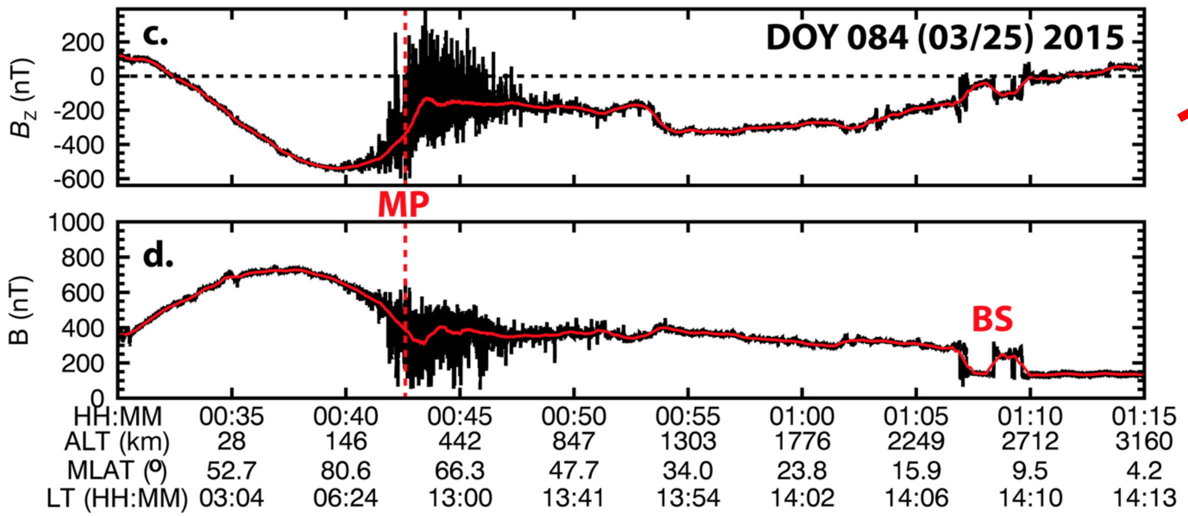
- $+B_Z$ prior to magnetopause crossing indicates dayside magnetosphere
- Large amplitude fluctuations (flux transfer events) are signatures of enhanced magnetopause reconnection

From G. DiBraccio (NASA/GSFC)

A tug-of-war exists between induction effects and magnetic reconnection. For the most extreme CME events, the dayside magnetosphere disappears.



Slavin et al. (2019)

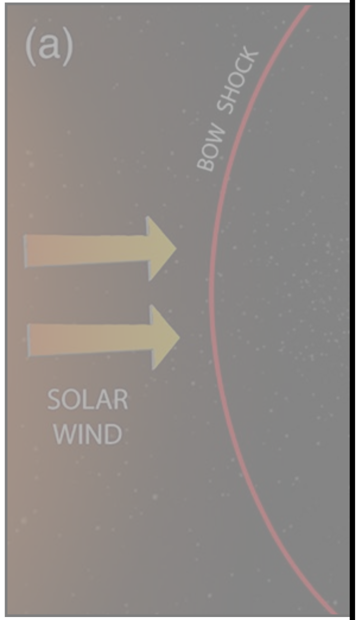


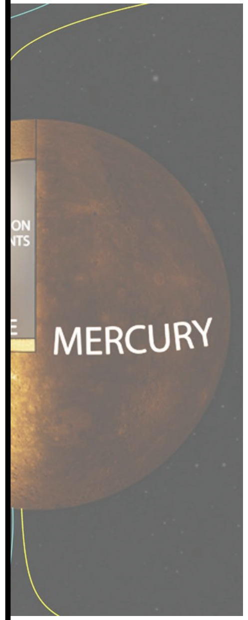
- Interplanetary shock and CME impact
- B_Z never turns northward before magnetopause crossing
- Enhanced fluctuations indicate high rates of reconnection

From G. DiBraccio (NASA/GSFC)

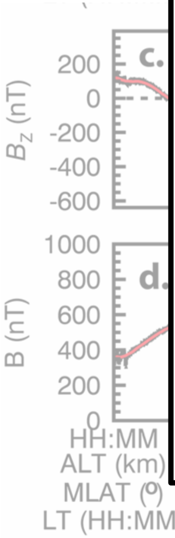
A tug-of-war exists between induction effects and magnetic reconnection.

