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NExSS

MAVEN
Mars Atmosphere and Volatile Evolution Mission
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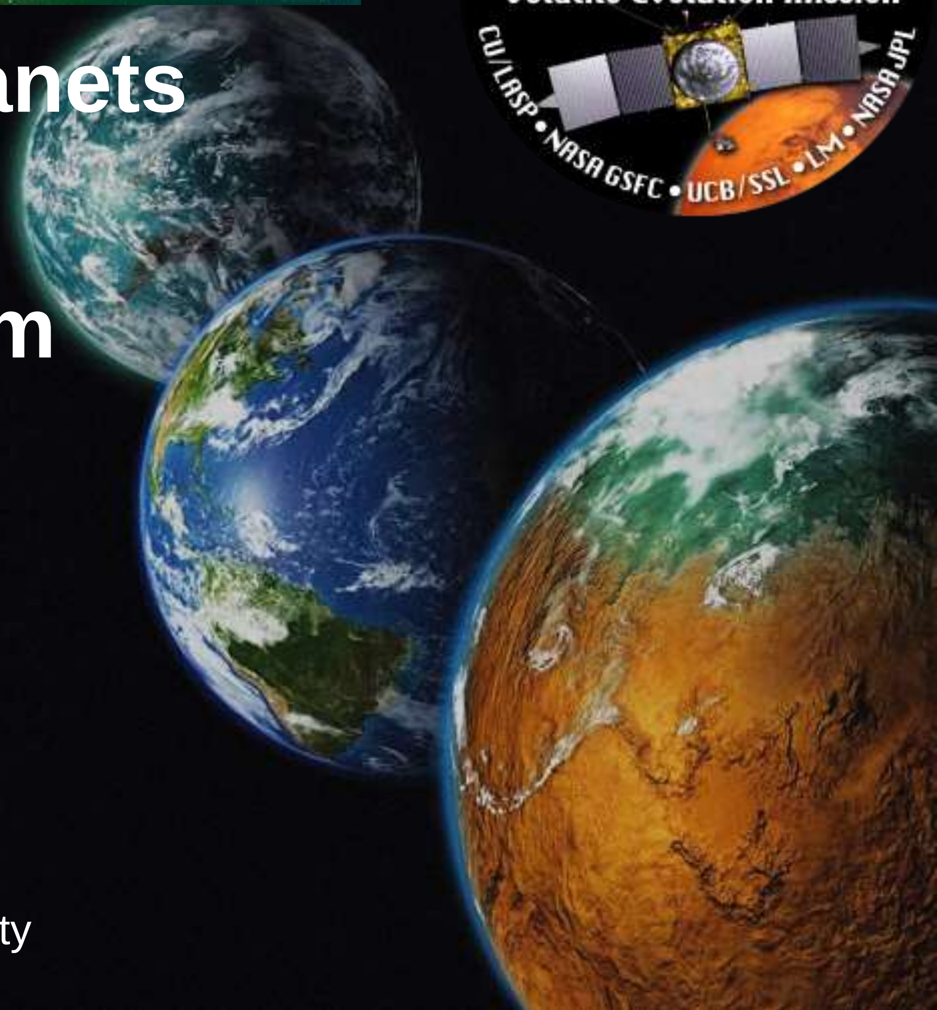
Are "Habitable" Exoplanets Really Habitable? -- A perspective from atmospheric loss



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Outline

- ❑ Motivation
- ❑ Model descriptions and inputs
- ❑ Multi-fluid MHD Model Applications

Ocean Planets, Proxima Centauri b, TRAPPIST-1 system

- ❑ Summary

Motivation: Volatile Loss

Credit: Ice Age 5 Movie

Where did the water and atmosphere on Mars go?

Image Credit: Blue Sky Studios

Movie *Ice Age: Collision Course*

Where did the water and atmosphere on Mars go?

