Mass Ejections caused by Magnetic Reconnections in the Ionosphere of Mars

Yudong Ye

Sun Yat-sen University,

Zhuhai, Guangdong, China

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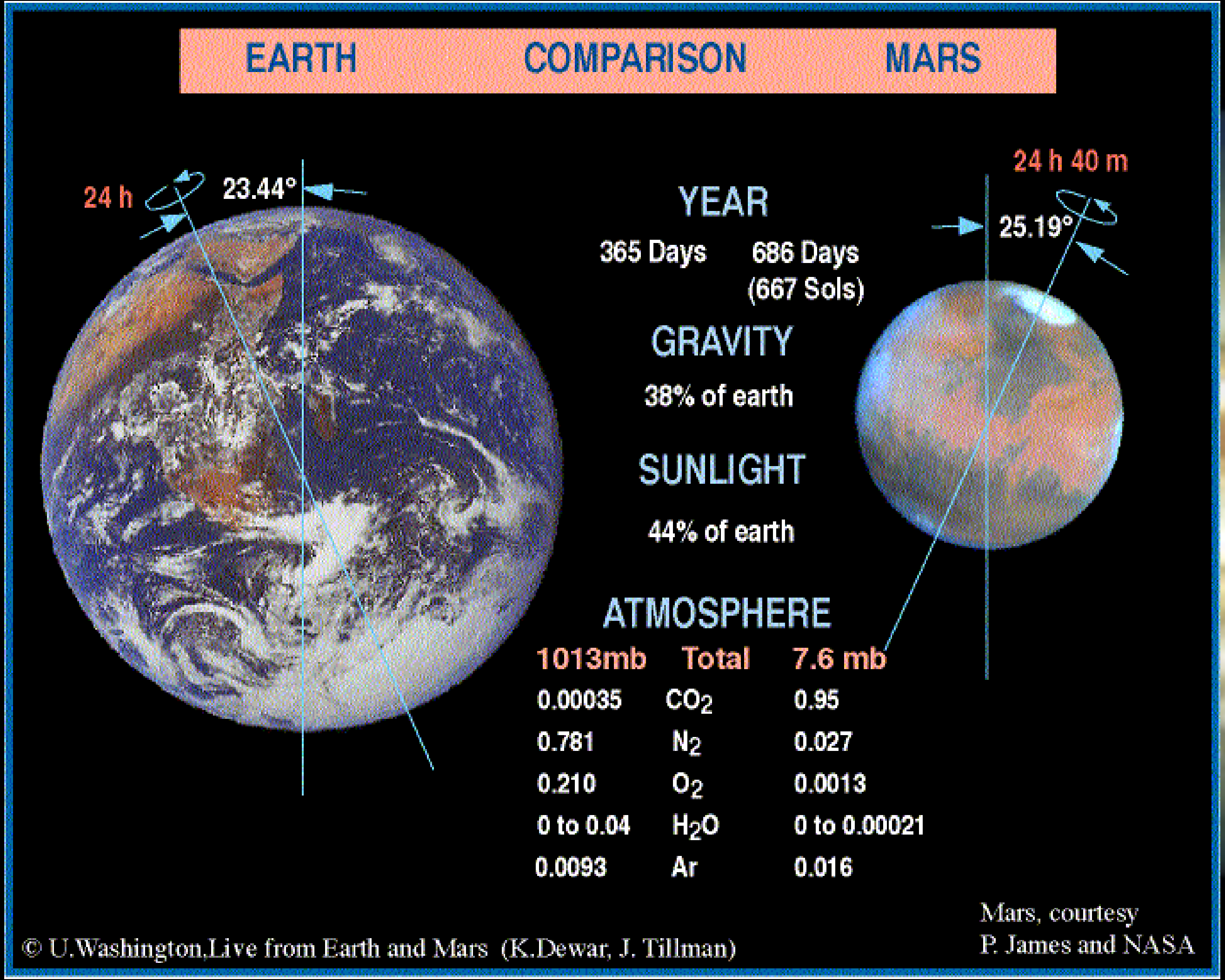
Outline

- Backgrounds
  - Brief of Mars and Martian Space Environment
  - Data Sources: MAVEN Satellite and Onboard Instruments
- Mass Ejection Case Study
  - 2016 Event Overview
  - Magnetic Reconnection Analysis
  - Magnetic Topology Analysis
  - Ejected Mass and Mass Loss Rate Estimation
  - Discussion and Conclusion

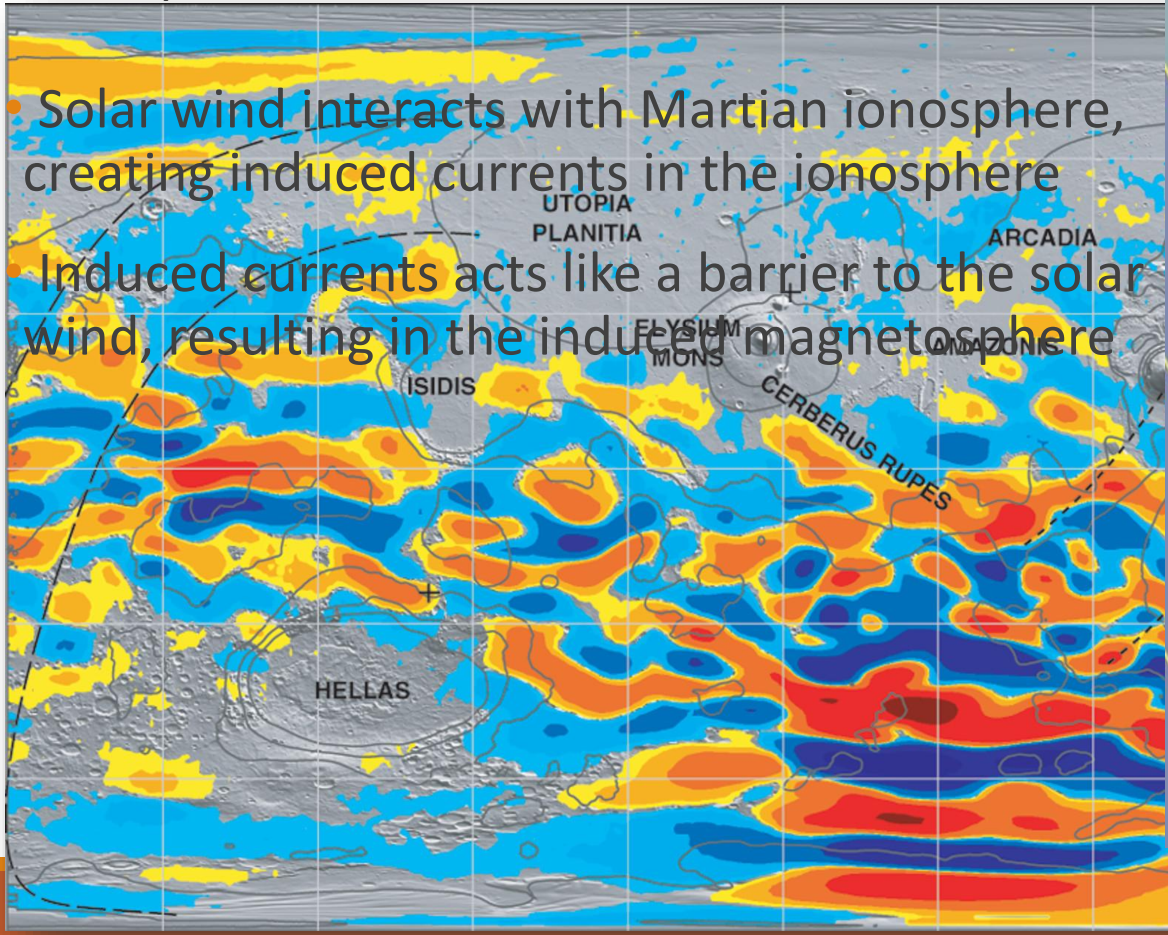


- Mars is about half the size of Earth. Martian gravity is approximately one-third of Earth's gravity.
- A Martian day (sol) lasts 24 hours and 40 minutes, slightly longer than an Earth day.
- Mars is a red desert planet with no liquid water currently on its surface.
- Mars has a much thinner atmosphere compared to Earth.
- Carbon dioxide is the dominant component of Martian atmosphere.

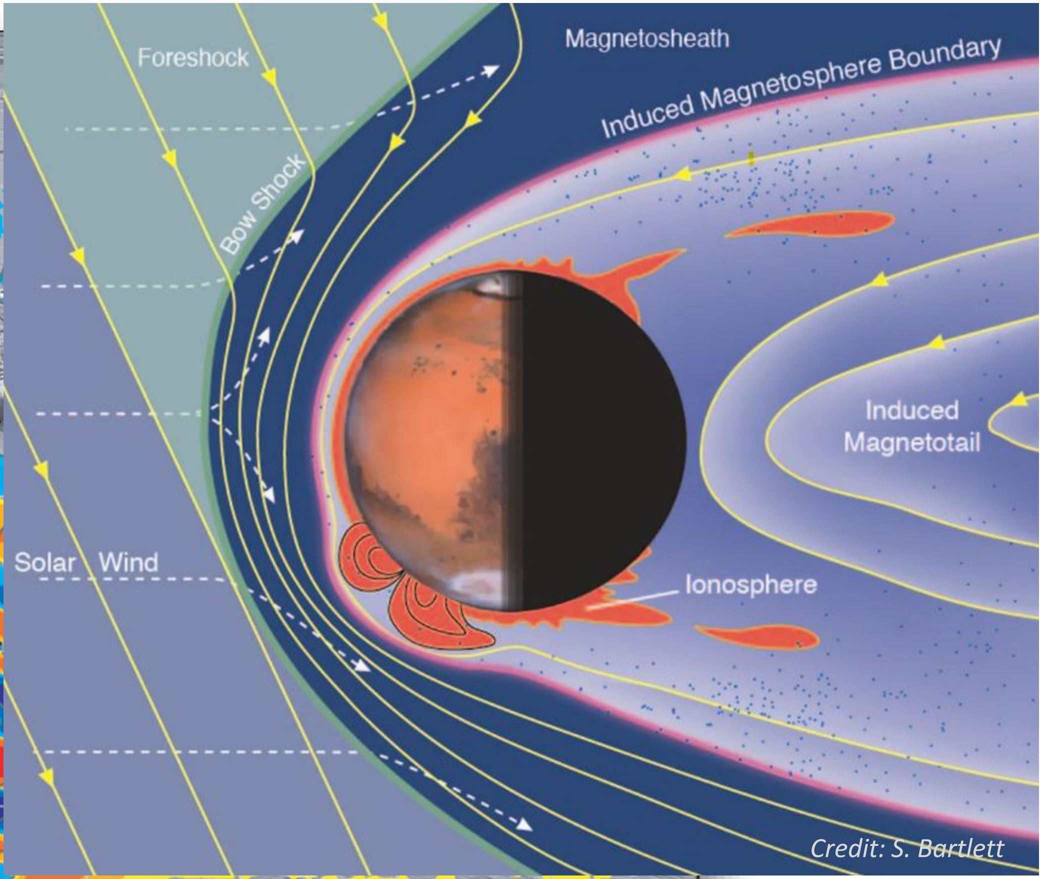
Credits: NASA/Lunar and Planetary Laboratory