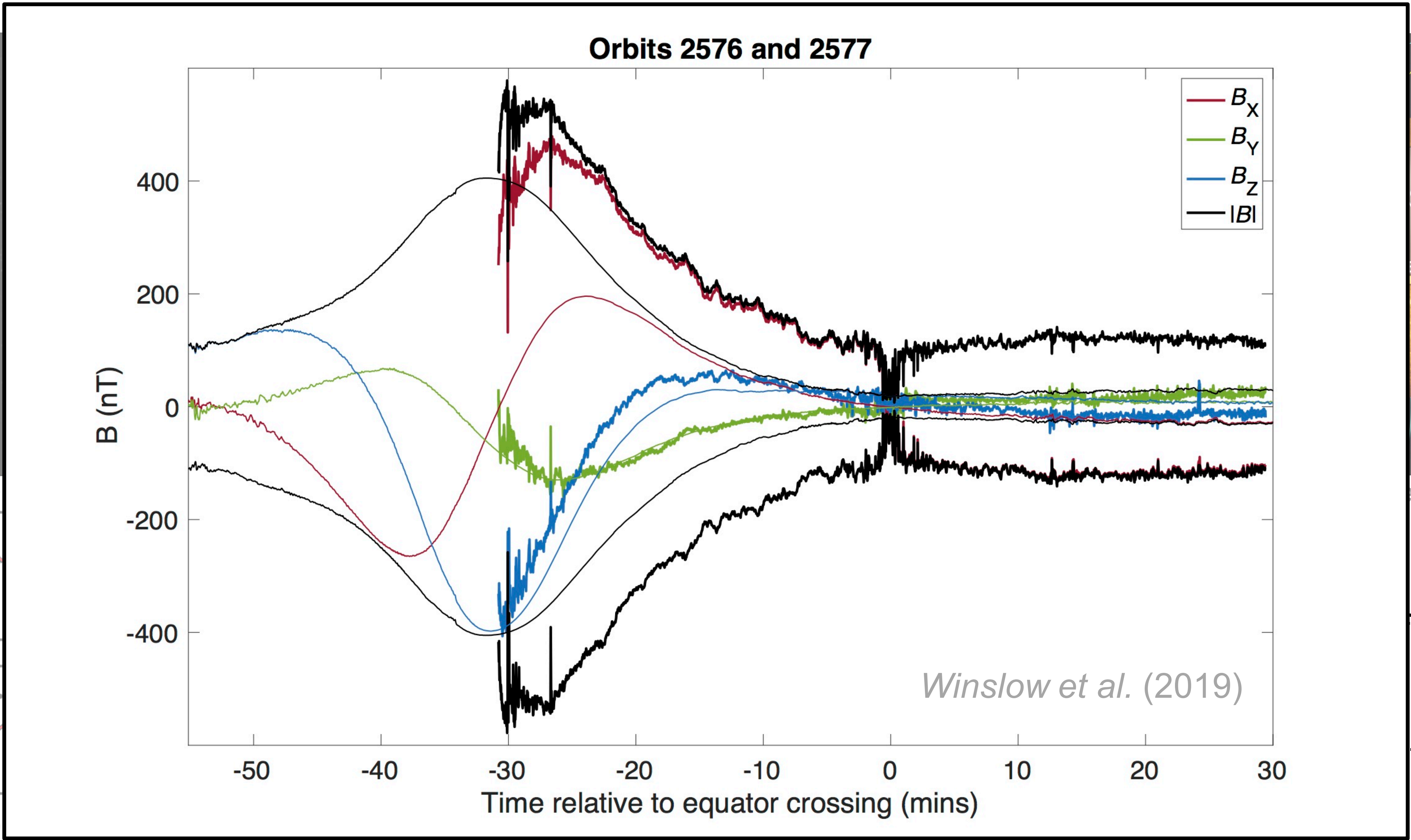
For the most extreme CME events, the dayside magnetosphere disappears.





et al. (2019)