Image Credit: Blue Sky Studios

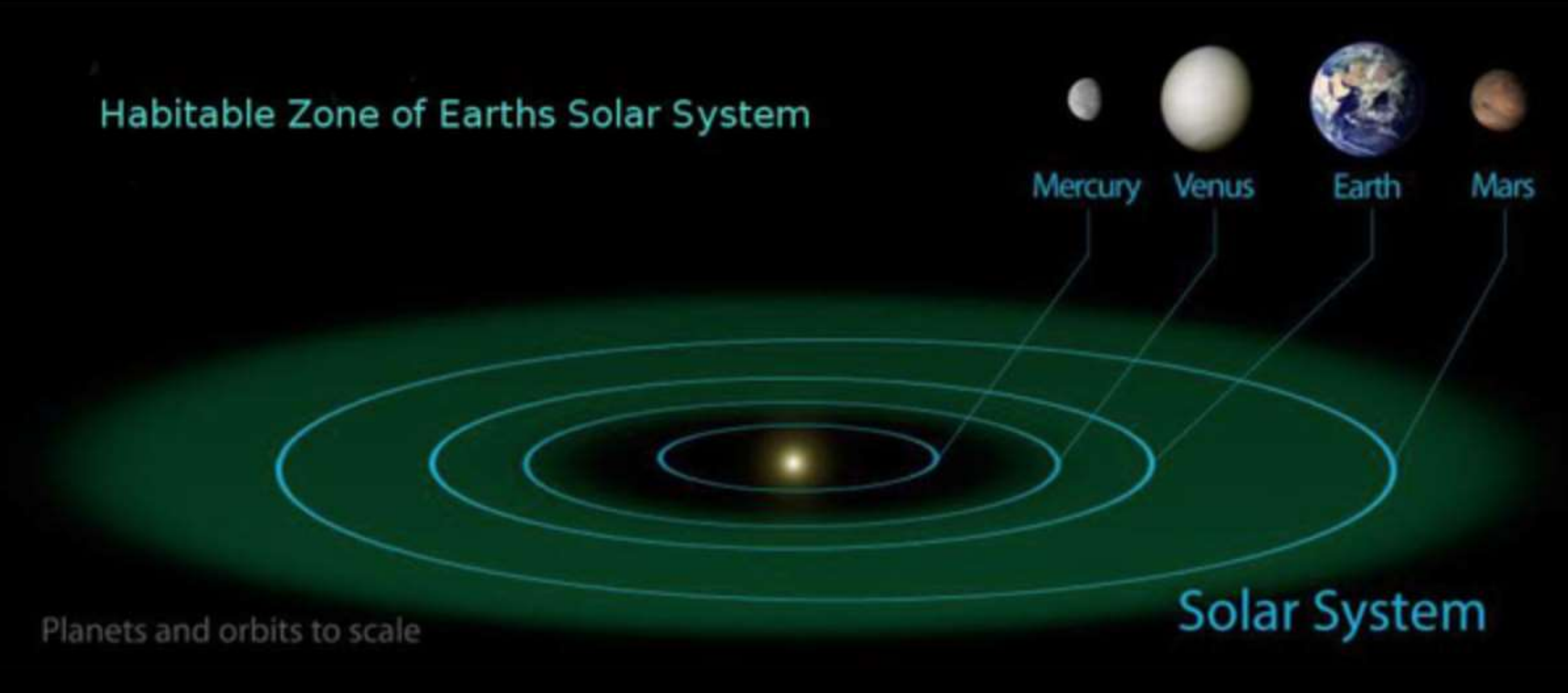
Movie *Ice Age: Collision Course*

Ion Escape

solar wind -- the constant outpouring of solar particles that sweeps out into space

Credit: NASA MAVEN TEAM

Habitable Zone of our Solar system



3-D BATS-R-US Multi-Fluid MHD (MF-MHD) for Water Worlds [Dong et al. 2017a, *ApJL*]

- **Three ion fluids**: H^+, H_2O^+, e^-;
- **Spherical grids**:
  - Computational domain: $-40R_M \leq X \leq 25R_M$, $-50R_M \leq Y, Z \leq 50R_M$
  - Radial resolution varies from 5 km in the ionosphere (~100 km) to thousands of kms far from the planet.
  - Angular resolution is 3º.
- **Inner boundary conditions**
  - Inner boundary at 100 km
  - Ions are in photochemical equilibrium (SZA and optical depth considered)
  - Absorbing boundary condition for U, B
- **Chemical reactions**
  - Photoionization
  - Charge exchange
  - Electron impact ionization
  - Electron recombination

