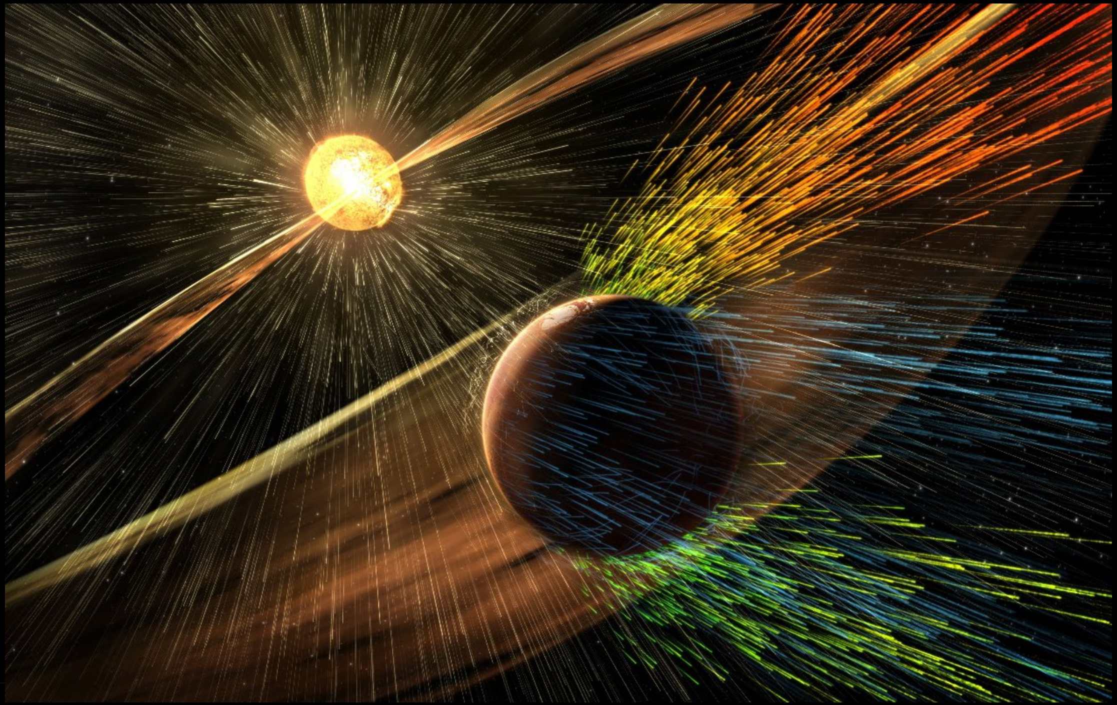


Solar system studies of atmospheric escape

lessons from the MAVEN mission

Mike Chaffin

October 1 2023

ExoPAG San Antonio

Follow the water

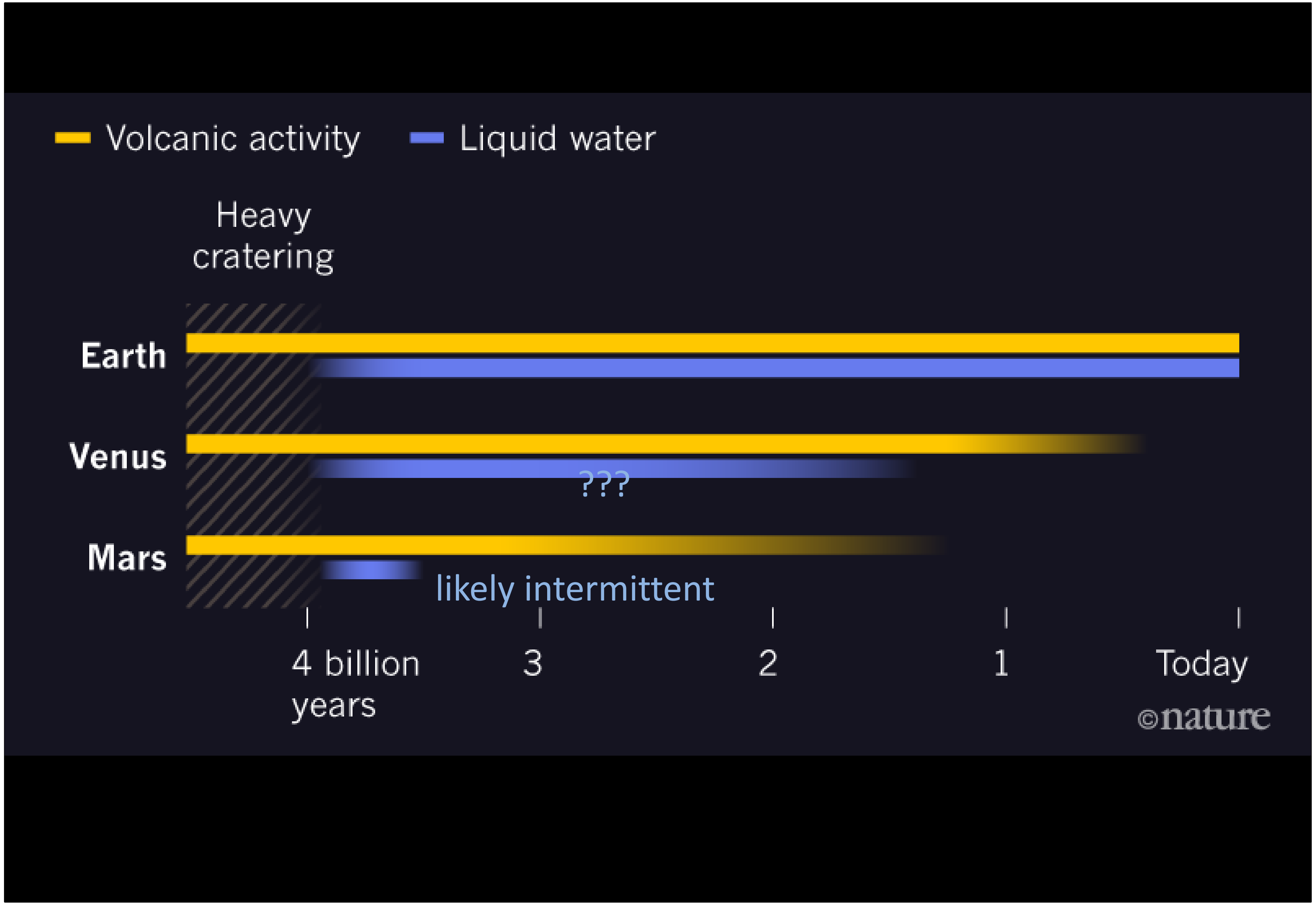
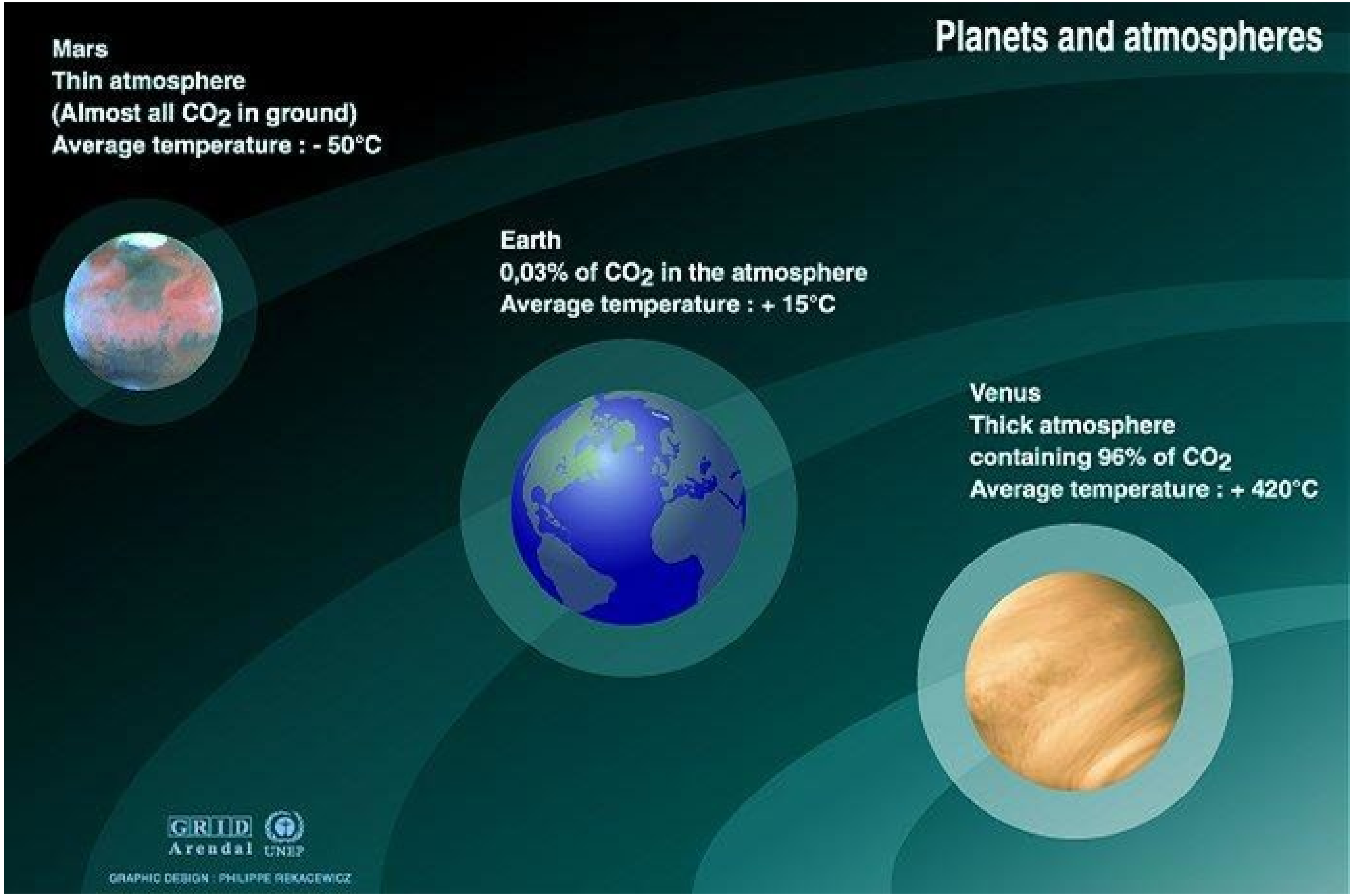


Image courtesy of Darby Dyar, Nature

- Habitability is a major question for our terrestrial neighbors and exoplanets
- This heavily relies on the presence of liquid water and atmospheric pressure
  - Post- hydrodynamic
  - Post-bombardment

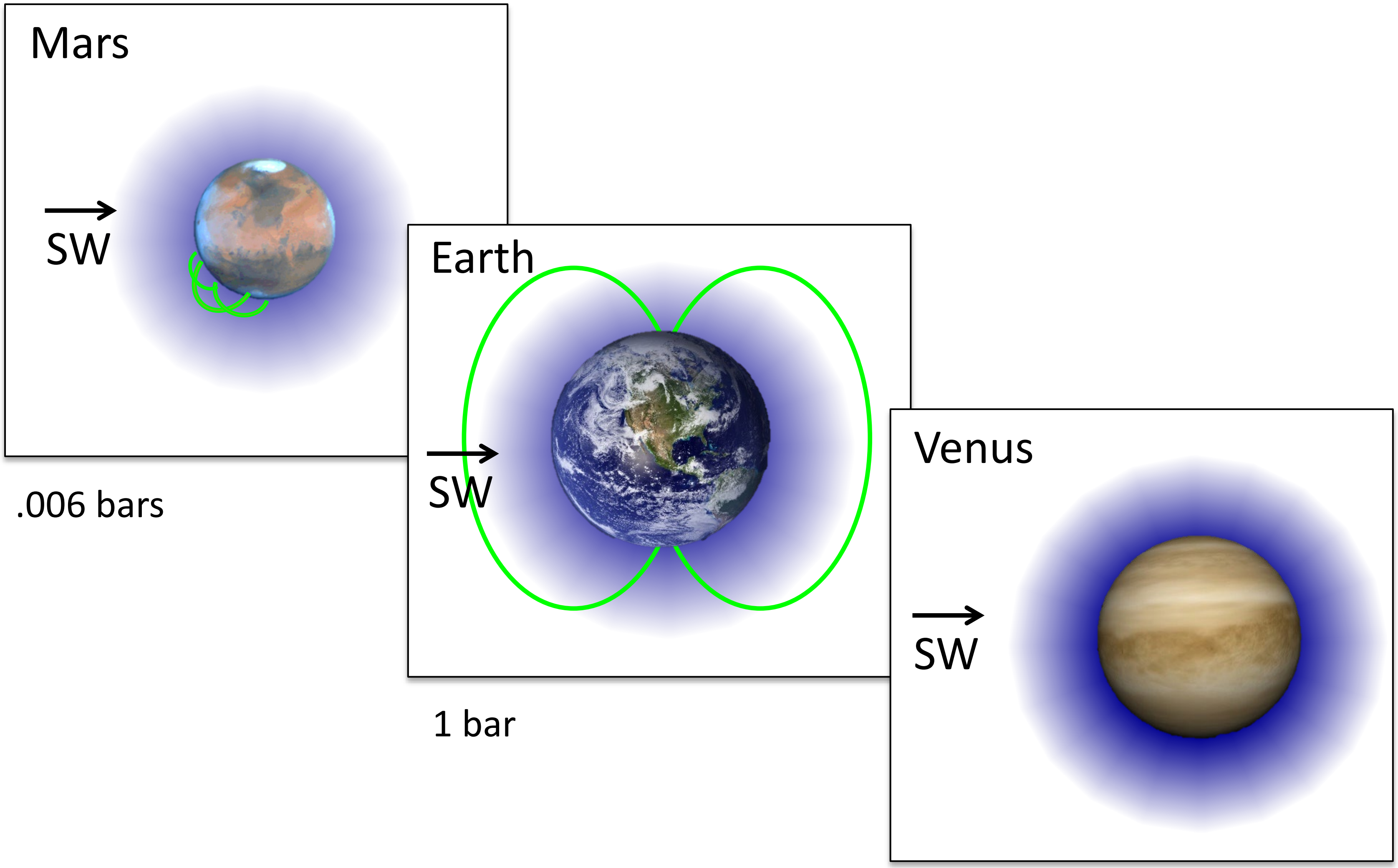
How do we know there was water?

Terrestrial planets: atmospheres



- Both Earth and Venus have a thick atmosphere capable of sustaining liquid water

Terrestrial planets: atmospheres



.006 bars

1 bar

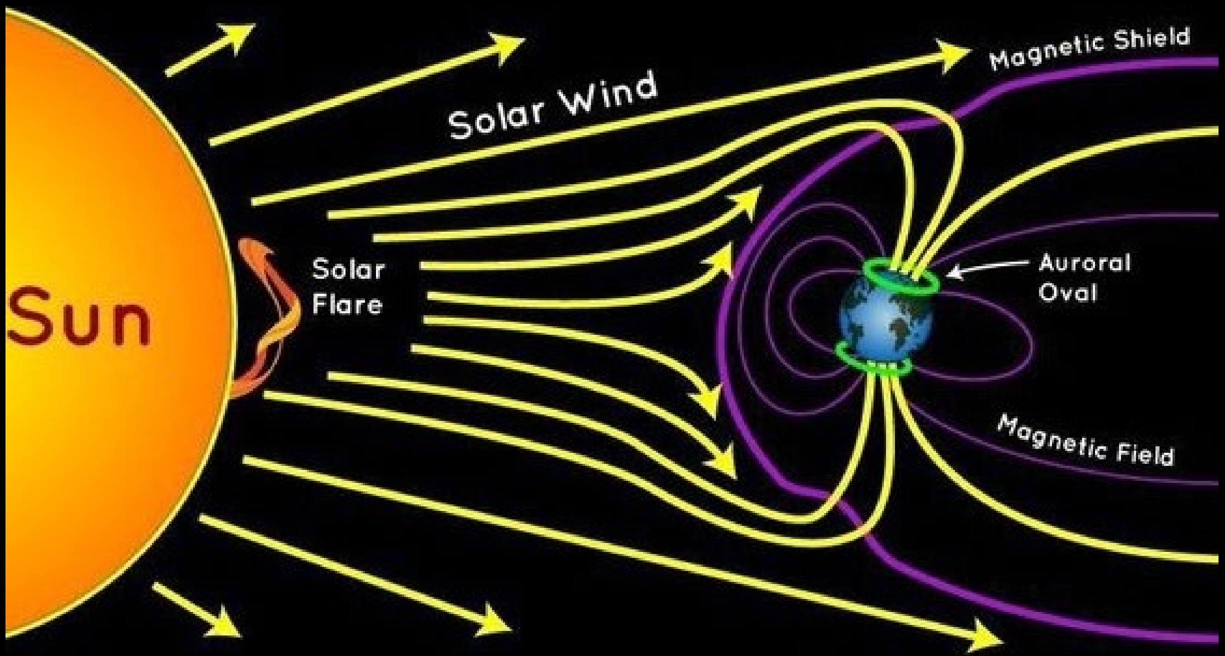
90 bars

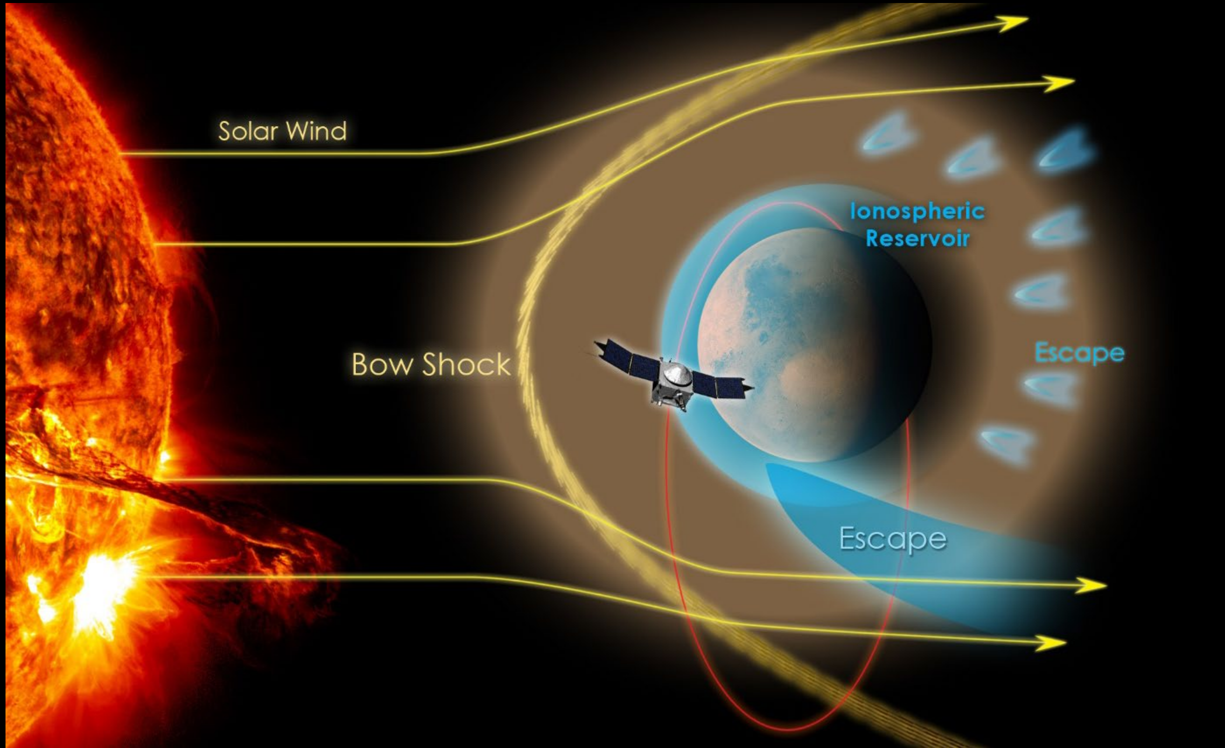
- Both Earth and Venus have a thick atmosphere capable of sustaining liquid water
- However, unlike Earth, Venus and Mars lack a dipole magnetic field
- A magnetic field significantly influences the physics that drive atmospheric escape