E impact

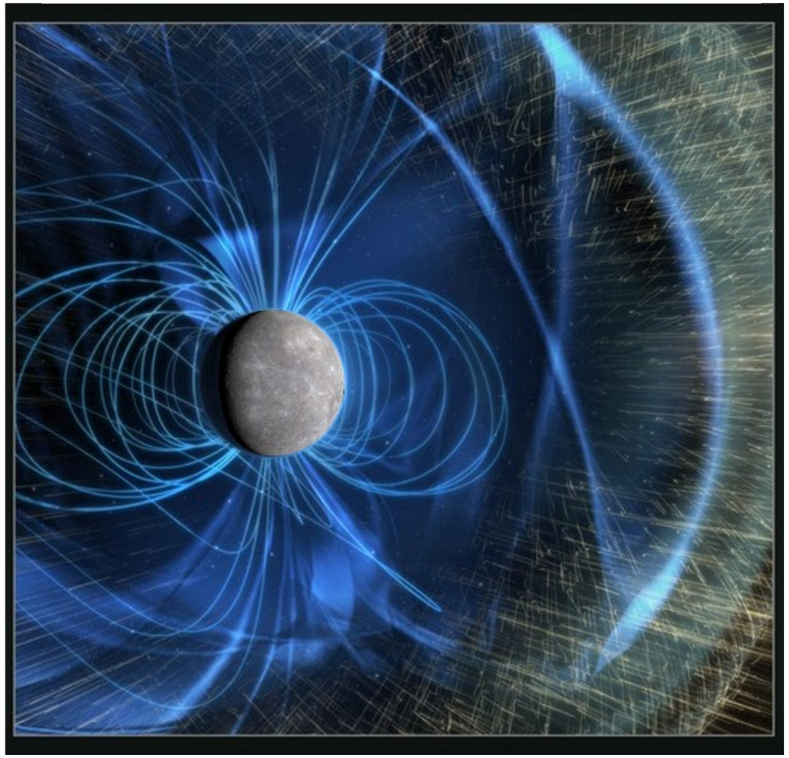
fore

te high

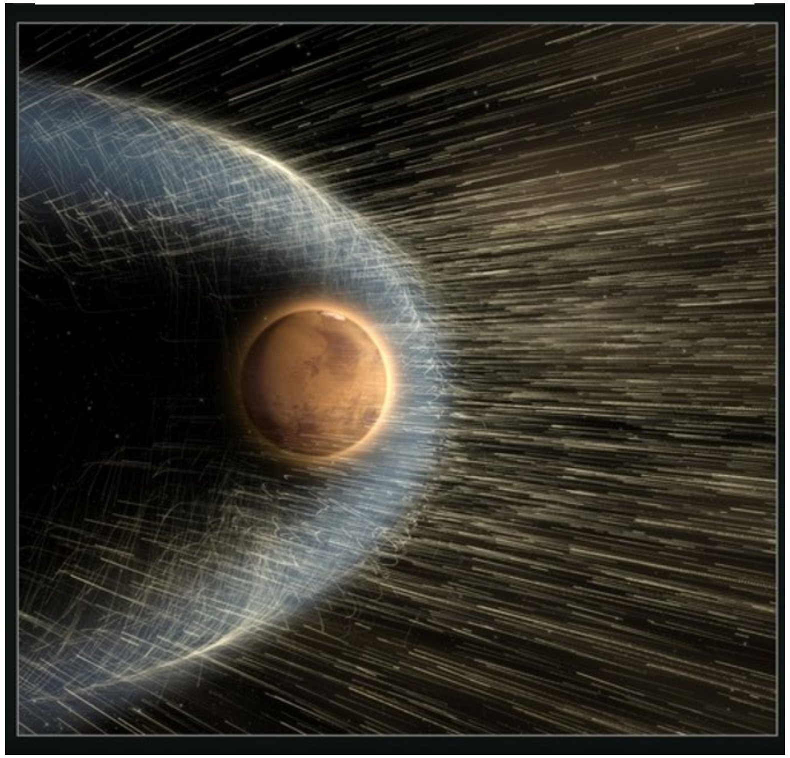
From G. DiBraccio (NASA/GSFC)

During Mercury's disappearing dayside events, the planetary surface is exposed to the solar wind and is no longer protected by the global planetary magnetic field. This creates a scenario that is similar to Mars. *Mercury can become Mars-like during extreme solar events!*