Martian Crustal Field
Induced Magnetosphere

- No intrinsic magnetic field, only crustal magnetic field mainly in the southern hemisphere
- Solar wind interacts with Martian ionosphere, creating induced currents in the ionosphere
- Induced currents acts like a barrier to the solar wind, resulting in the induced magnetosphere



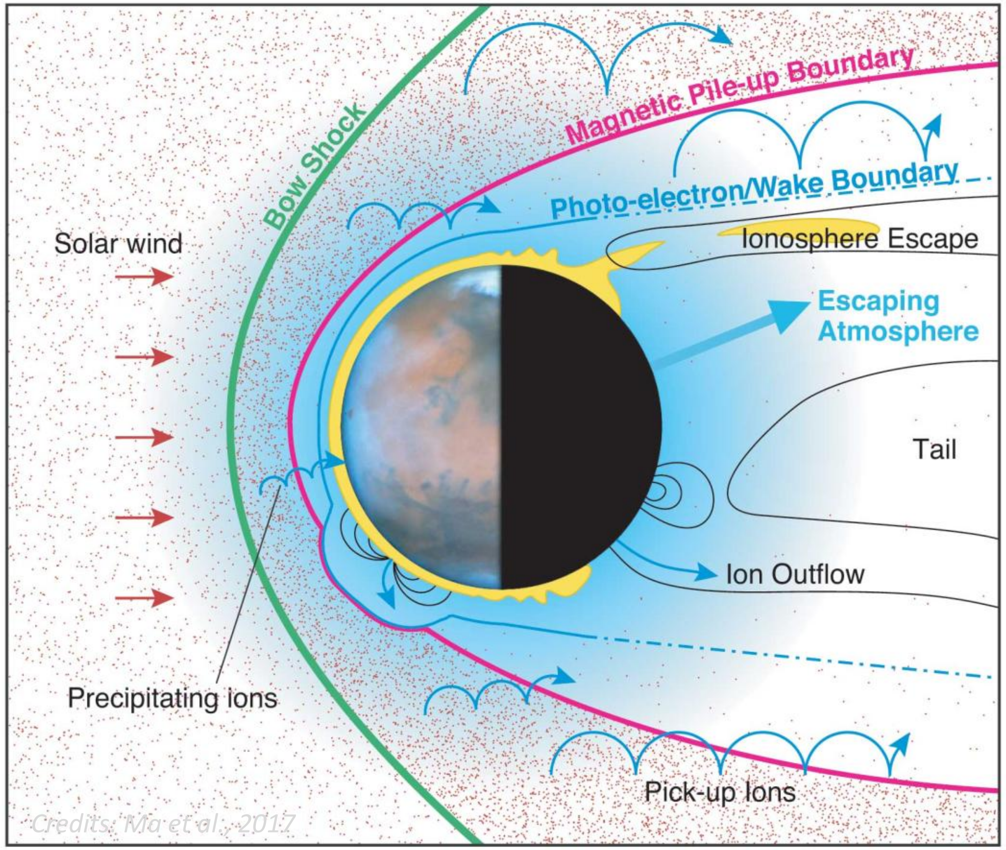
Credits: Connerney et al., 2005



Credit: S. Bartlett

Atmosphere Loss on Mars

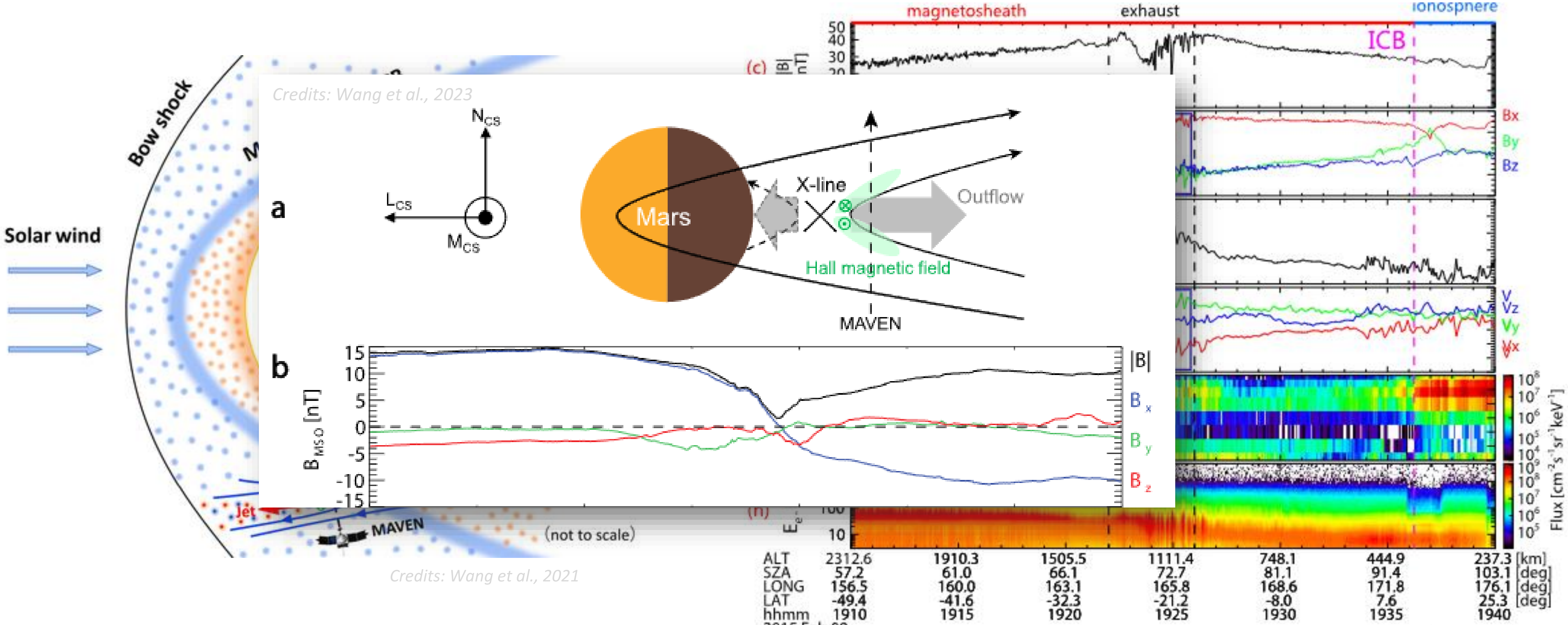
- Thermal Loss (Jeans' Escape)
  - Mainly H atoms, forming H corona surrounding Mars
- Photochemical Loss
  - Hot O, through chemical processes resulting from the absorption of solar EUV photons
- Sputtering Loss
  - Neutral atoms, resulting from collision of accelerated O^+ ions with molecules in the upper atmosphere
- Oxygen ion Loss
  - O ions (O^+ and O_2^+), acerated by an electric field
  - Pick-up, mass-loading, magnetic field interactions, et al.



Escape energy (eV)	H	O	O_2
Mars	0.13	1.8	3.6
Earth	0.6	9.7	19.4

Magnetic Reconnections on Mars

Magnetic reconnections have been detected at the magnetopause, in the magnetosheath, the magnetotail, and the ionosphere.

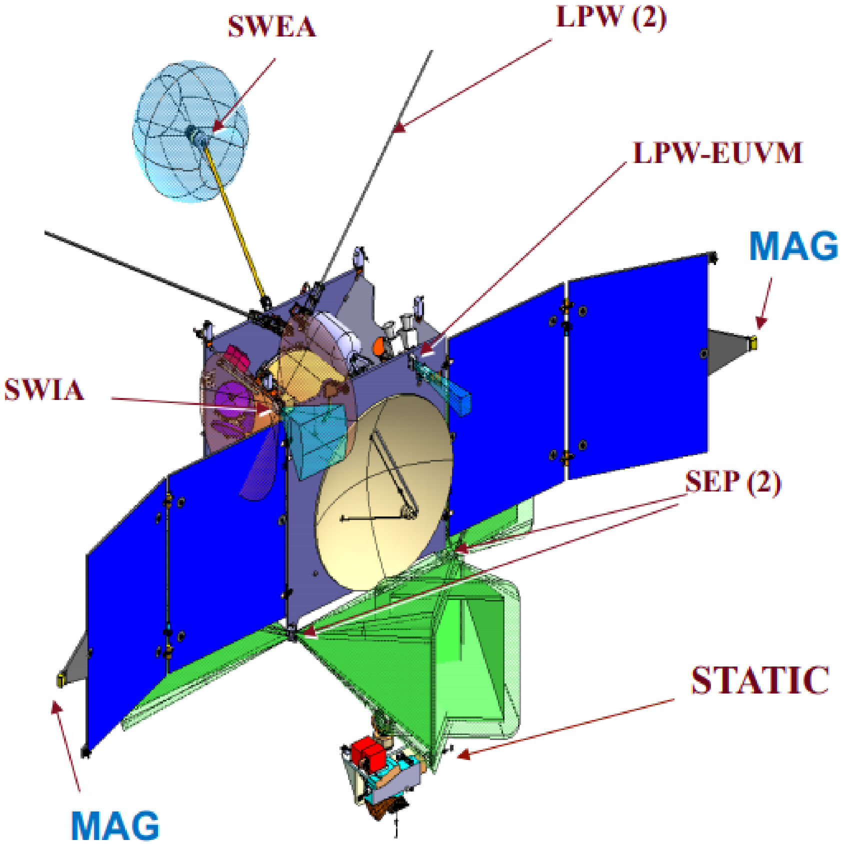


Credits: Wang et al., 2023

Credits: Wang et al., 2021

Credits: Xu et al., 2023

Data Sources: MAVEN and its Instruments



Solar **W**ind **I**on **A**nalyzer (SWIA) – SSL

Solar **W**ind **E**lectron **A**nalyzer (SWEA) – CESR / SSL

Langmuir **P**robe and **W**aves (LPW) – LASP / SSL

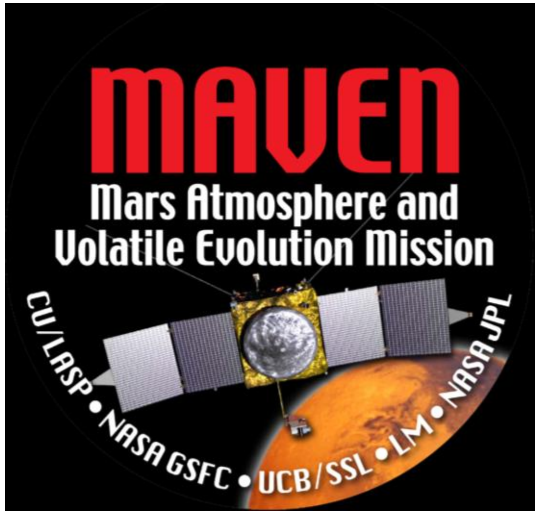
LPW/**E**xtreme **U**ltra-**V**iolet (LPW-EUV) – LASP