Magnetospheres 101

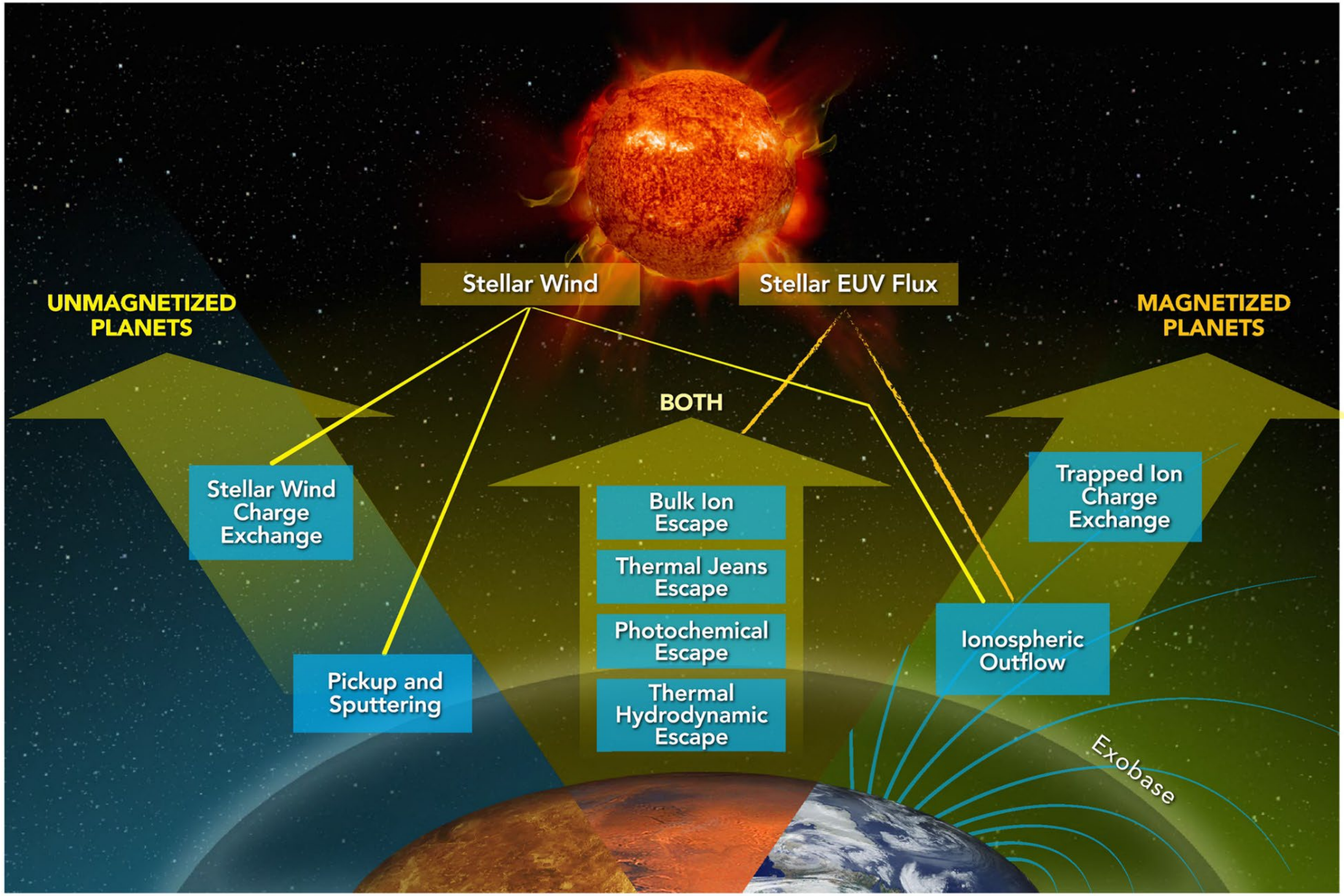
- The **solar wind** is a stream of charged particles (protons, electrons, alphas) originating from the solar corona
- As the sun rotates, the stream of particles form a spiral and carry the sun's magnetic field out with it
- This magnetic field is the **interplanetary magnetic field, or IMF**

Courtesy of GSFC





Basic atmospheric escape processes



Gronoff et al 2019

Neutral escape

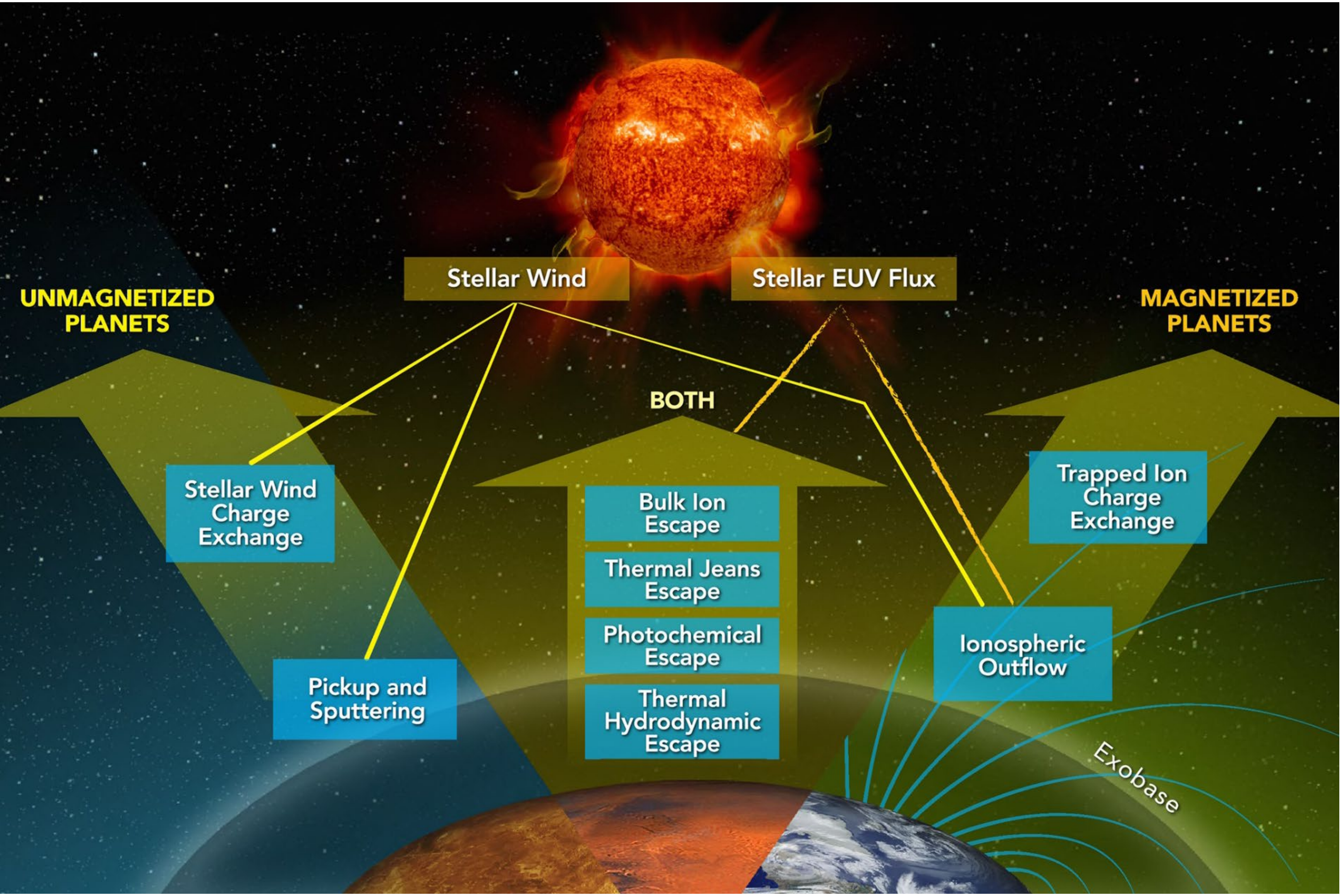
- Jeans <-> Hydrodynamic
- Photochemical
- Sputtering

Ion escape

- Polar wind
- Ion outflow / fountain
- Auroral wind
- Pickup / bulk ion

Escape velocity

	Venus	Earth	Mars
		Escape velocity	
	10.4 km/s	11.2 km/s	4.9 km/s
		Escape energy	
H	0.6 eV	0.7 eV	.14 eV
O	8.9 eV	10.3 eV	2.1 eV
O_2	17.8 eV	20.6 eV	4.2 eV



We often focus on escape processes and energy inputs…

Supply from below is equally important!

Two paradigms for atmospheric escape

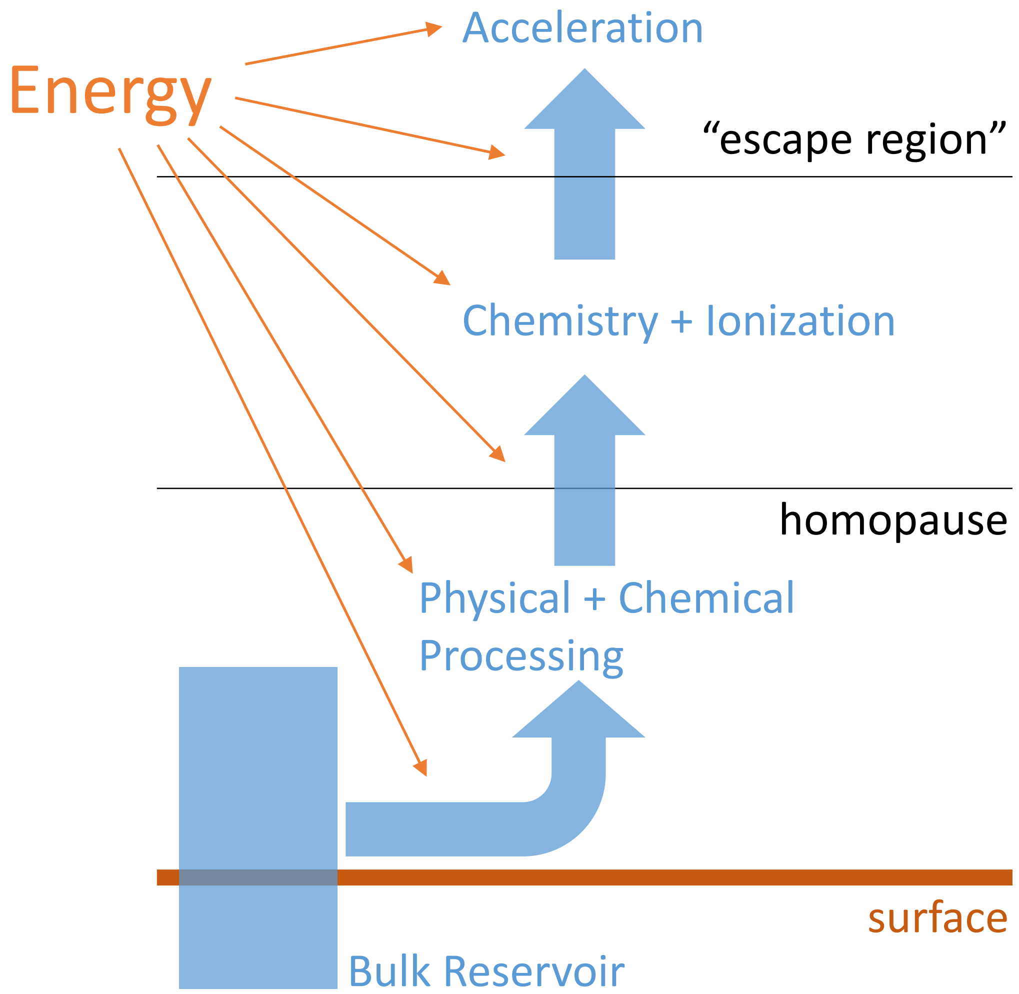
Energy Limited Escape

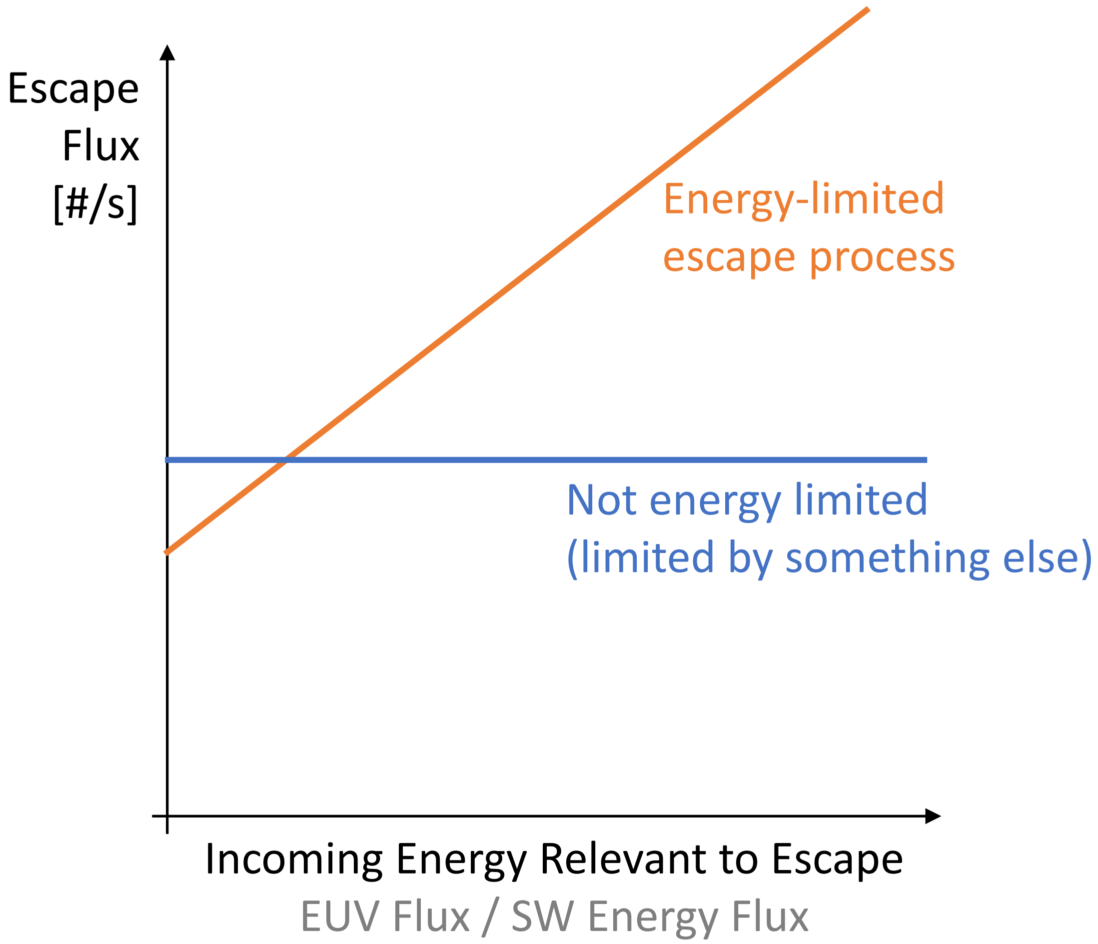
- Abundant supply to escape region
- Escape energy difficult to obtain
- Escape process itself limits loss
- Typical for major species (N, O, C)
- “Photoevaporation” parameterized by stellar flux, escape efficiency

Supply / Diffusion Limited Escape

- Supply to escape region difficult
- Abundant escape energy
- Loss is limited well below escape region
- Typical for light minor species (H)
- Situation for H escape at Venus, Earth, Mars

What is an energy limit anyway?





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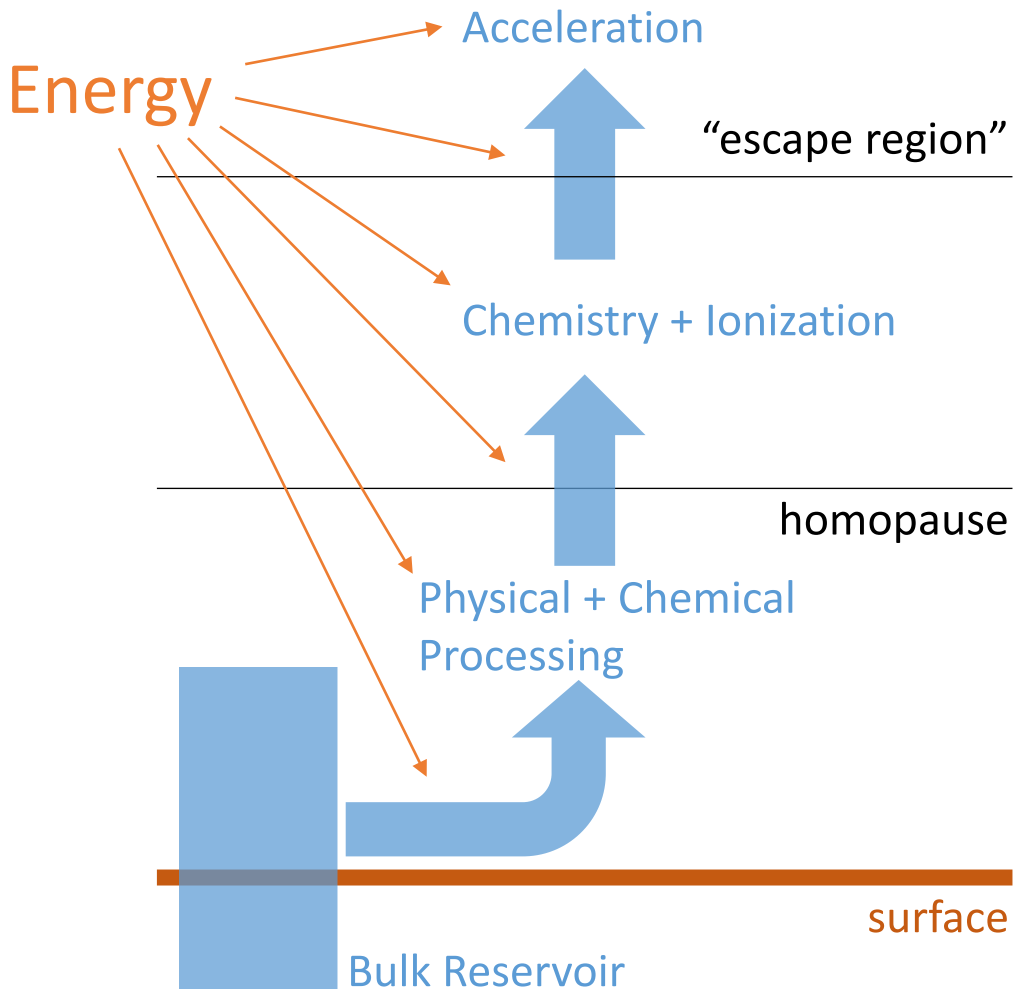
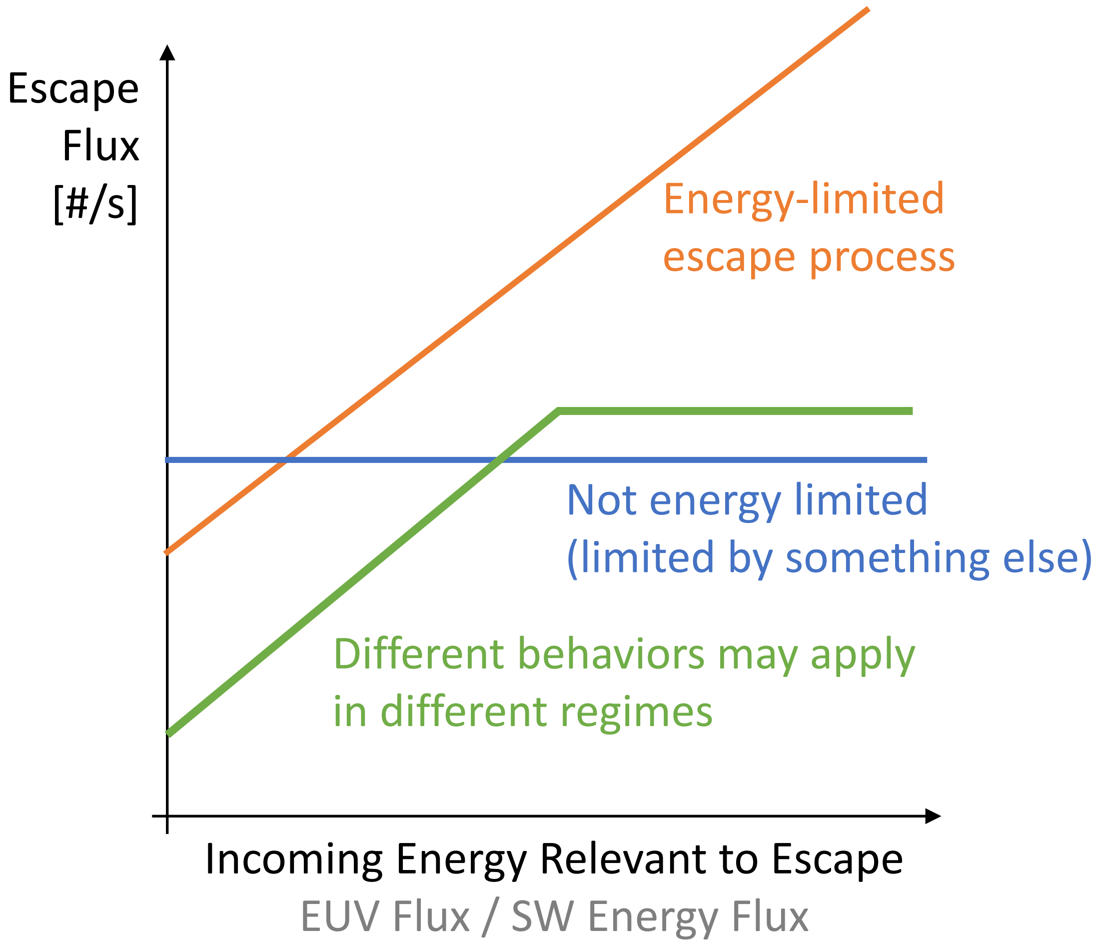




