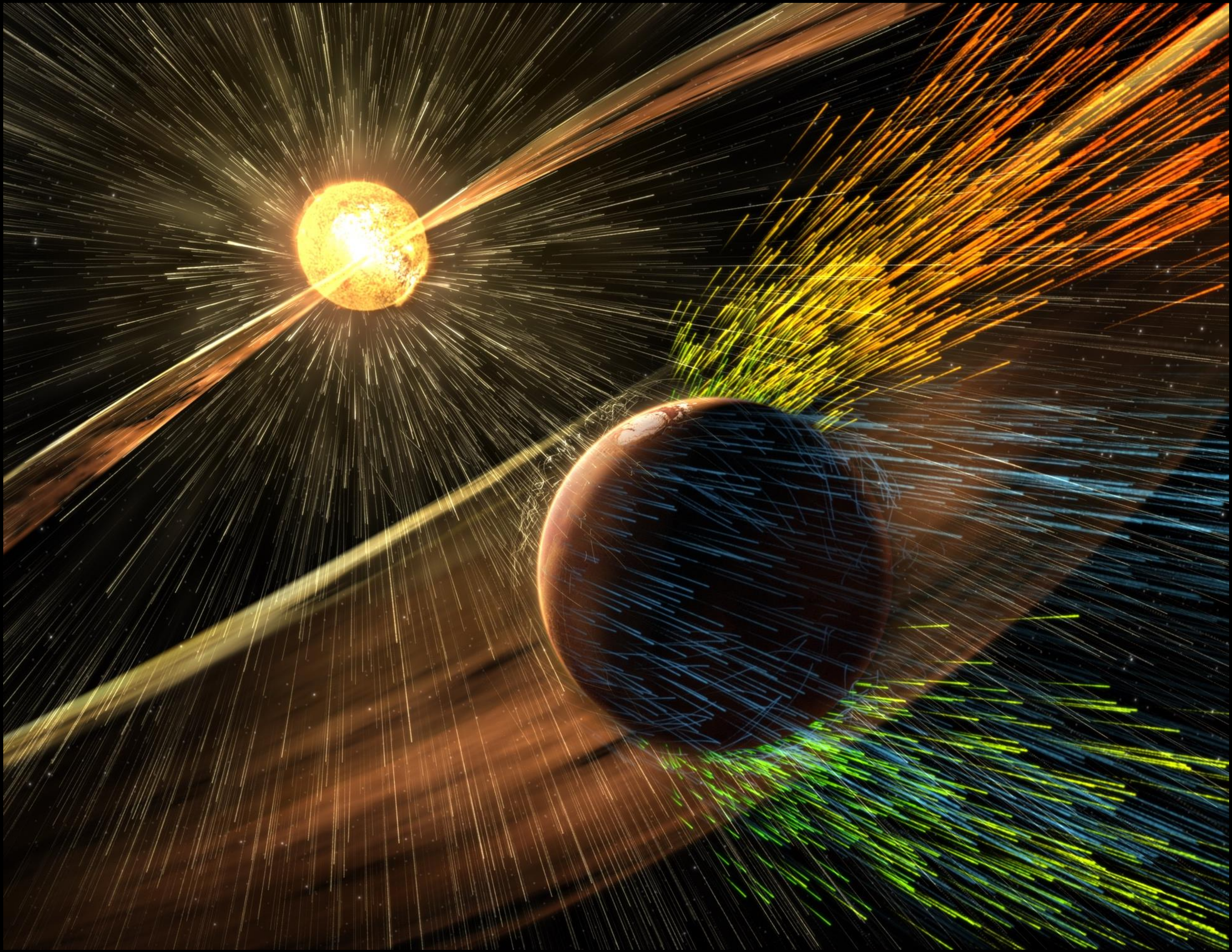
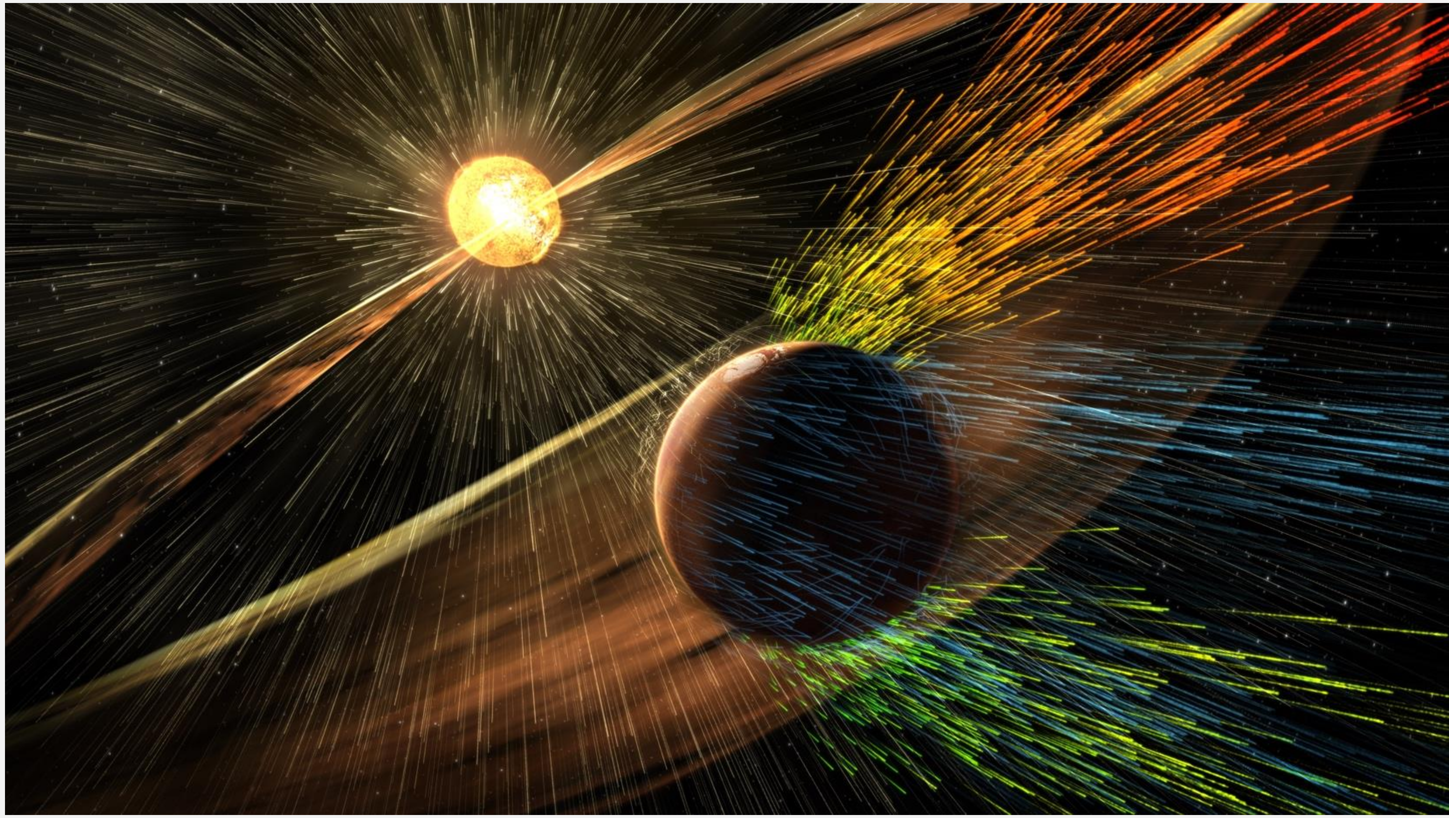
Planetary Habitability II

(Atmospheric Escape)

Dave Brain
U. Colorado



October 2015



Dave: “Can you make a graphic that looks something like this?”

NASA: “Yes.”

1. General Requirements for Atmospheric Escape

Question

What requirements for a particle to escape from a planet's atmosphere?

-

Requirements for an atmospheric particle to escape

1. Escape Energy

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$\text{Þ} \quad v = \sqrt{\frac{2GM}{r}}$$

2. Directed Upward

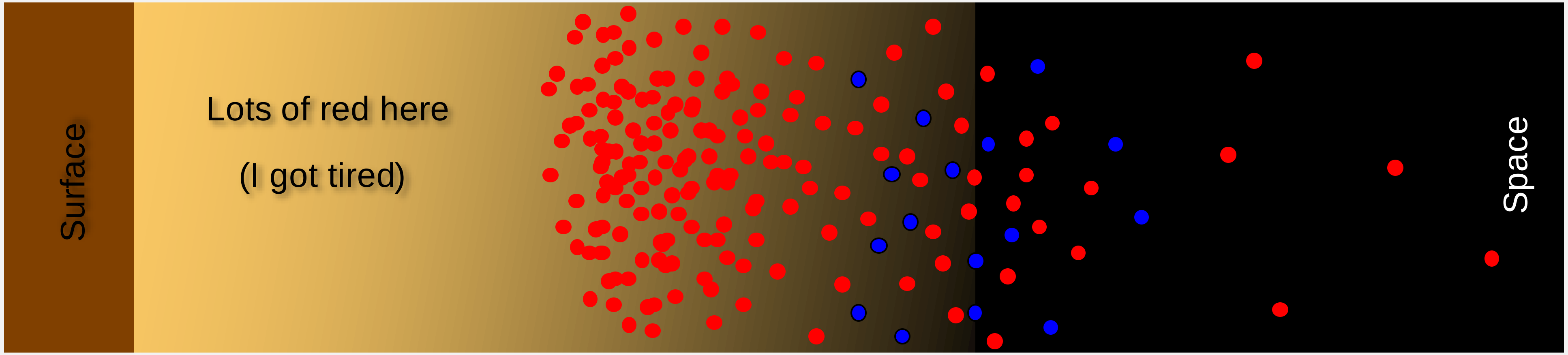
3. No Collisions

Escape from exobase region

$$\frac{kT}{mg} = \frac{1}{ns}$$

	Venus	Earth	Mars
v_{esc}	10 km/s	11 km/s	5 km/s
$E(H^+)$	0.5 eV	0.6 eV	0.1 eV
E(O)	9 eV	10 eV	2 eV

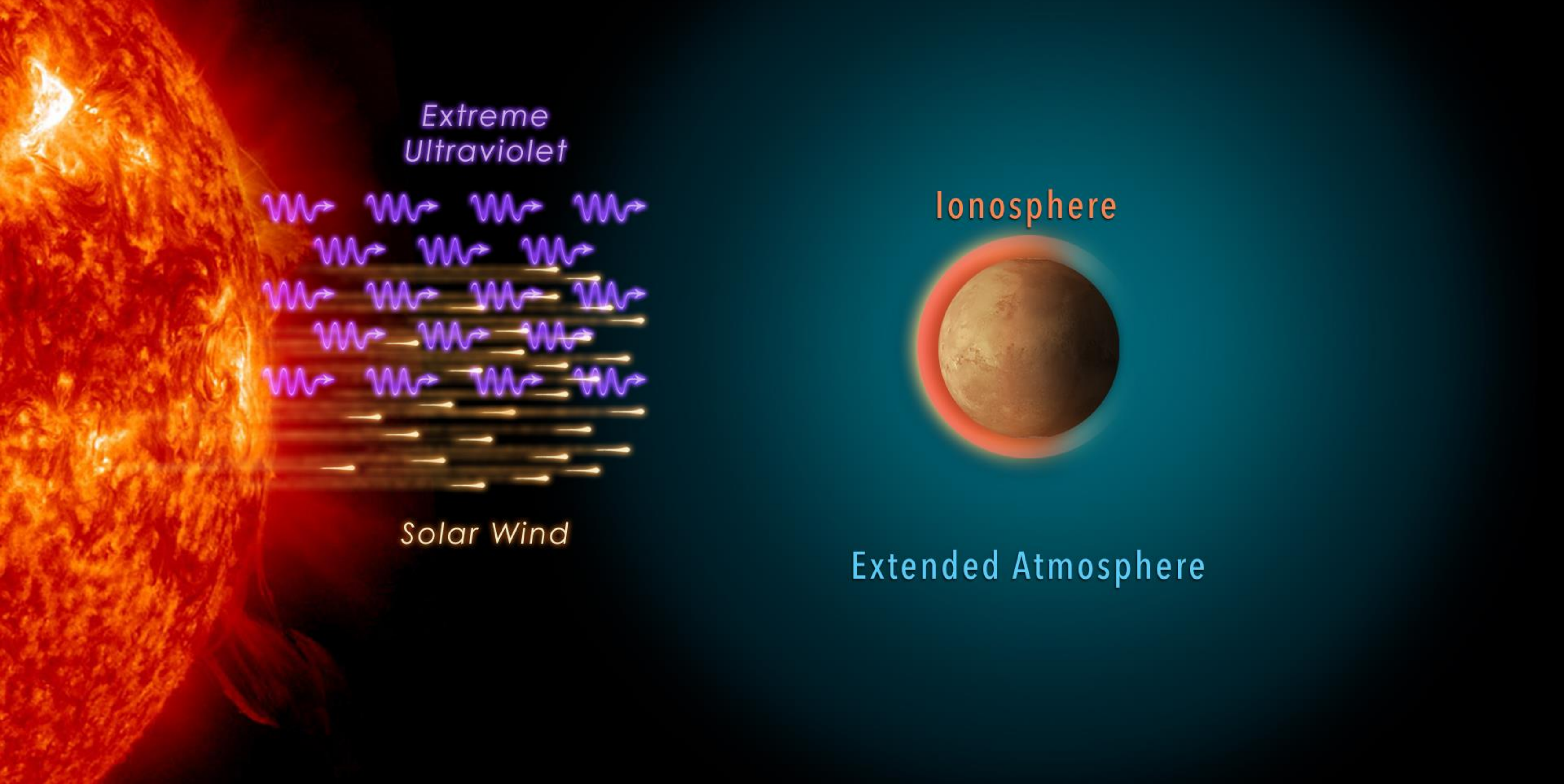
Reservoirs for escape



Thermosphere	Ionosphere	Exosphere
T(z) ⇧	Density << neutral density	“collisionless”
Diffusive separation	Chapman peaks from incident energy	Ballistic trajectories
V: ~120-250 km CO_2, CO, O, N_2	V: ~120-300 km O_2^+, O^+, H^+	V: ~250-8,000 km H
E: ~85-500 km O_2, He, N_2	E: ~75-1000 km NO^+, O^+, H^+	E: ~500-10,000 km H, (He, CO_2, O)
M: ~80-200 km CO_2, N_2, CO	M: ~80-200 km O_2^+, O^+, H^+	M: ~200-30,000 km H, (O)

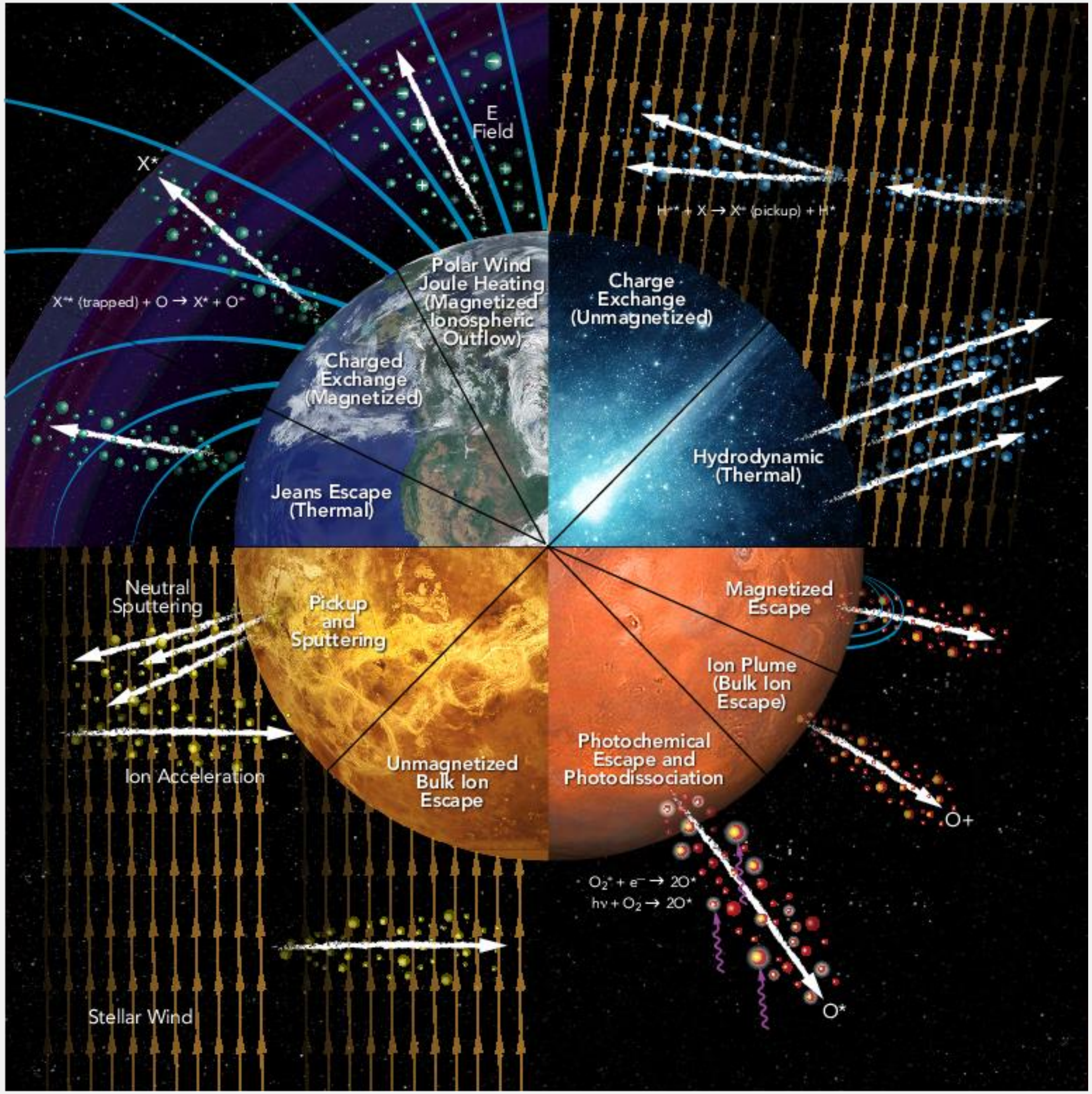
2. Atmospheric Escape Processes

Our star drives atmospheric escape (actually *many* processes!)