Mercury

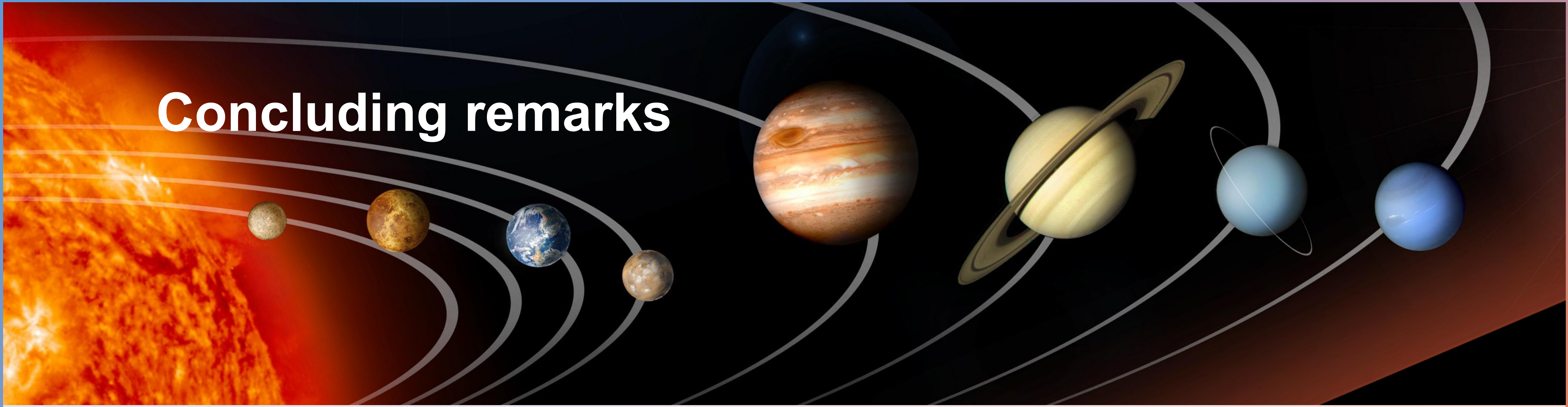


Mars



From G. DiBraccio (NASA/GSFC)
Figures adapted from NASA/GSFC

Concluding remarks

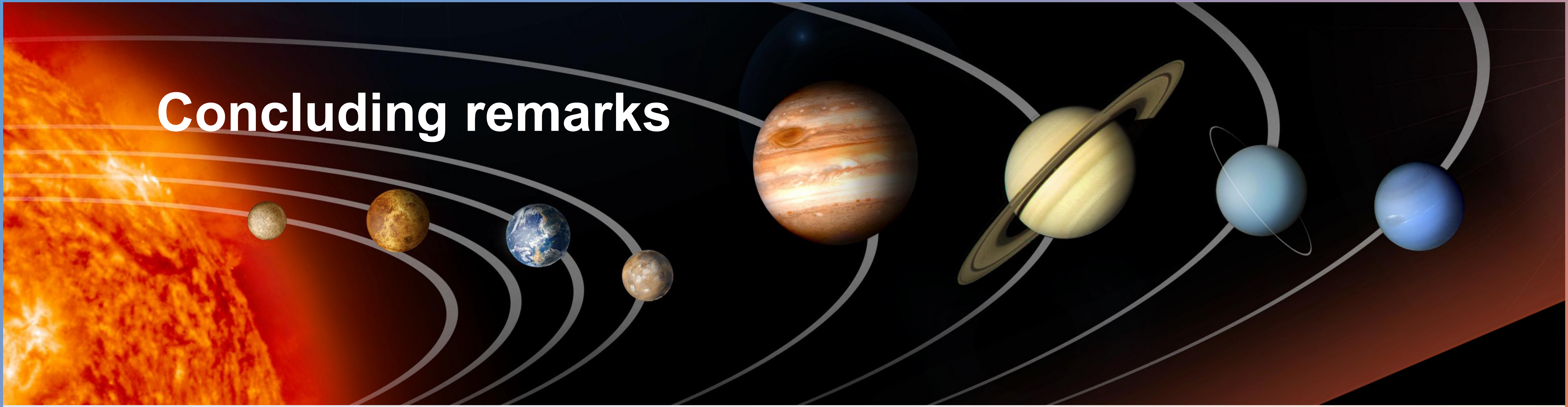


This *very quick* overview didn't include a discussion about how the outer planets interact with the interplanetary environment, and only a small snippet was shown regarding how the inner planets respond to active and quiescent solar conditions.