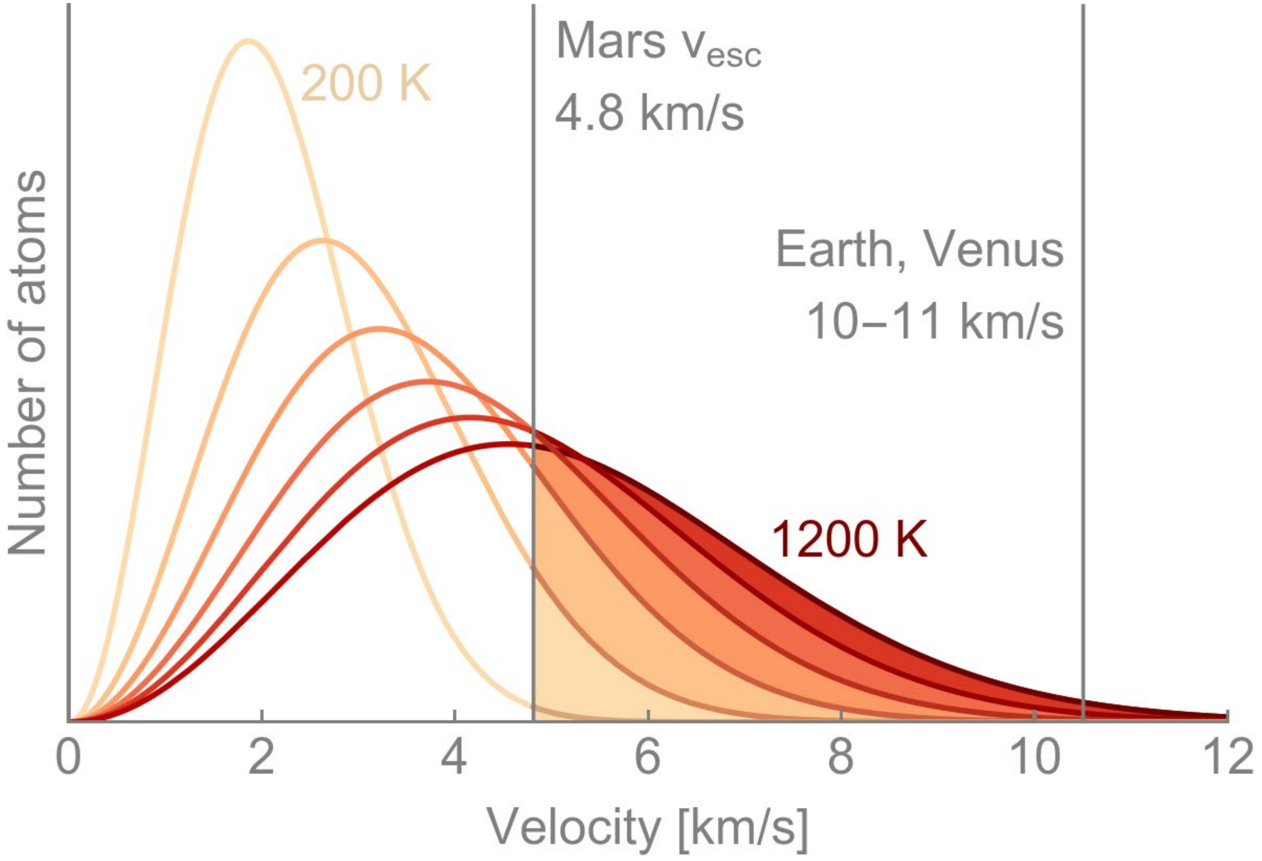
Jeans Escape: Thermal H Loss to Space

- At the highest altitudes, H atoms in the tail of the thermal velocity distribution can escape
- Described by *Jeans parameter* λ:

$$\lambda = \frac{\text{gravitational potential energy}}{\text{gas kinetic energy}}$$

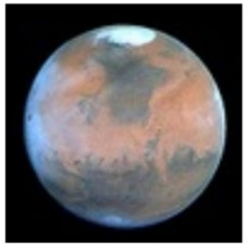
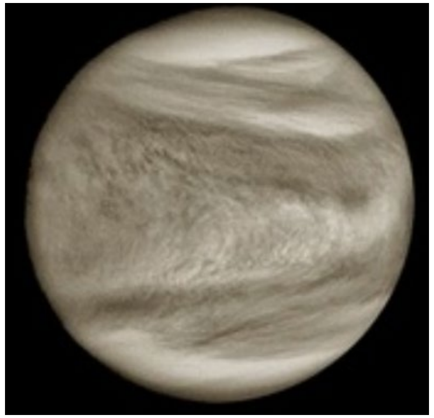
$$= \left(\frac{v_{\text{escape}}}{v_{\text{thermal}}}\right)^2 = \frac{GMm_{\text{H}}}{kTr_{\text{exo}}}$$

higher λ => less escape



- If λ < 2-3, fluid effects matter and escape is hydrodynamic

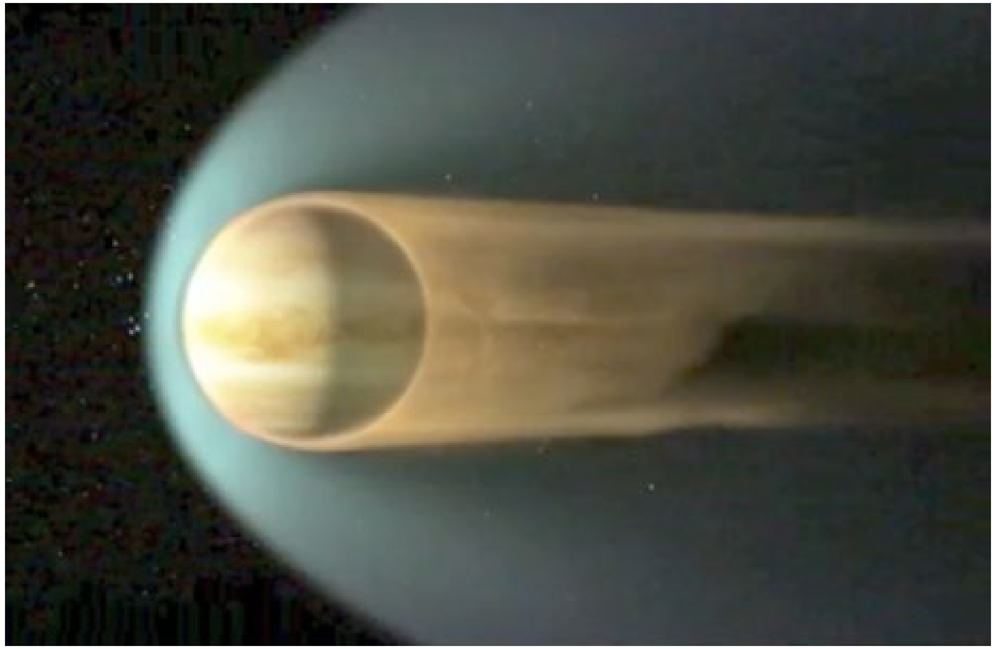
Jeans Escape at Venus, Earth, Mars

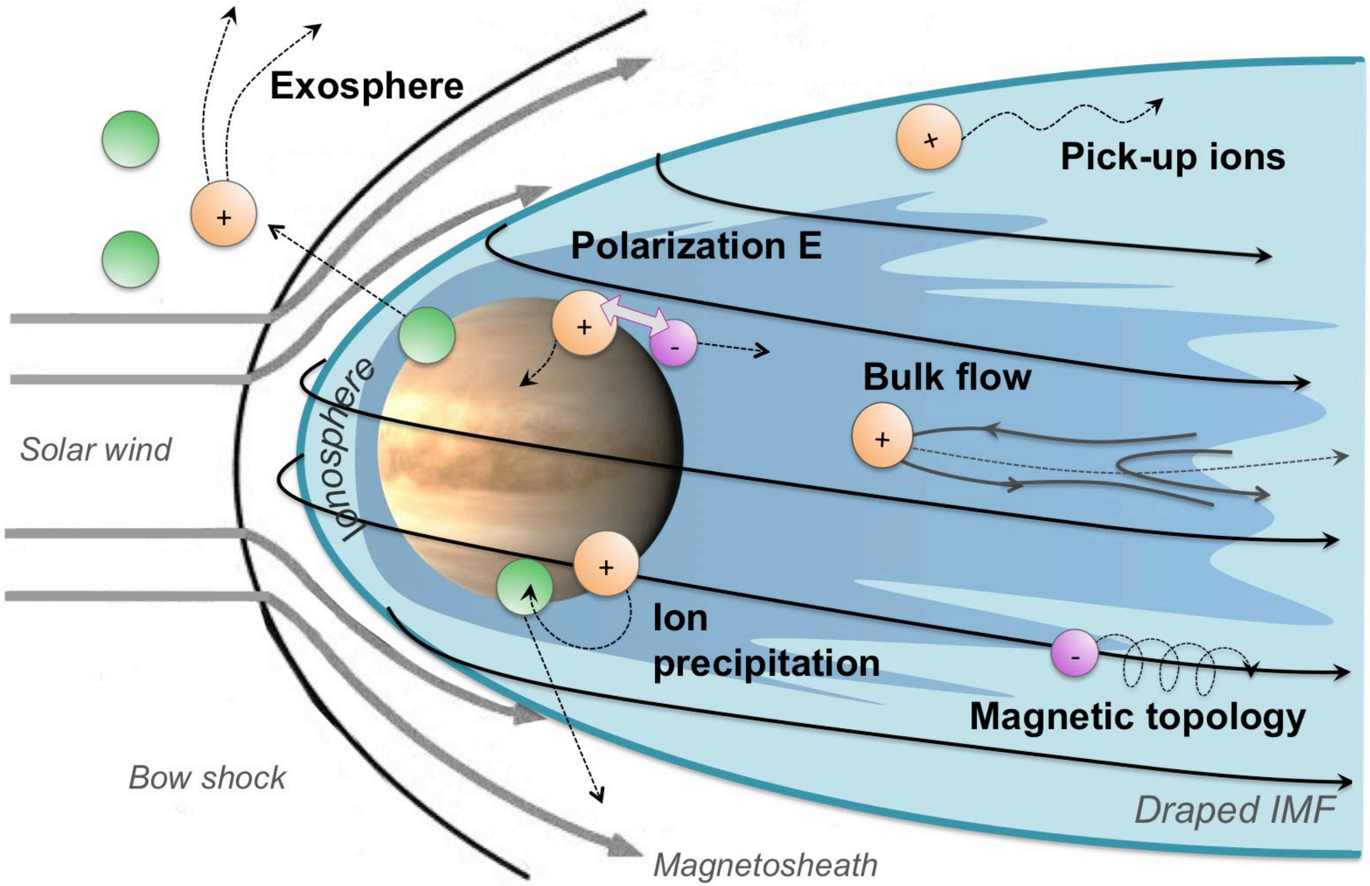
			
Thermosphere	hot -- O_2/N_2 -- 1000 K	cold -- CO_2 -- 220 K	cold --- CO_2 --- 275 K
Gravity	high --- 11 km/s	low --- 5 km/s	high --- 10 km/s
Jeans Escape	substantial --- $\lambda \approx 8$	substantial --- $\lambda \approx 7$	insignificant --- $\lambda \approx 24$

If Jeans escape were the only mechanism,
Venus would still have all its original water

Ion escape: unmagnetized planets

- The neutral upper atmosphere at Mars and Venus gets ionized and those ions sense electric and magnetic fields, which accelerate the ions past the escape velocity





- Ions can escape in several ways
  – These ion escape processes all depend on the **solar wind**

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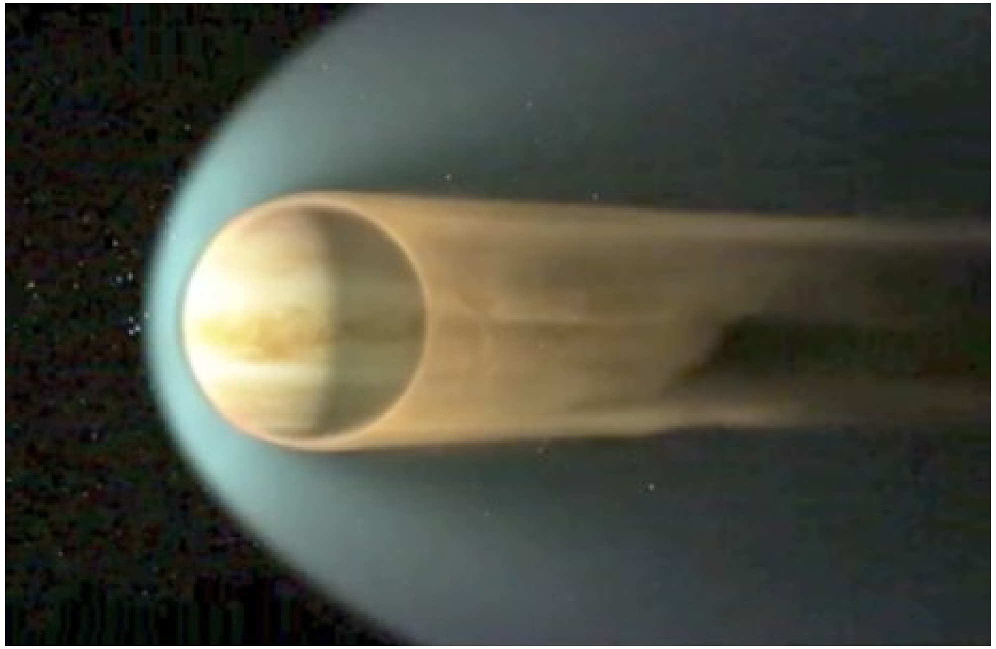