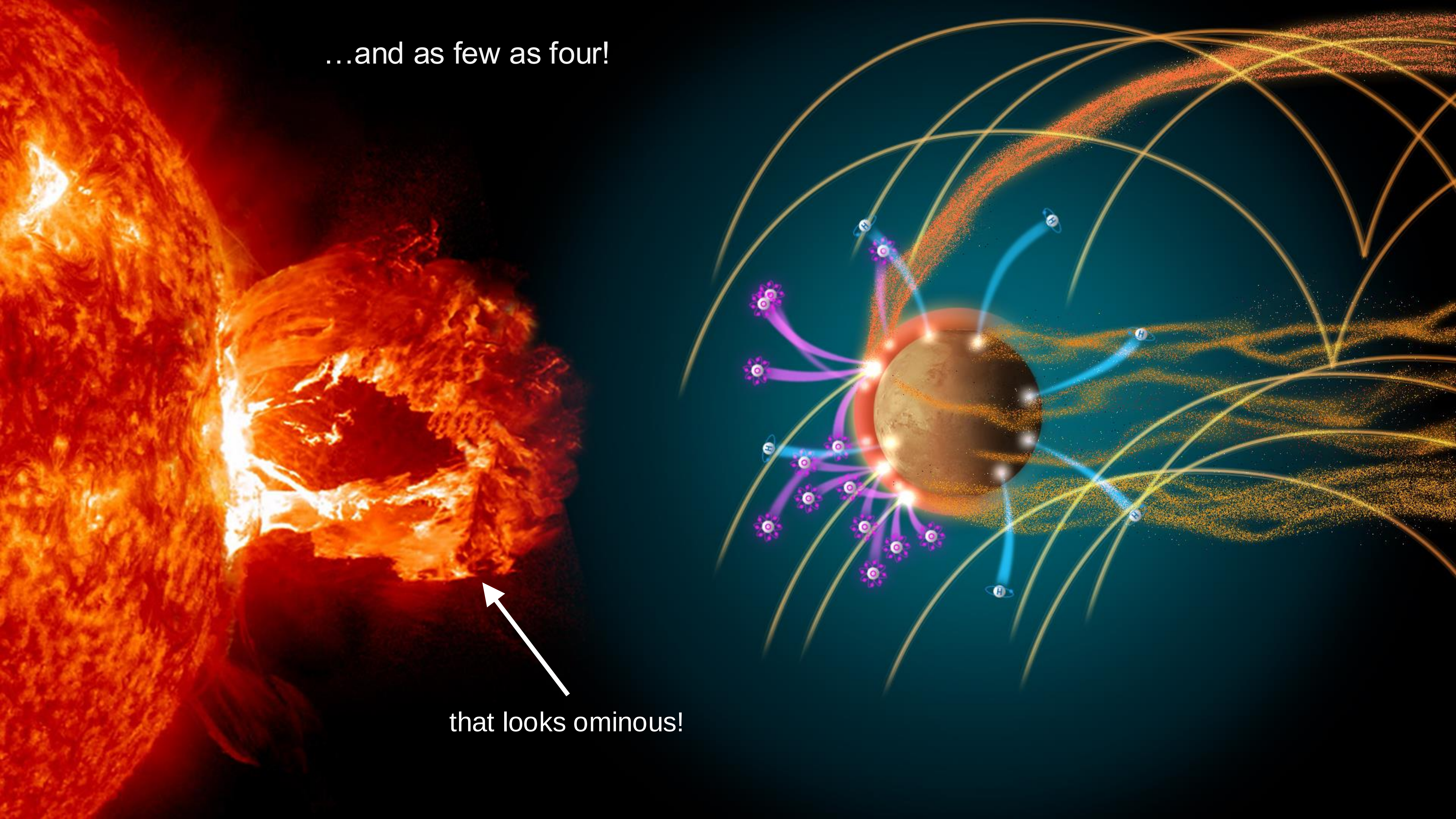


Escape processes

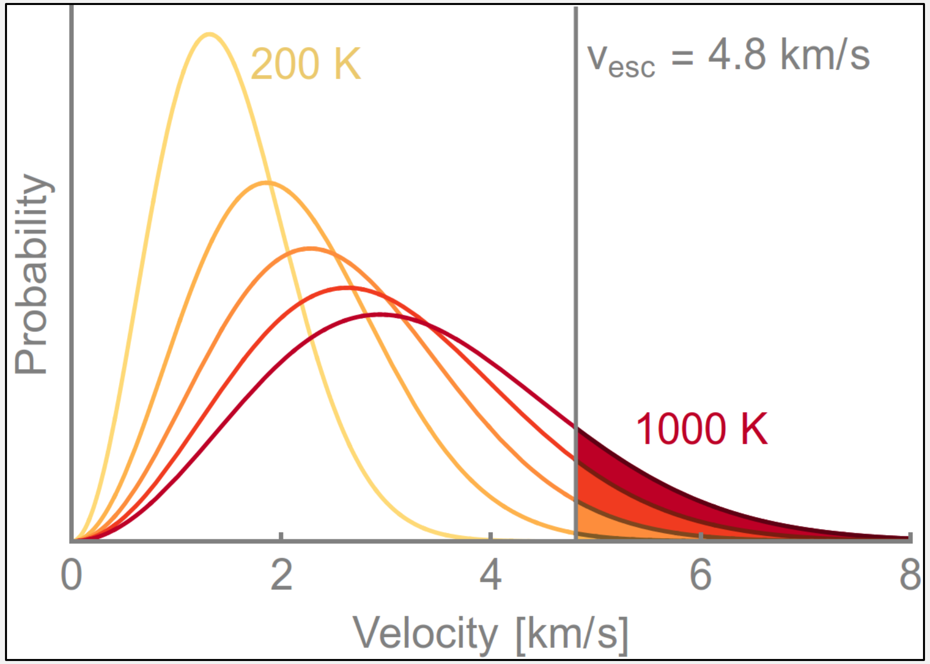
There are as many as 10 distinct escape processes, depending upon how you count…



Gronoff et al., 2020


…and as few as four!
that looks ominous!

Thermal processes



Courtesy M. Chaffin

Thermal escape
or Jeans escape
or photoevaporation?

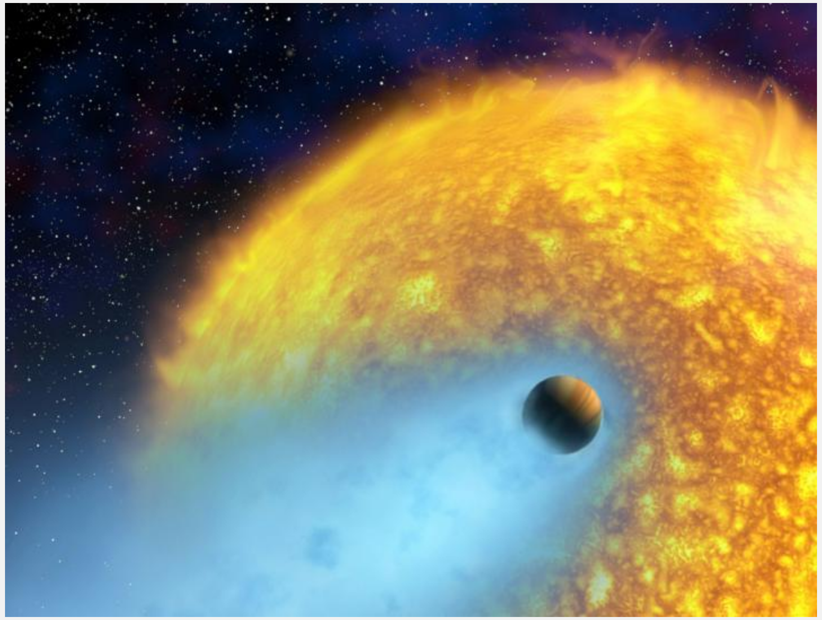
$$\lambda_{esc} = \frac{E_{escape}}{E_{thermal}}$$

$$\Phi = \frac{n_{exo} v_{th}}{2\sqrt{\pi}} (1 + \lambda_{esc}) e^{-\lambda_{esc}}$$

$$\lambda_{esc} < \sim 3$$

Hydrodynamic escape
or Blowoff / outflow
or photoevaporation

NASA / ESA / Vidal-Madjar

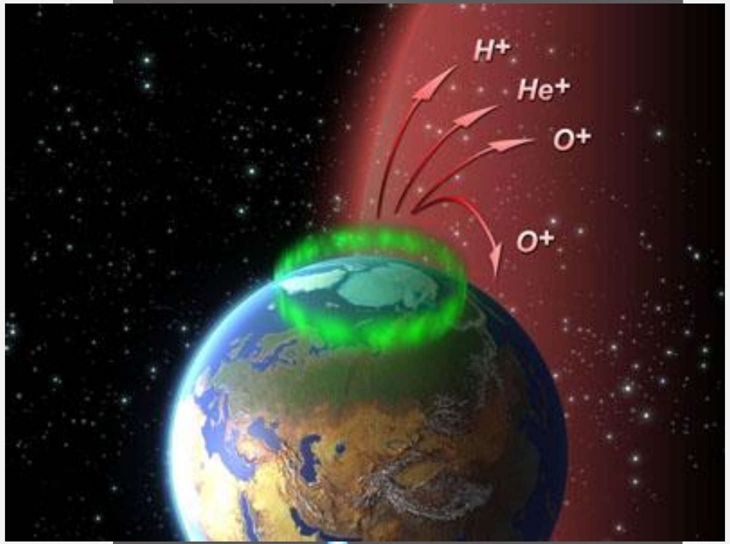


Non-thermal processes

Photochemical escape

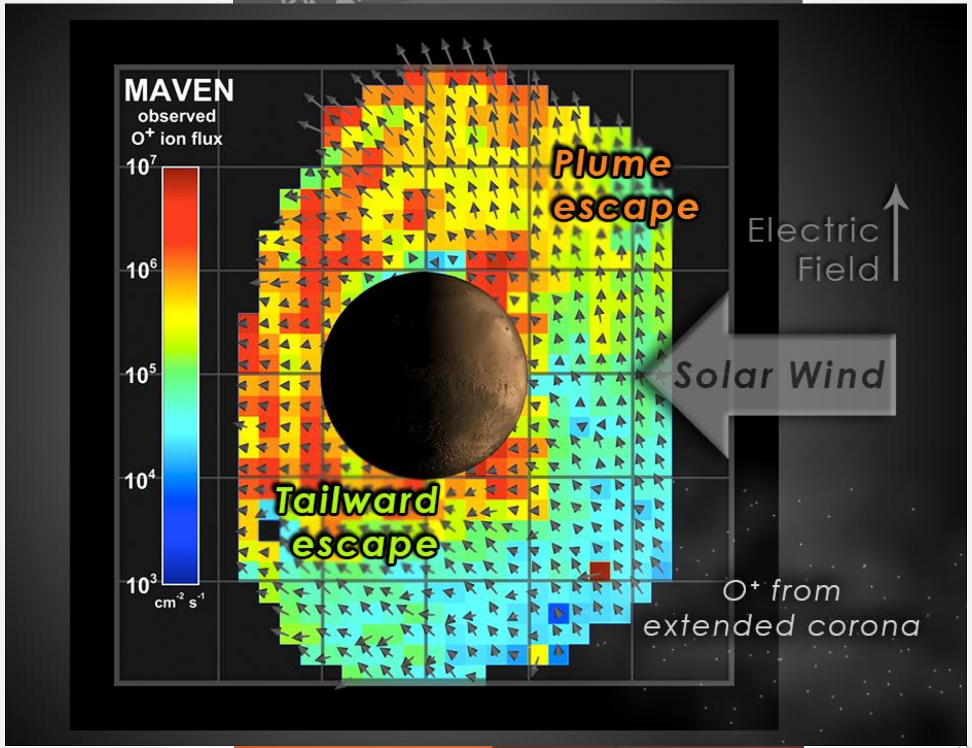
- Exothermic chemical reactions provide energy for escape
- Typical reactions: $O_2 + h\nu \rightarrow O_2^+ + e^-$

  $O_2^+ + e^- \rightarrow O^* + O^*$



Sputtering

- Particles can be splashed out of atmospheres
- Requires incident solar wind or atmospheric particle!
- Process has never been unambiguously observed



Ion escape

- Sunlight (or collisions) ionize a high-altitude neutral particle
- Electric fields accelerate the particle, giving it escape velocity
- Magnetic fields influence the trajectory of the particle

More on ion escape

$$E = -\vec{v} \times \vec{B} + \frac{1}{ne}\vec{J} \times \vec{B} - \frac{1}{ne}\vec{\nabla}P_e + \cdots$$

Pickup

Hall

Electron Pressure Gradient

- Electric fields accelerate charged particles
- Can loosely identify pickup, Hall, and pressure gradient escape
- Highlights that *combinations* of mechanisms can accelerate ions

A few comments

- Different processes are important for different species
- The importance of a process can vary with time
- Not all processes operate at a given planet
- Some processes fractionate an atmosphere, and others do not
- Magnetic fields should directly impact some processes, while other processes are indirectly impacted (or not impacted at all)

Question

Suppose a planet loses oxygen atoms at a rate of 10^{26} s^{-1}.

How much atmosphere (in bars) would be lost in 4 Gy at this rate?

Helpful information:

1 bar = 10^5 Pascals
$R_P \sim 3400$ km
$g_P \sim 3.8$ m/s^2

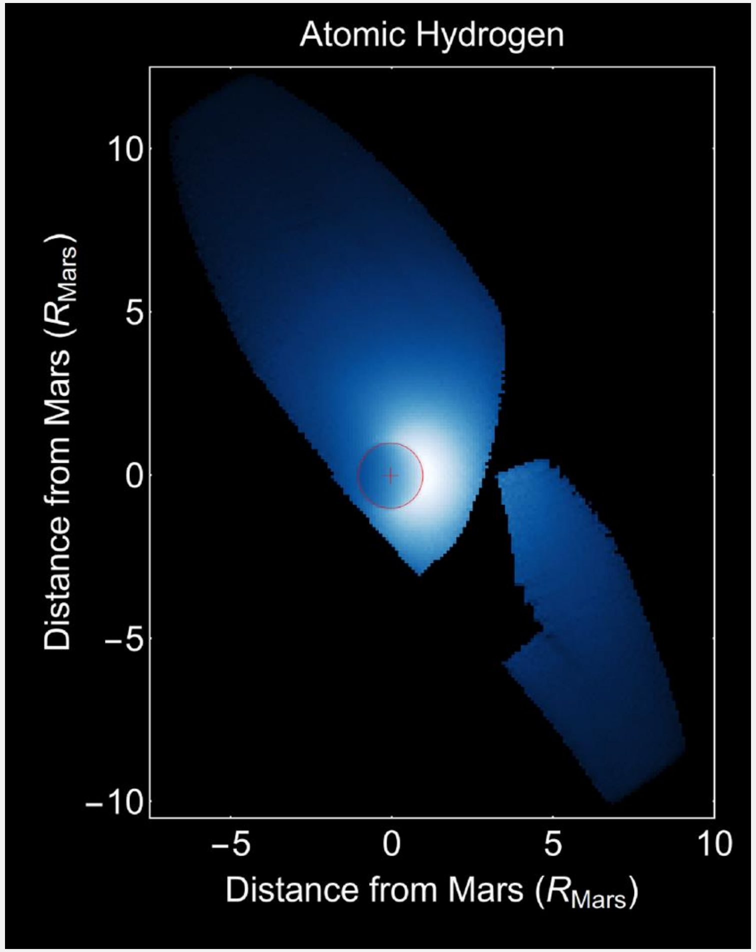
Atomic number of oxygen = 8
1 year ~ π x 10^7 s

$$\Delta P = \Delta \frac{F}{A} = \frac{\Delta F}{A} = \frac{\Delta m \; g_P}{A} = \frac{\Phi \; m_O \; \Delta t \; g_P}{4 \, \pi \, R_P^2} = \sim 100 \; mbar$$

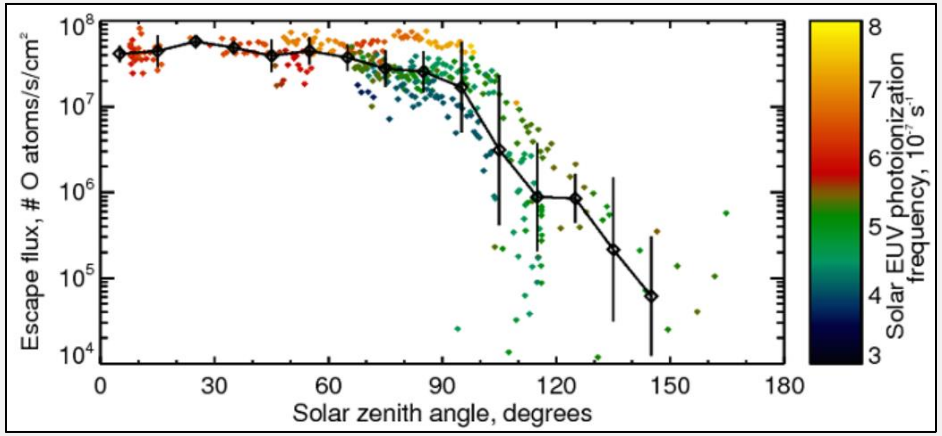
Is this enough to change climate?
Is it a lot?
Is it a little?