Bottom line: Solar eruptive events and quiescent conditions impact a planetary system in different and sometimes similar ways, depending whether the planet has an intrinsic vs induced magnetosphere and the characteristics of the planet's ionosphere and upper atmosphere.

Observations from planetary missions contribute to a larger heliospheric dataset!

Concluding remarks



This *very quick* overview didn't include a discussion about how the outer planets interact with the interplanetary environment, and only a small snippet was shown regarding how the inner planets respond to active and quiescent solar conditions.

Bottom line: Solar eruptive events and quiescent conditions impact a planetary system in different and sometimes similar ways, depending whether the planet has an intrinsic vs induced magnetosphere and the characteristics of the planet's ionosphere and upper atmosphere.

Observations from planetary missions contribute to a larger heliospheric dataset!

Measurements from planetary missions have been used to study the influence and impact by a common space weather event (solar flares, CMEs, SEPs) observed at Earth and/or STEREO-A. Example shown below is for the September 2017 event period.

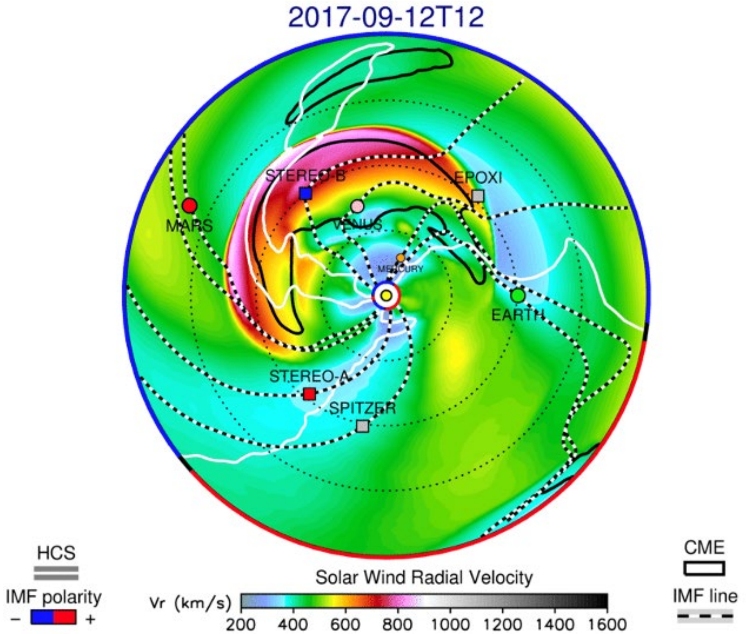
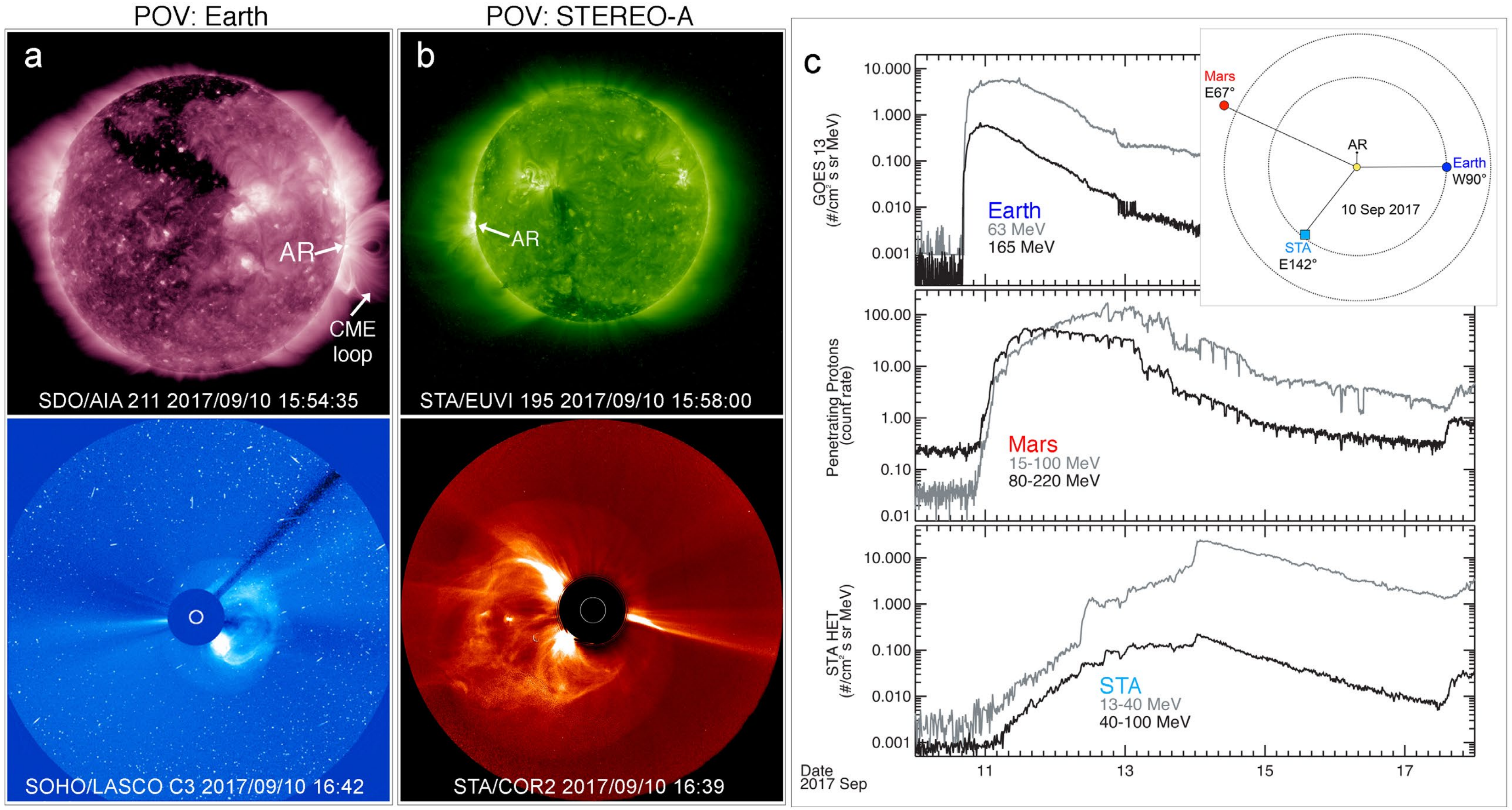