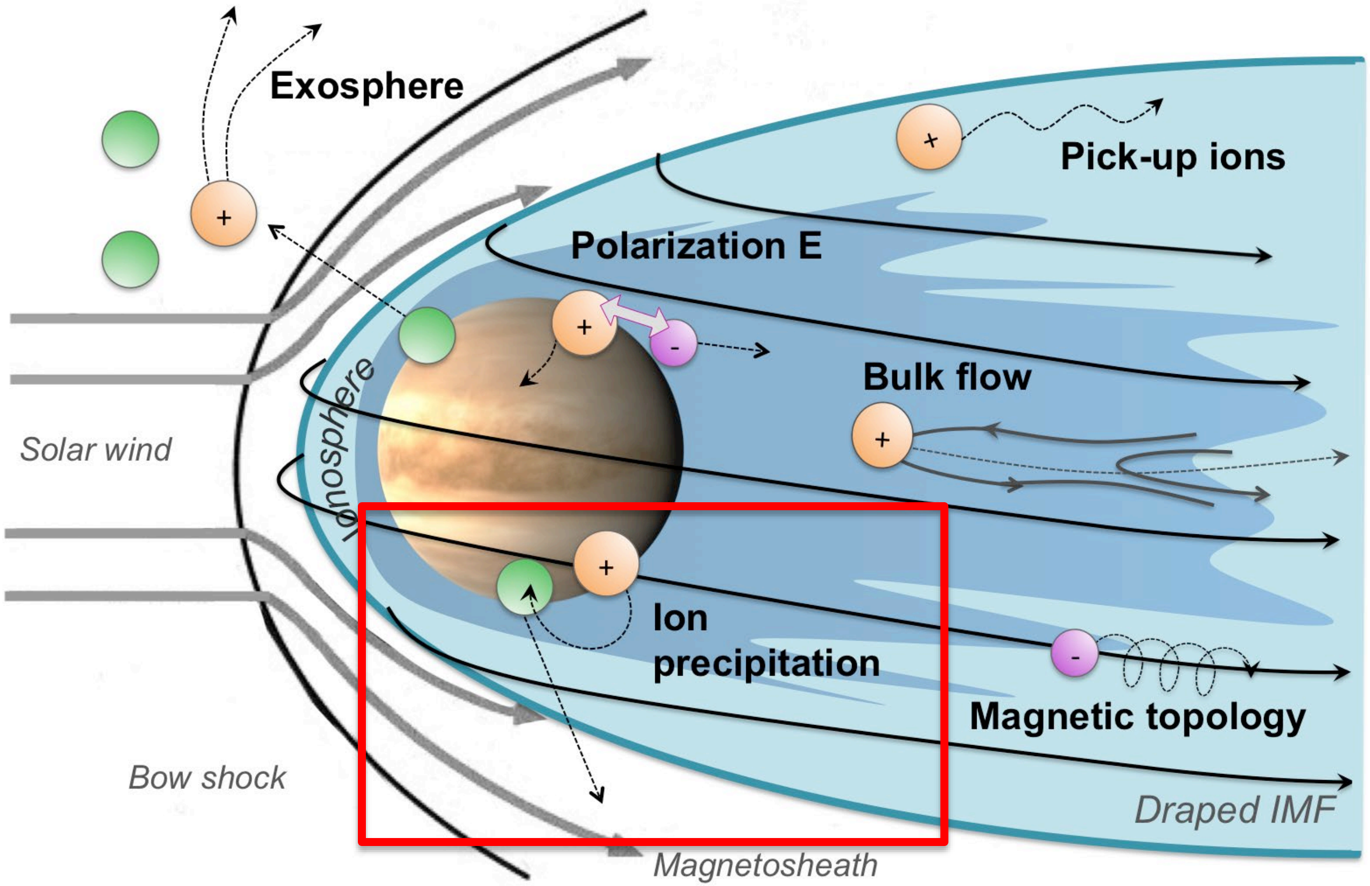

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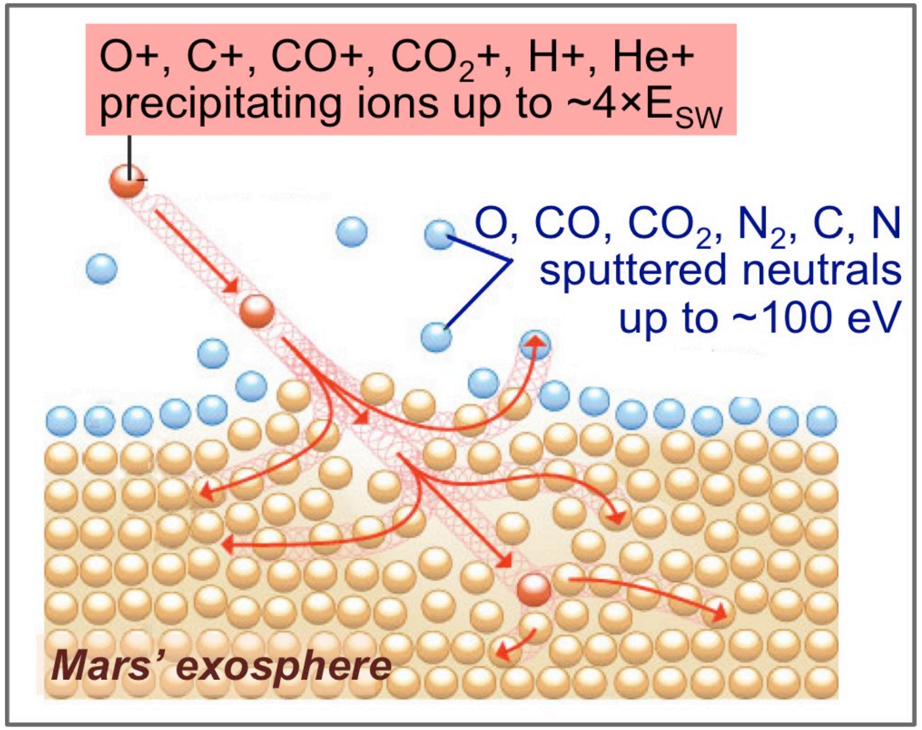
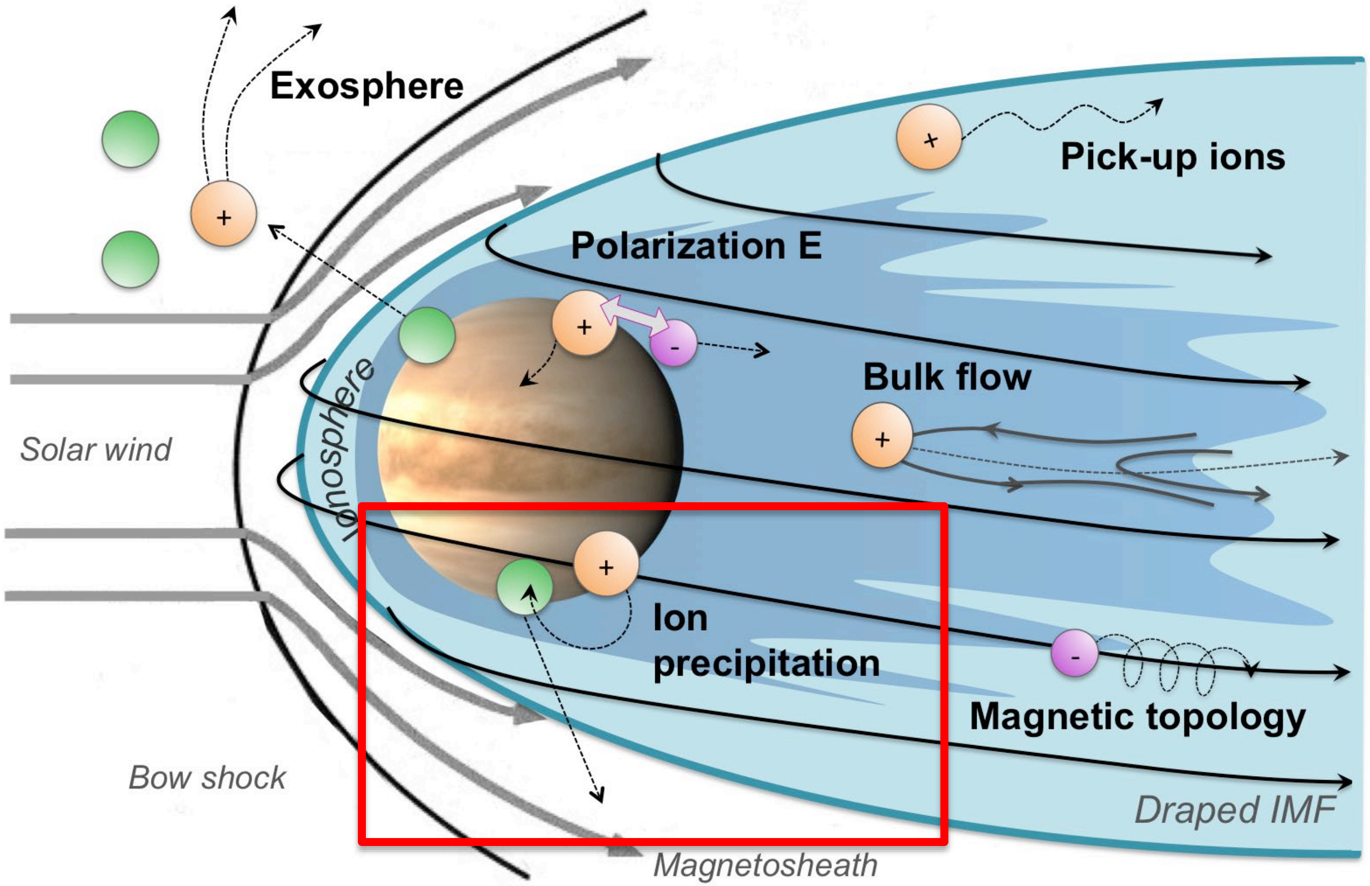
Ion escape → Sputtering





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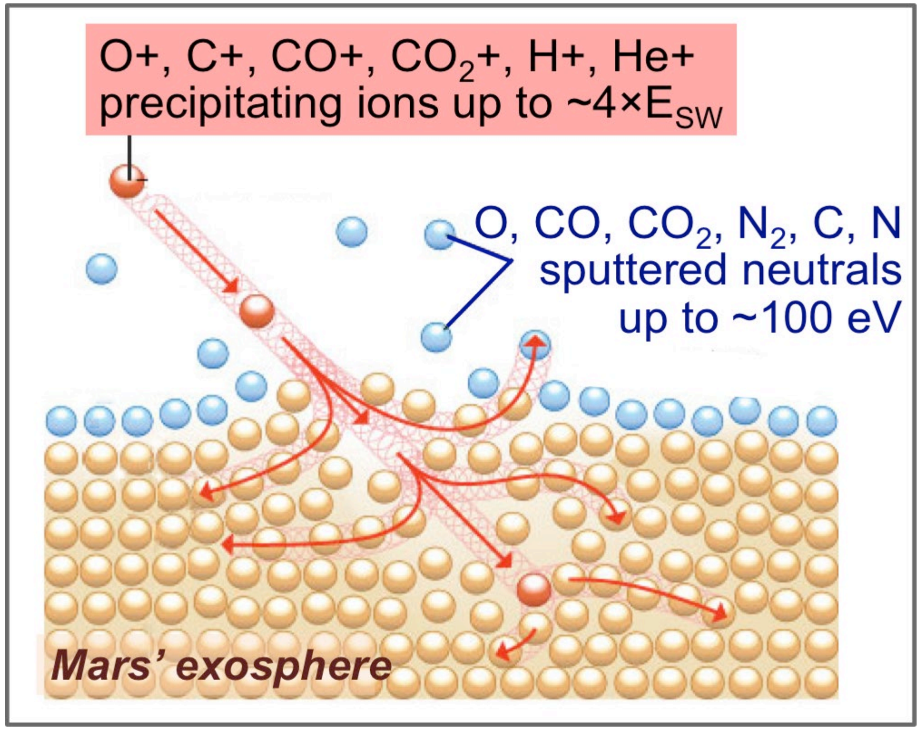
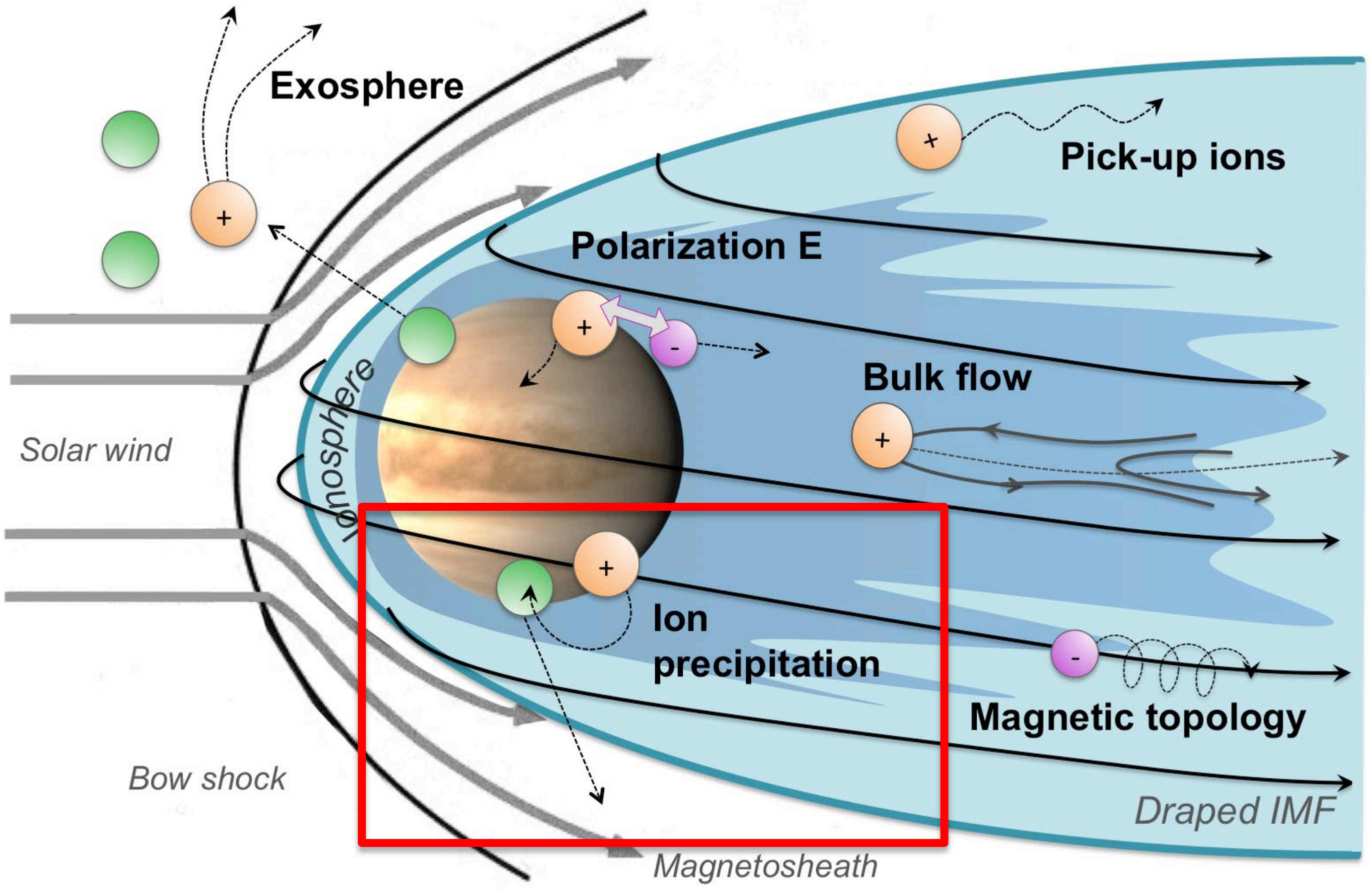
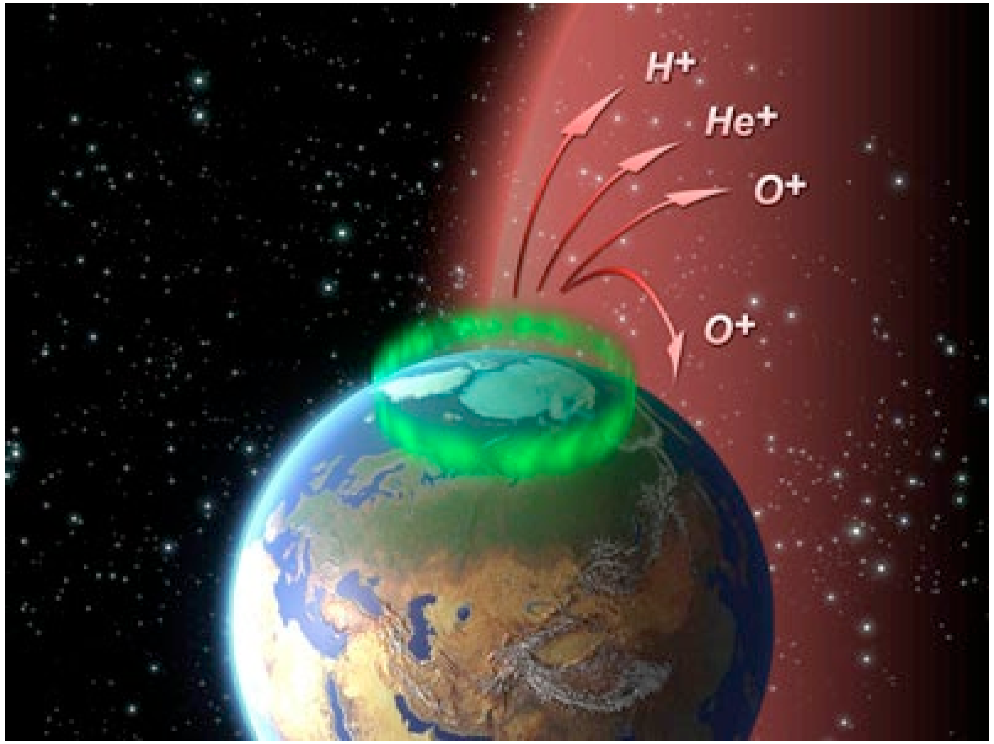


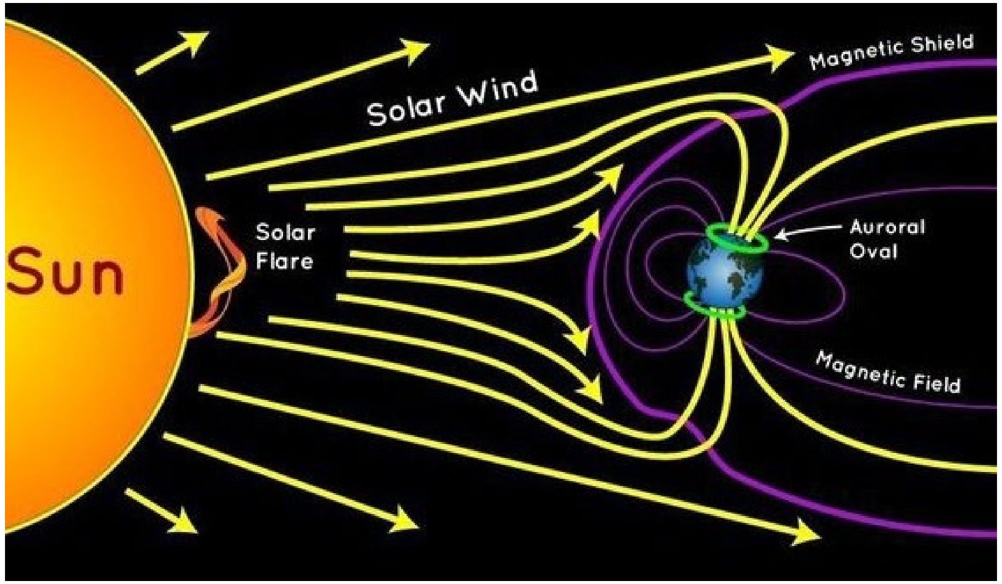


H+ / light ions

O+ / heavy ions

- Ions can escape in several ways
  - These ion escape processes all depend on the **solar wind**



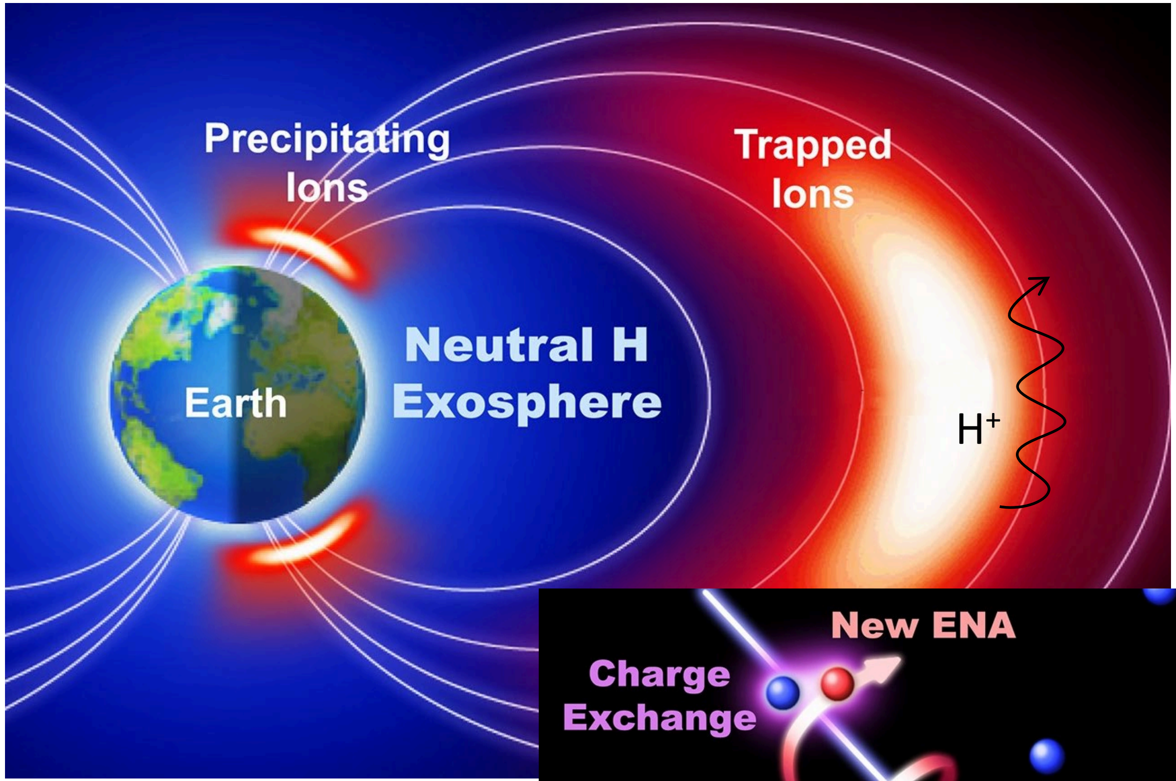


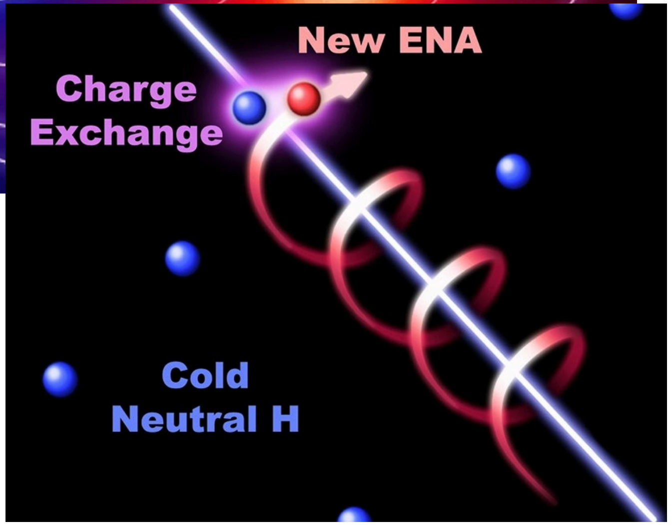
Ion escape: magnetized planets

- Classic light ion 'polar wind'
  - H+ and He+ escaping along open lines
  - Ambipolar diffusion is main driver
  - Ambipolar on draped fields at Venus
- Cusp 'ion fountain'
  - Solar wind enters along open field and enables heating and heavy ion escape
- 'Auroral wind' with heavy ions
  - Auroral oval on closed field lines
  - Electron precipitation causes heating and lifts heavy oxygen
  - Highly variable but most intense