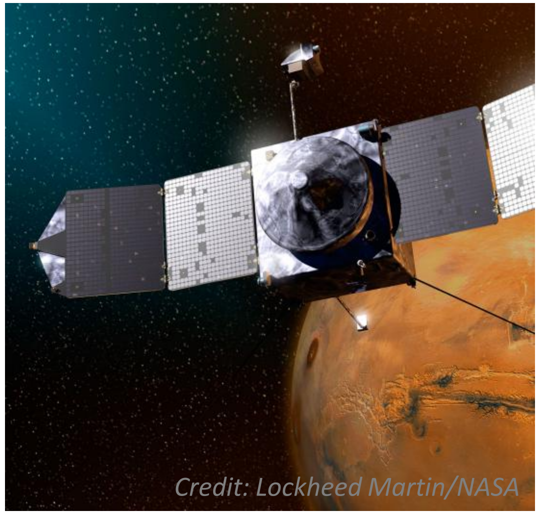
Solar **E**nergetic **P**article Detector (SEP) – SSL

Magnetometer **(MAG) – GSFC**

Supra-**T**hermal **a**nd **T**hermal **I**on **C**omposition (STATIC) - SSL

Credit: Connerney et al., 2012.



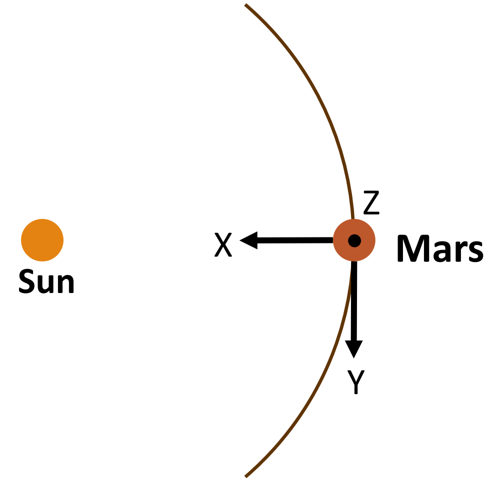


Credit: Lockheed Martin/NASA

Coordinates Systems

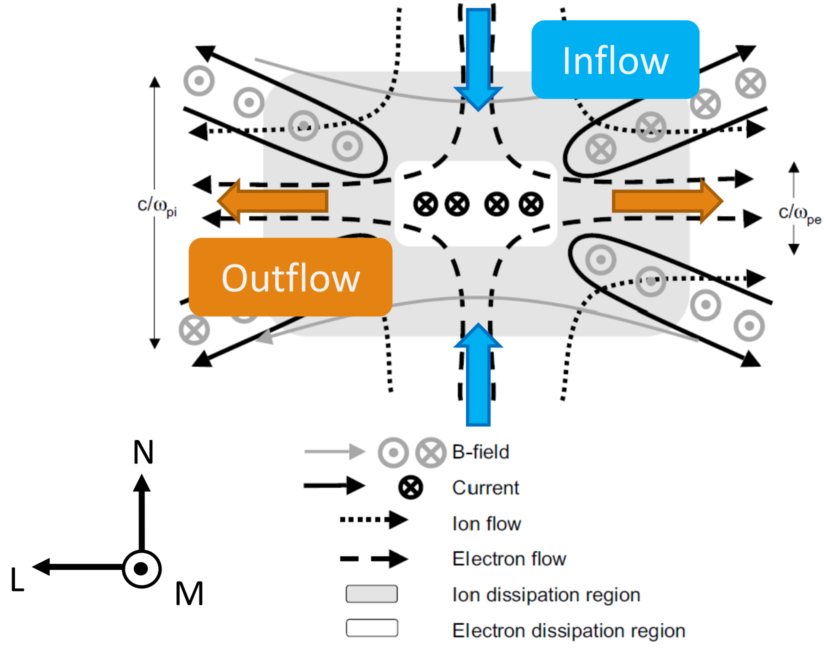
Mars Solar Orbital Coordinate (MSO)

- X : points from Mars to the Sun
- Y : points antiparallel to Mars' orbital velocity
- Z : completes the right-handed coordinate system



Current Sheet Coordinate (LMN)

- L : along the antiparallel magnetic fields
- M: along the X line
- N : along the current sheet normal



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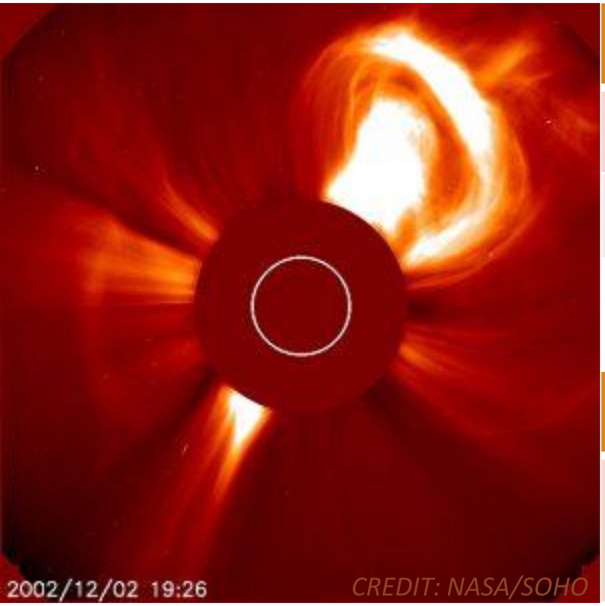
Mass Ejection in Martian Ionosphere?



Solar Atmosphere	**Martian Ionosphere**
Complex magnetic topologies	
Very low plasma beta	
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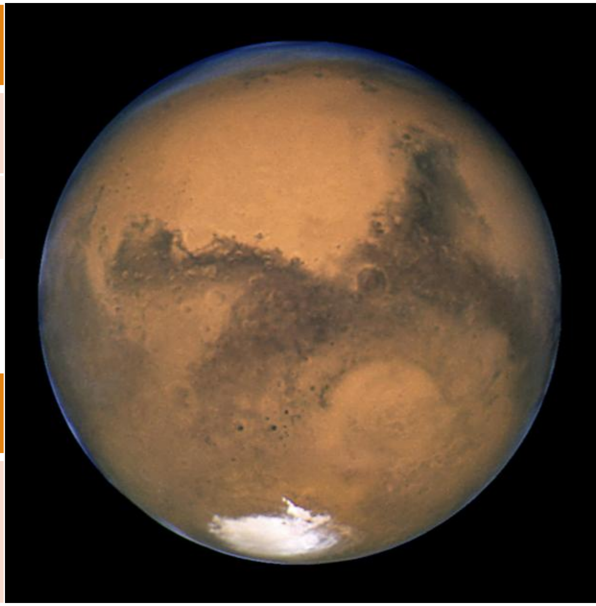
Facilitate the Occurrence of Magnetic Reconnections	
Coronal Mass Ejection (CME)	**Ionospheric Mass Ejection (IME)**