Image credit: NASA/CCMC



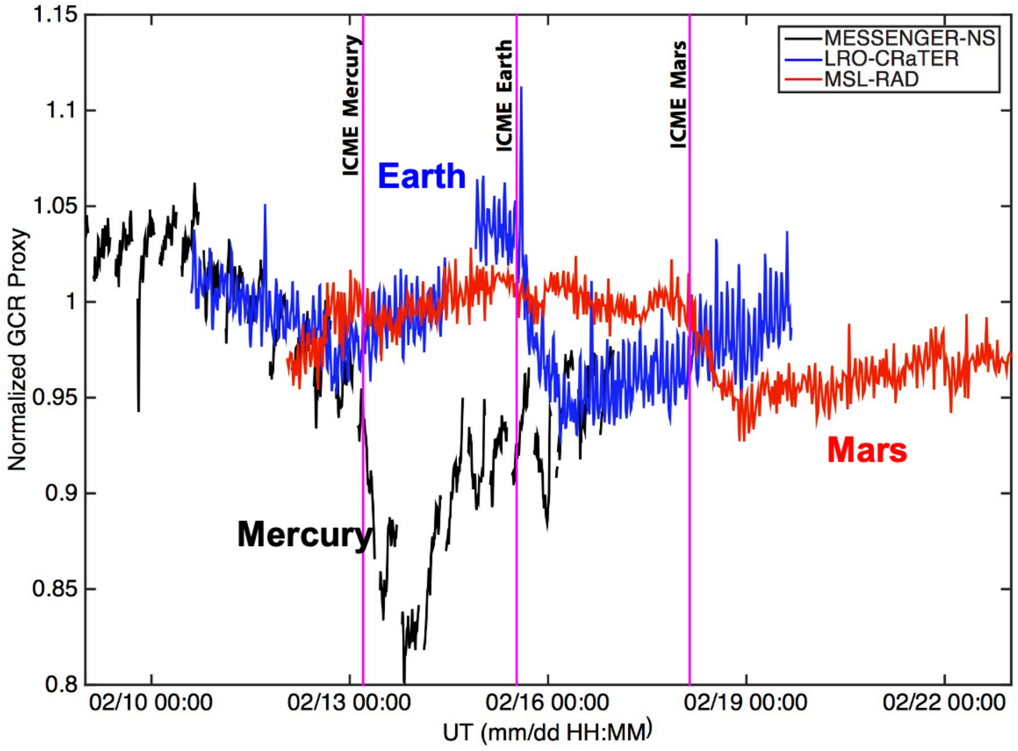
Lee et al. (2018)