Courtesy of GSFC

Hydrogen Escape from Earth





Goldstein and McComas 2018

Earth H loss can occur via *plasmasphere charge exchange*
[as in Yung+1989 photochemical model]

- ~85% Jeans loss at solar max,
- ~85% plasmasphere loss at solar min [Joshi+2019]

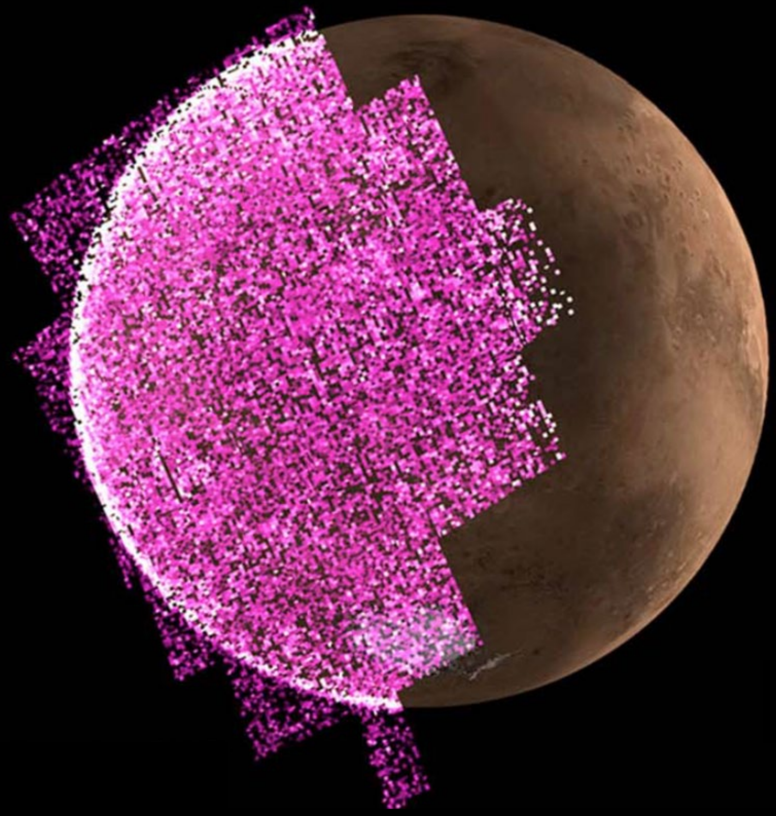
Heavy species loss rate uncertain due to lack of magnetotail measurements

- We need an Earth escape mission! (many heliophysics white papers)

Mars has multiple kinds of aurora

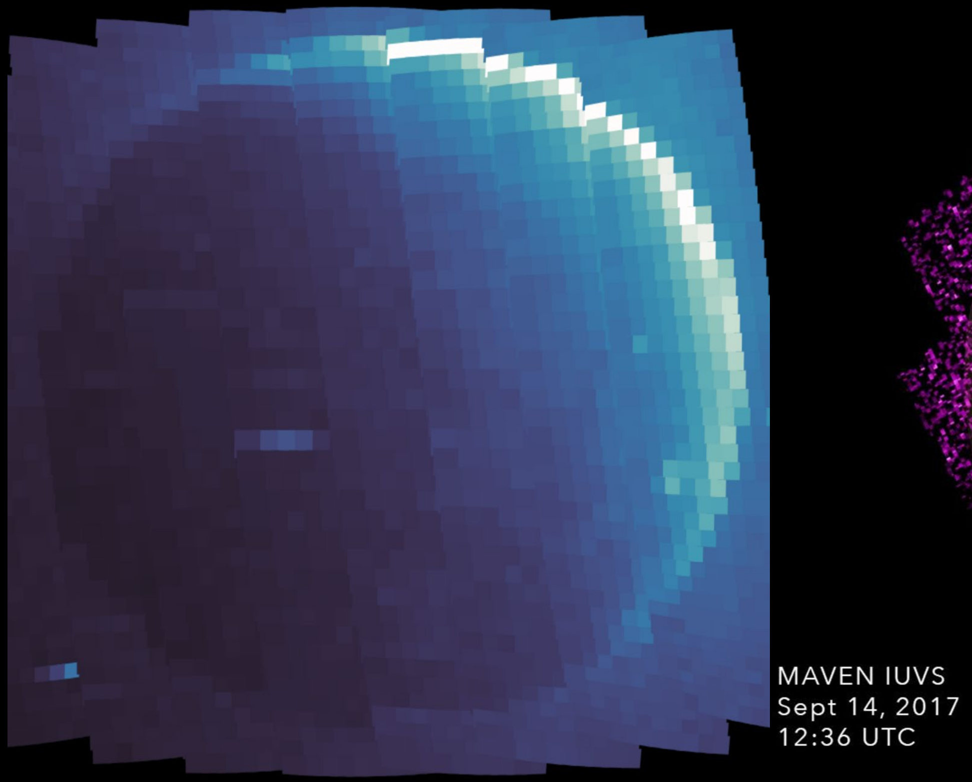
most occur only because it *lacks* an intrinsic global dipole field

Diffuse Aurora



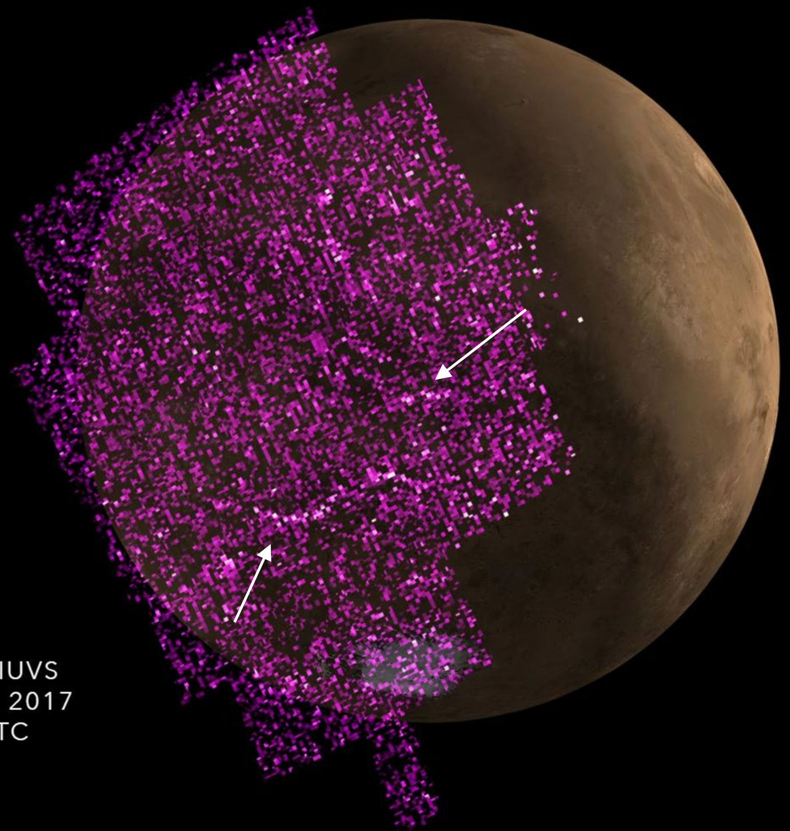
During strong space weather events, global aurora can engulf the planet, as in this image from September 2017

Proton Aurora



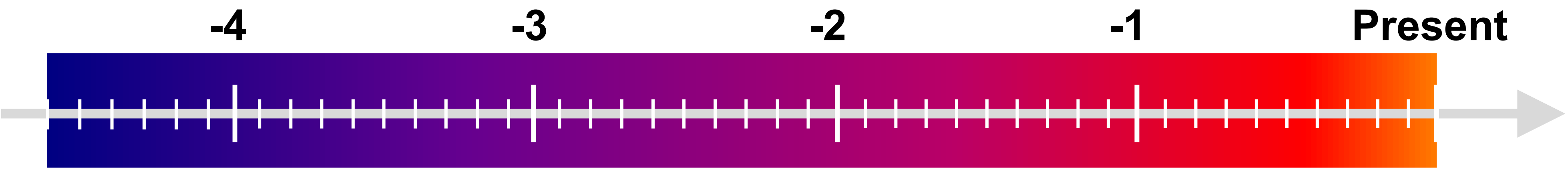
Solar wind protons colliding with the neutral atmosphere emit H spectrum photons around the limb

Discrete Aurora



Faint emissions form arcs around remanent magnetic fields locked in regions of Mars' crust, first seen by MEX/SPICAM

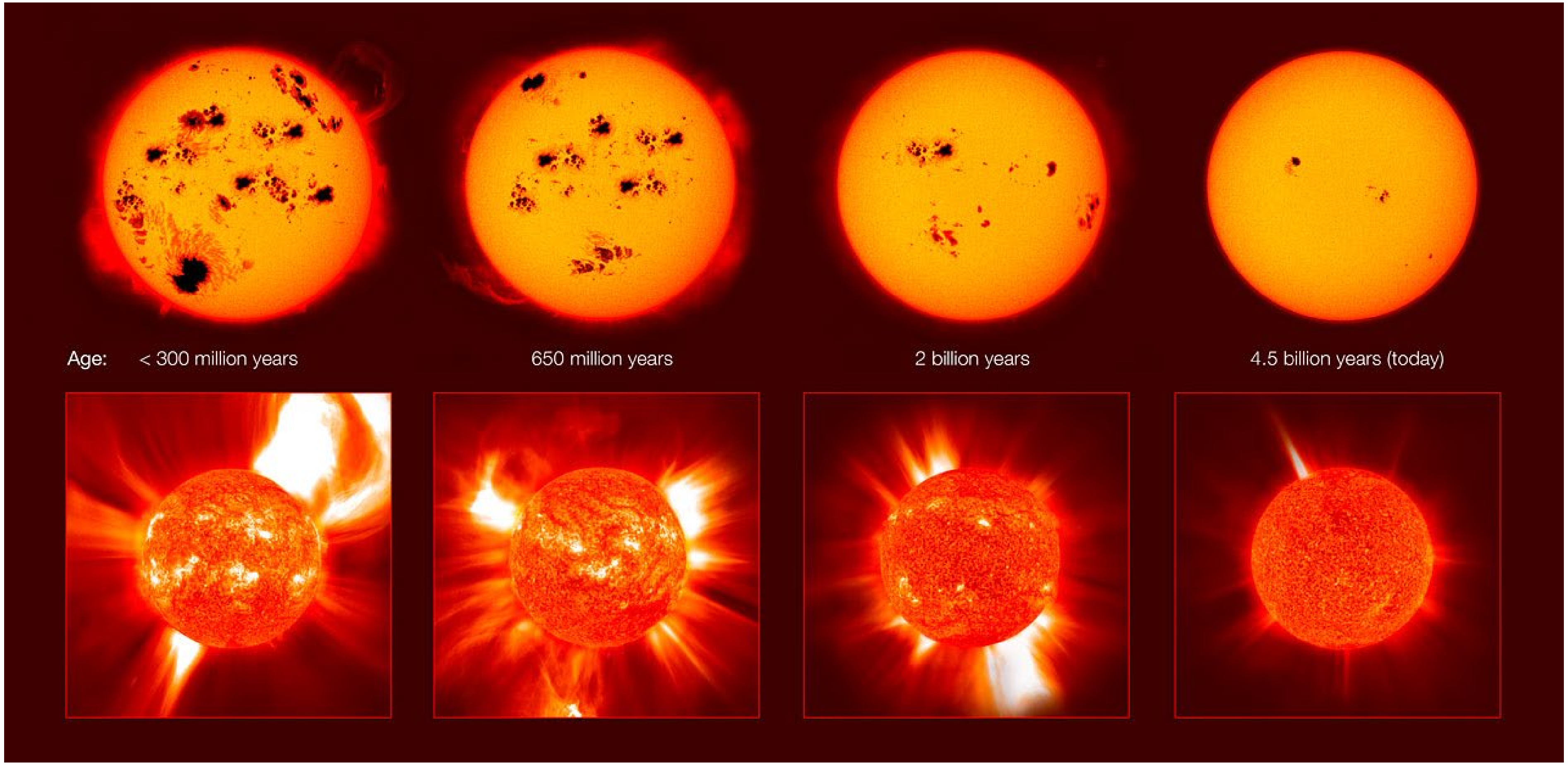
The early Sun



The early Sun was rotating much faster than it is today, and is believed to have been much more active:

XUV: 50 – 100x
winds: 100 – 200x

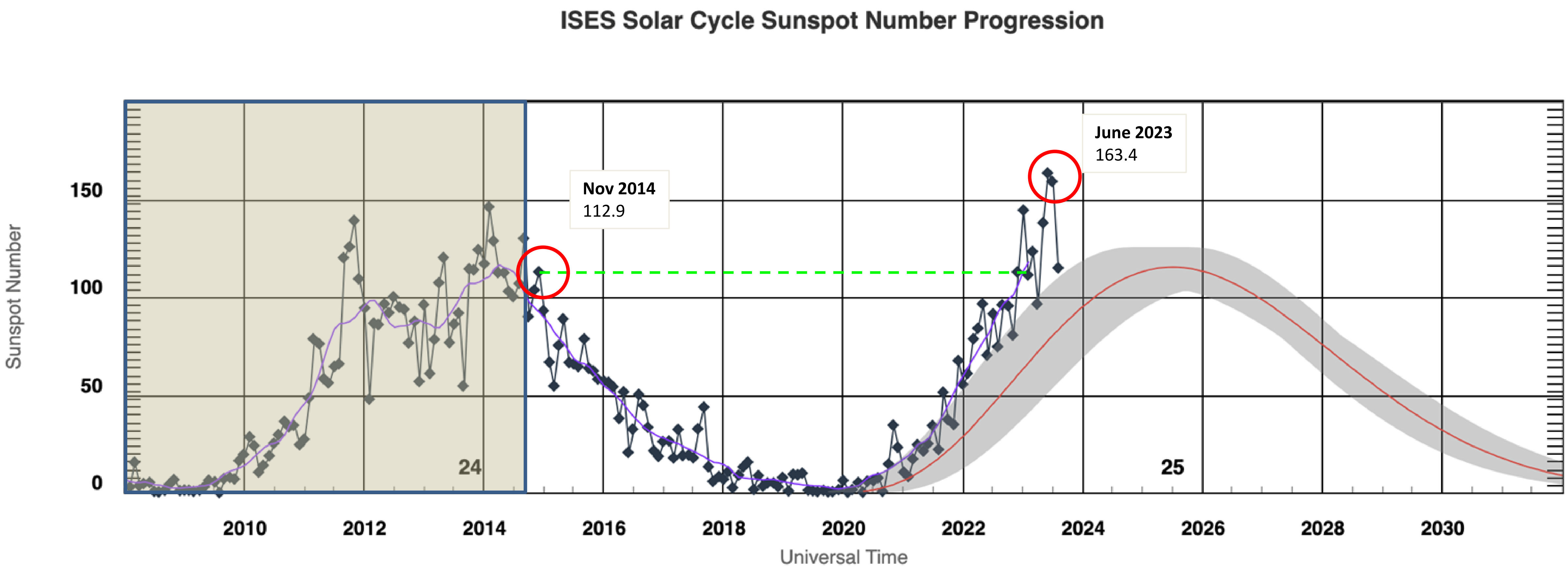
As it loses angular momentum, it spins down