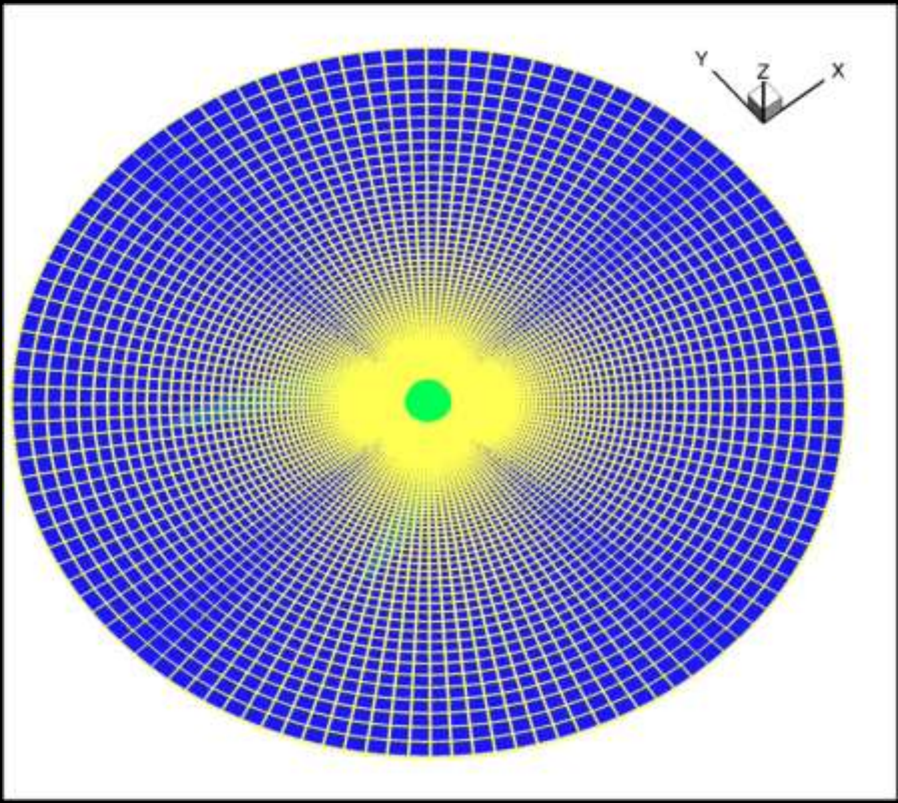
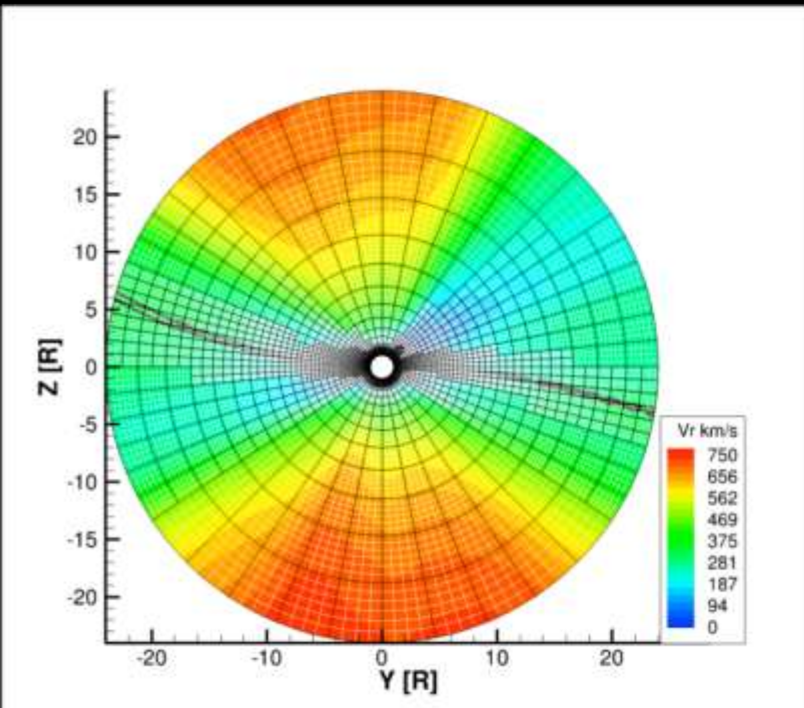