Observations at Mercury, Earth, and Mars have been used to characterize the evolution of ICMEs and the related Forbush Decreases (Fds) in the inner heliosphere.

Winslow et al. (2018) found that:

- Fds are steeper, deeper, and of shorter duration closer to the Sun.
- Fd size strongly dependent on ICME B.
- Hint of possible exponential drop-off of Fd size with radial distance from the Sun (see complementary study *Witasse et al.* (2017).

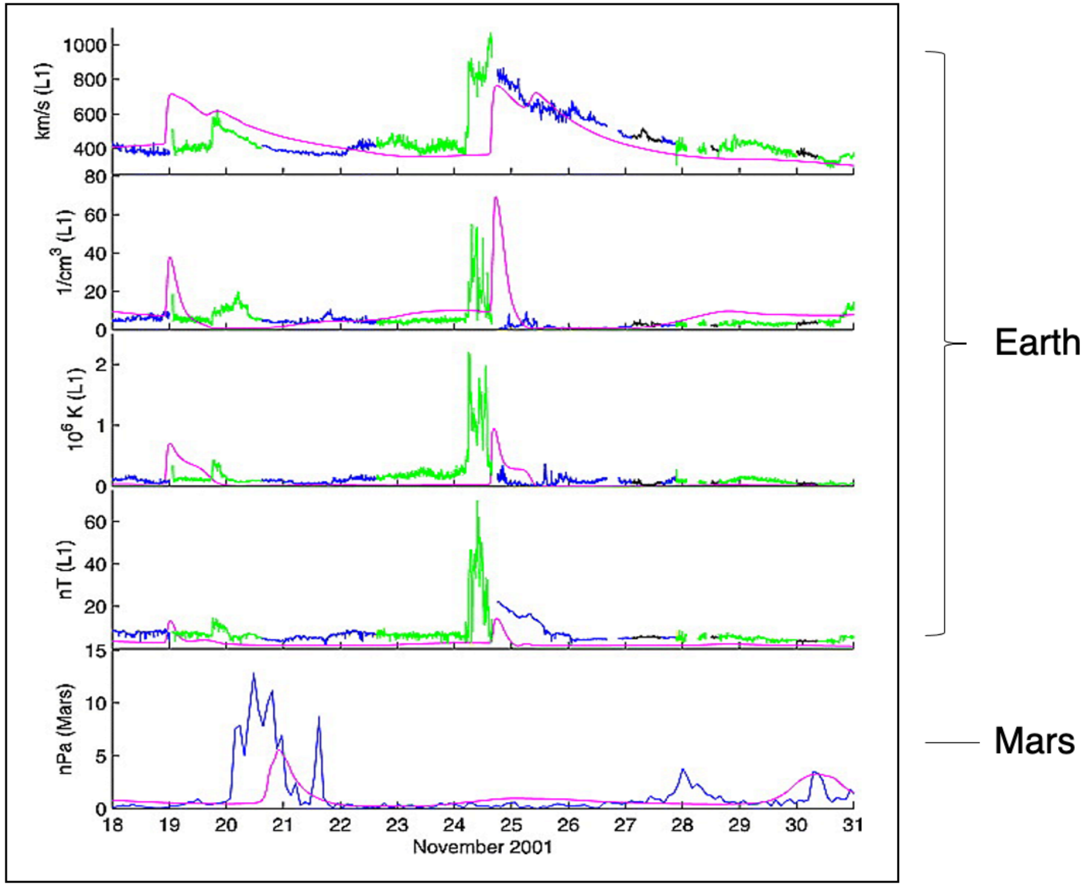
From R. Winslow (UNH)