3. Observations of Escape

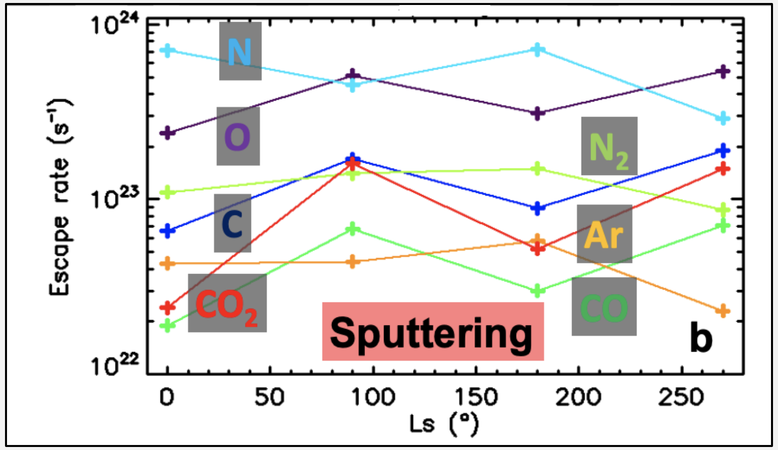
Atmospheric escape from Mars



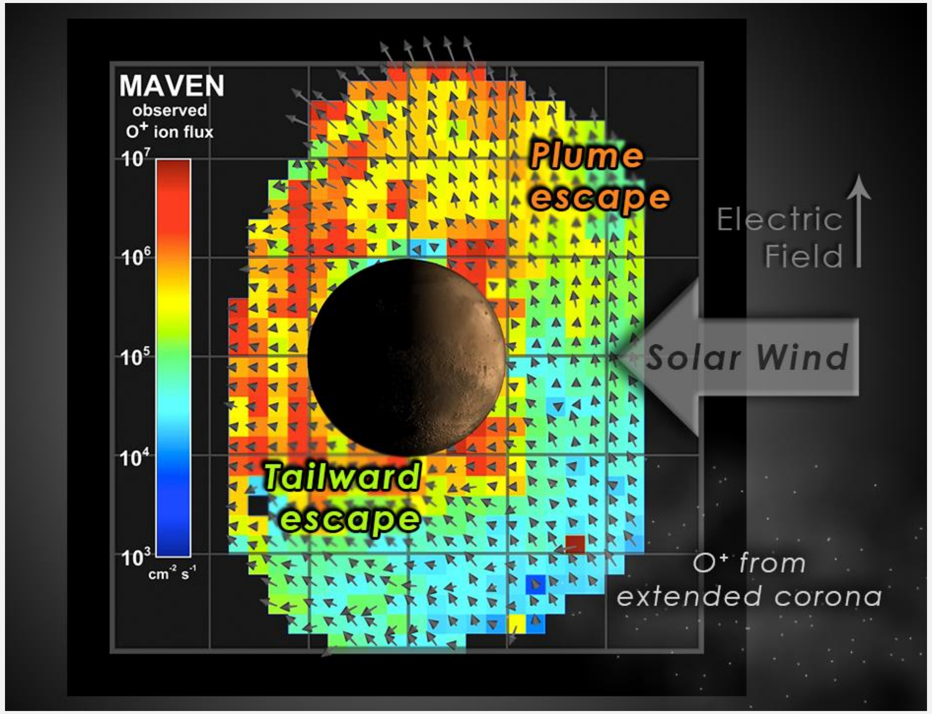
Thermal Escape (H) ~10^{26} s^{-1}



Photochemical Escape (O)
~1-5 × 10^{25} s^{-1}



Sputtering Escape (N,O,C,etc.)
~ 10^{23} s^{-1}



Ion Escape (O^+, O_2^+, CO_2^+) ~7 x 10^{24} s^{-1}

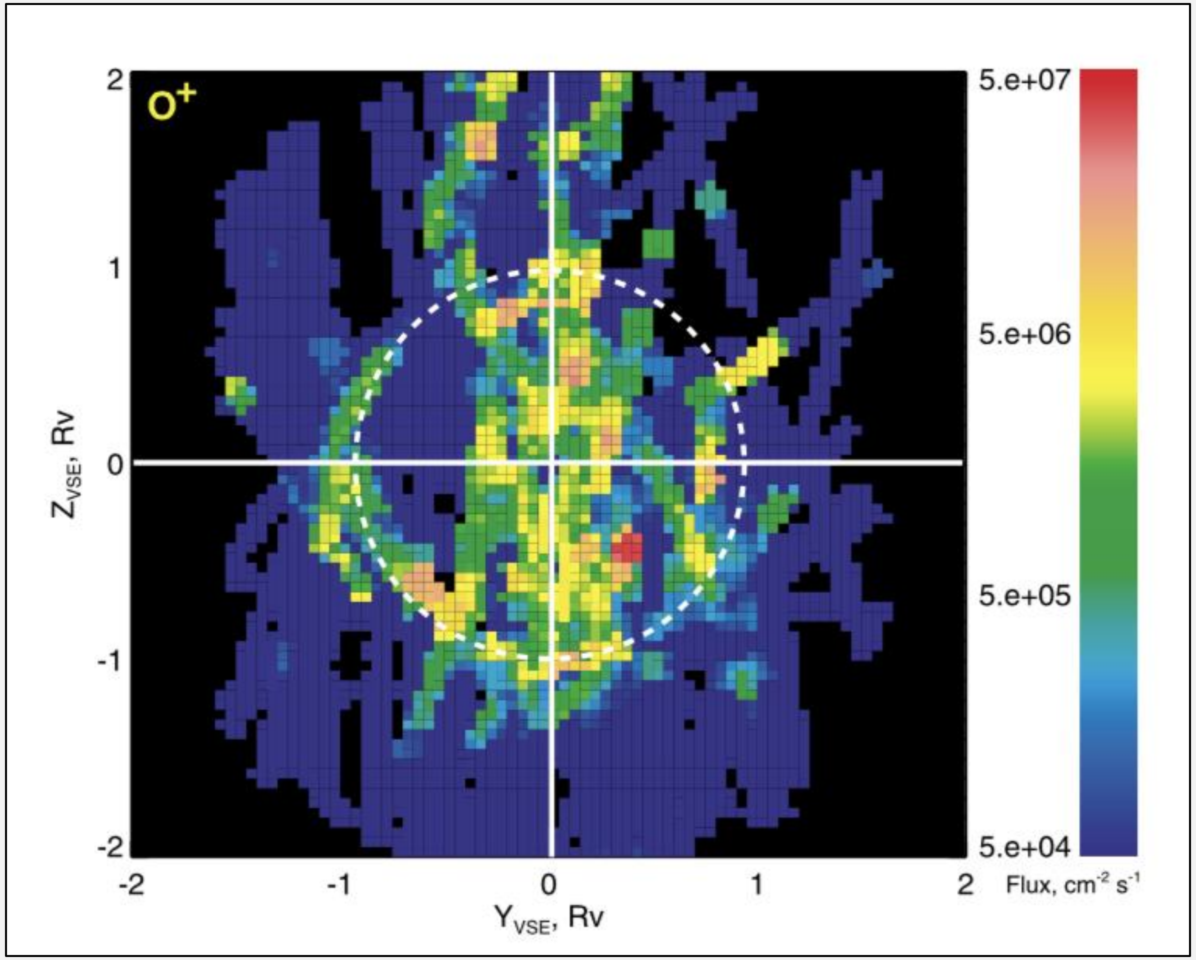
Atmospheric escape from Venus

~~Thermal Escape (H)~~

~~Photochemical Escape (O)~~

Sputtering Escape (N,O,C,etc.)   ~ ??? s^{-1}

Ion Escape (O^+, O_2^+, CO_2^+, H^+) ~5 x 10^{24} s^{-1}



Fedorov et al., 2011

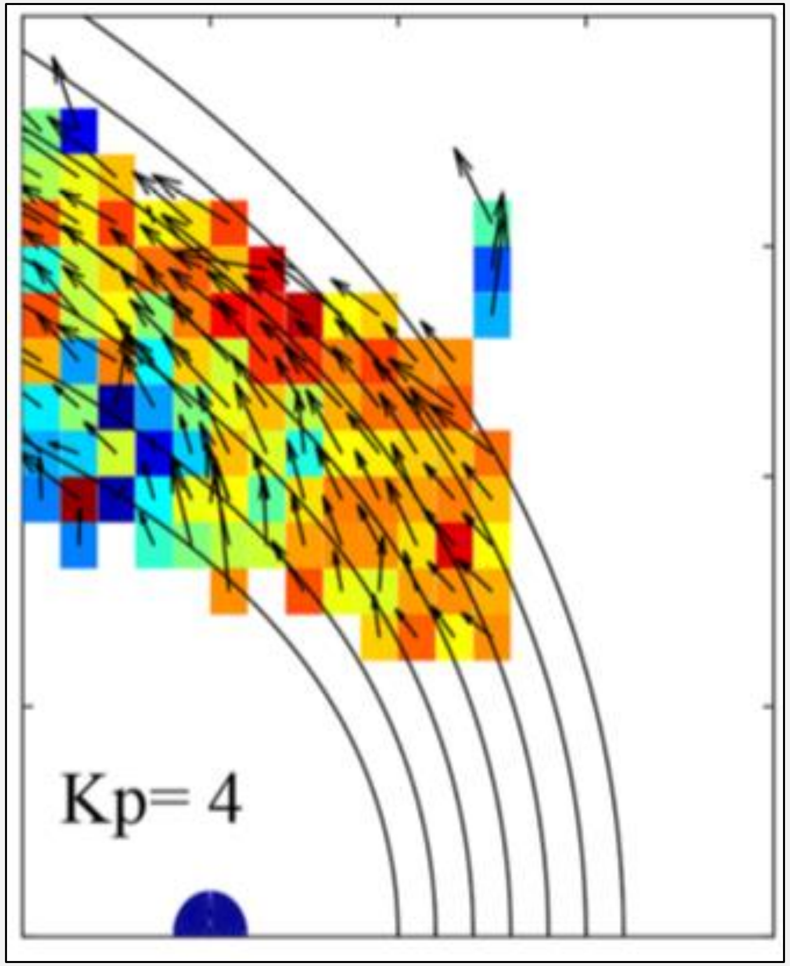
Atmospheric escape from Earth

Thermal Escape (H) ~ 10^{26} s^{-1}

~~Photochemical Escape (N,O)~~

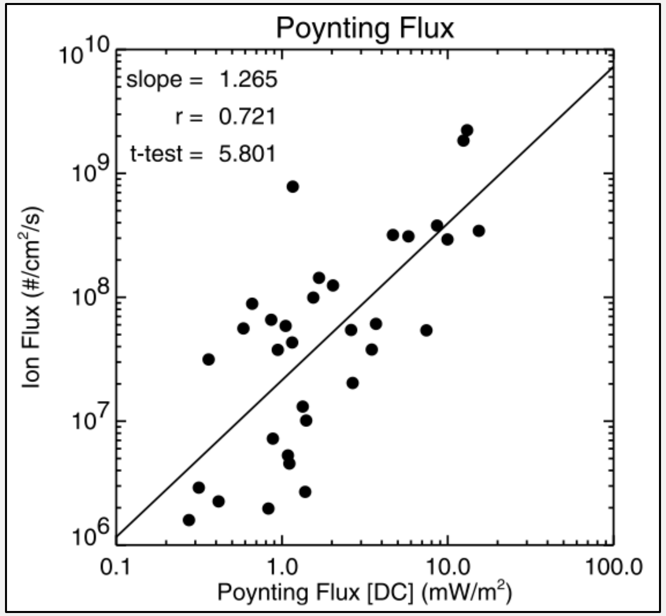
~~Sputtering Escape (N,O,C,etc.)~~

Ion Escape (O^+, H^+) ~10^{25} - 10^{26} s^{-1}

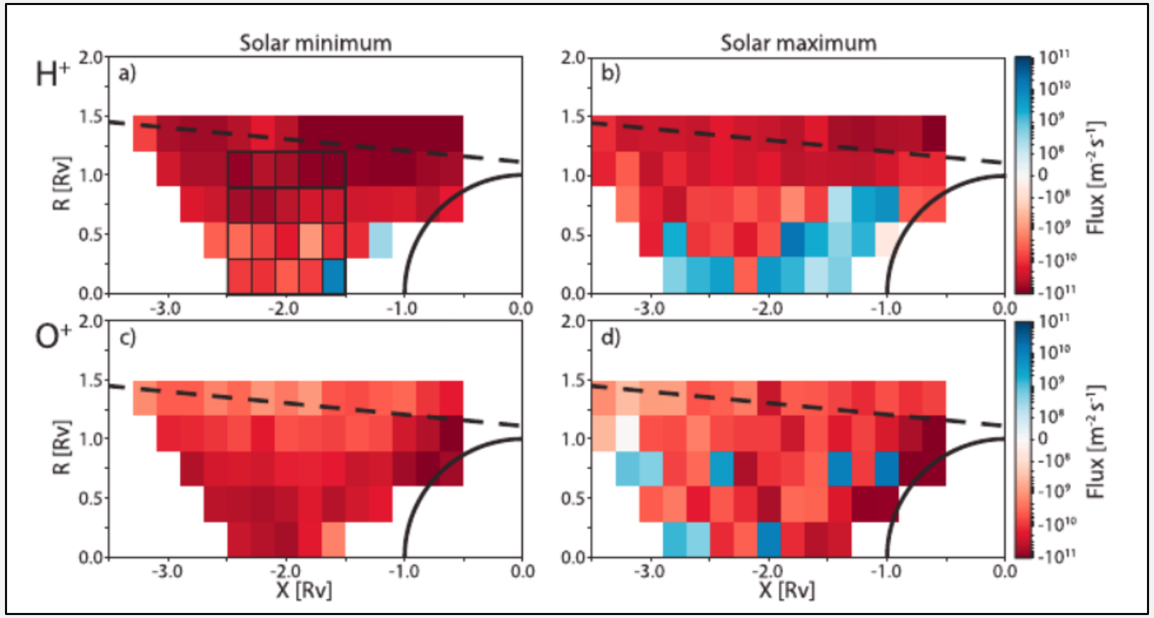


Slapak et al., 2017

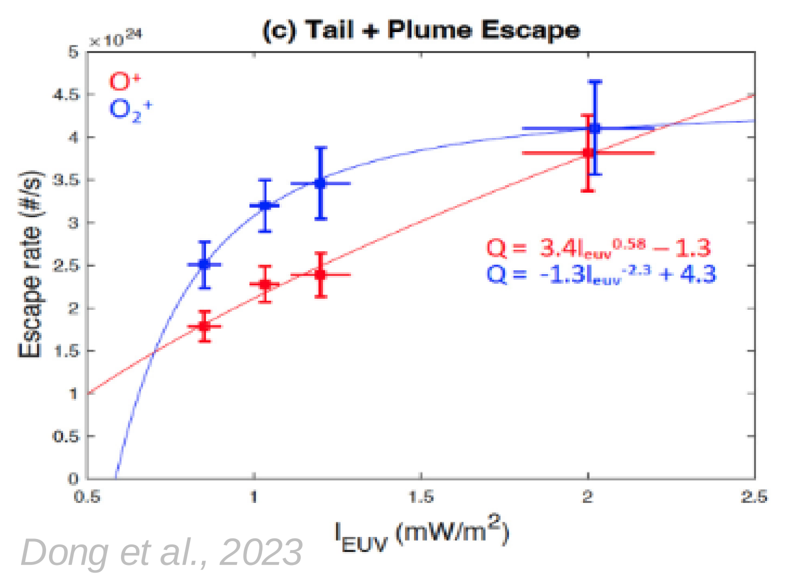
Variability in escape



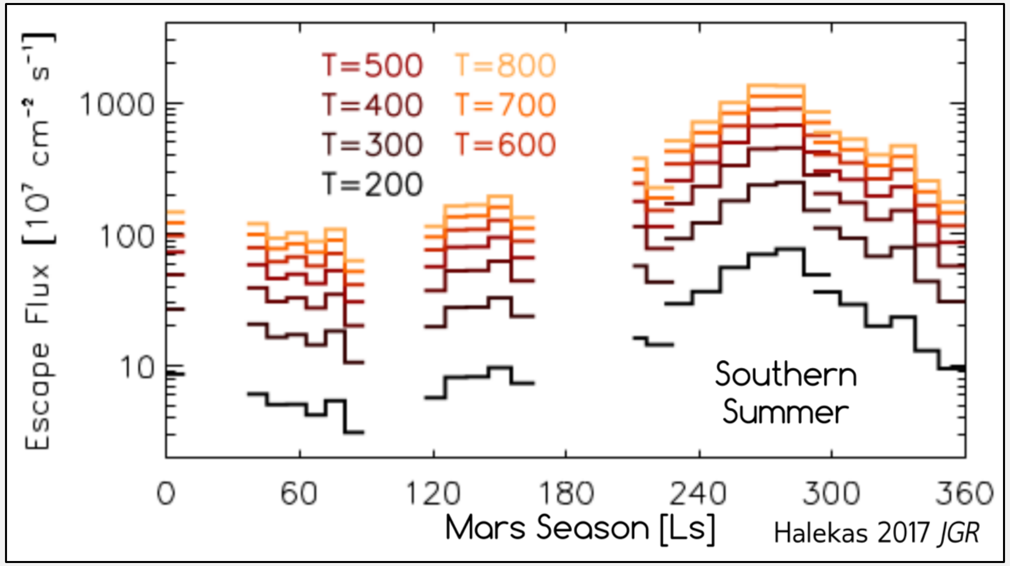
Strangeway et al., 2005



Persson et al., 2018