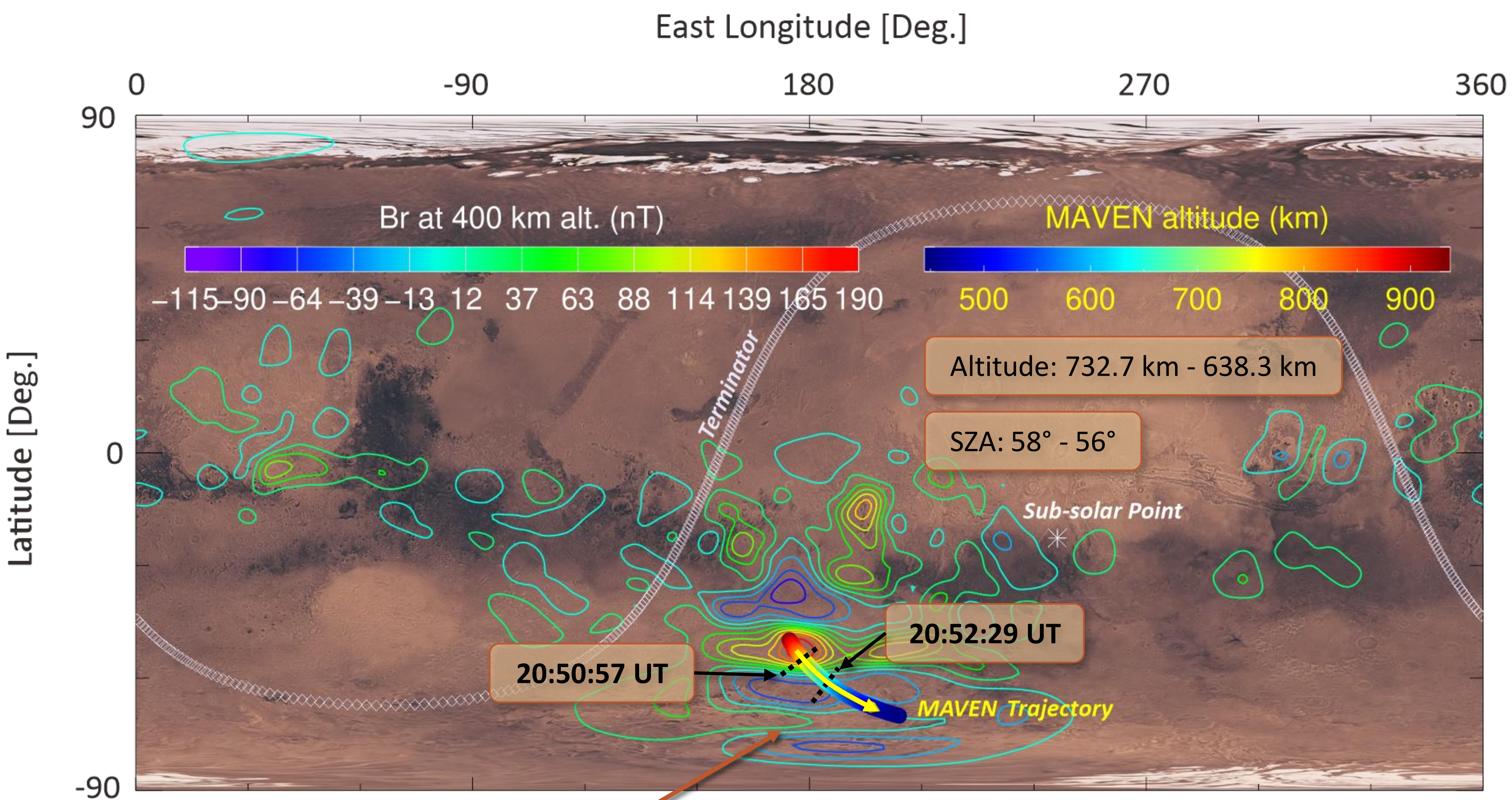


Explosive atmospheric ejection phenomena

How to detect IMEs?

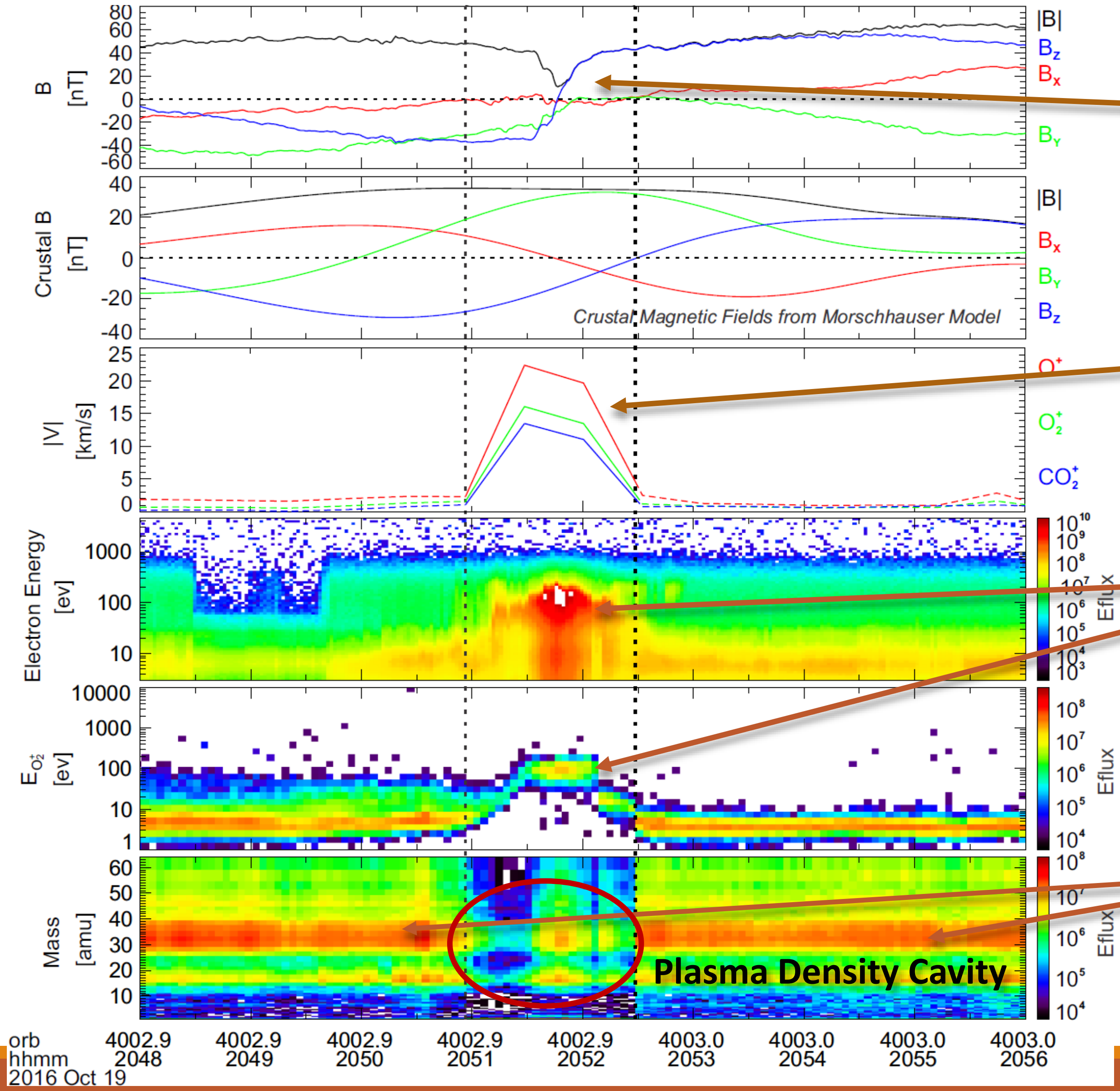
Density cavity in the ionosphere left by the mass ejection

19 December 2016 IME Event



Contour plot of crustal magnetic field Br at 400 km computed from the spherical harmonic model (Morschhauser et al., 2014)

Case Overview



- Dip in |B|
- Magnetic field reversal

Plasma jet

Electron heating & O_2^+ acceleration

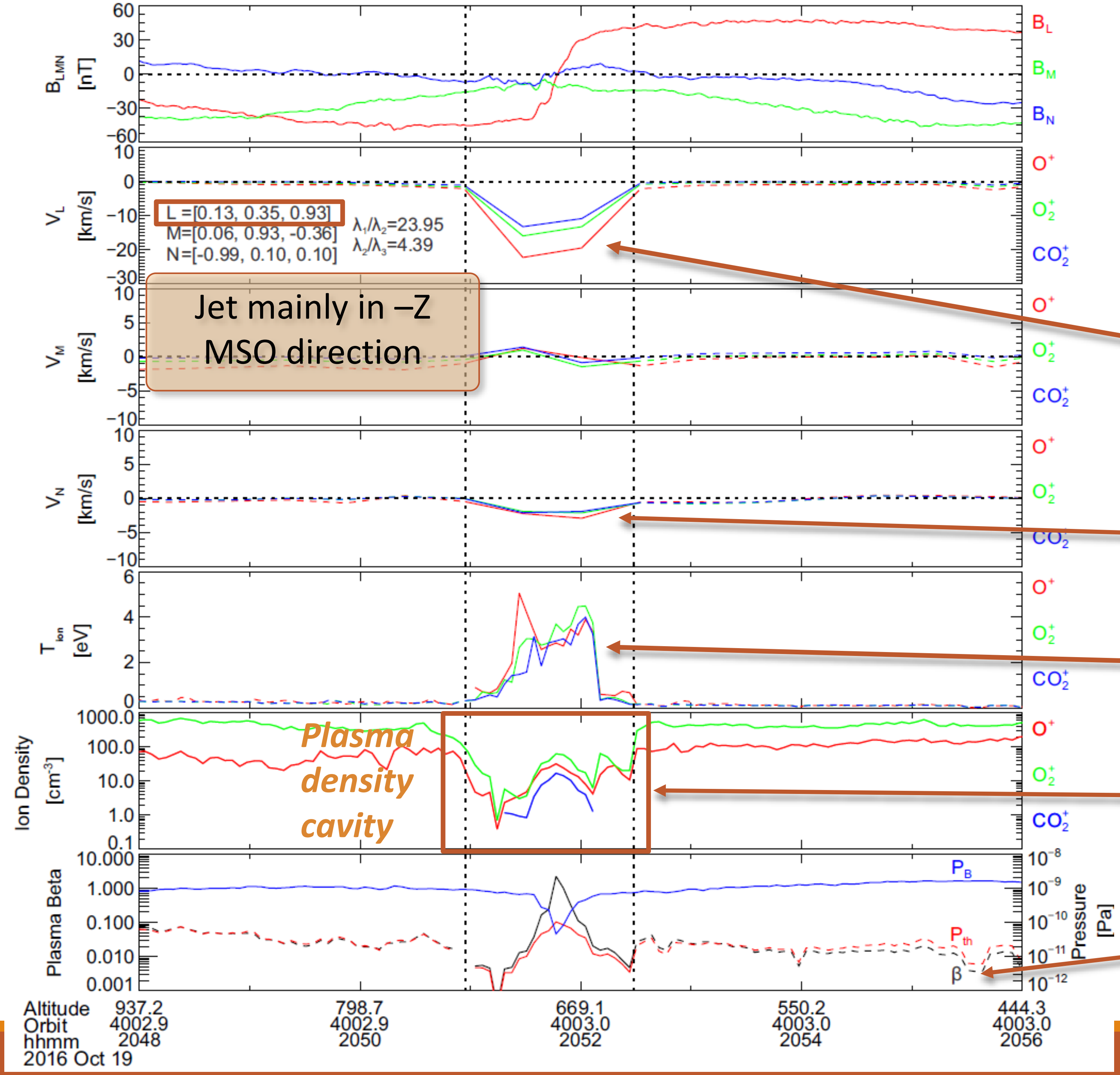
Magnetic Reconnection Signals

Heavy ions outside of the exhaust (mainly O_2^+)