	Magnitude of decrease	Duration of decrease (h)	Slope of decrease
Mercury	15%	59.2	-0.16 (FD1: -0.21; FD2: -0.37)
Earth	9%	69.9	-0.12
Mars	6%	206.6	-0.07

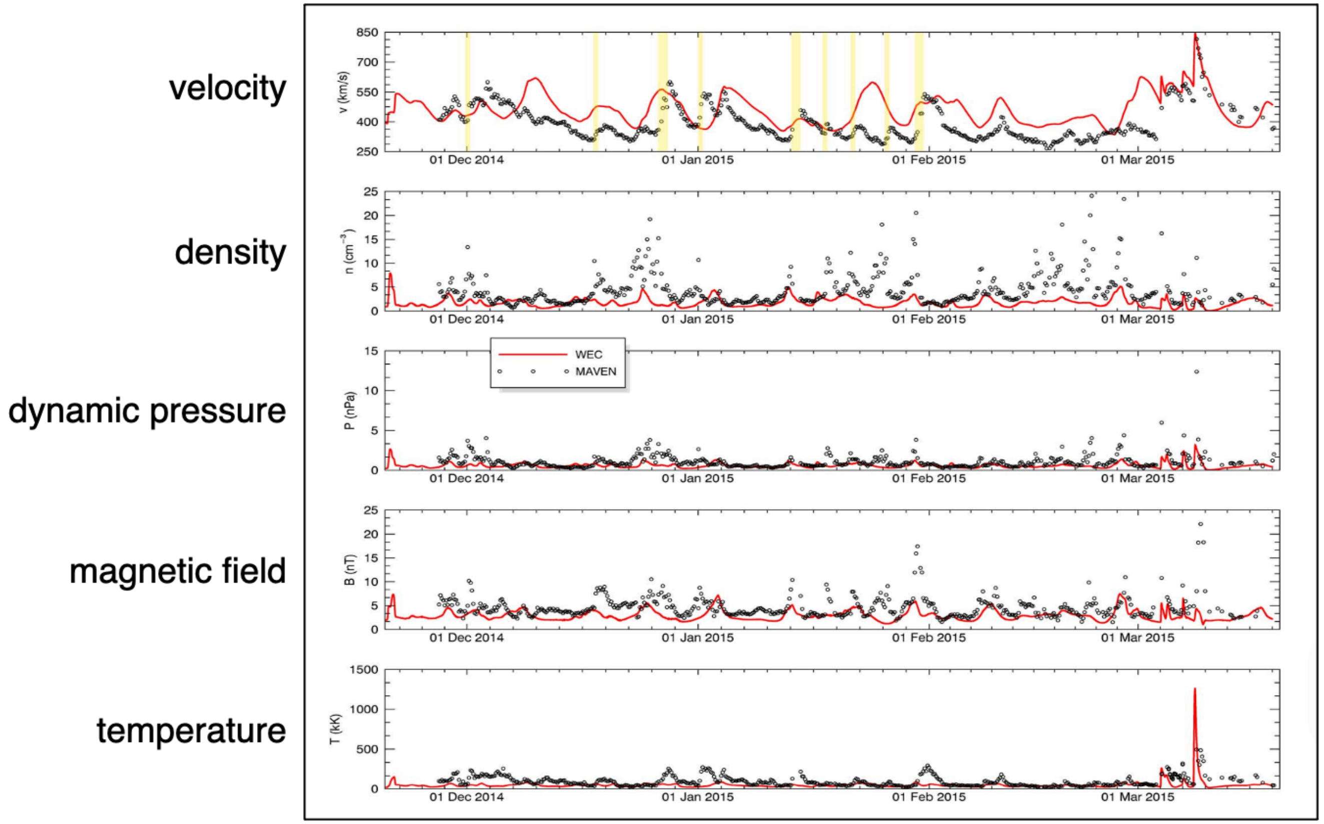
Observations from planetary missions have been used to better constrain 3D solar wind models (below) and SEP models (e.g., *Luhmann et al.*, 2018).

Geotail, ACE, MGS, WSA-Enlil



Falkenberg et al. (2011)

MAVEN, WSA-Enlil



Dewey et al. (2016)