Dong et al., 2023



Halekas, 2017

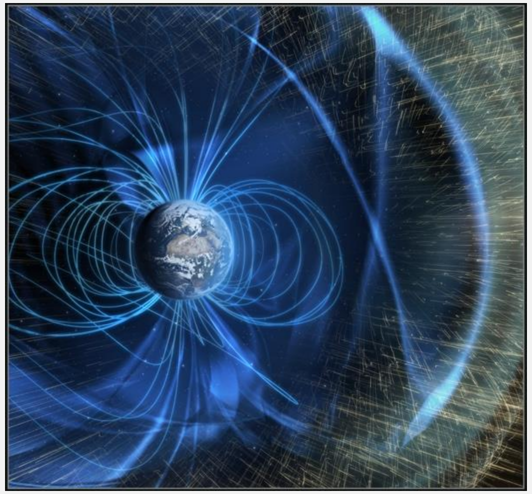
4. Influence of Magnetic Fields

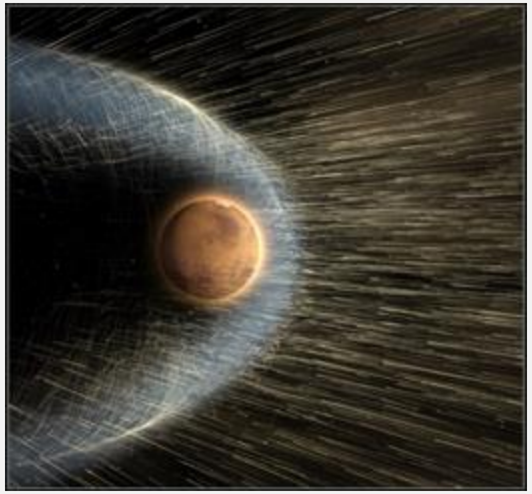
Question

How should planetary magnetic fields influence atmospheric escape?

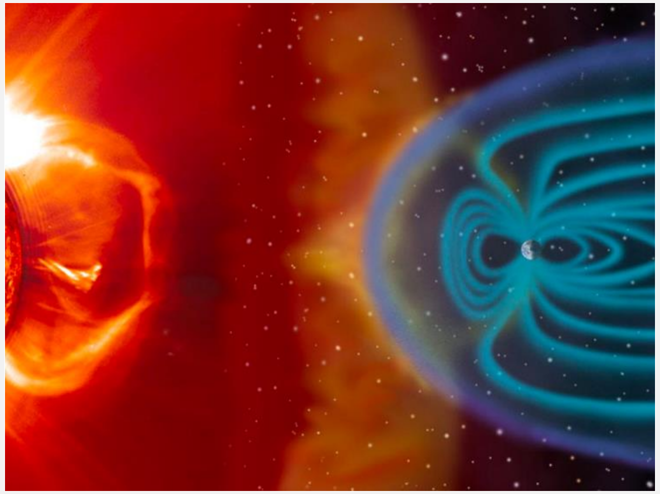
1. A planet’s magnetic field should reduce escape rates
2. A planet’s magnetic field should increase escape rates
3. A planet’s magnetic field shouldn’t influence escape rates
4. It depends
5. Look! A jackalope!

Arguments for and against

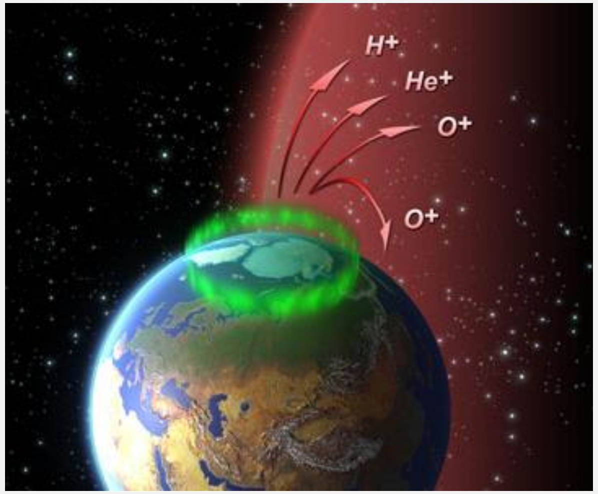




NASA SVS



SOHO / LASCO / EIT



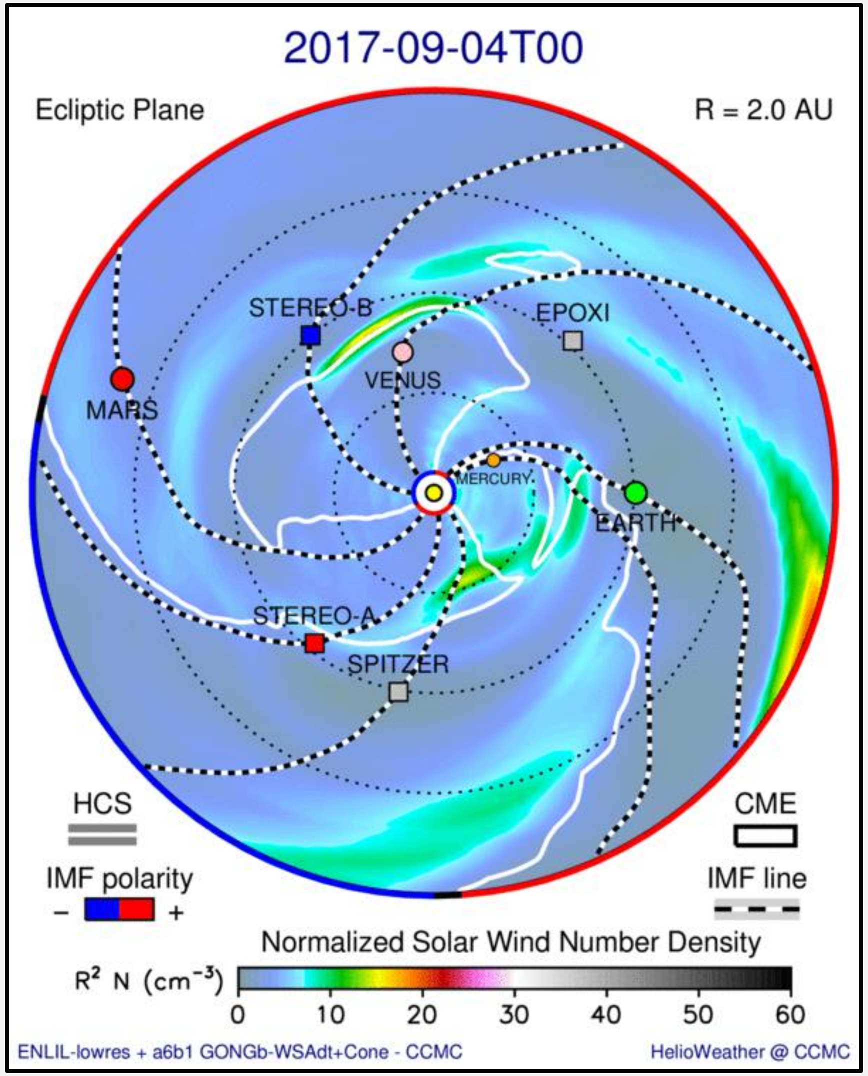
NASA / ESA

Magnetic fields prevent stellar wind particles from stripping an atmosphere

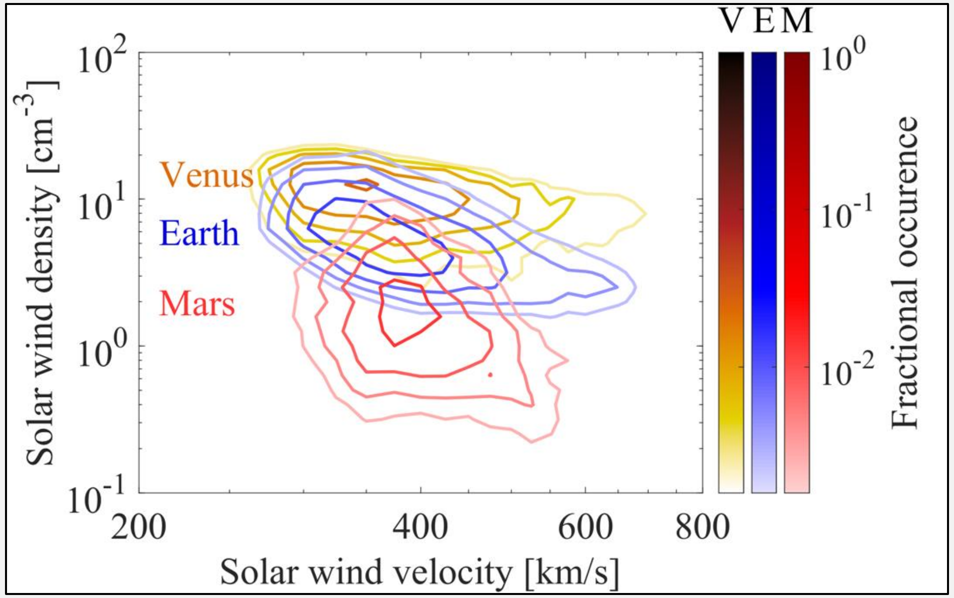
?

Magnetic fields transmit energy from the solar wind to the atmosphere, driving escape

Approach 1: Compare Venus, Earth, and Mars



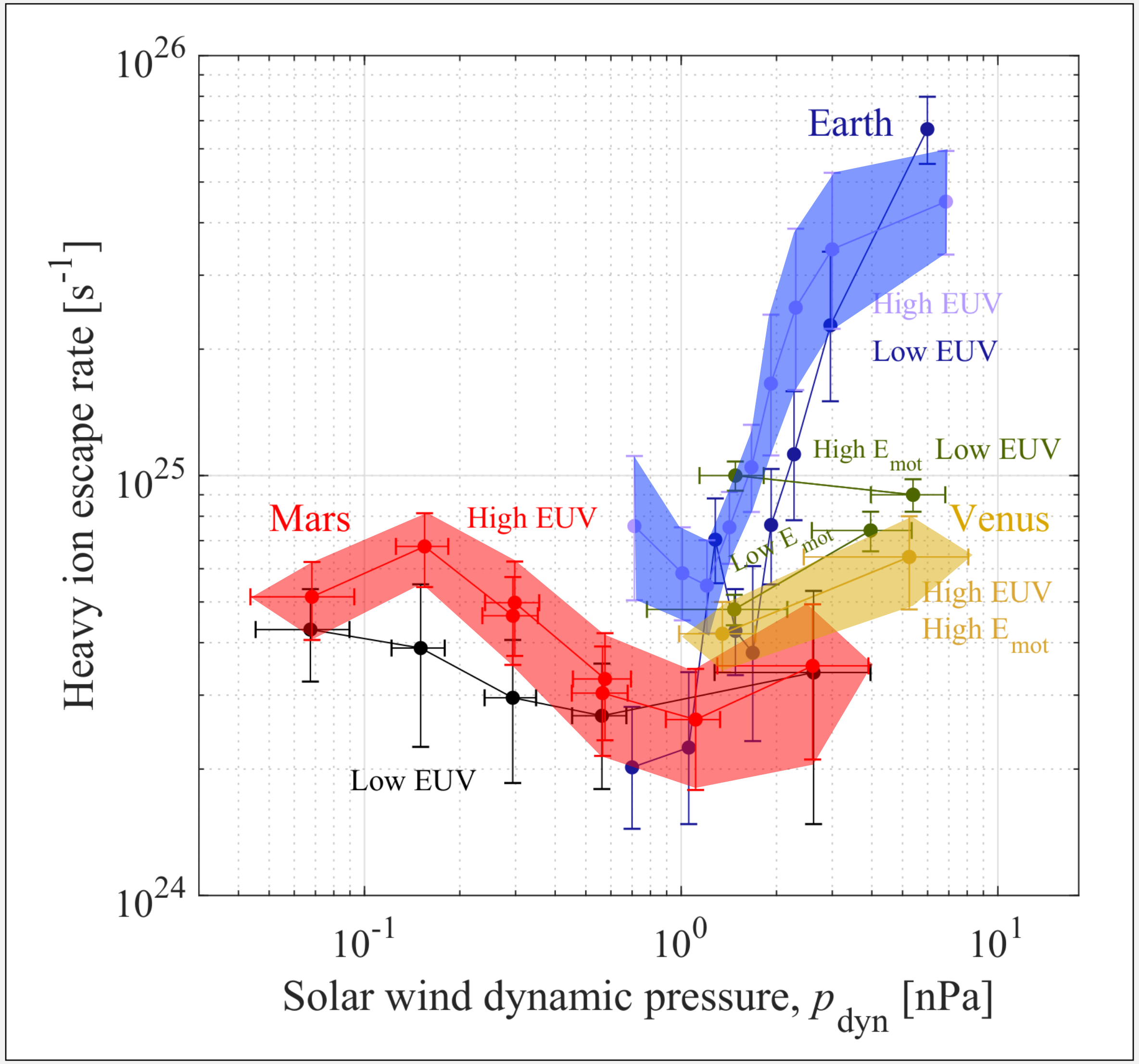
Courtesy L. Mays - GSFC



Courtesy R. Ramstad

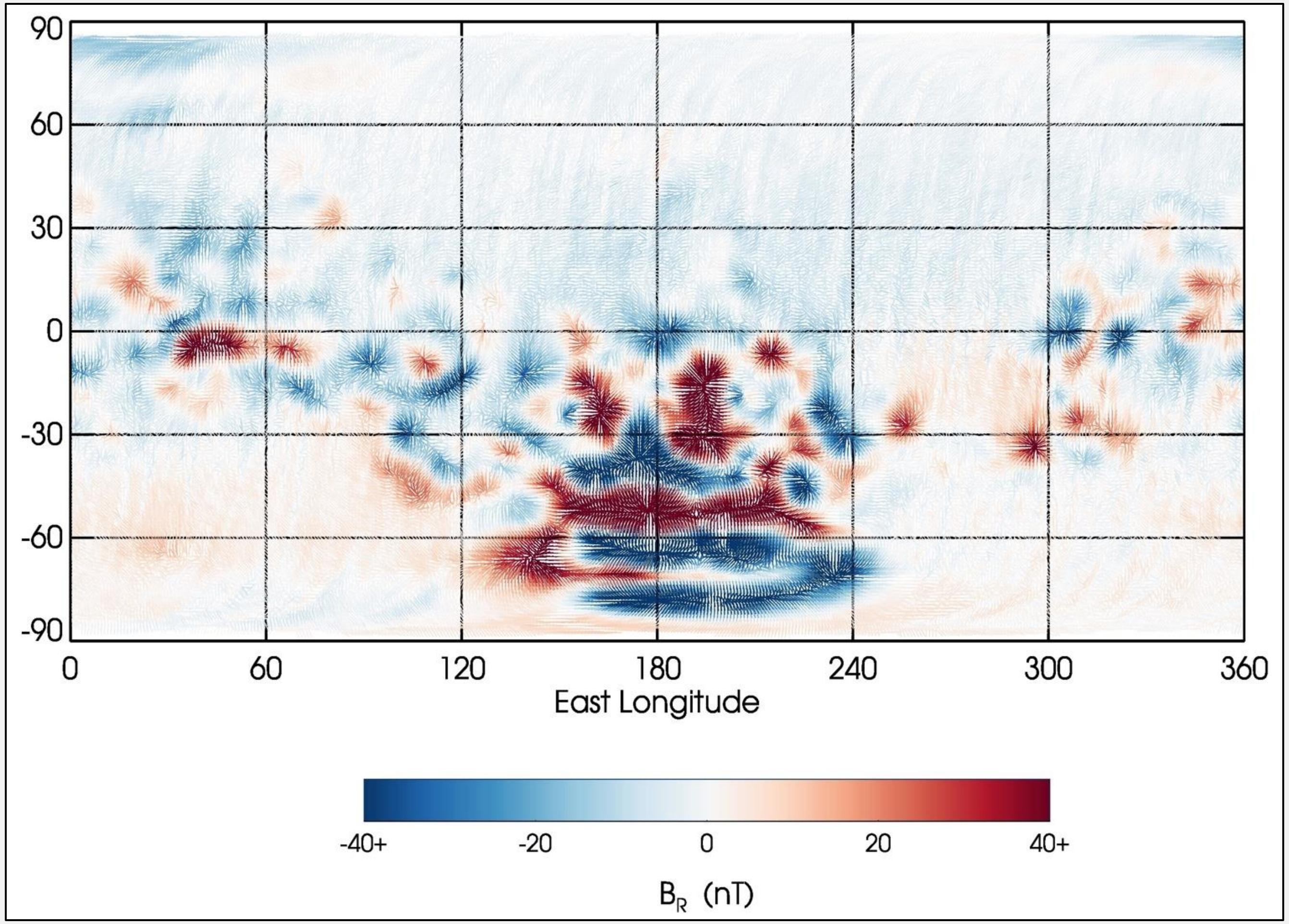
The three planets don’t experience the same set of driving conditions