MAVEN in the Ionosphere

行星环境与宜居性研究实验室
Planetary Environmental and Astrobiological Research Laboratory

Magnetic Reconnection Analysis



Jet mainly in –Z MSO direction

Reconnection jet ~ 20 km/s

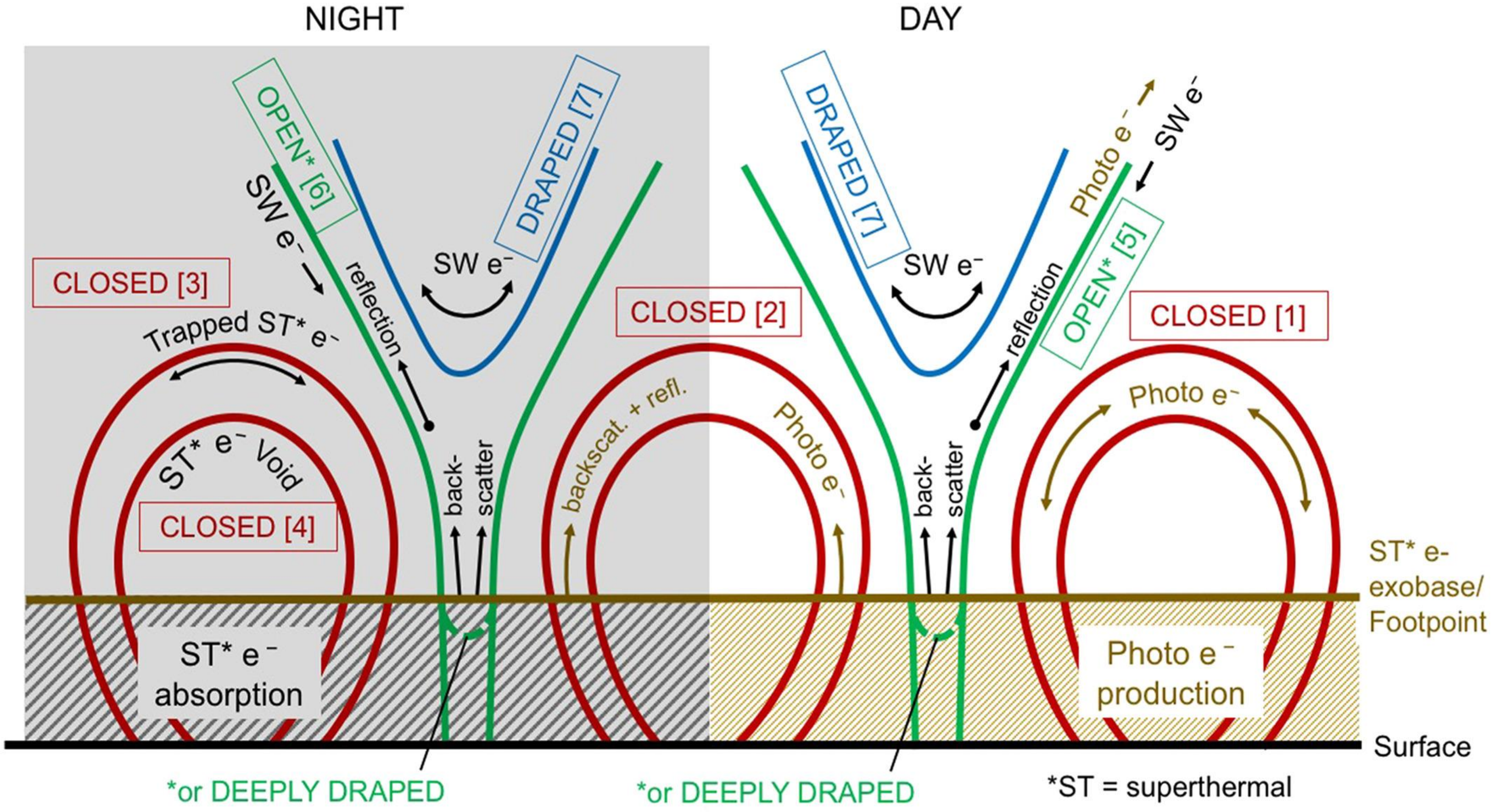
Local inflow velocity ~0.35 km/s

Heating

Densities dropped by almost two orders

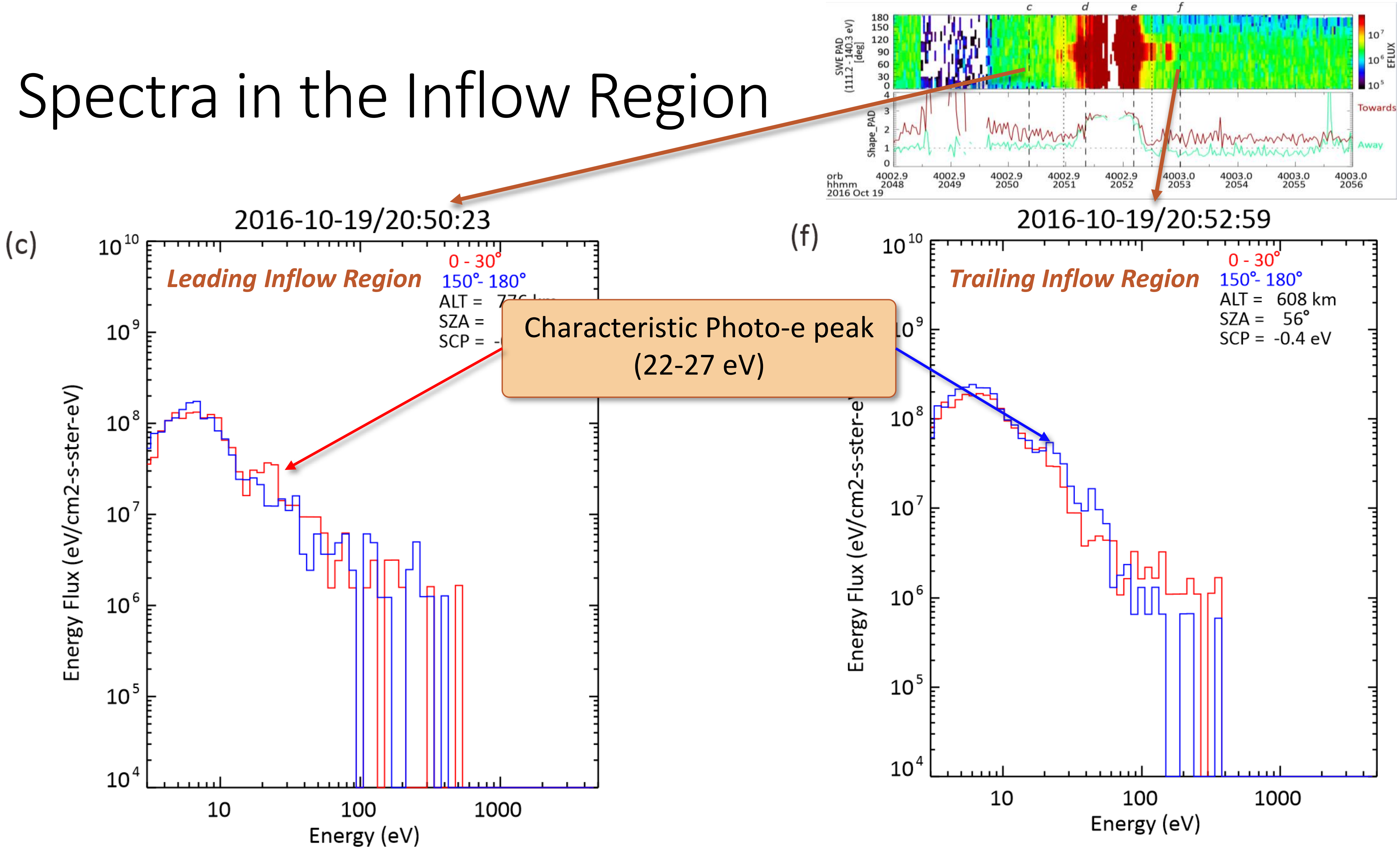
Very low plasma beta

Magnetic Topology Analysis

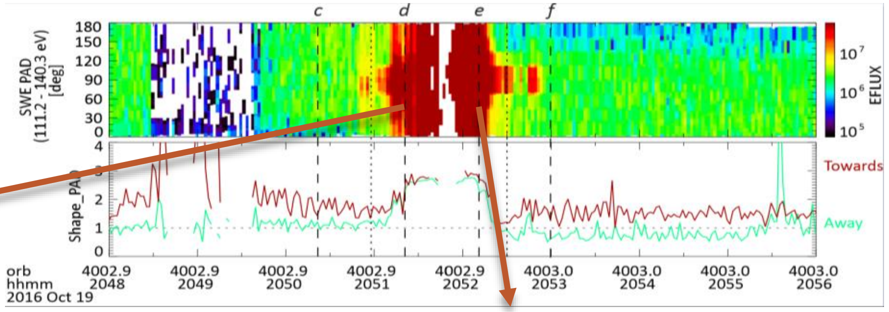


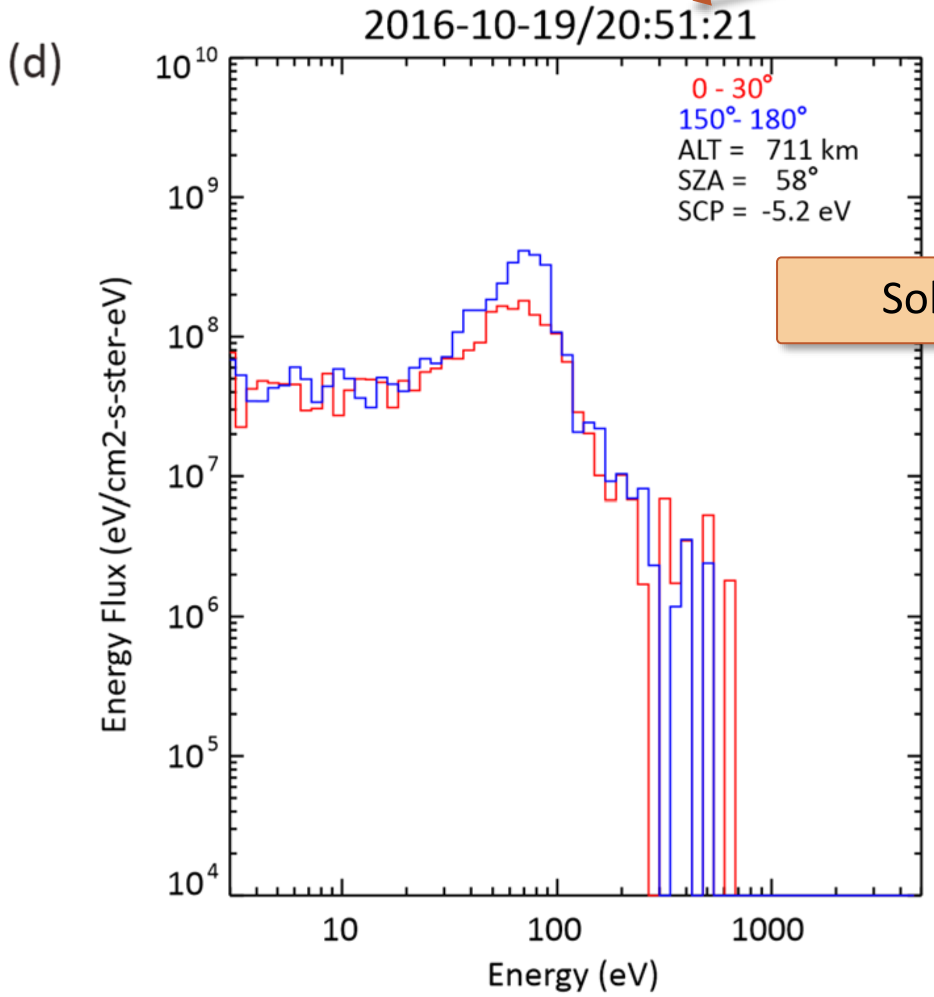