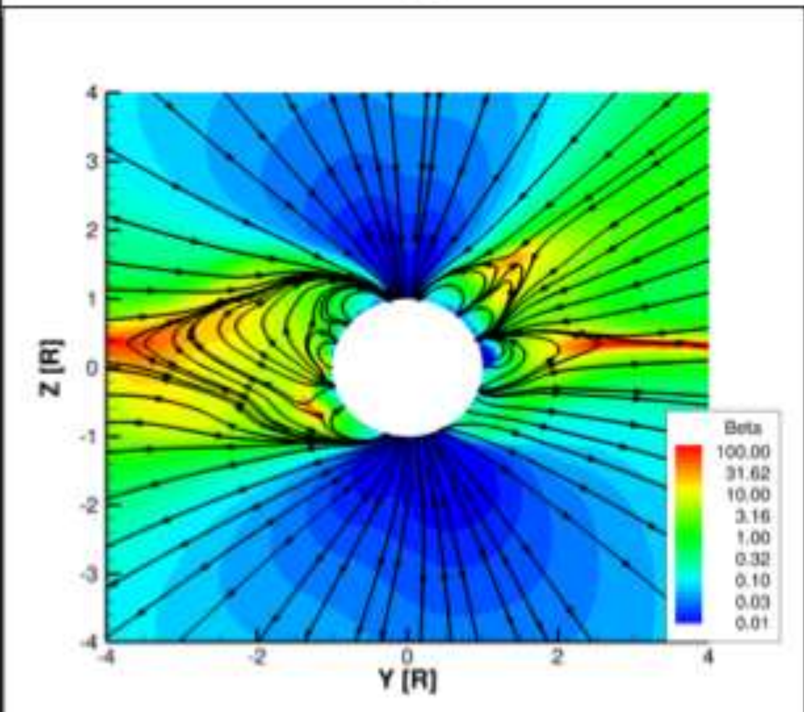
Illustration of the grid system used in the calculation.

X axis: from planet to star
Z axis: normal to planet's orbital plane (+: upward)
Y axis: completes the right-hand coordinate system

Alfvén Wave Solar Model (AWSoM)



Velocity



Plasma Beta

- Data-driven inner boundary condition by synoptic magnetograms.
- Coronal heating and solar wind accelerating by Alfven waves.
- Physically consistent treatment of wave reflection, dissipation, and heat partitioning between the electrons and protons.
- Model starts from upper chromosphere including heat conduction (both collisional and collisionless) and radiative cooling.
- Adaptive mesh refinement (AMR) to resolve structures (e.g., current sheets, shocks).

References: van der Holst et al. 2010, Manchester et al. 2012, Jin et al. 2012, Sokolov et al. 2013, Oran et al. 2013, Jin et al. 2013, van der Holst et al. 2014