Approach 1: Compare Venus, Earth, and Mars

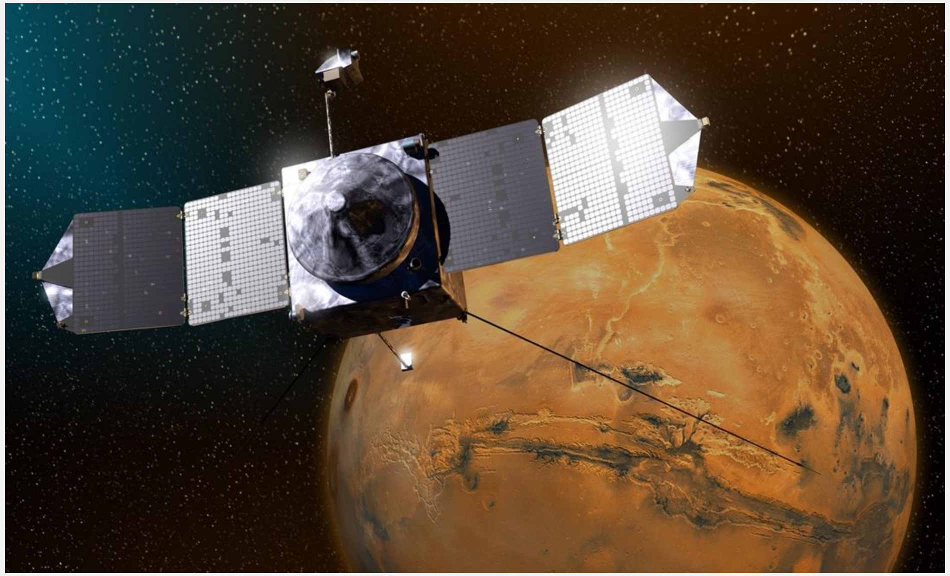


Ramstad and Barabash, 2020

Approach 2: Study Mars

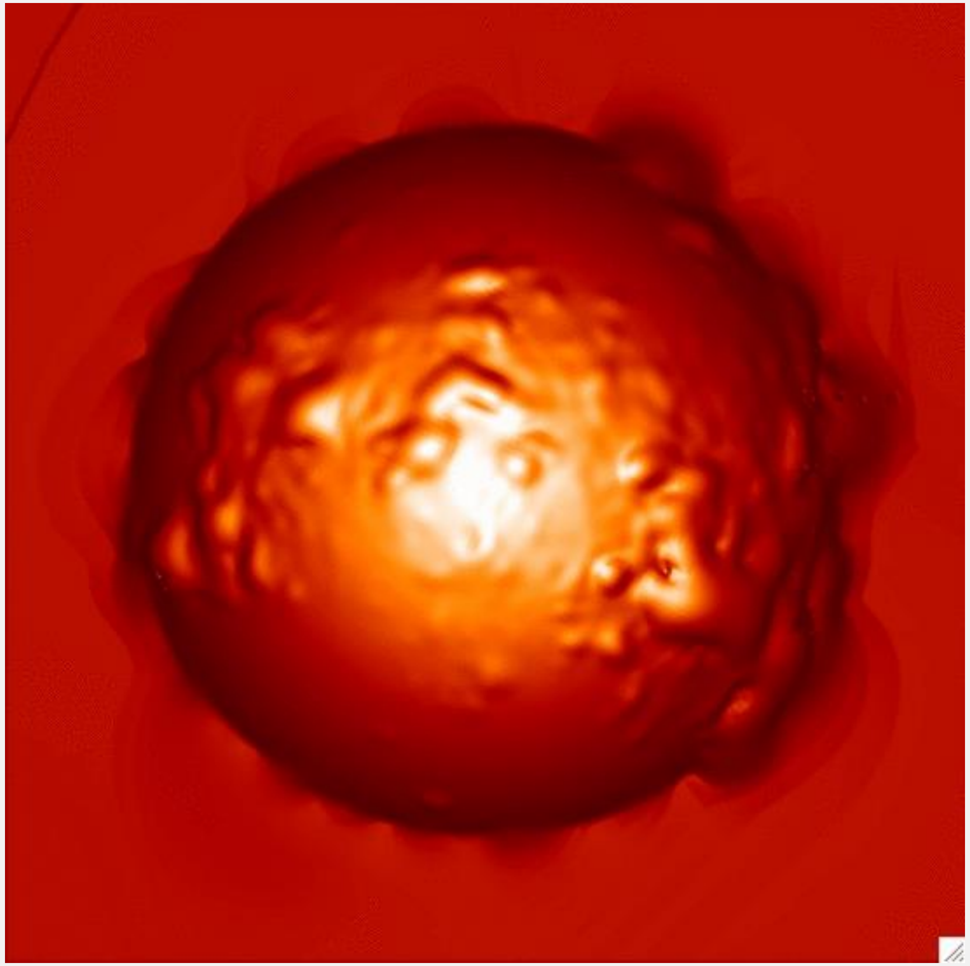


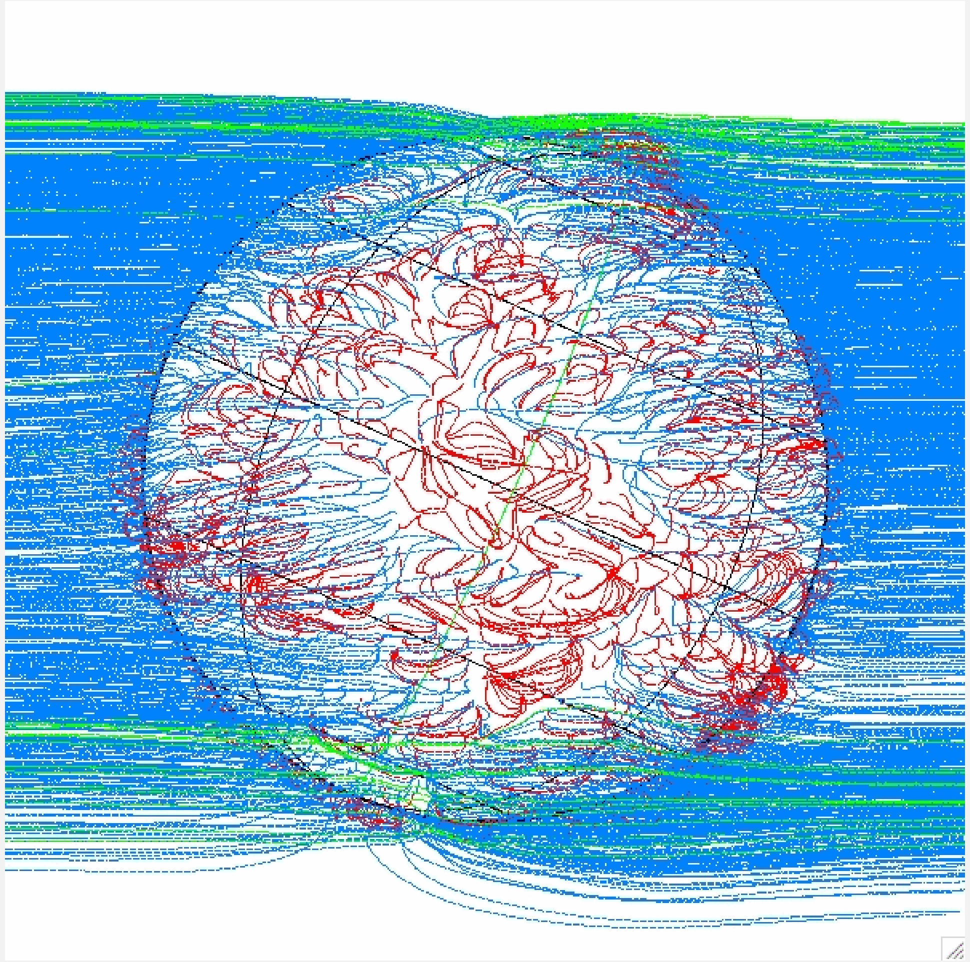
Brain et al., 2017
After Brain et al., 2002