Credits: Xu et al., 2019

Spectra in the Inflow Region



Spectra in the Exhaust





Solar wind electrons

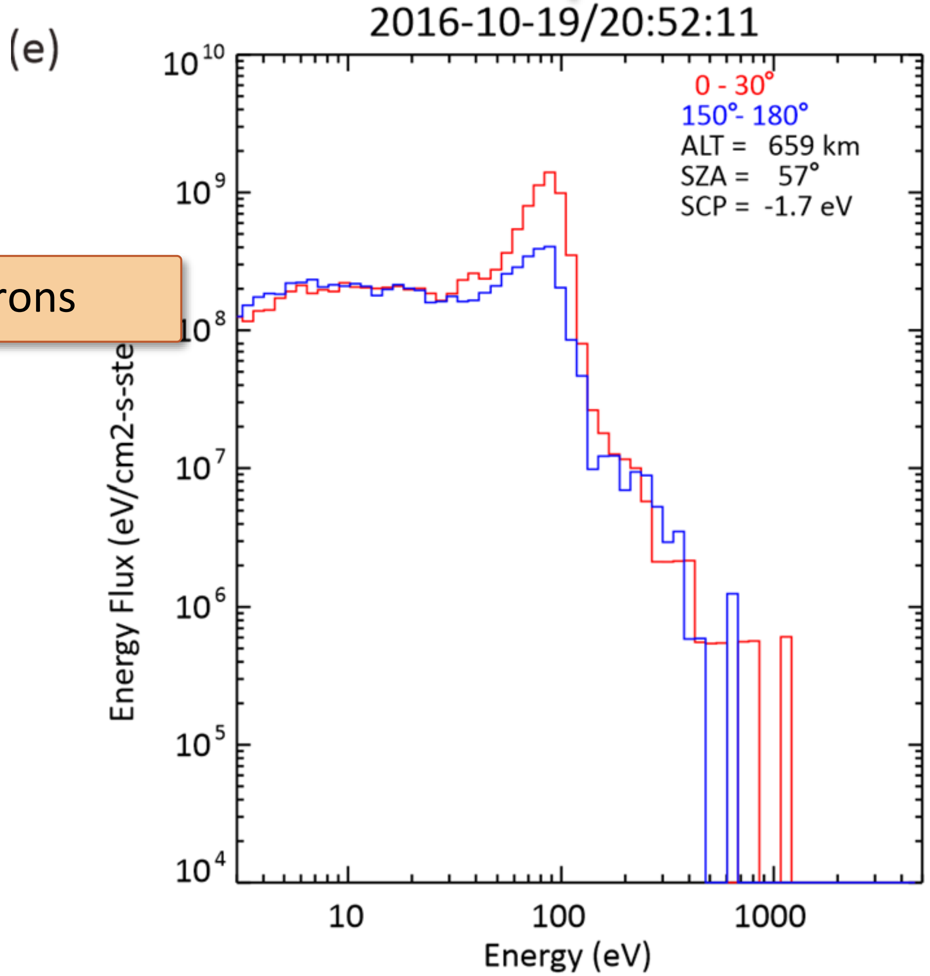
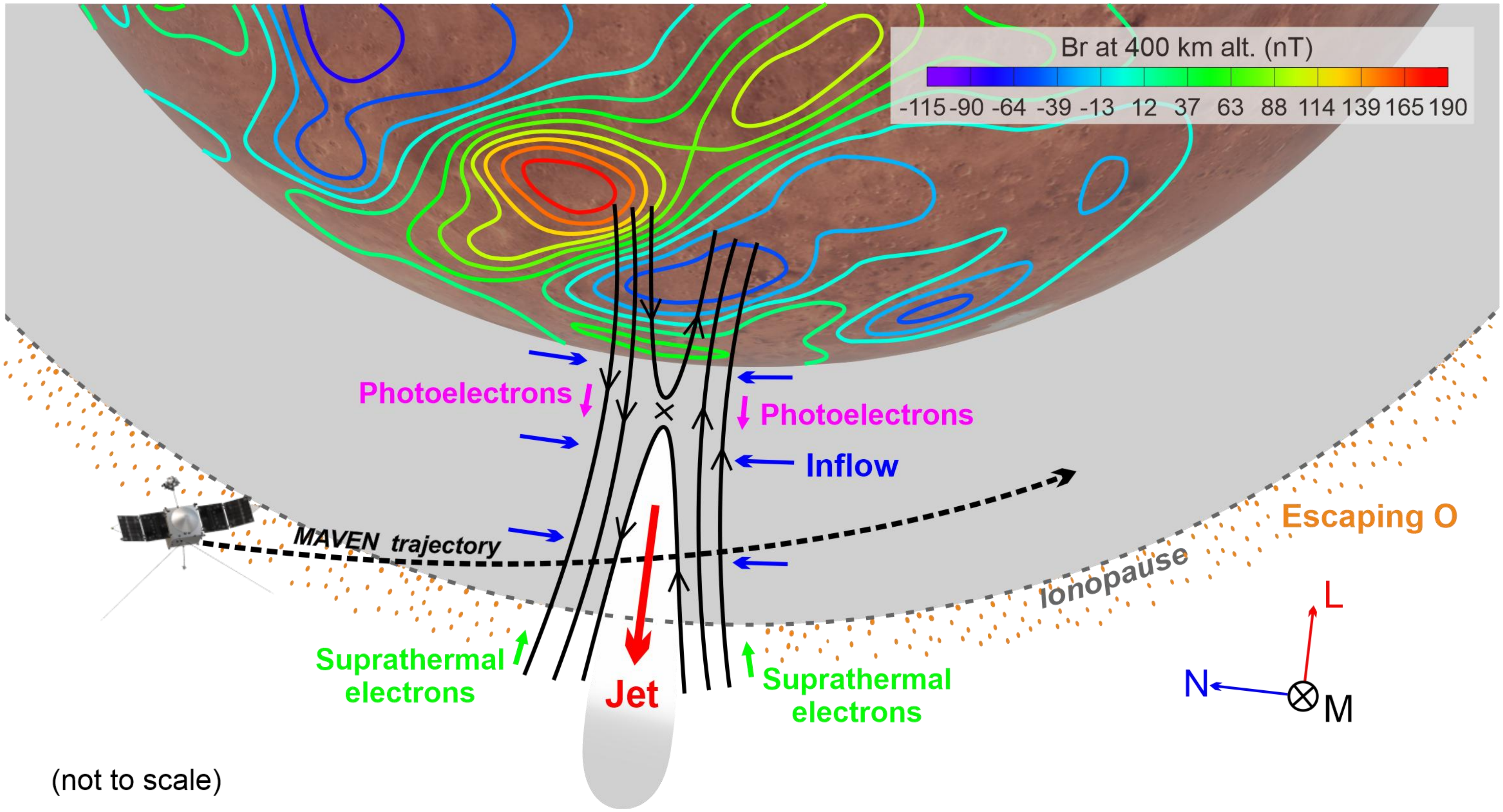
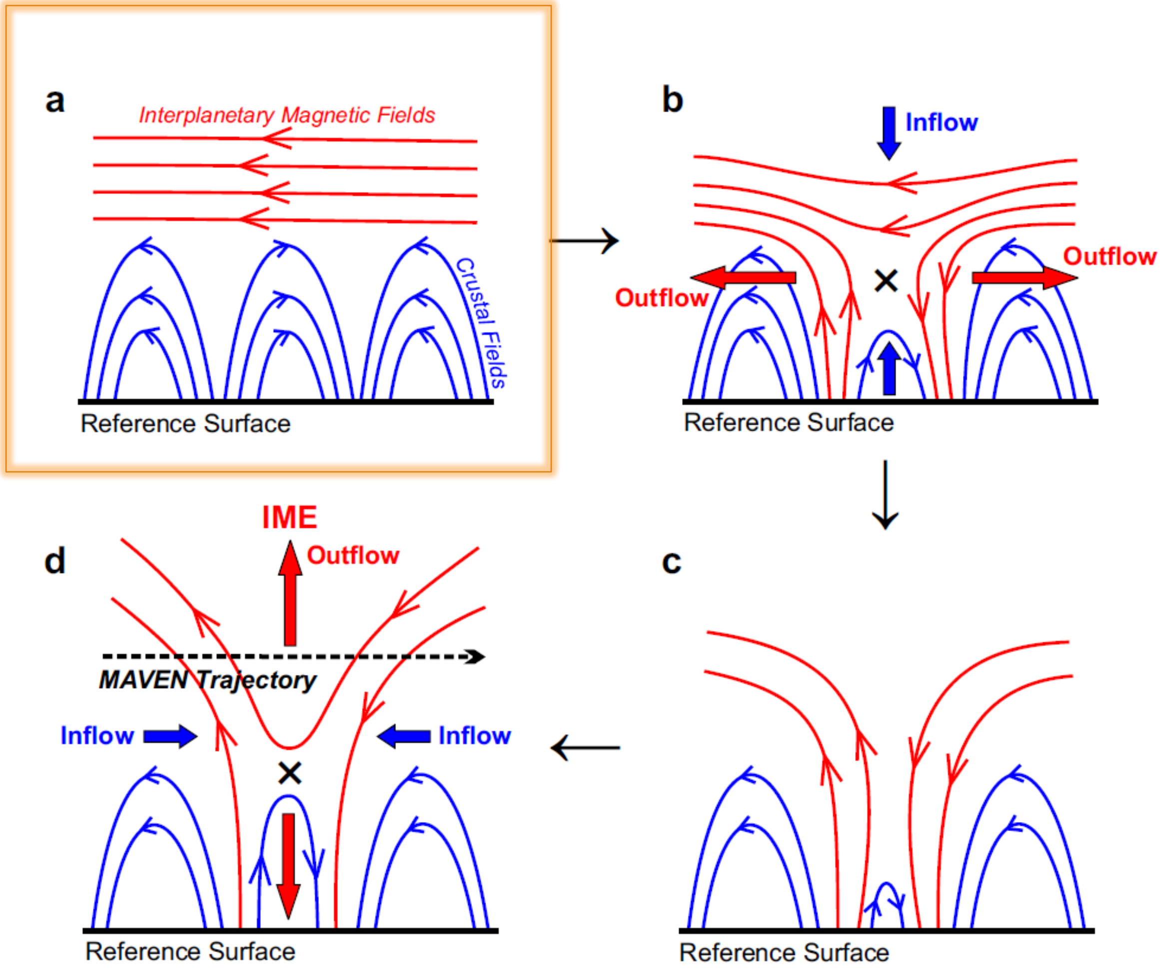


Diagram of MAVEN Crossing



Possible Mechanism of IMEs



[illegible] resulting in magnetic reconnections between them

Ejected Mass in a Single IME

Using ion densities measured by MAVEN in the same orbit with a periapsis altitude of 179 km around 55^{o} SZA.