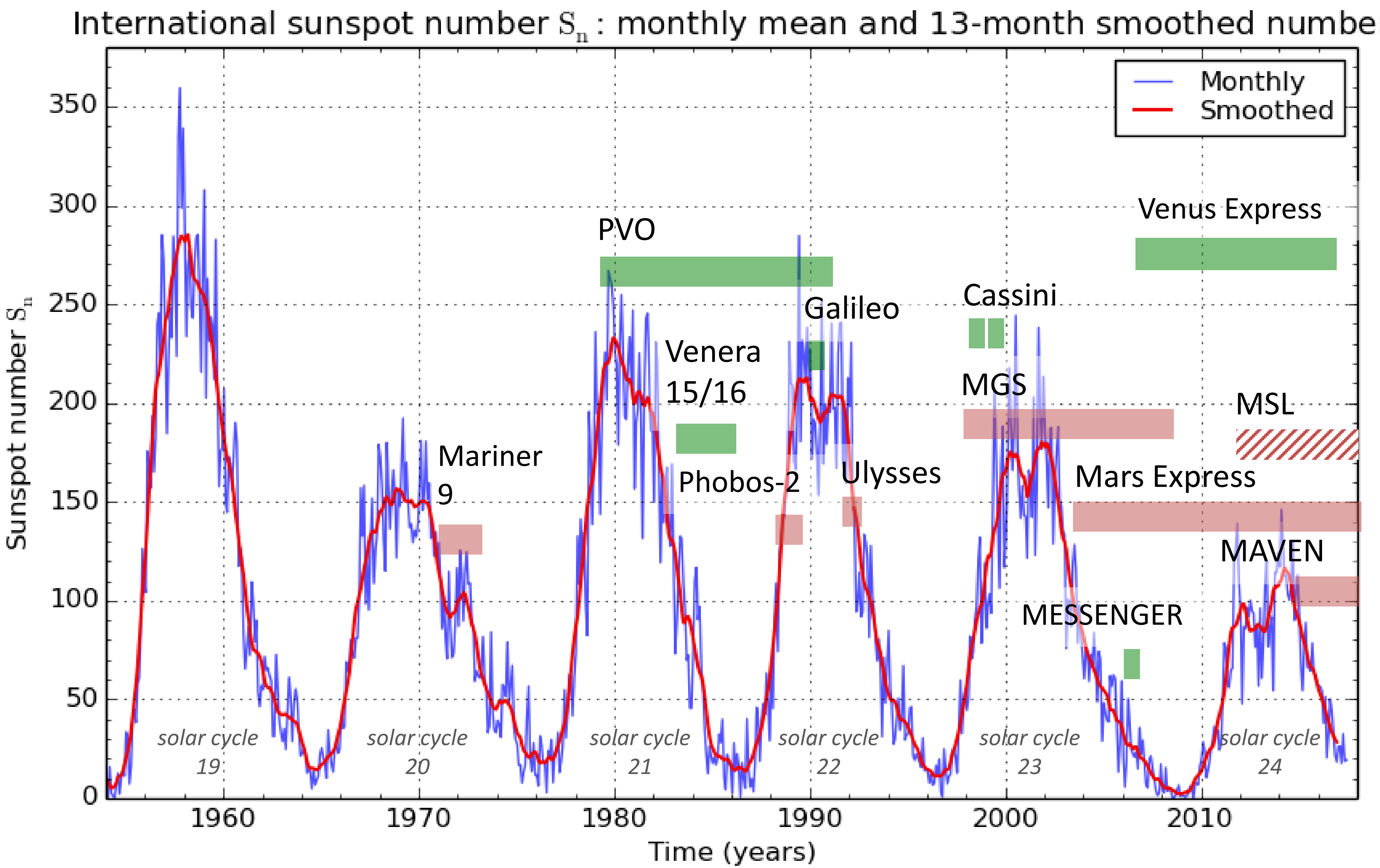
Credit: IAU/E. Guinan

Solar cycle

- MAVEN is now at a mission high for sunspot number / solar activity



Past plasma observations at Mars and Venus



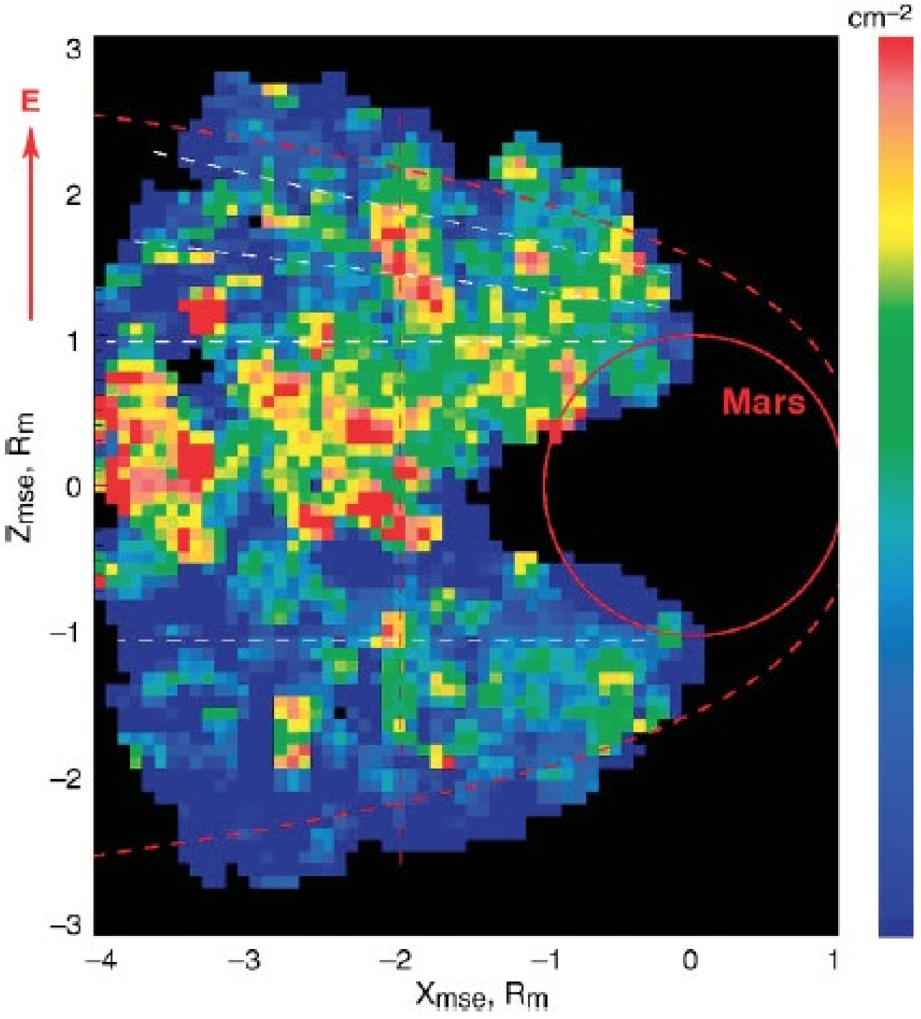
MEX and VEX: ion escape

Similar instruments observed planetary ion escape

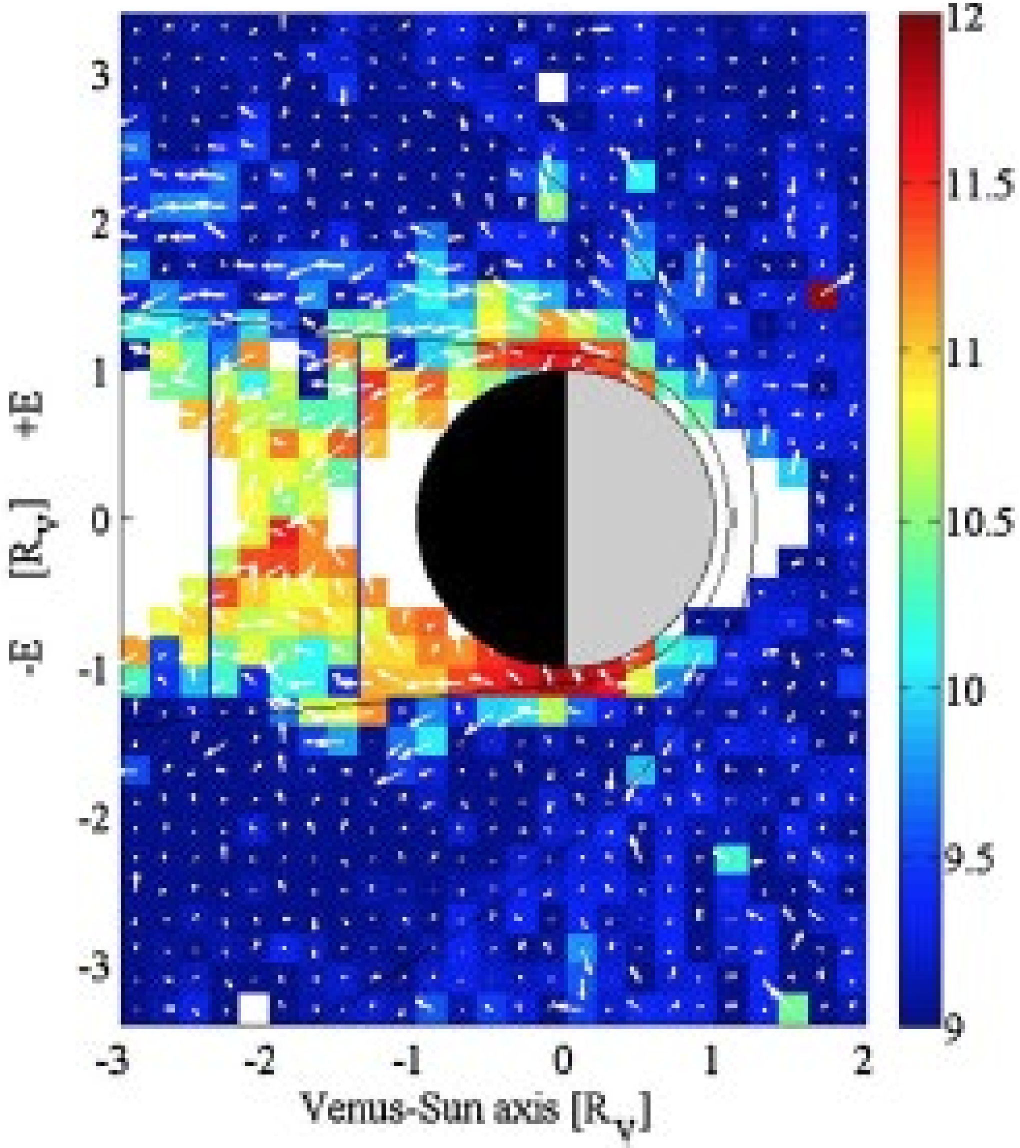
Present Venus ion escape (10^{25}/s) is 10x higher than at Mars (10^{24}/s)

At Venus, significant unknowns remain about acceleration processes and solar-cycle variation

MEX- Mars



Heavy ion flux [m^{-2} s^{-1}]



Nordström et al [2013]

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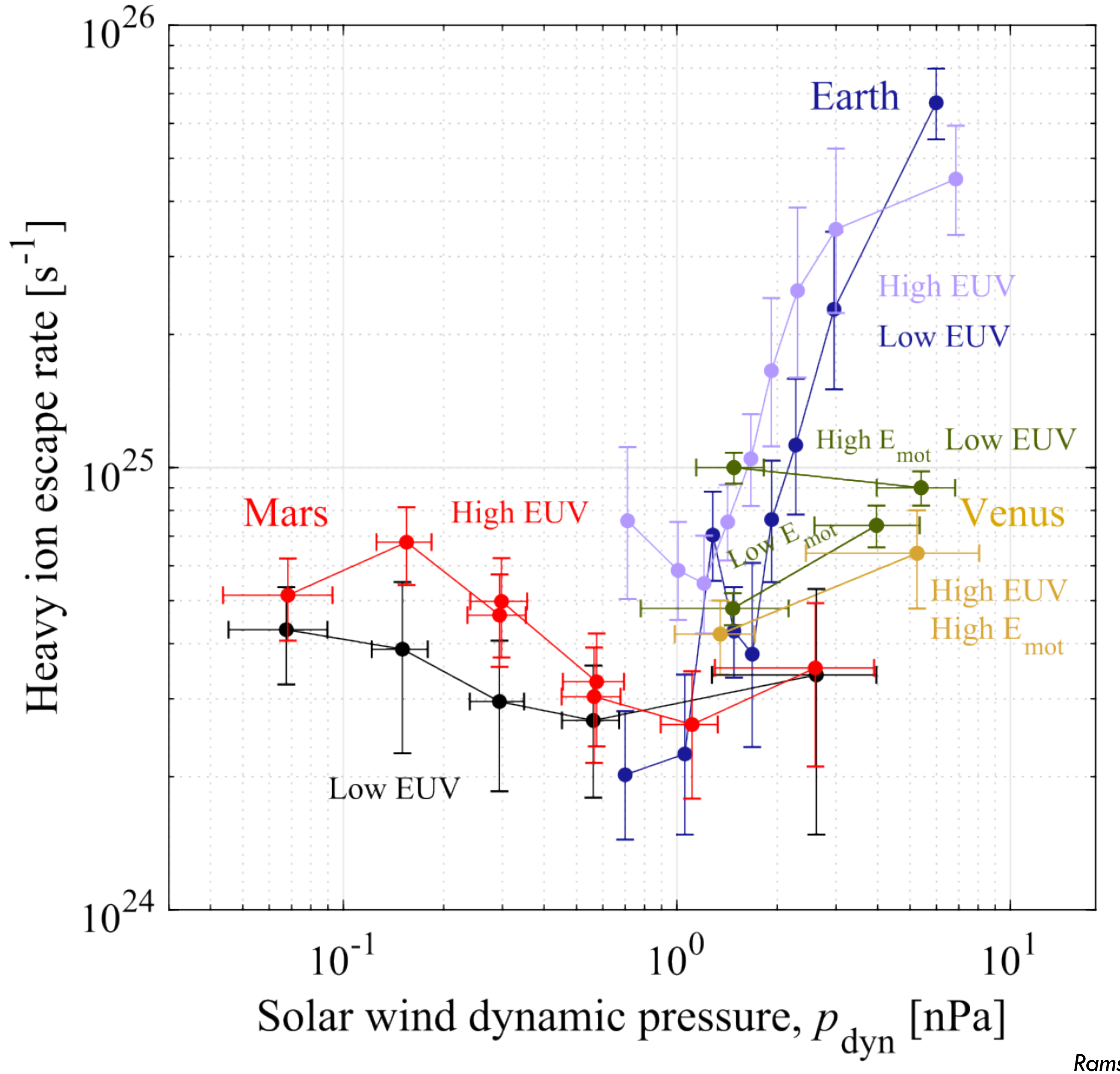
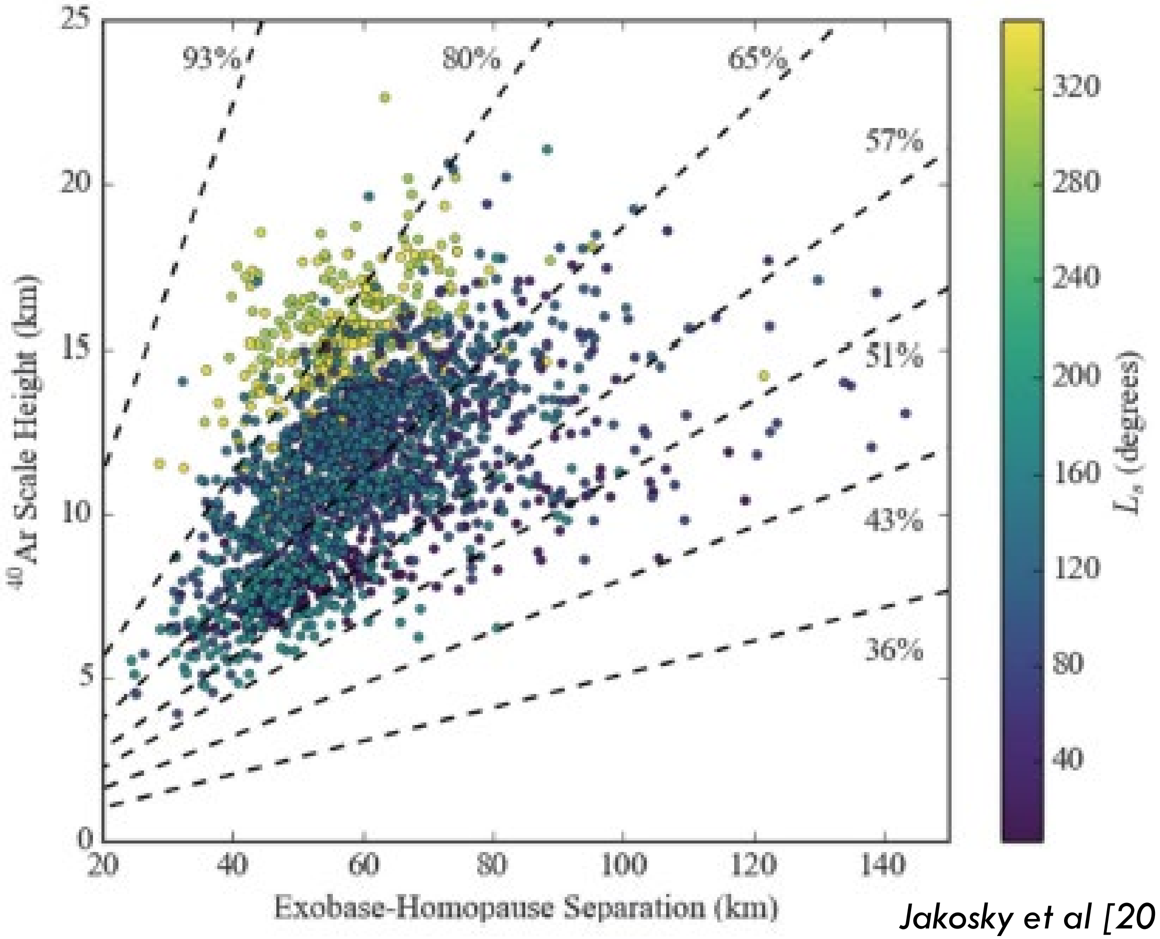
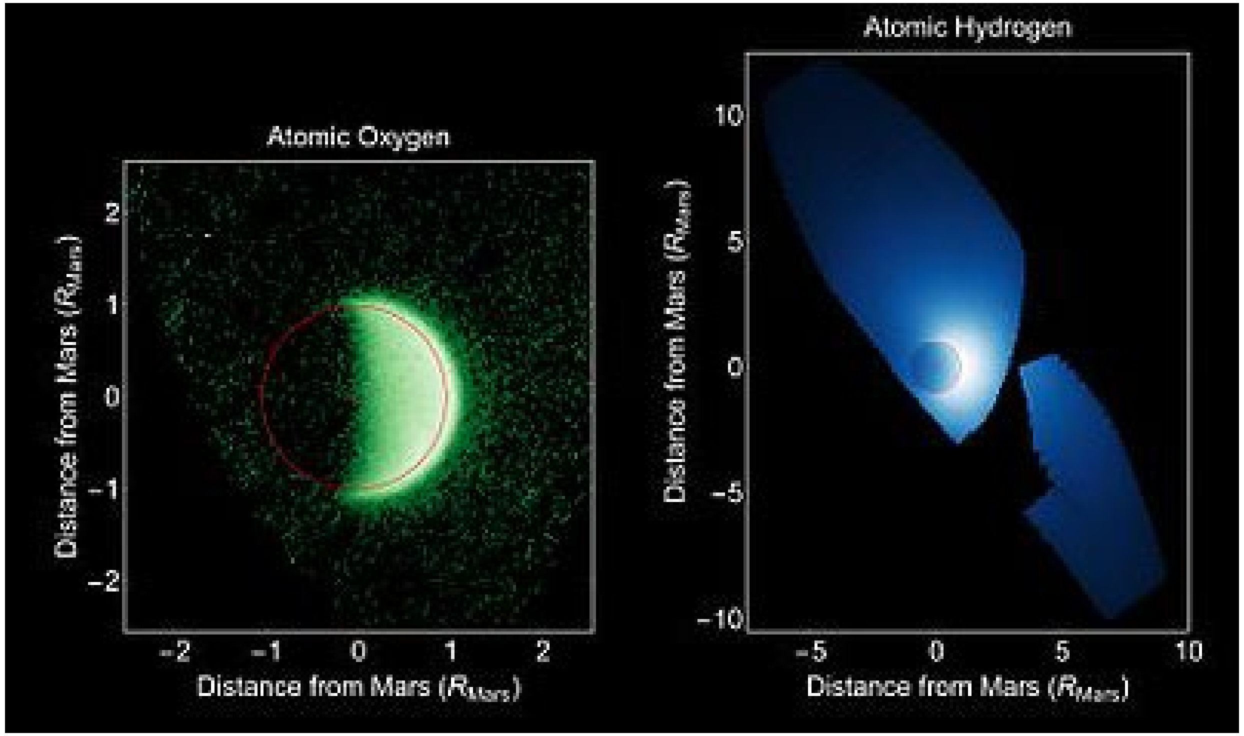


Ramstad & Barabash (2021)

MAVEN: photochemical and sputtered escape



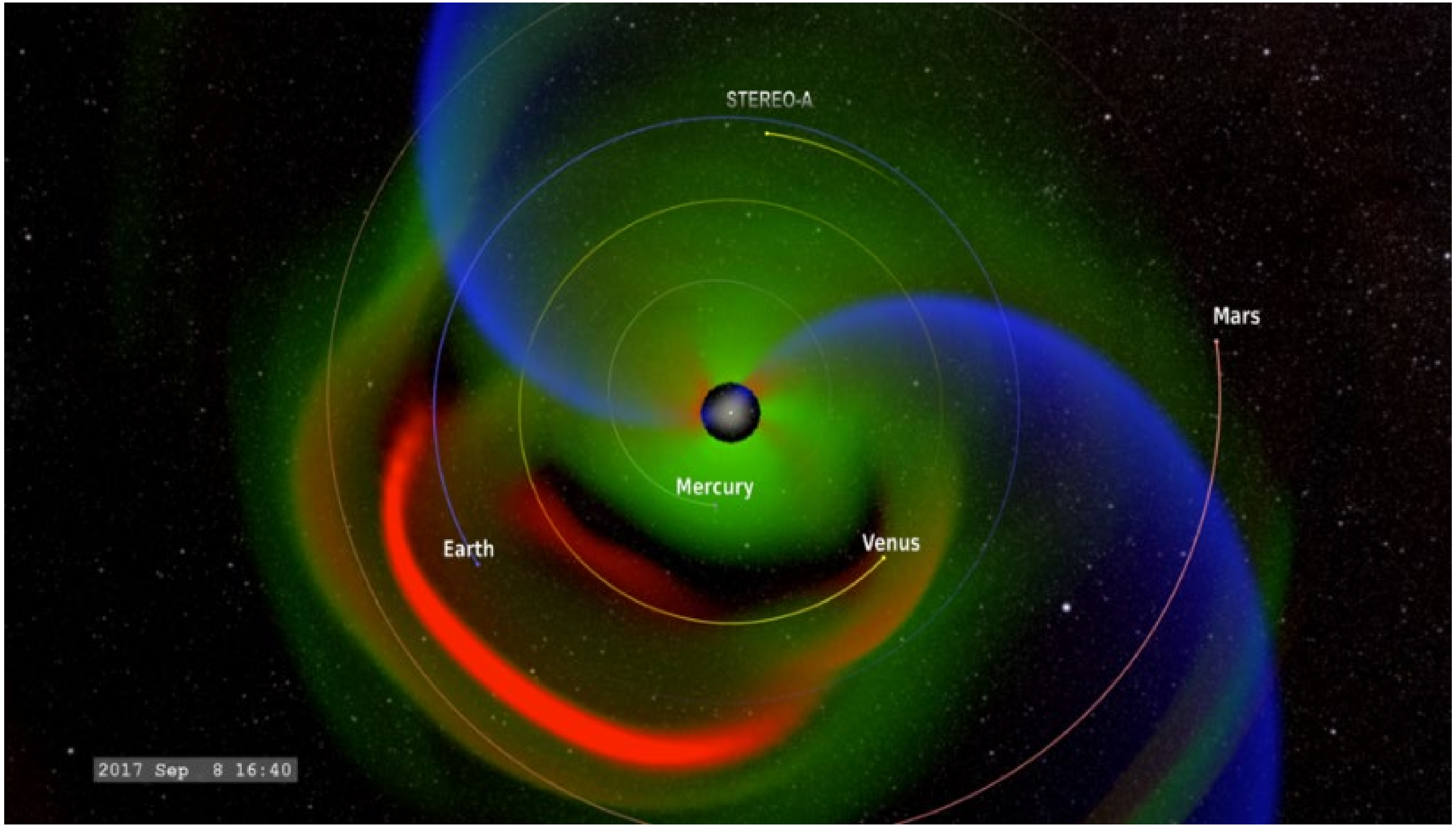
Jakosky et al [2017]