Topic One

The dehydration of water worlds via atmospheric losses

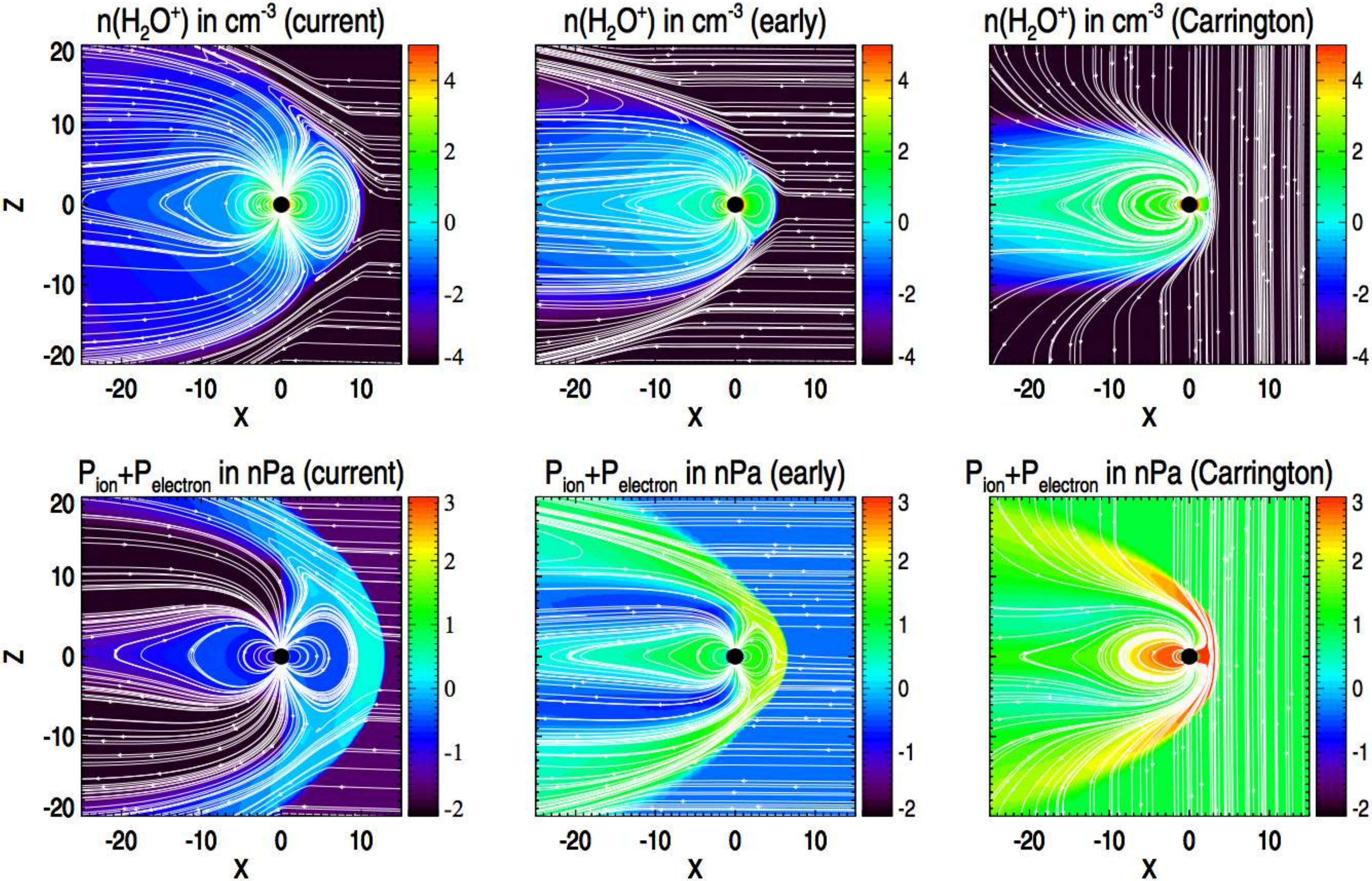
News story: www.universetoday.com

Water Worlds Stellar Wind Input Parameters

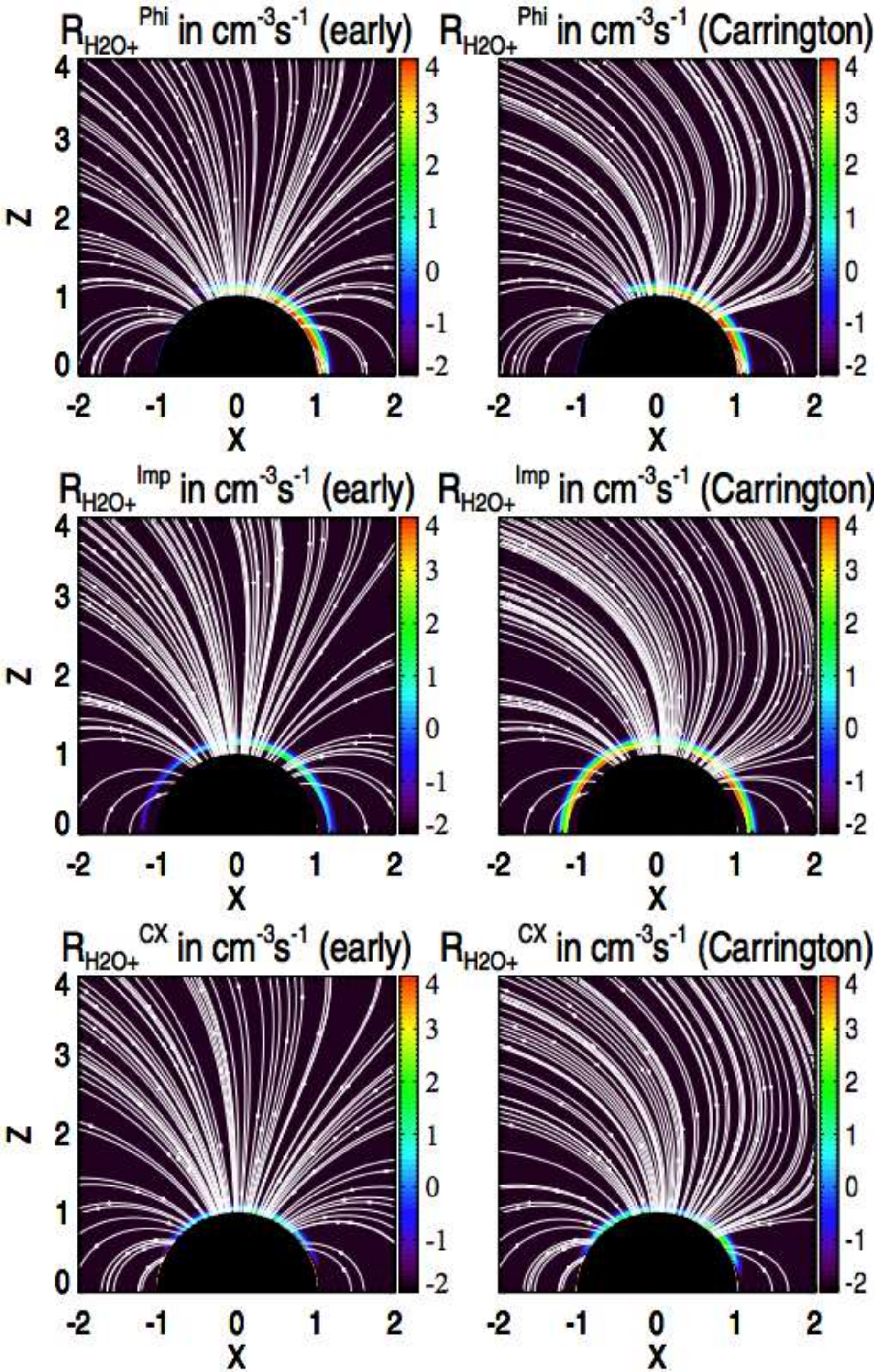
	n_{sw} (cm^{-3})	v_{sw} (km/s)	IMF (nT)	Radiation	H_2O^+ loss rate (s^{-1})
Current	8.7	(-468, 0, 0)	(-4.4, 4.4, 0)	1 EUV	6.7×10^{25}
Early	136.7	(-910, 0, 0)	(-15.6, 30.2, 0)	12 EUV	6.0×10^{26}
Carrington Event	424.5	(-1937.5, 6.7, -13.0)	(0, 23.0, -194.3)	12 EUV	7.3×10^{27}

Illustration showing the possible surface of TRAPPIST-1f, one of the newly discovered planets in the TRAPPIST-1 system. Credits: NASA/JPL-Caltech