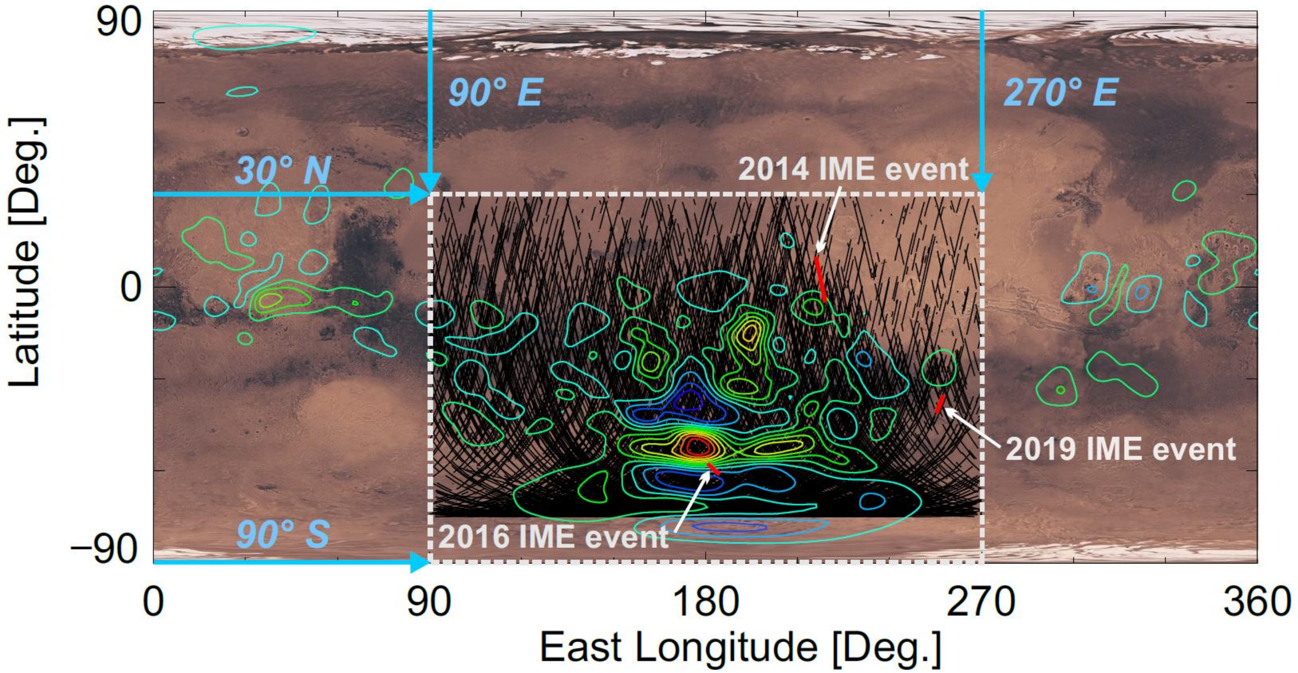
- Ignore the tilt of the exhaust
- Reconnection X line spanned 550 km
- Width of the exhaust calculated to be 132 km
- Assume 99% of the ionospheric plasma in the volume of the reconnection exhaust from an **altitude of ~300 km** to the **ionopause** has been ejected

Total loss of O up to **1.3 kg**

Ion loss rate increased by **2.4×10^{24} s^{-1}**

Comparable to the global O ion loss rate

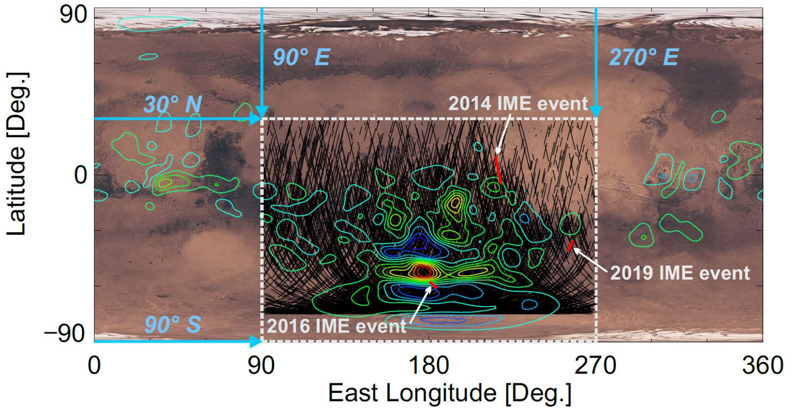
Search for Possible IMEs



- MAVEN in the dayside of Mars (SZA ≤ 90°)
- MAVEN above the strong crustal fields region
  - longitudes between 90°E and 270°E
  - latitudes between -90°S and 30°N

- Check data segments for magnetic reconnection signatures with a density cavity of heavy ionospheric ions in the ionosphere ($\rho_{O_2^+} > 1000\ cm^{-3}$)
- 9322 track segments
- Identified three IME events on **18 October 2014**, **19 December 2016**, and **19 April 2019**

Cumulative Ion Loss



- Occurrence Rate Estimation
  - $T_{potential}$: the total MAVEN flight time in potential IME regions
  - $T_{dayside}$: the duration the potential regions remain on the dayside during a Martian day (Sol).
  - Occurrence rate is calculated as $3/T_{potential}$, given that three IME events are identified within $T_{potential}$. Further calculated as $(3/T_{potential} * T_{dayside})$ per Sol
  - $T_{potential}$ ~440 min, and $T_{dayside}$ ~660 min = an IME occurrence rate of about 1.5 per Sol
  - Considering the global crustal field, the rate can reasonably be doubled to be **3 per Sol**
- Cumulative Mass Estimation in 4.2 Billion Years