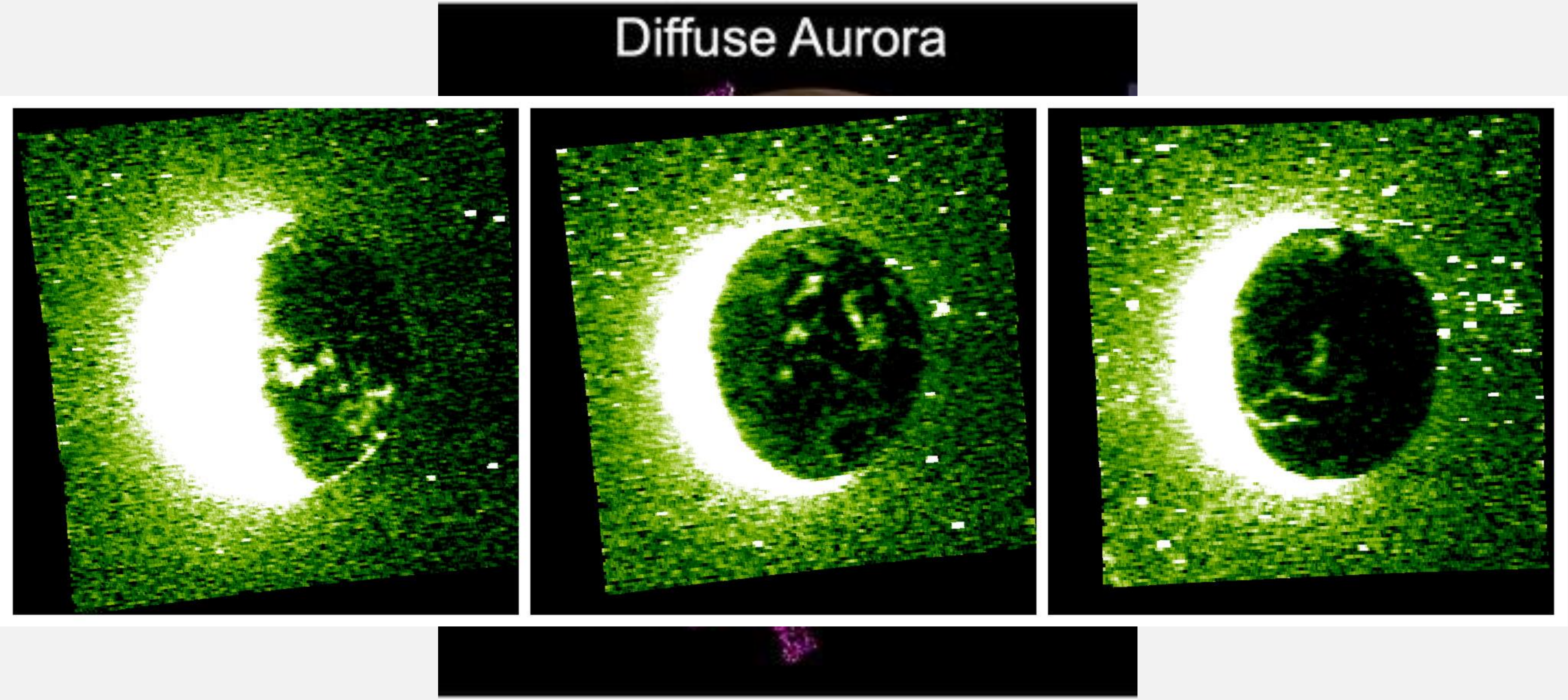
NASA / GSFC

Study Mars interlude: Mars is actually pretty interesting

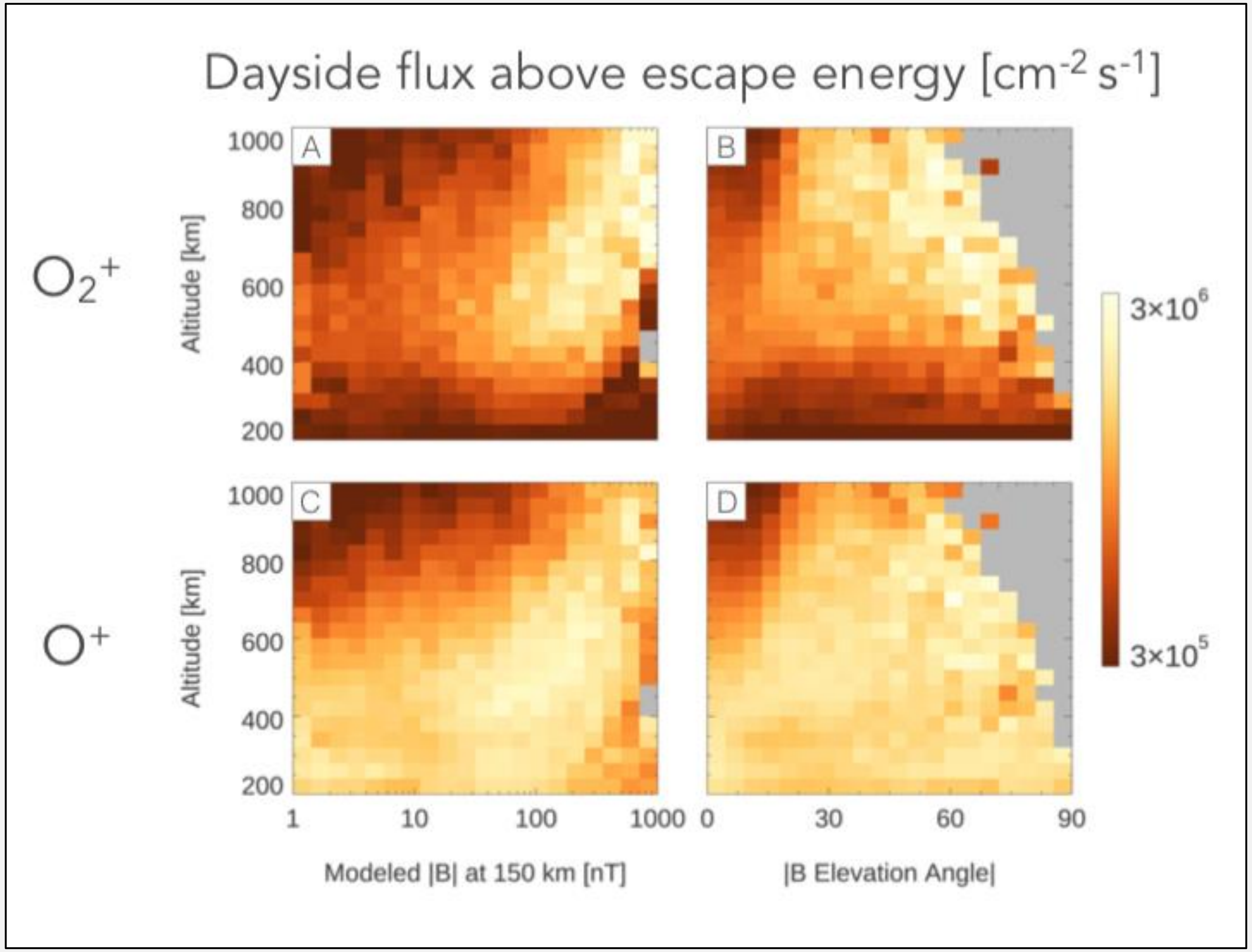




Study Mars interlude: Mars is actually pretty interesting

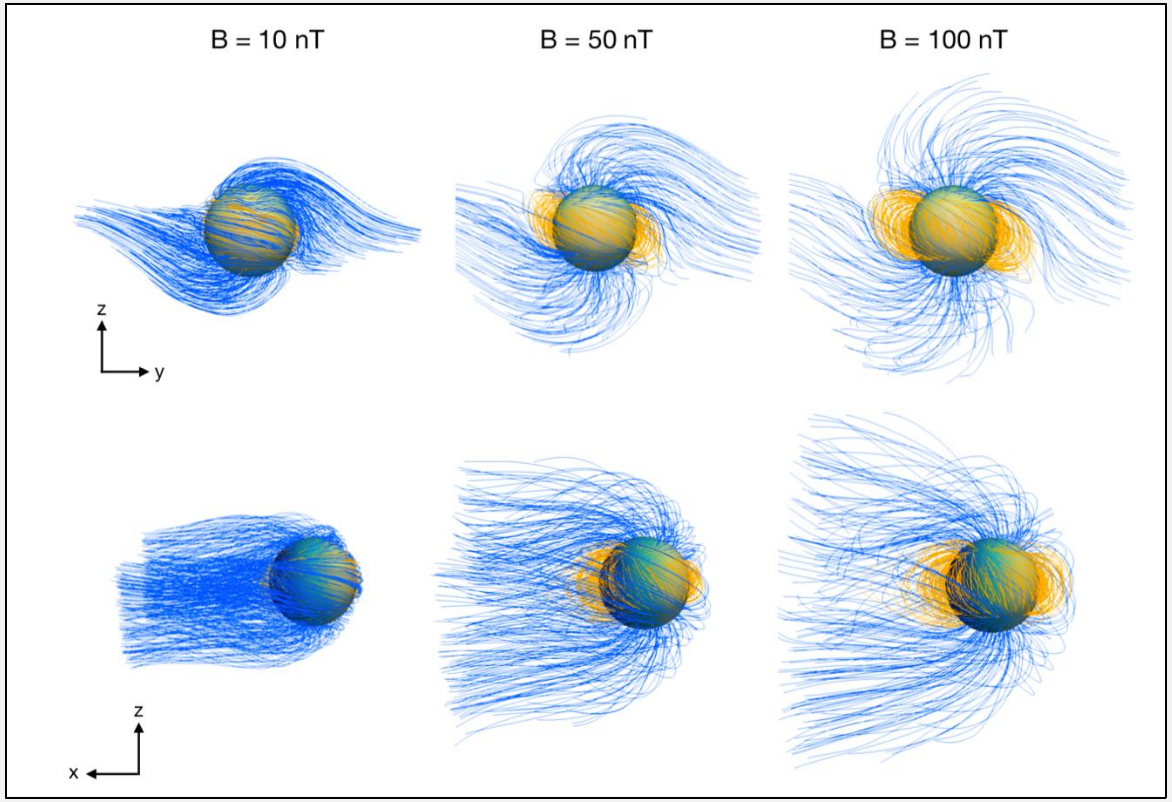


Approach 2: Study Mars

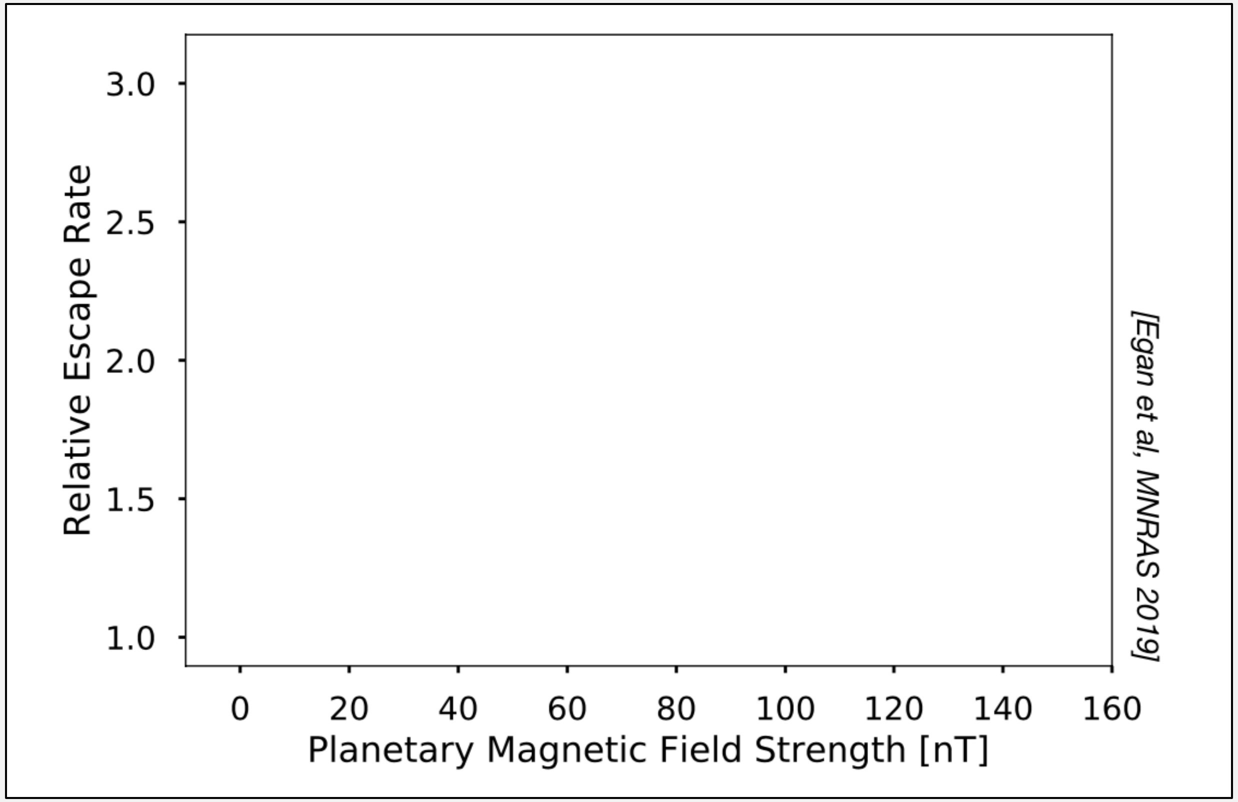


Weber et al., 2021

Approach 3: Use models



Egan et al., 2019



Egan et al., 2019

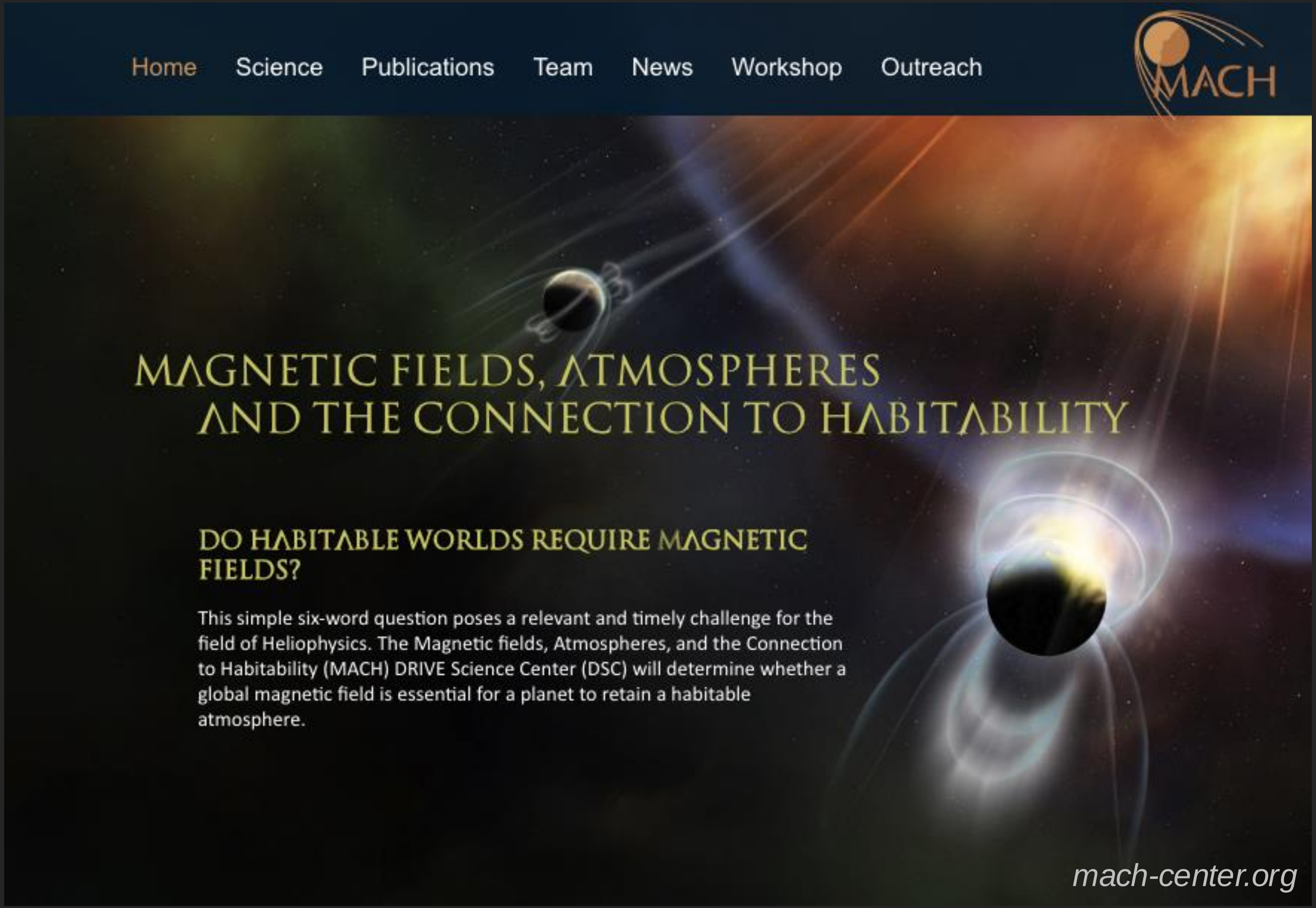
5. Next Steps

A recently funded effort will model planetary atmospheric escape for ~200 star-planet combinations

The effort is called:

“Retention of Habitable Atmospheres in Planetary Systems”

The effort is part of the MACH Center



mach-center.org

Science Question

How do the properties of a planet and its host star influence its ability to retain an atmosphere?

Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

● Earth
■ Solar system
▲ Extrasolar

	Team Member	Institution	Role	Responsibilities
■	Dave Brain	U. Colorado	PI	Direction of team; Model validation; Web interface; Scaling laws
■	Michael Chaffin	U. Colorado	Co-I	Thermal and photochemical escape modeling
▲	Ofer Cohen	UMass Lowell	Co-I	Stellar wind and IMF modeling
▲	Kevin France	U. Colorado	Co-I	Stellar EUV spectra creation
●	Katherine Garcia-Sage	NASA GSFC	Co-I	GITM upper atmosphere modeling
●	Alex Glocer	NASA GSFC	Co-I	PLANET-ITTR upper atmosphere modeling
■	Yingjuan Ma	UCLA	Co-I	BATS-R-US magnetosphere modeling
▲	Rachel Osten	STSci	Co-I	Stellar flare spectra
▲	Aline Vidotto	U. Leiden	Co-I	Transit light curve pipeline
▲	Zachory Berta-Thompson	U. Colorado	Coll.	Transit light curve advice and support
■	Jean-Yves Chaufray	LATMOS	Coll.	Thermal escape modeling and support
■	Tom Cravens	U. Kansas	Coll.	Photochemical escape estimates; Model validation
■	Yoshifumi Futaana	IRF Kiruna	Coll.	Model validation for Venus-like planets
■	Mats Holmstrom	IRF Kiruna	Coll.	FLASH modeling; Model validation
■	Riku Jarvinen	FMI	Coll.	RHybrid modeling support
●	Lynn Kistler	UNH	Coll.	Model validation for Earth-like planets
▲	Ravi Kopparapu	NASA GSFC	Coll.	Connection to CHAMPS; exoplanet interpretation
■	Francois Leblanc	LATMOS	Coll.	Exosphere/sputtering modeling; Model validation
●	Dan Marsh	NCAR	Coll.	Upper atmosphere modeling advice and support
■	Aimee Merkel	U. Colorado	Coll.	Model validation for Mercury-like planets; Web interface
●	Laura Peticolas	Sonoma State	Coll.	Broadening Impacts support (funding sought separately)
■	Robin Ramstad	U. Colorado	Coll.	Model validation for Mars- and Venus-like planets; Scaling laws
■	Shotaro Sakai	Tohoku U.	Coll.	REPPU-Planets modeling
●	Kanako Seki	U. Tokyo	Coll.	TET & REPPU-Planets modeling support; Model validation
▲	Kevin Stevenson	JHU-APL	Coll.	Connection to CHAMPS; exoplanet case selection
●	Robert Strangeway	UCLA	Coll.	Model validation for Earth-like planets
■	Naoki Terada	Tohoku U.	Coll.	TET & TEDSMC modeling; REPPU-Planets support

Table 3: Team member science responsibilities

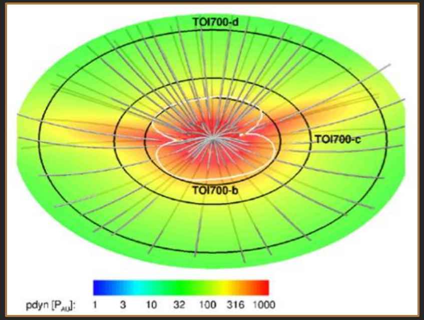
Objectives

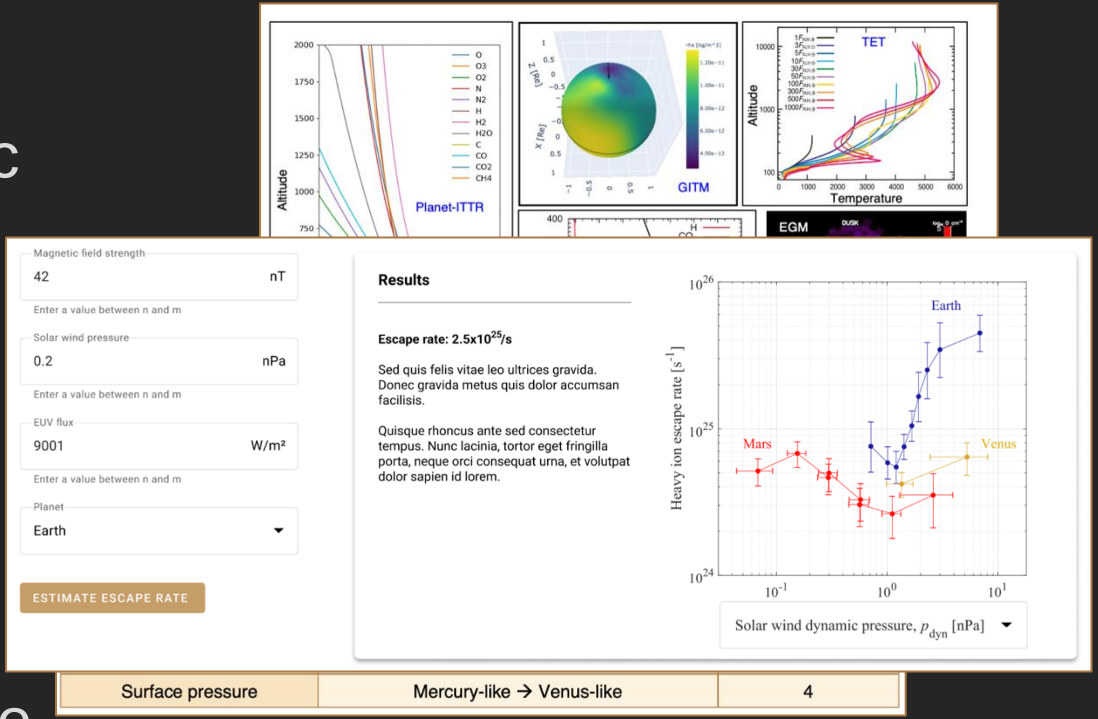
1. Compute inputs for atmospheric escape for an ensemble of star-planet scenarios

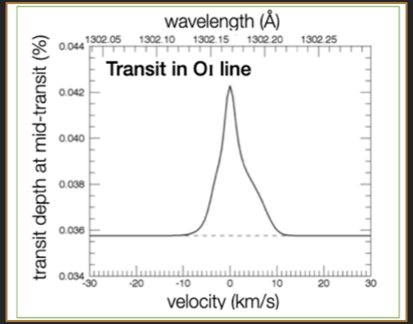
2. Improve and link models for atmospheric escape from any planet

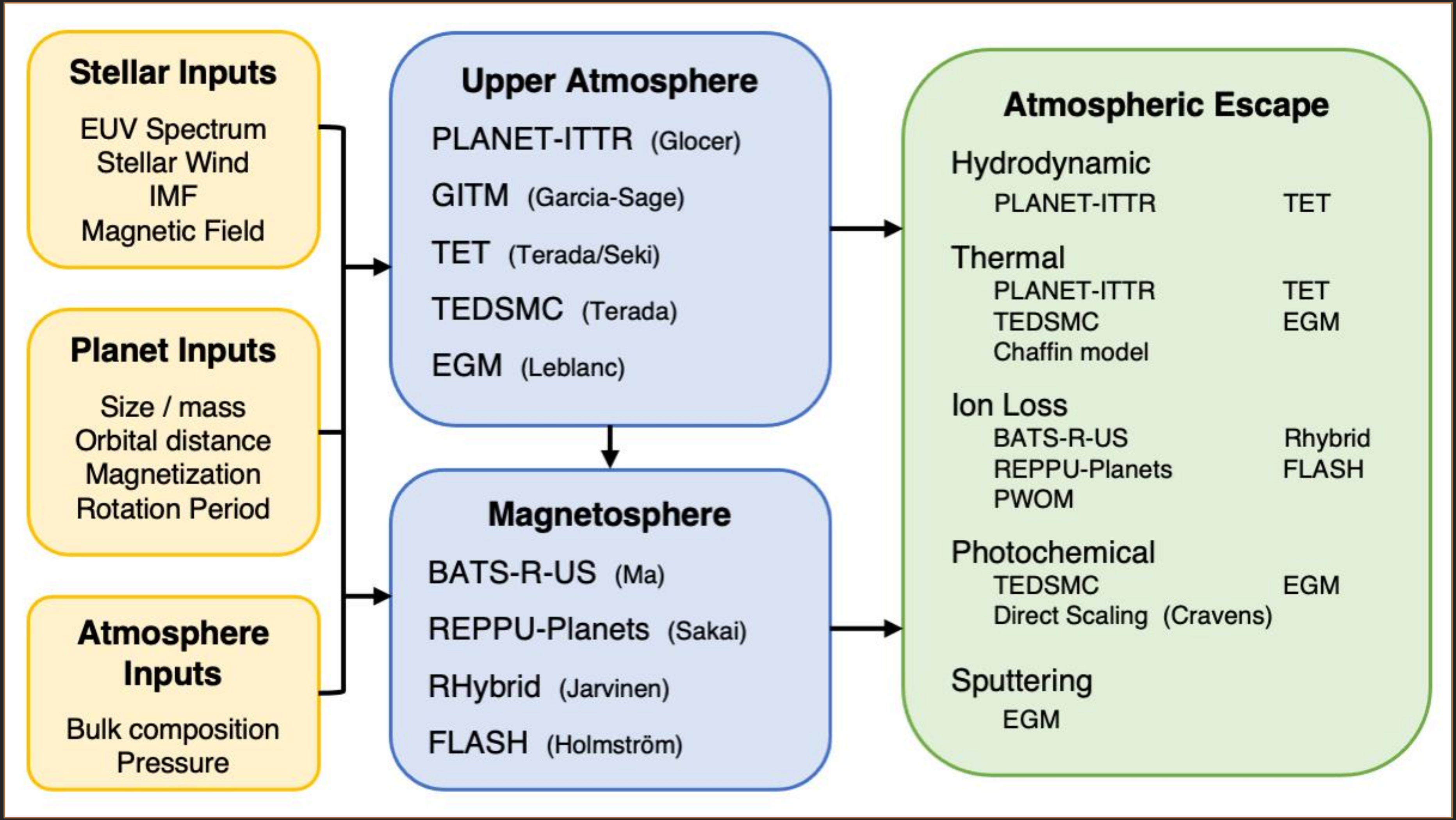
3. Construct a multi-dimensional model library for atmospheric escape