Water Worlds/Ocean Planets



Dong et al., 2017a, *ApJL*



Photoionization

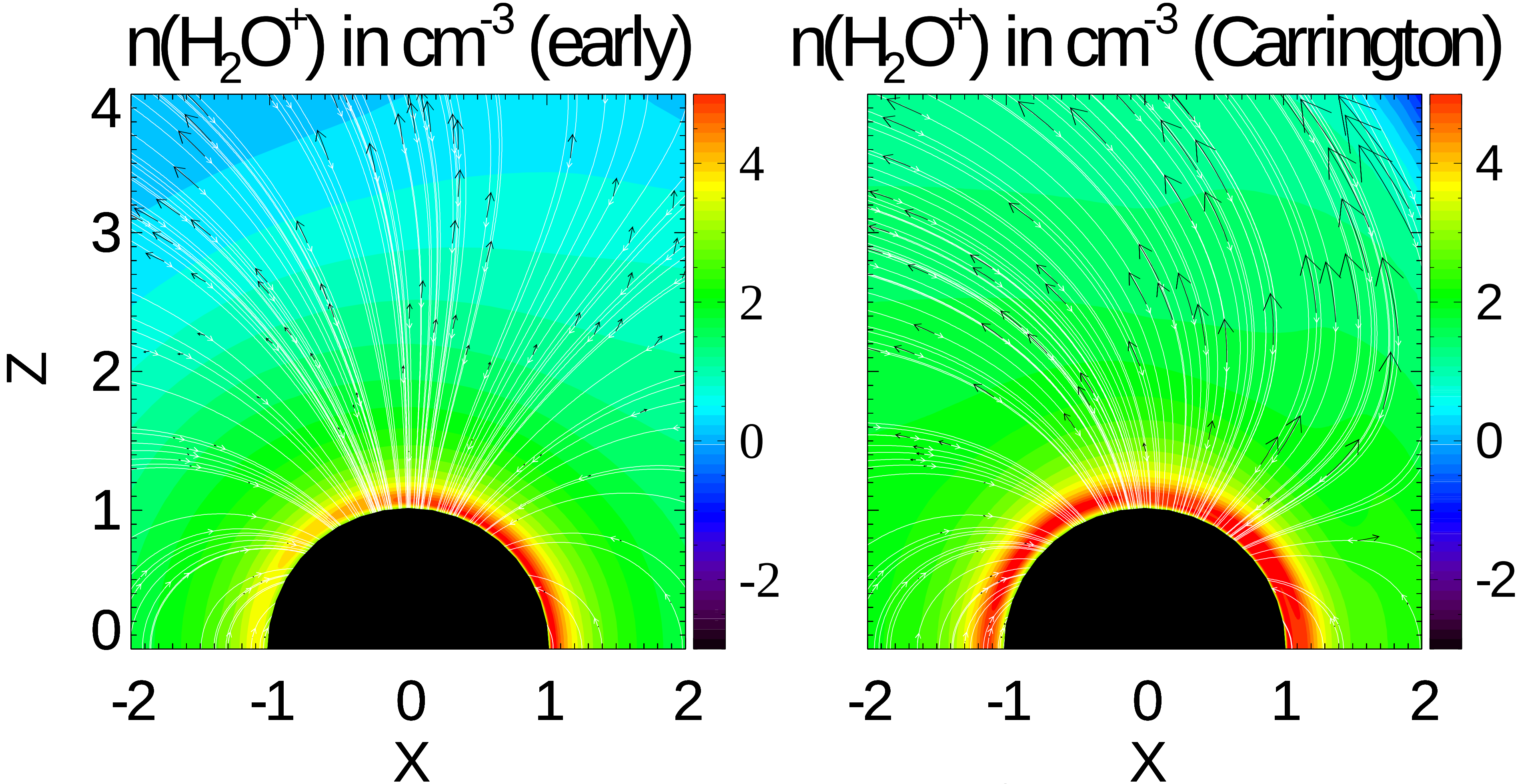
Electron impact ionization

Charge exchange

Dong et al., 2017a, *ApJL*

Water escape via polar cap

Dong et al., 2017a, *ApJL*



Earth-like oceans (with a total mass of ~ 10^{24} g) will not be evaporated over Gyr timescales as the ion escape rates are far too low (by 3-4 orders of magnitude) for a Sun-like Star.

An active Red Dwarf by Chuck Carter.