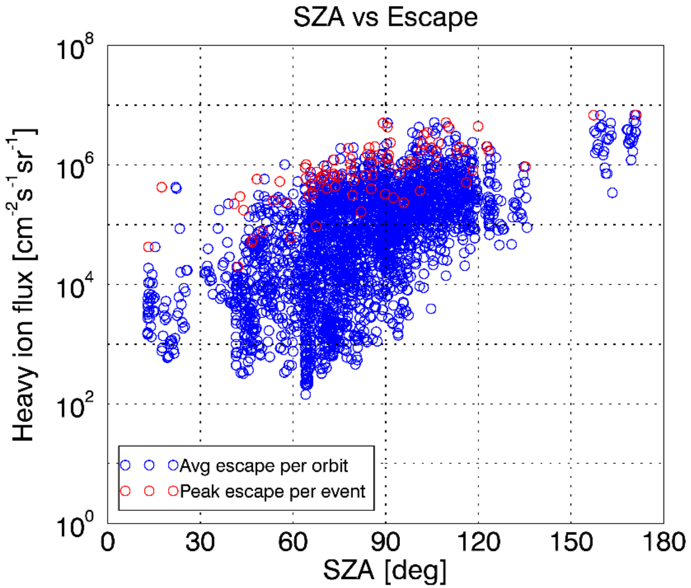
Courtesy of MAVEN

- MAVEN found present-day photochemical escape to be the **dominant** escape process for heavy species at Mars;
  at Venus, only H and D escape this way
- Isotope measurements show that 65% of Argon has been removed from the atmosphere through sputtering

Space Weather

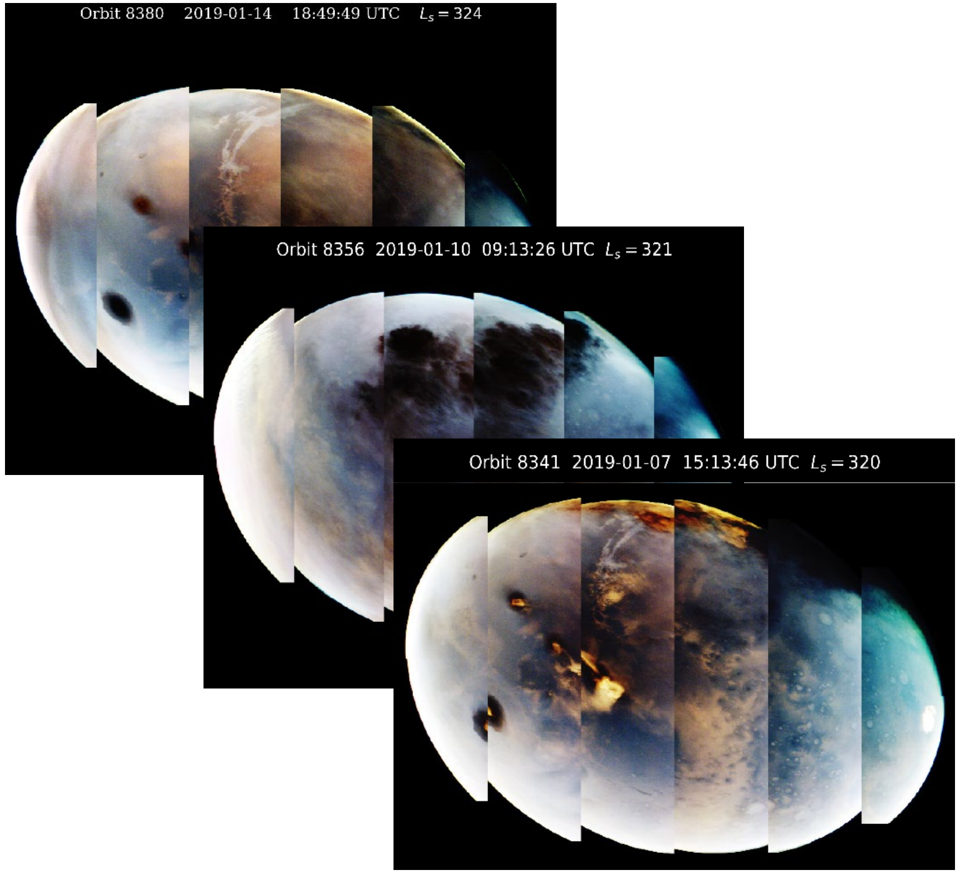


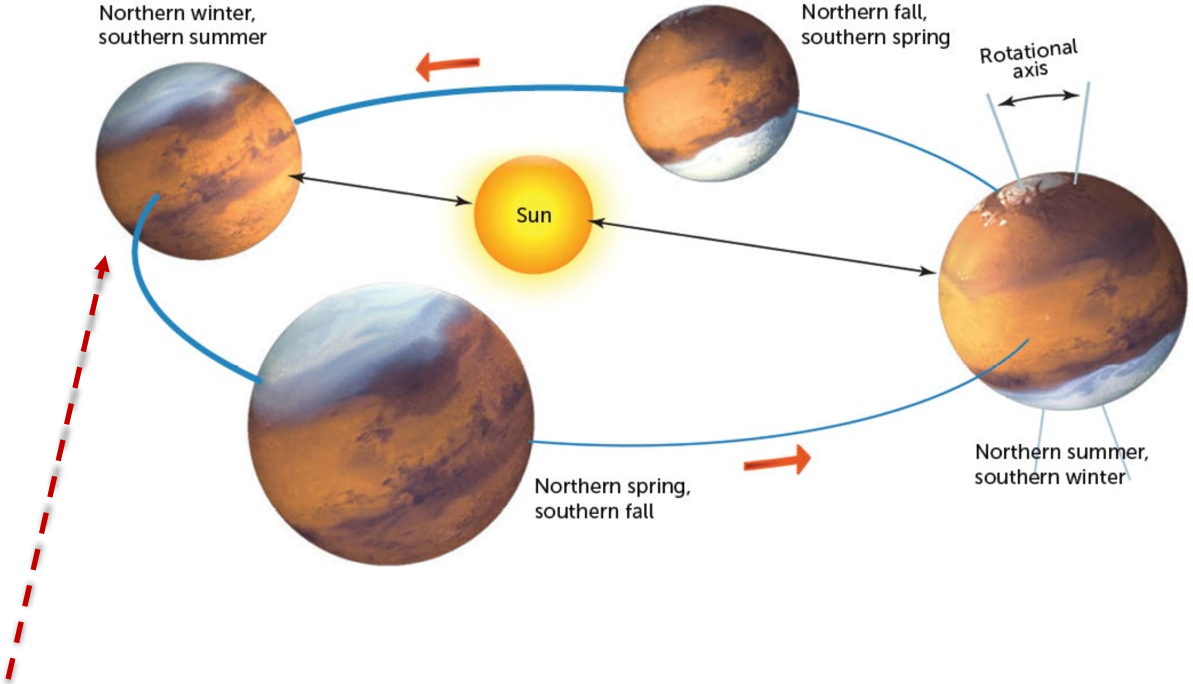
Solar storms such as coronal mass ejections can boost escape by orders of magnitude



Lee et al 2018, Curry et al. 2020

Dust and atmospheric erosion

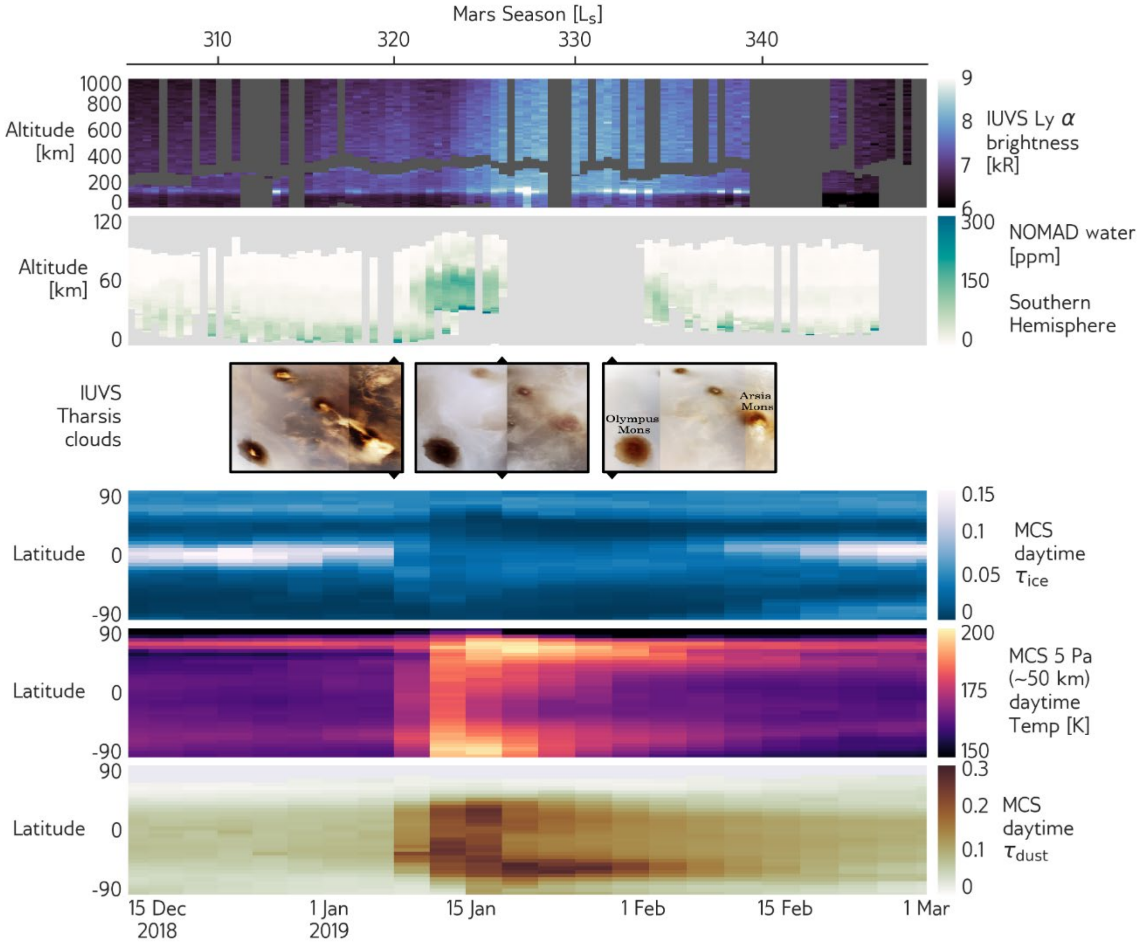




- Dust season occurs at Mars southern summer (near perihelion)
- Dust storms can be local or global and have a huge effect on ground assets (RIP solar powered rovers)

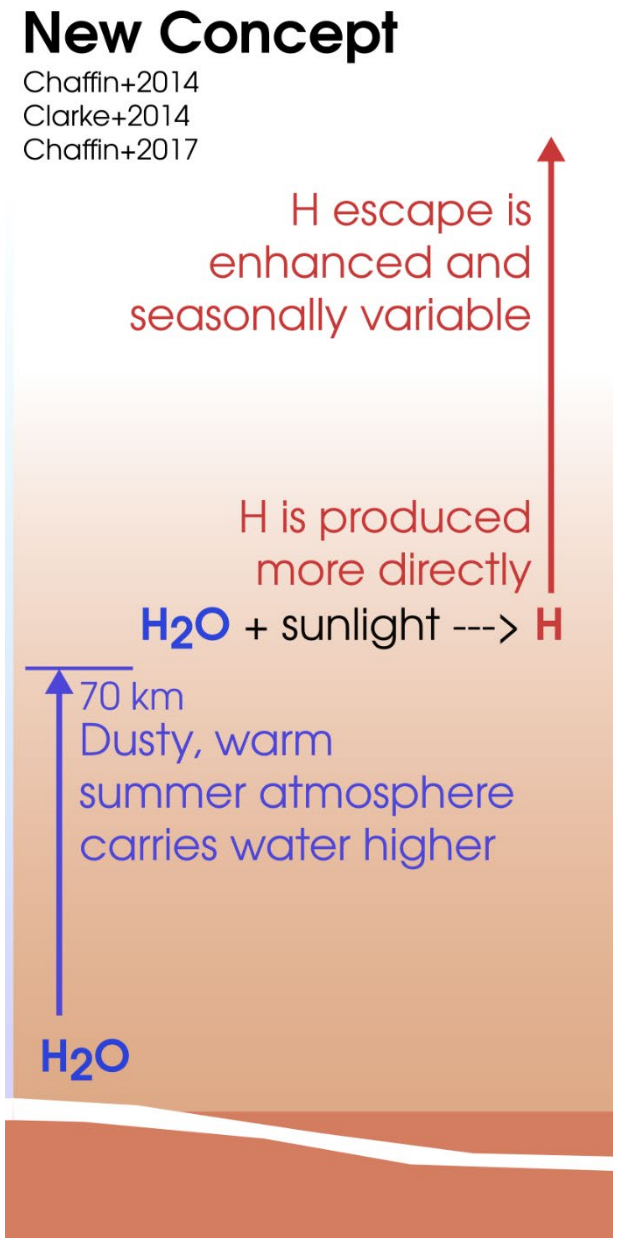
Courtesy of MAVEN IUVS

Dust and atmospheric erosion

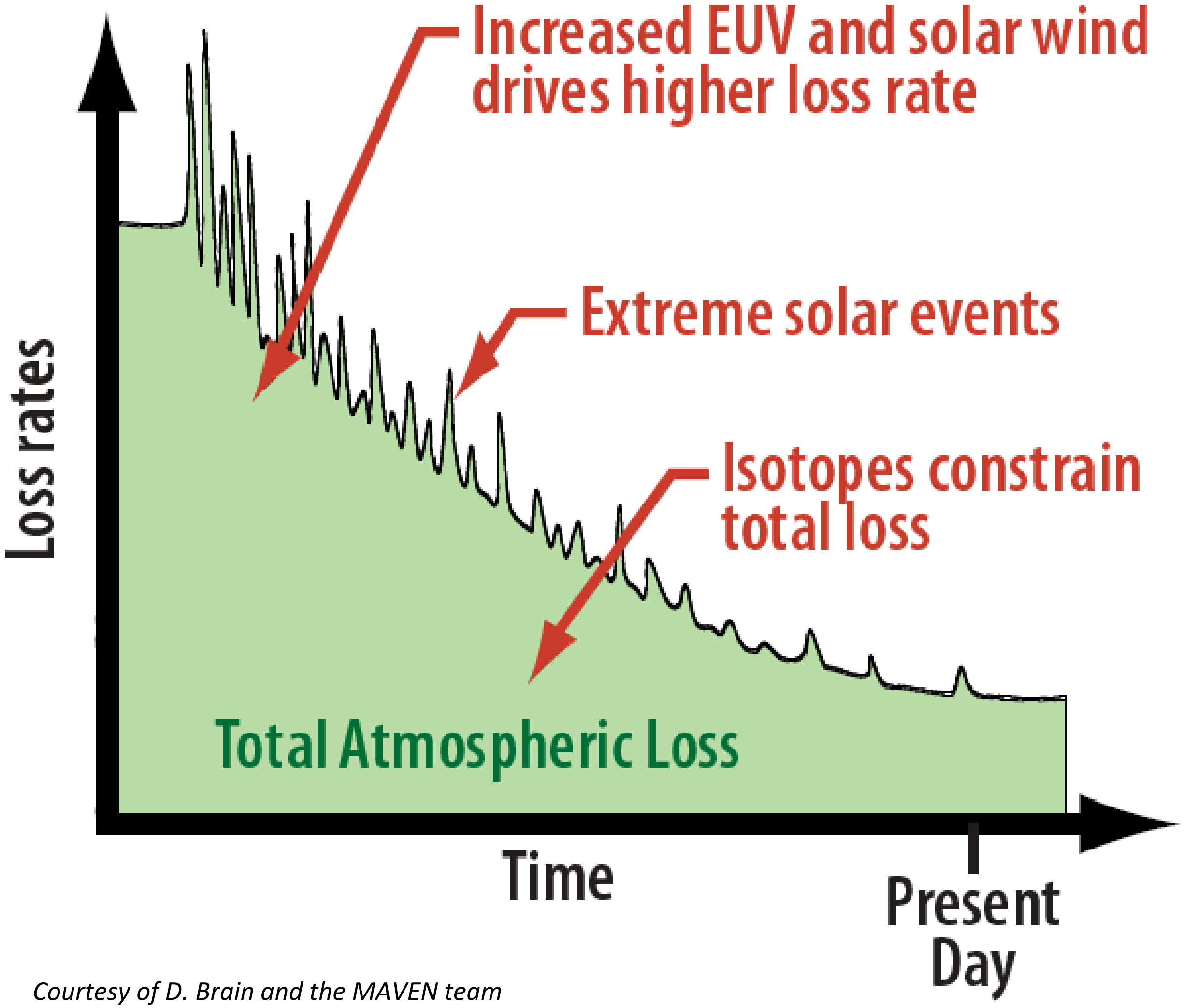


Chaffin+2021

- MAVEN works with MRO and TGO to observe dust
- In 2018, MAVEN saw a ~5-10x boost in H loss during a regional dust storm vs. quiescent periods



How much atmosphere has been lost at Mars?



Courtesy of D. Brain and the MAVEN team

An *extrapolation* back in time with current escape rates, scaled to extreme rates during a more active sun, suggests that the total escape rate would be responsible for the loss of a significant amount of water and / or atmosphere.