4. Apply the model library to understand the connection between atmospheric escape, habitability, and observations





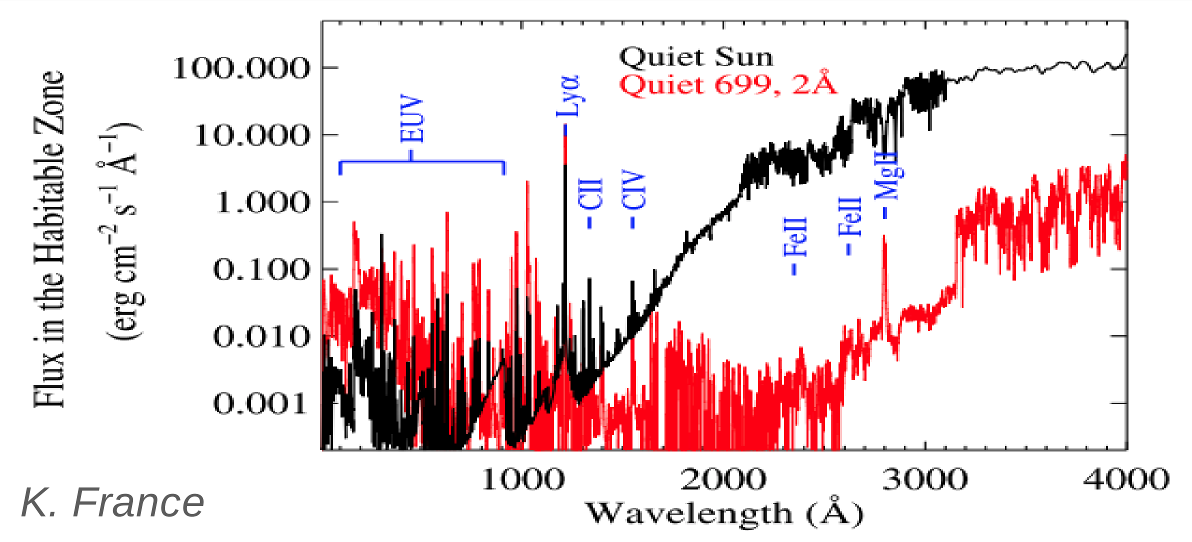


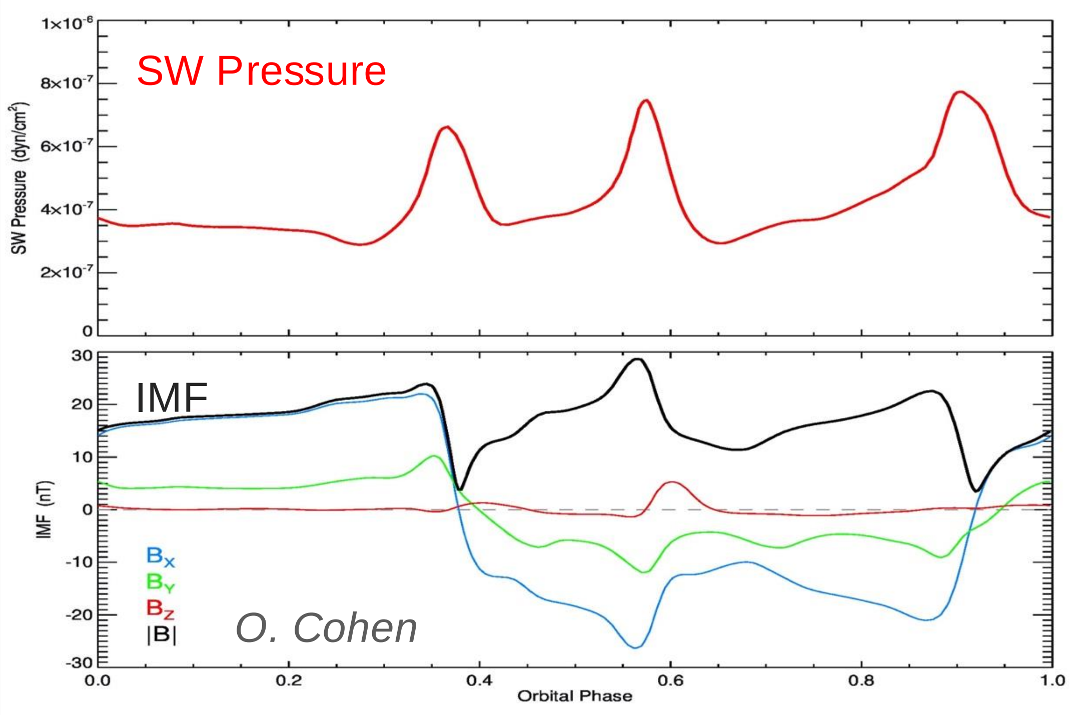


Multiple competing models allow us to estimate uncertainties

“Mars as an exoplanet”

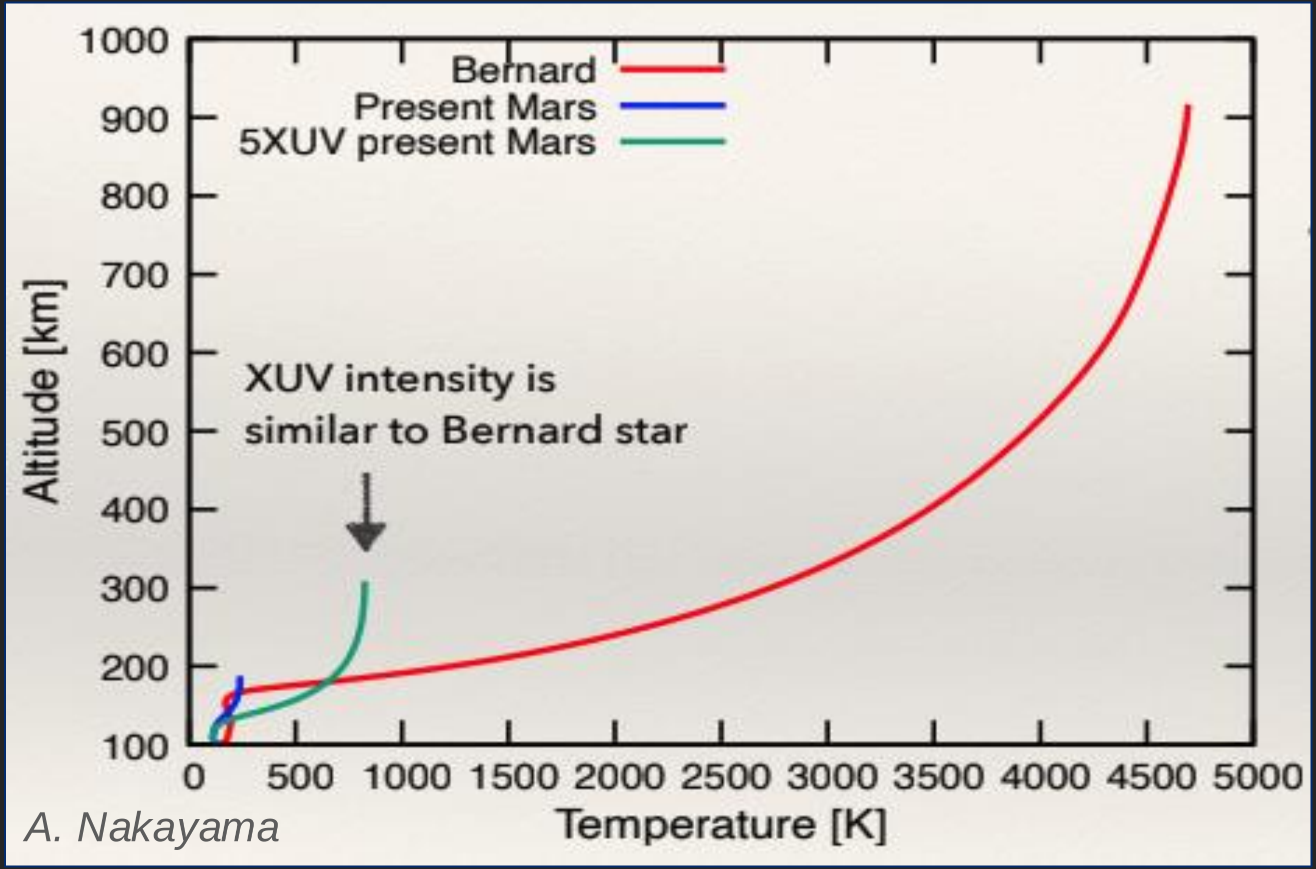
Assume present-day Mars orbits Barnard’s star at a distance that receives the same stellar flux as Mars does in our own solar system. How would atmospheric escape change?

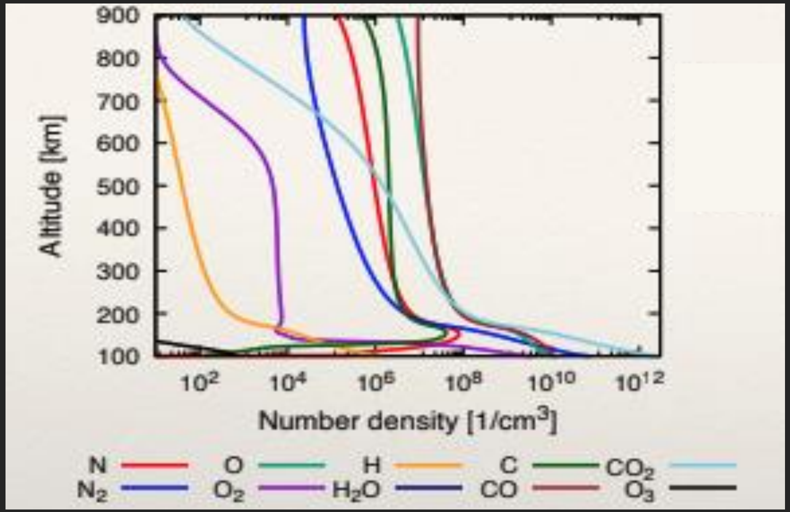


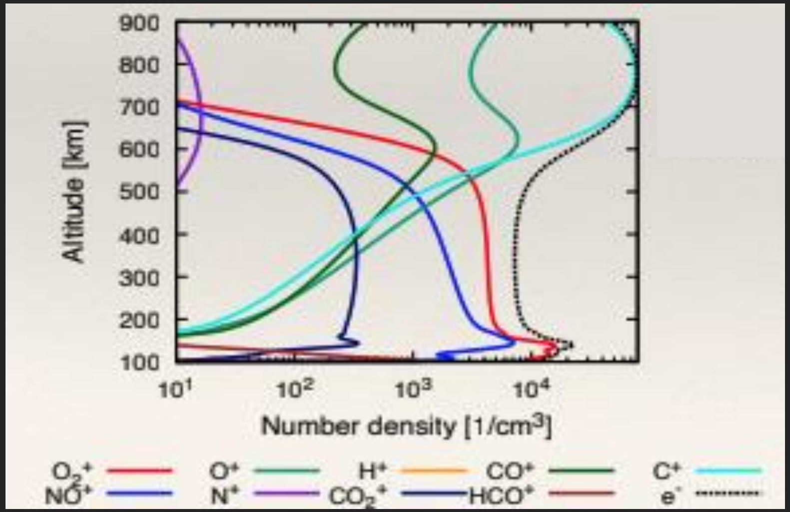


"Mars as an exoplanet"

How would the thermosphere change?

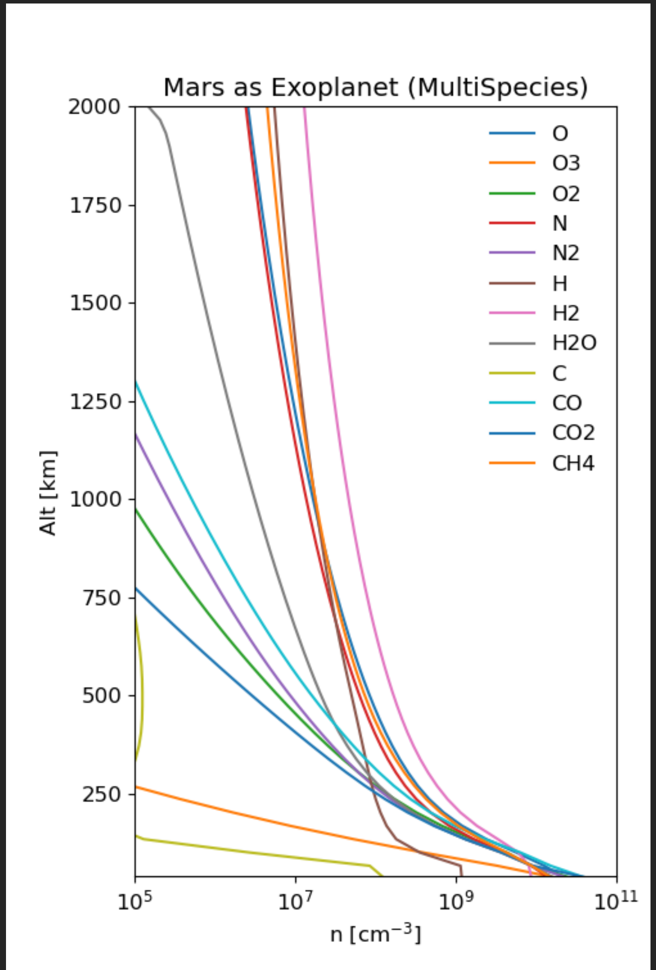




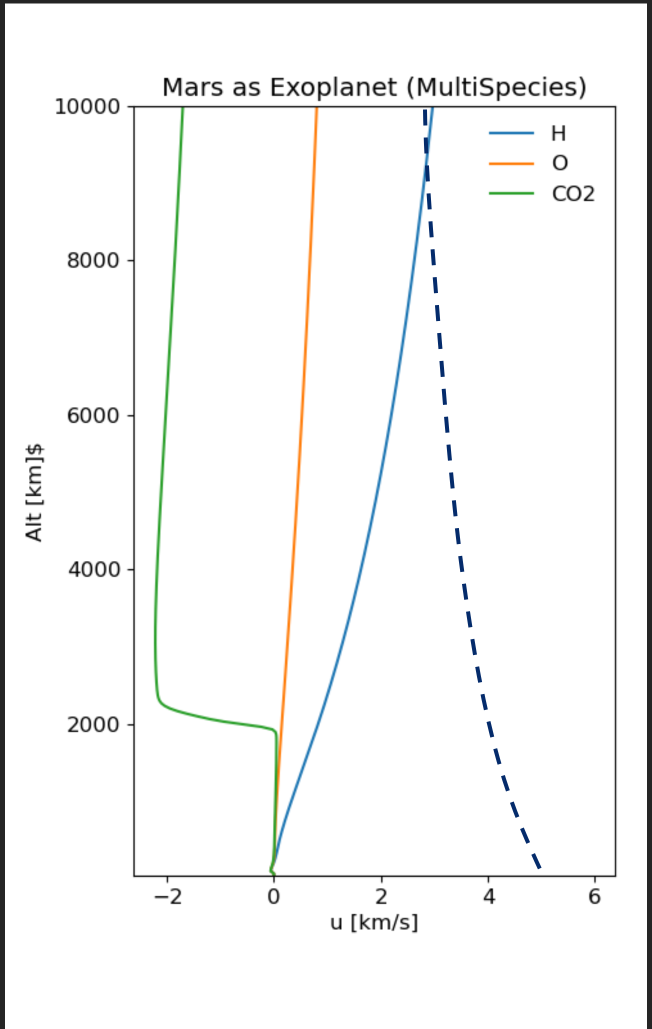


“Mars as an exoplanet”

Would hydrodynamic escape occur?