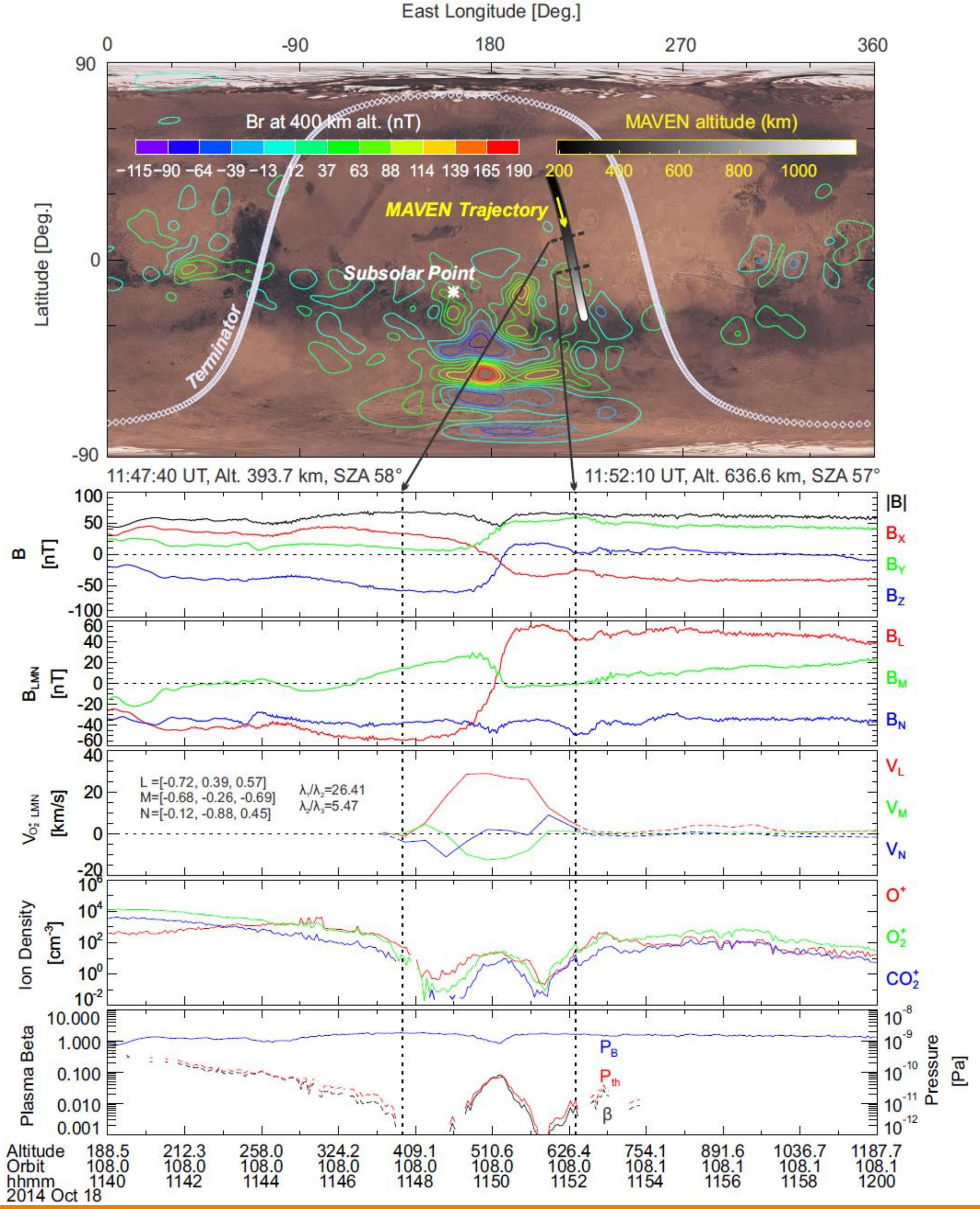
365 Earth Days per Year

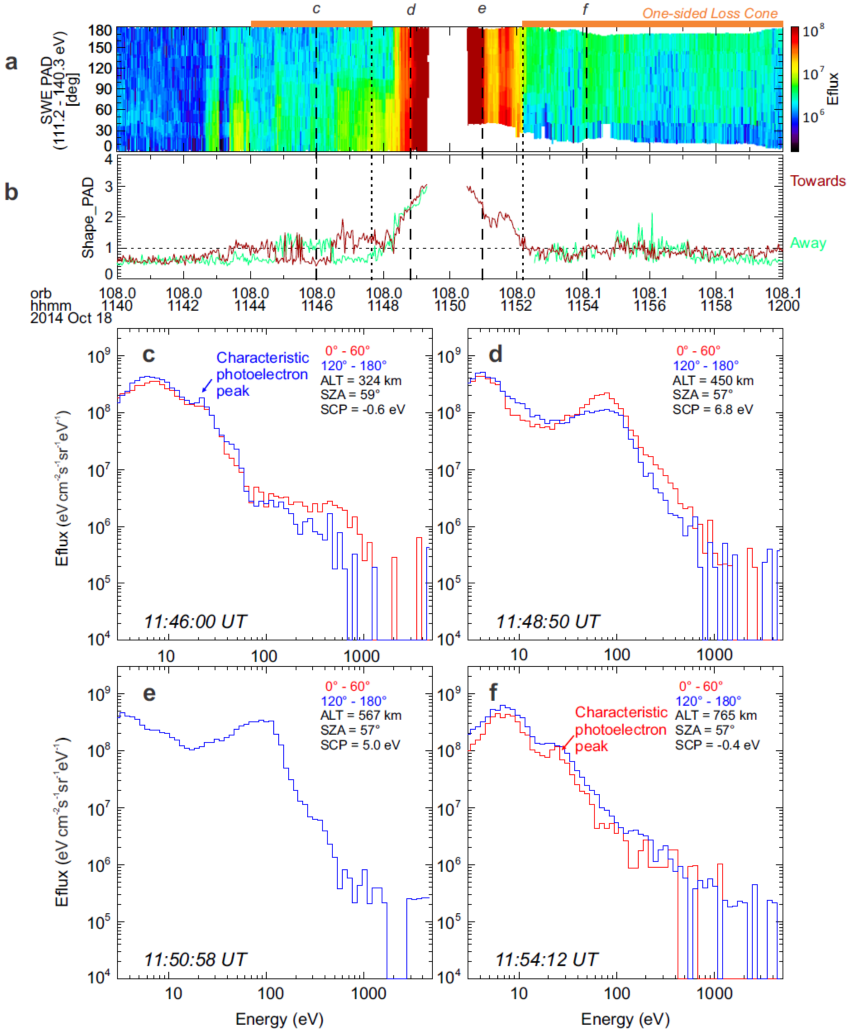
$$Total\ O\ ion\ loss = 1.3 \times 3 \times \frac{4.2 \times 10^{9} \times 365}{1.025} = 5.8 \times 10^{12}\ \boldsymbol{kg}$$

1.3 kg per IME

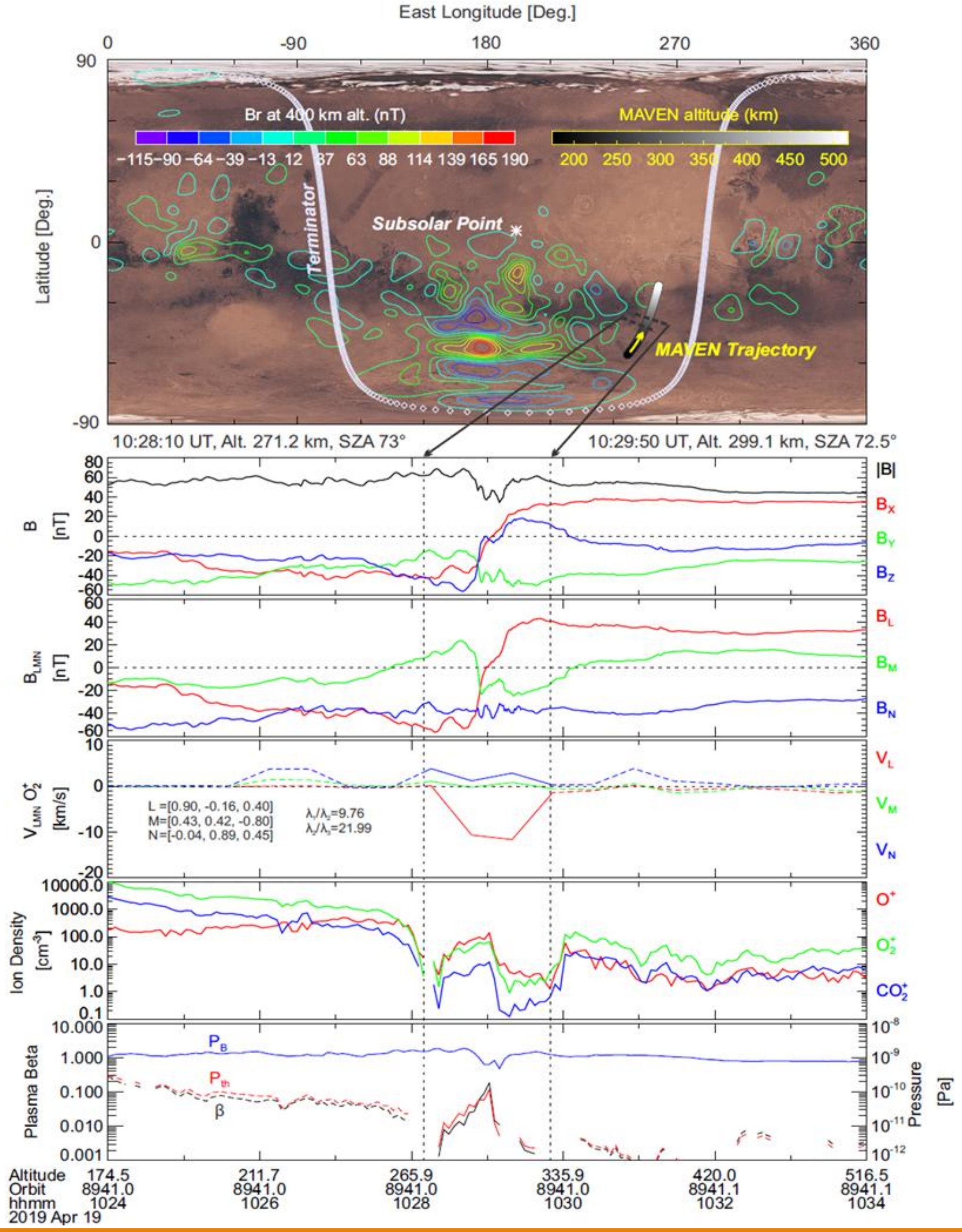
3 IMEs per Sol

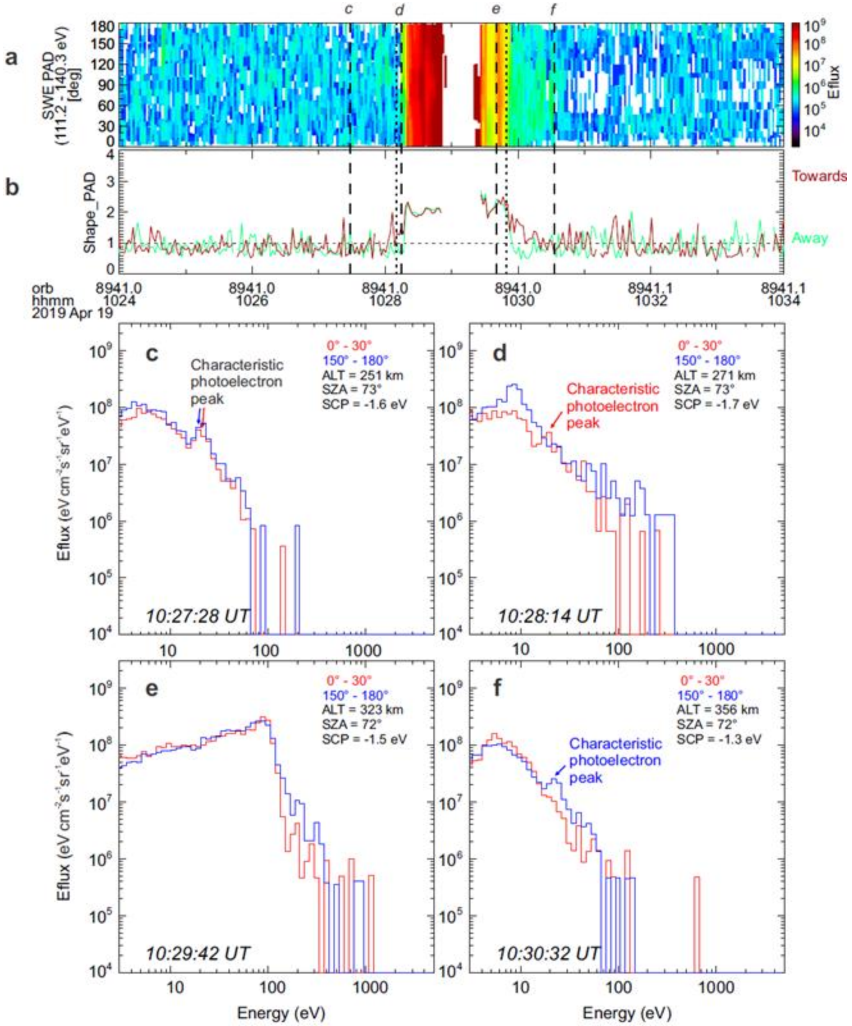
1 Sol ~ 1.025 Earth Day





18 October 2014 Event





19 April 2019 Event

Discussion and Conclusion

- Explosive mass ejections can occur on Mars-like planets with an atmosphere and crustal fields, in addition to stars.
- Magnetic reconnection can effectively eject ionospheric mass.
- Some giant flux rope were probably ejected from the ionosphere in the form of IMEs.
- Occurrence rate of the IME on Mars should be much higher than that revealed by MAVEN observations.
- IMEs partial contributed the atmospheric loss in Mars, especially in the early age of the solar system when the solar wind was much stronger than present.

Thanks for your attention!

ydye@outlook.com or
yeyd5@mail.sysu.edu.cn