Assumptions:

- Increase in EUV and solar wind
- Increase in solar events (CMEs, CIRs)
- Early atmospheres are based on GCM models with increased EUV
- Post-bombardment
- Post-hydrodynamic

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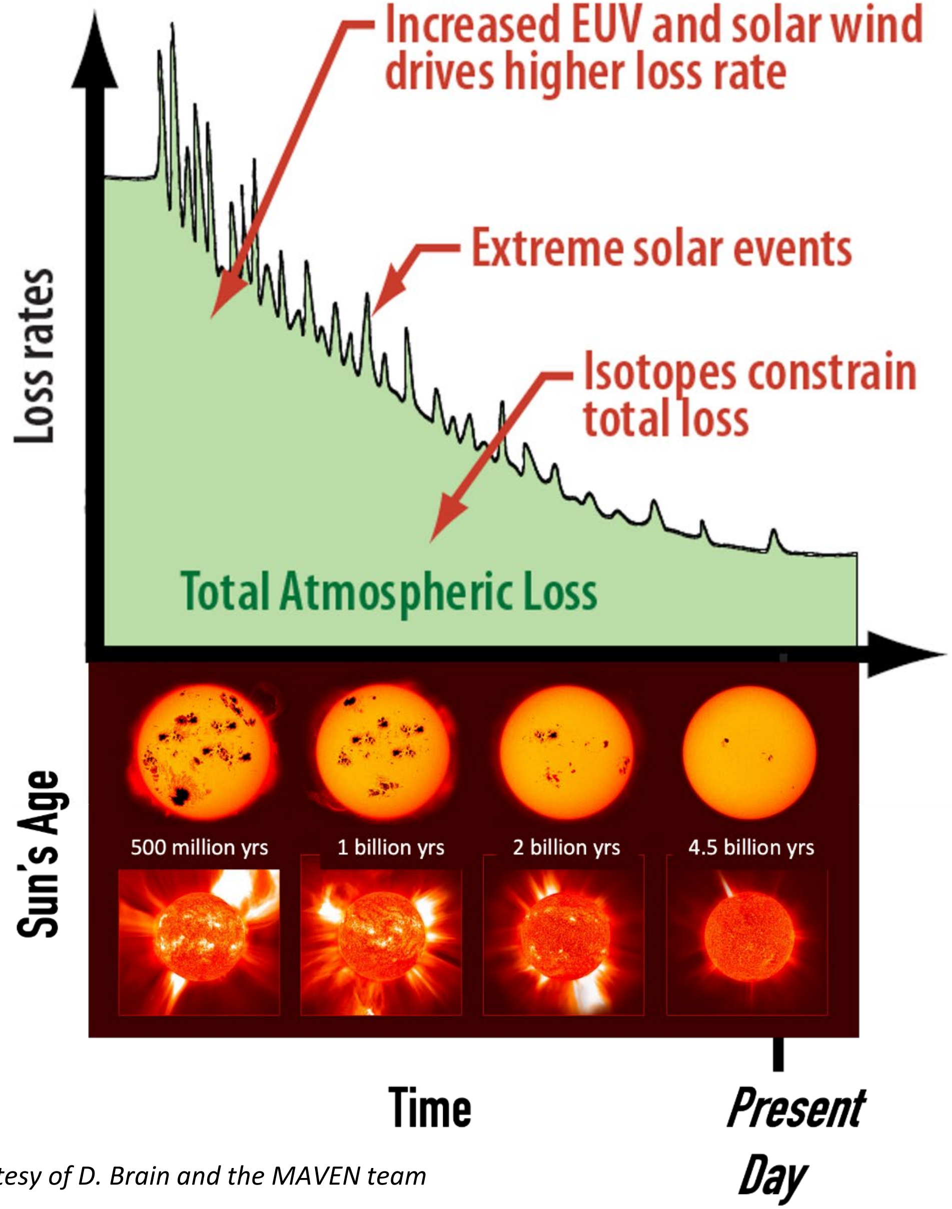

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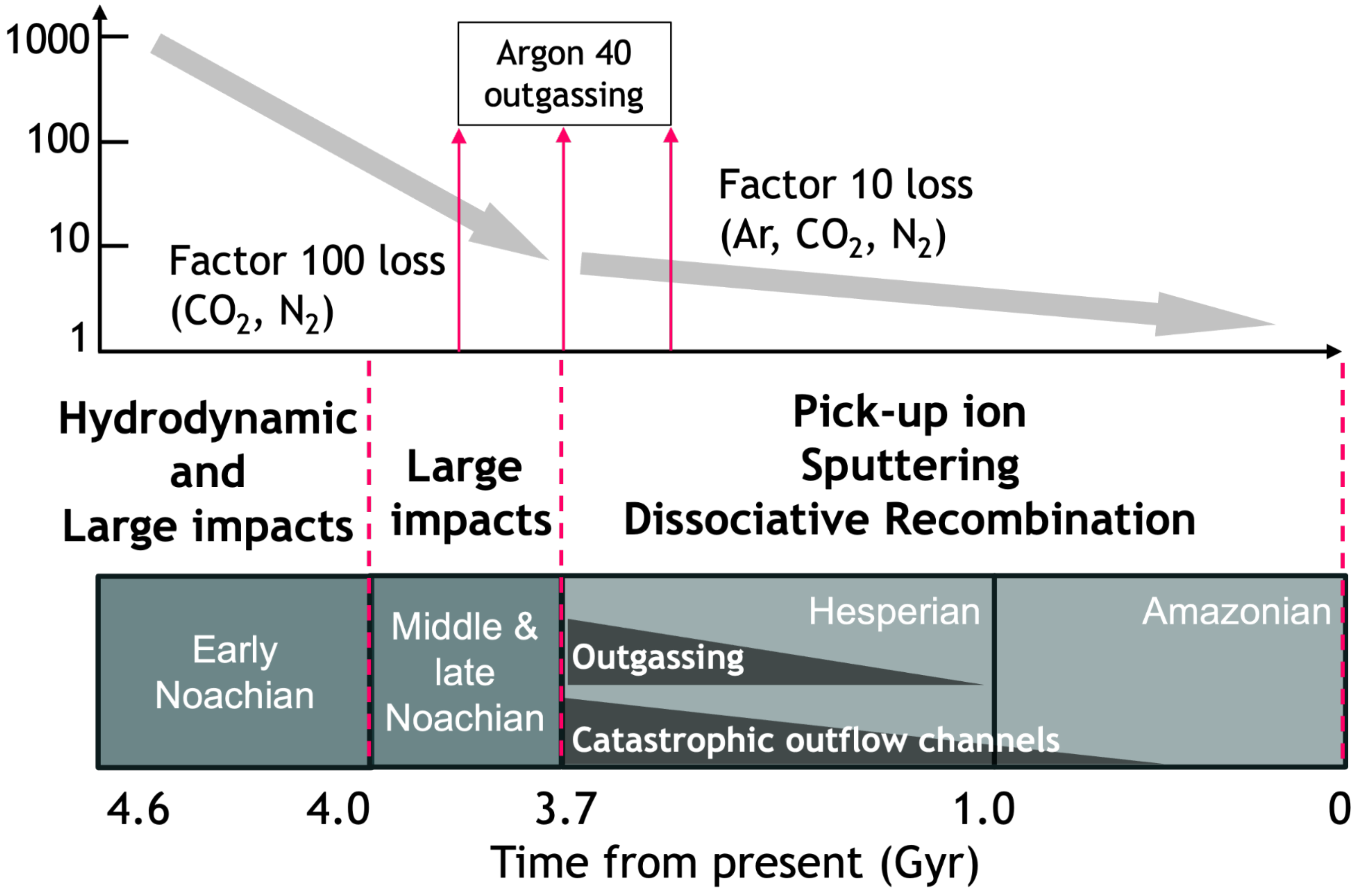
So how much atmosphere has been lost at Mars?



Courtesy of S.Curry,
adapted from Chassefiere et al 2007

Using MAVEN measurements and extrapolating back in time, Mars has lost *(at minimum)*

- **800 mbar of atmosphere**

OR

- **23 meters of water**

(true value depends on many unknowns)

Jakosky et al. [2018]
Chassefiere et al [2007]

VEX and PVO ion escape rates: implications

- Solar activity levels significantly differed for PVO and VEX, as did ion escape rates.
- What are the limits and the implications for water loss and crustal oxidation?

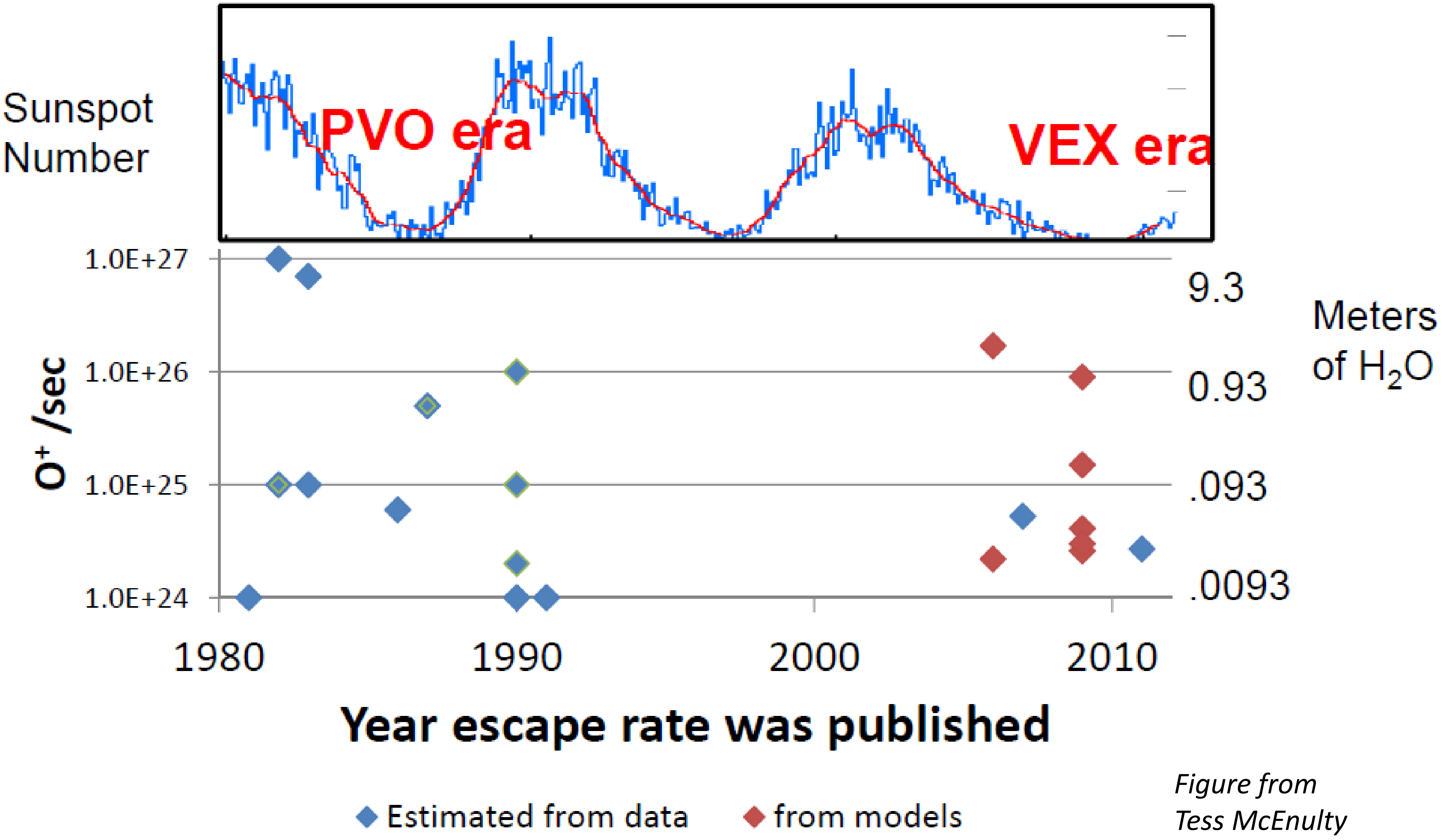


Figure from Tess McEnulty

What processes operate at different planets

	Mars	Venus	Earth	*Notes*
Neutral escape				
Hydrodynamic	X	X	X	*Cataclysmic*
Jeans	√	X	X	
Sputtering	√	√	X	*No magnetic field*
Photochemical	√	H and D only	H and D only	*Low gravity*
Ion escape				
Pick up ion	√	**√**	√	
Polar wind	X	X√*	√	
Auroral wind	X	X	√	*Magnetic field*
Ion outflow	X	X	√	*Magnetic field*

**same electric fields can accelerate particles along draped field lines*

What processes operate at different planets

	Mars	Venus	Earth	*Notes*
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Ion escape				
Pick up ion	√	√	√	
Polar wind	X	X√*	√	
Auroral wind	X	X	√	*Magnetic field*
Ion outflow	X	X	√	*Magnetic field*
		VOLCANISM	**VOLCANISM**	

**same electric fields can accelerate particles along draped field lines*

Follow the water

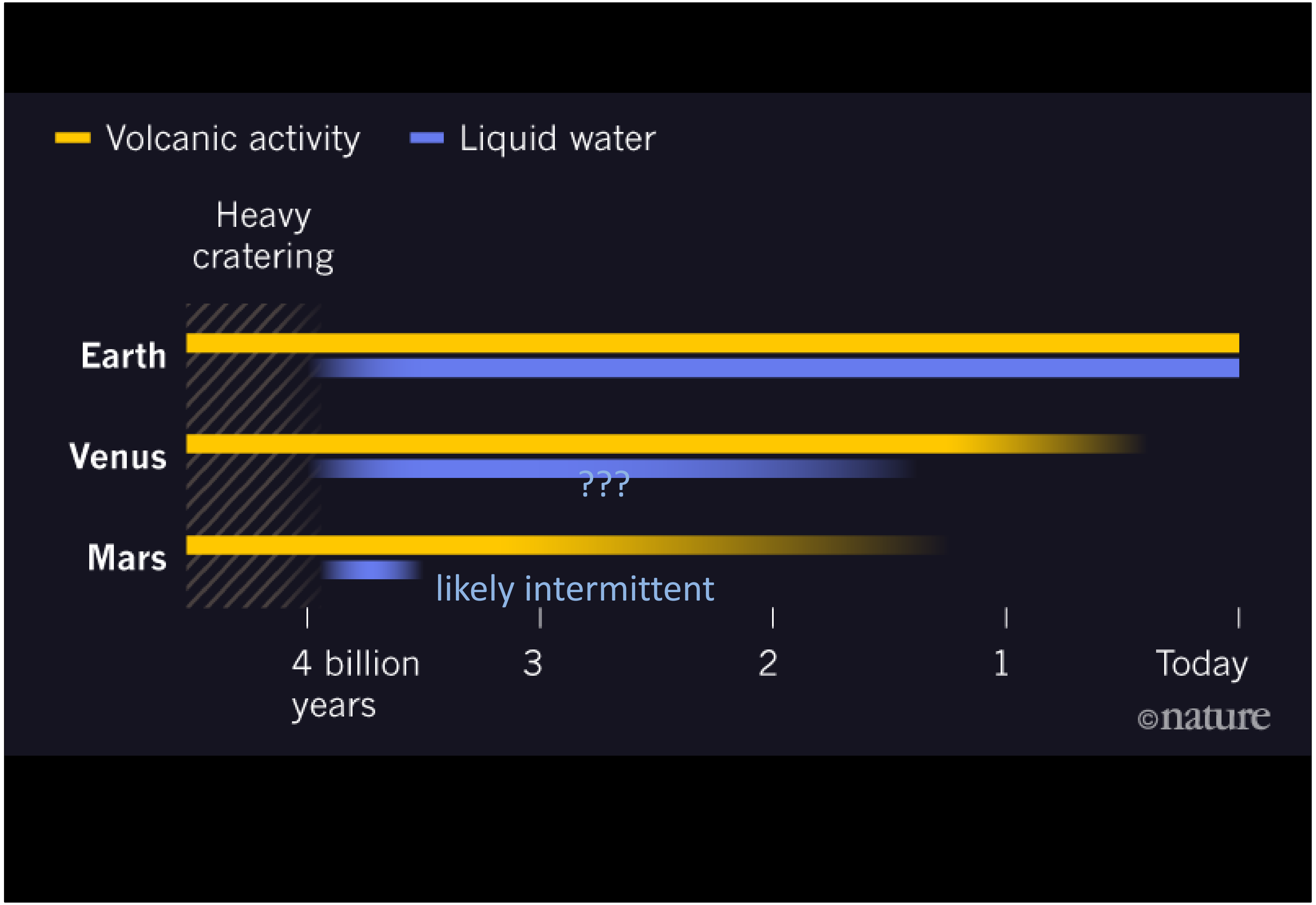


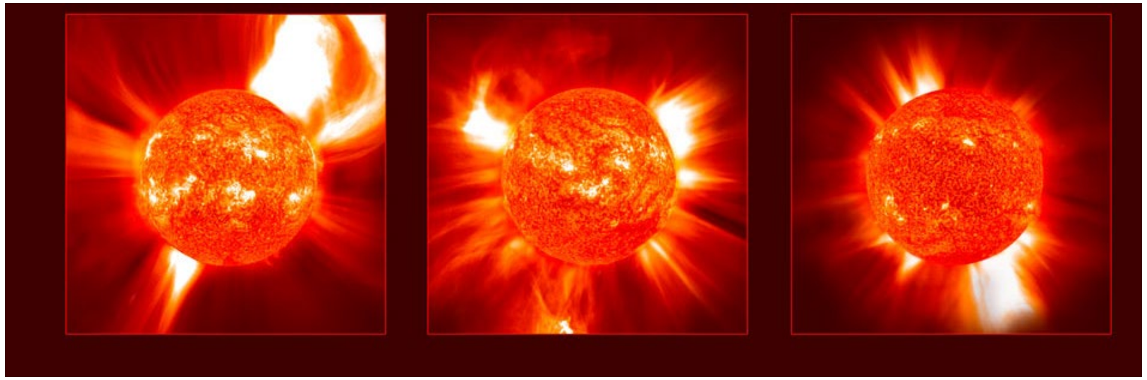
Image courtesy of Darby Dyar, Nature

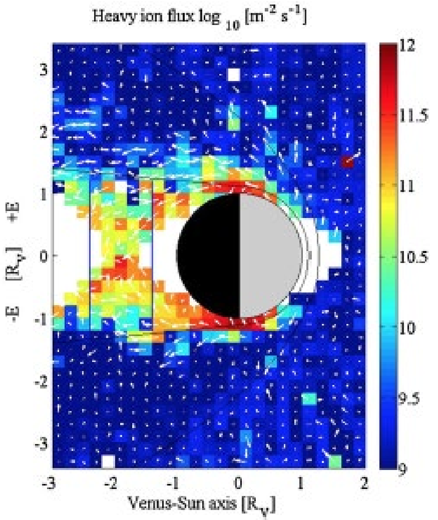
Major factors:

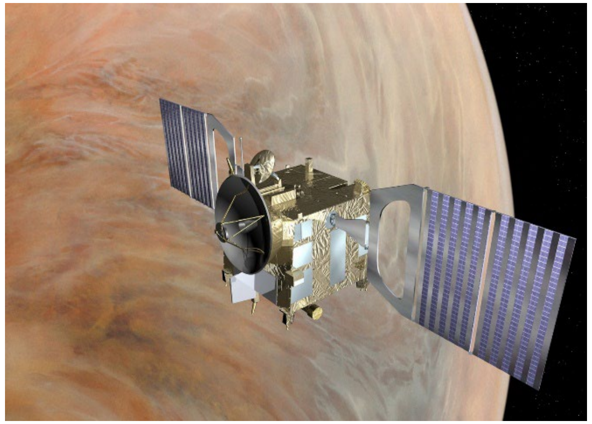
- Volcanism and outgassing
- Gravity
- Magnetic field
- Atmospheric composition

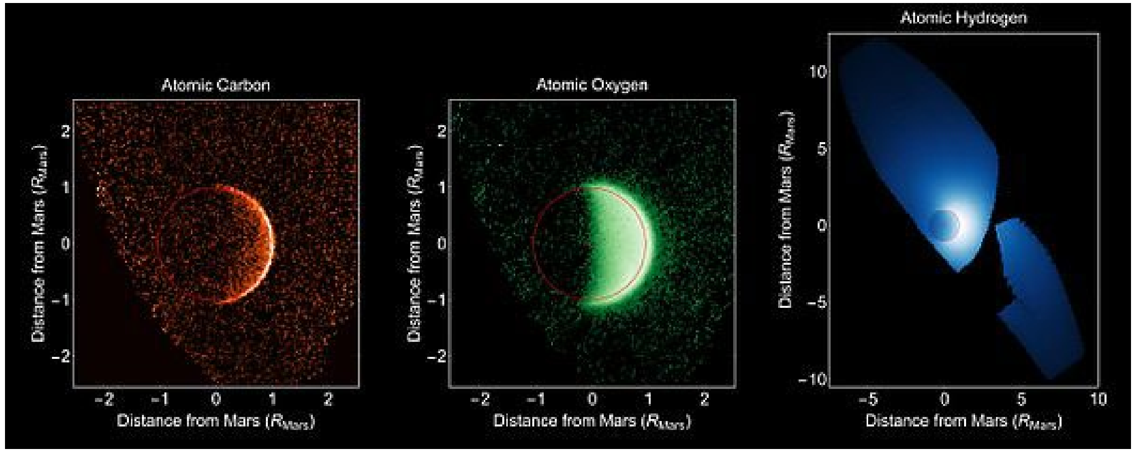
Conclusions

- PVO, VEX, MEX, and MAVEN have made initial measurements of atmospheric escape rates at Venus and Mars during different solar cycles
- The physics of atmospheric loss depends on planet size, magnetic field and atmospheric composition
- Understanding escape requires *system-level thinking*: lower/middle atmosphere and outgassing cannot be ignored!
- We need more measurements of:
  - atmospheres, isotopes, magnetic fields
  - kinetic scale structures and processes
  - proxies for the early sun/sun-like stars (via lunar measurements?)









Next steps

- **Mars**: understand coupled climate/escape system in the early atmosphere
- **Venus**: isotopic measurements (Go DAVINCI & EnVISION!), atmosphere system studies
- **Earth**: any mission at all dedicated to measuring atmospheric escape
- **Exoplanets**: can ongoing hydrodynamic escape on close-in exoplanets aid early solar system understanding?