A. Glocer



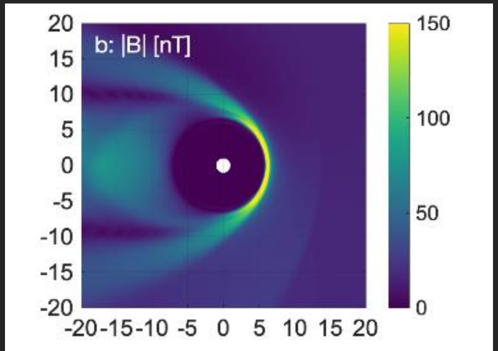
Escape parameter: ~2.5

1. 1 fluid, isothermal
2. 1 fluid, no conduction or diffusion
3. 1 fluid, conduction but no diffusion
4. Multispecies, 3 fluid, conduction, radiative cooling, eddy and molecular diffusion

"Mars as an exoplanet"

What is the ion escape flux?

REPPU-Planets

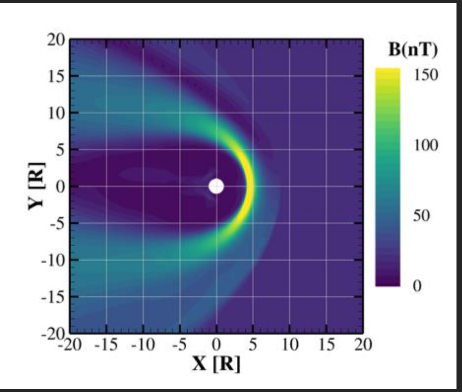


S. Sakai

$$\Phi_{O^+} = 6.7 \times 10^{27}$$

$$\Phi_{C^+} = 3.5 \times 10^{29}$$

BATS-R-US

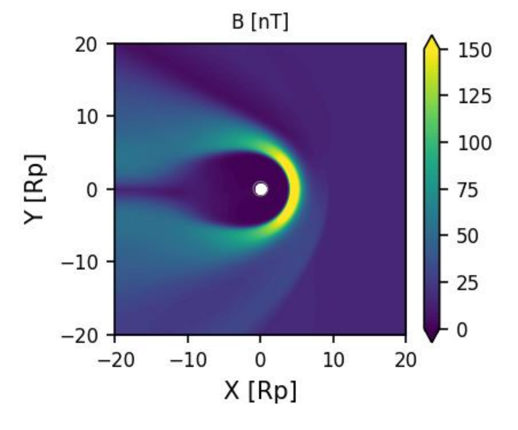


Y. Ma

$$\Phi_{O^+} = 3.2 \times 10^{28}$$

$$\Phi_{C^+} = 6.4 \times 10^{29}$$

MAESTRO

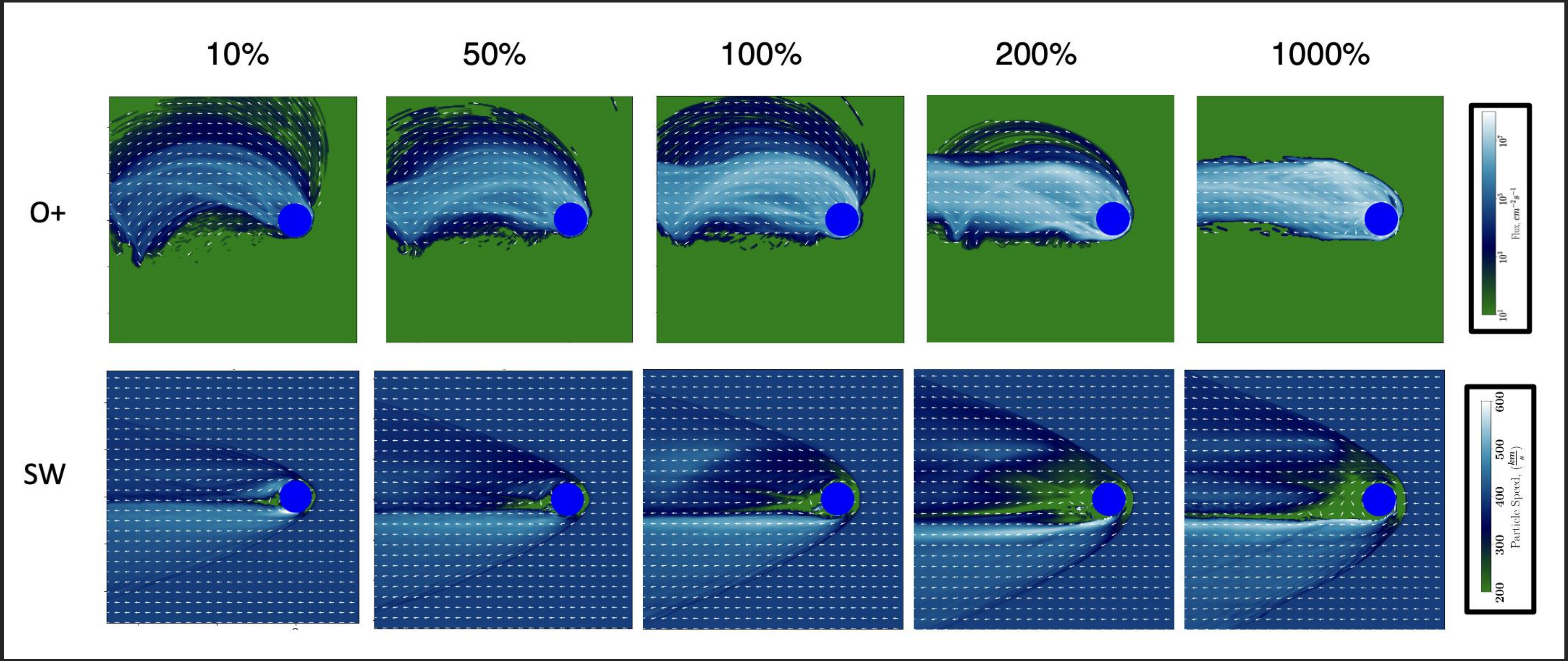


R. Sakata

$$\Phi_{O^+} = 1.3 \times 10^{28}$$

$$\Phi_{C^+} = 1.1 \times 10^{29}$$

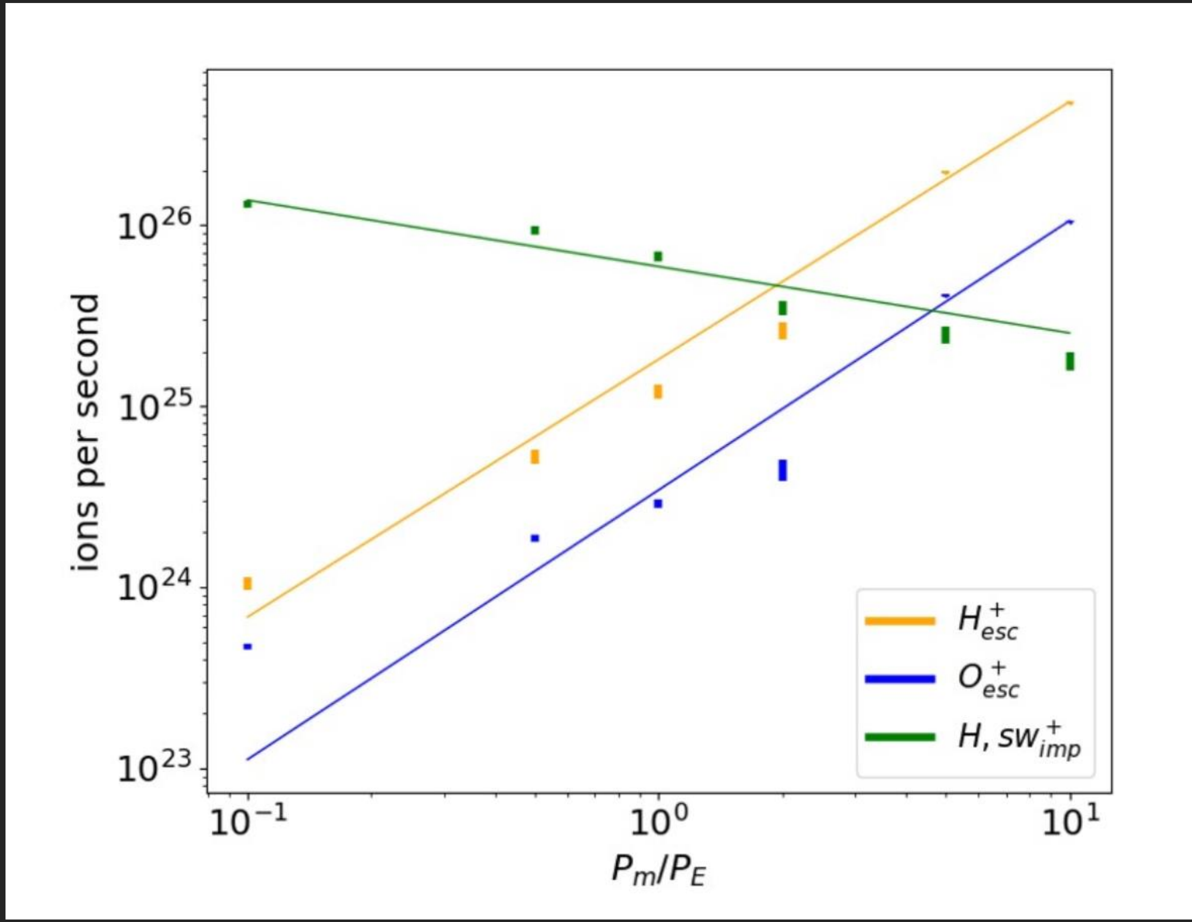
How does ion escape scale with ion production?

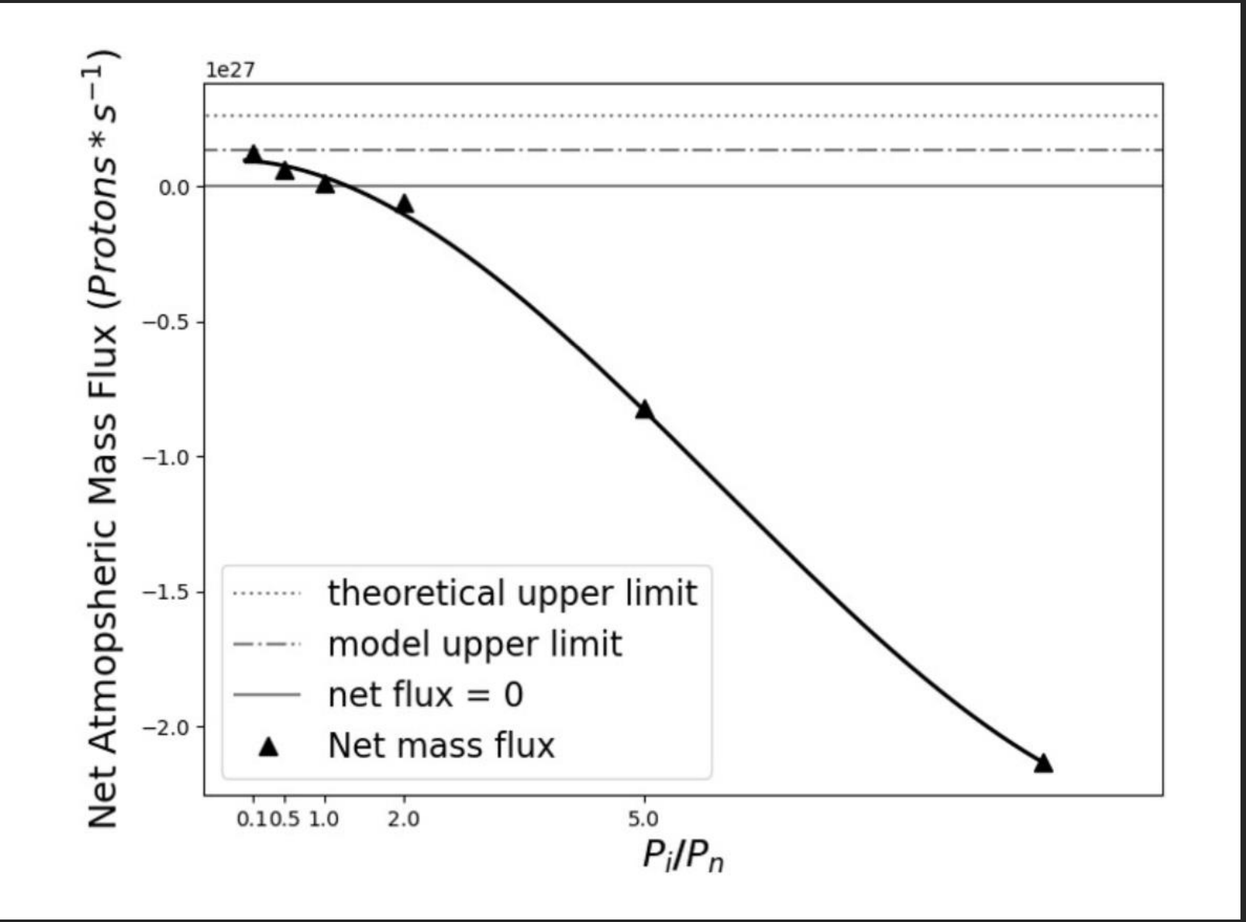


P. Hinton

We model umagnetized Earth for different ion production rates

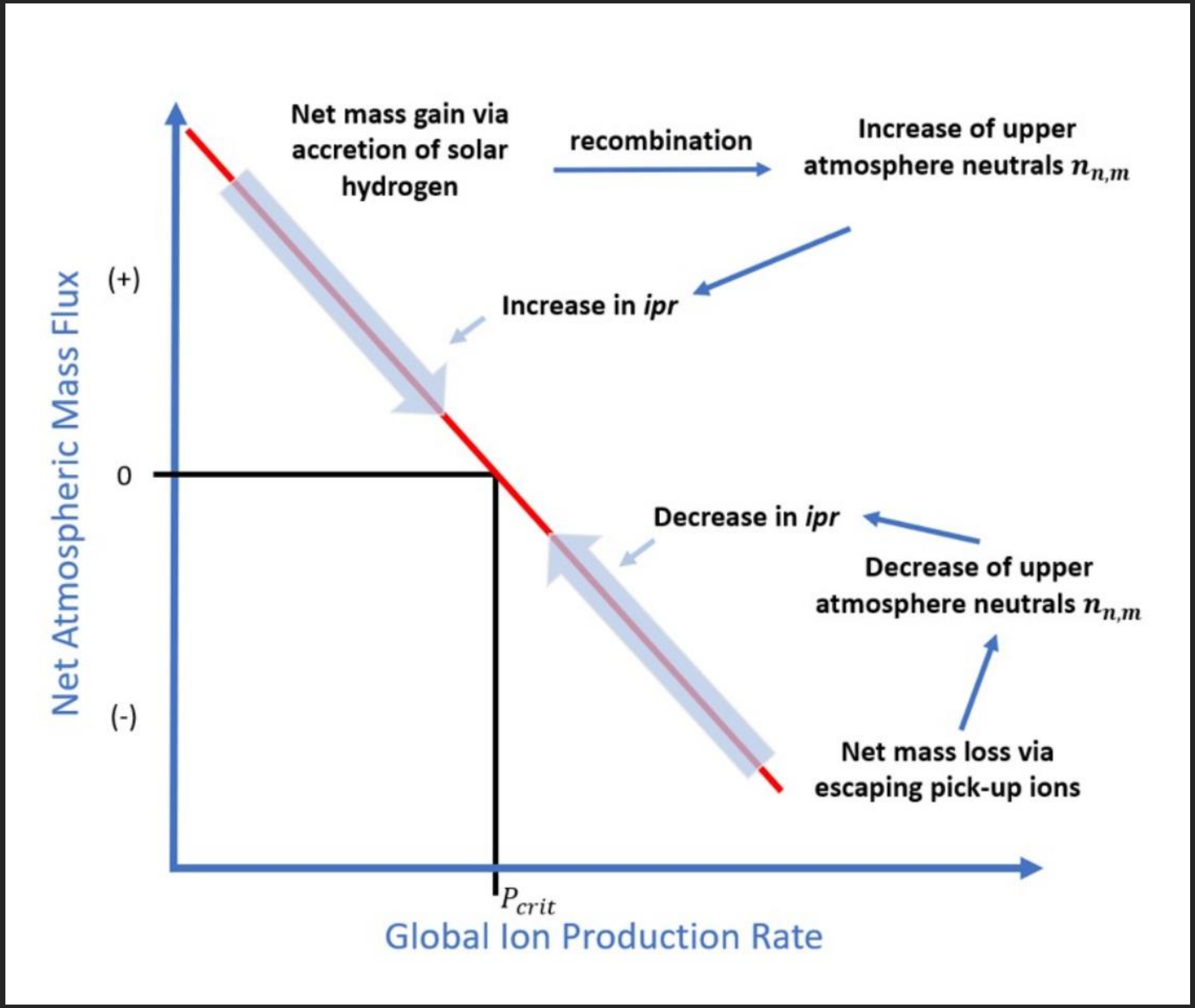
How does ion escape scale with ion production?





If ion production is low enough, Earth's atmosphere accumulates hydrogen, or even total mass

How does ion escape scale with ion production?



Negative feedback may result, so that atmospheres try to balance mass loss and accumulation