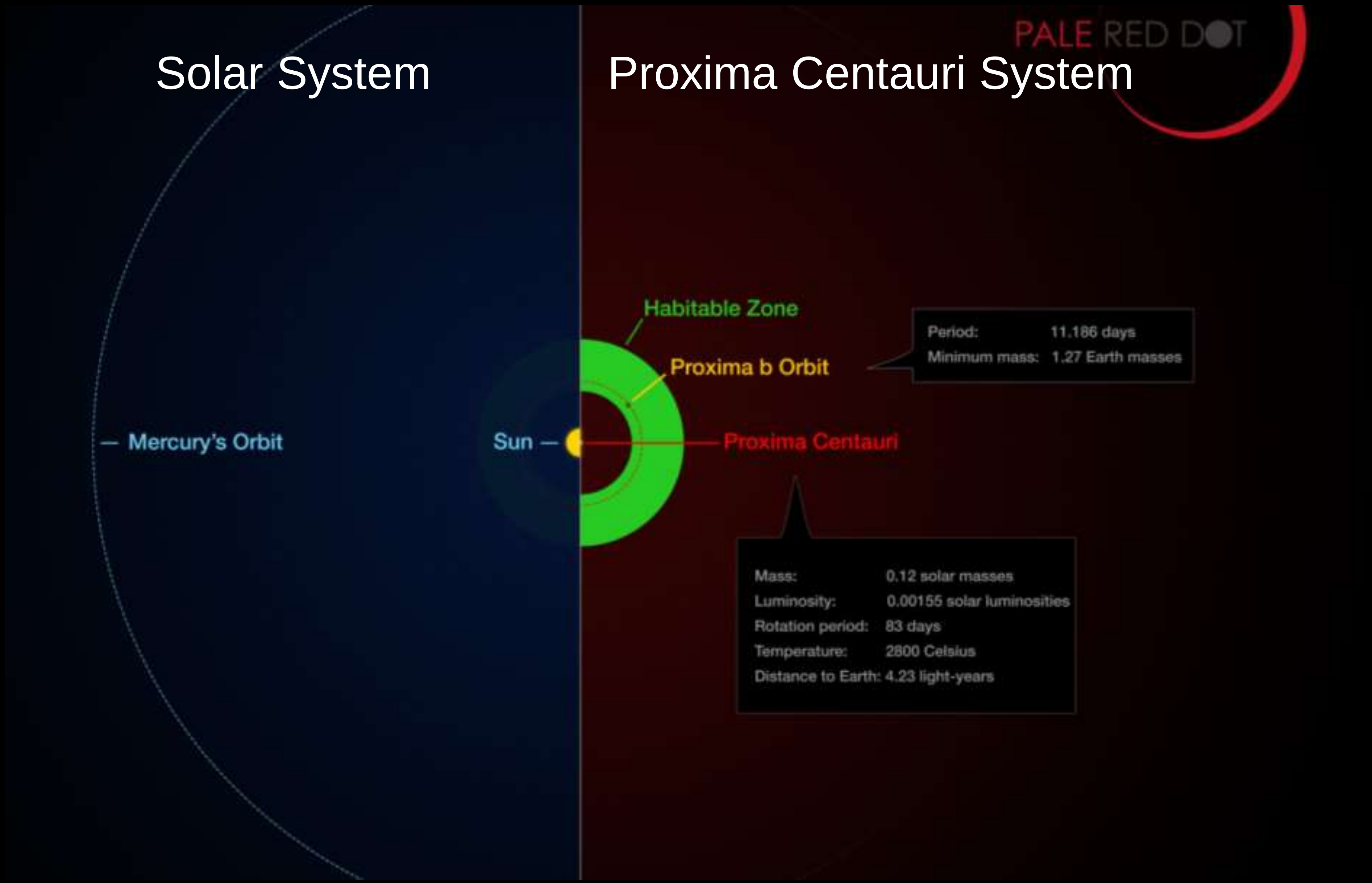
Topic Two

Is Proxima Centauri b habitable?

-- A study of atmospheric loss

News story: SPACE.COM

Proxima Centauri b (PCb)



PCb Stellar Wind Input Parameters

Cases	n_{sw} (cm^{-3})	T_{sw}(K)	v_{SW}(Km s^{-1})	IMF (nT)
C1	21400	8.42×10^5	(−833,150,0)	(0,0,−227)
C2	2460	9.53×10^5	(−1080,150,0)	(0,0−997)
Earth	7.1	2.5×10^5	(−400,0,0)	|B|=7

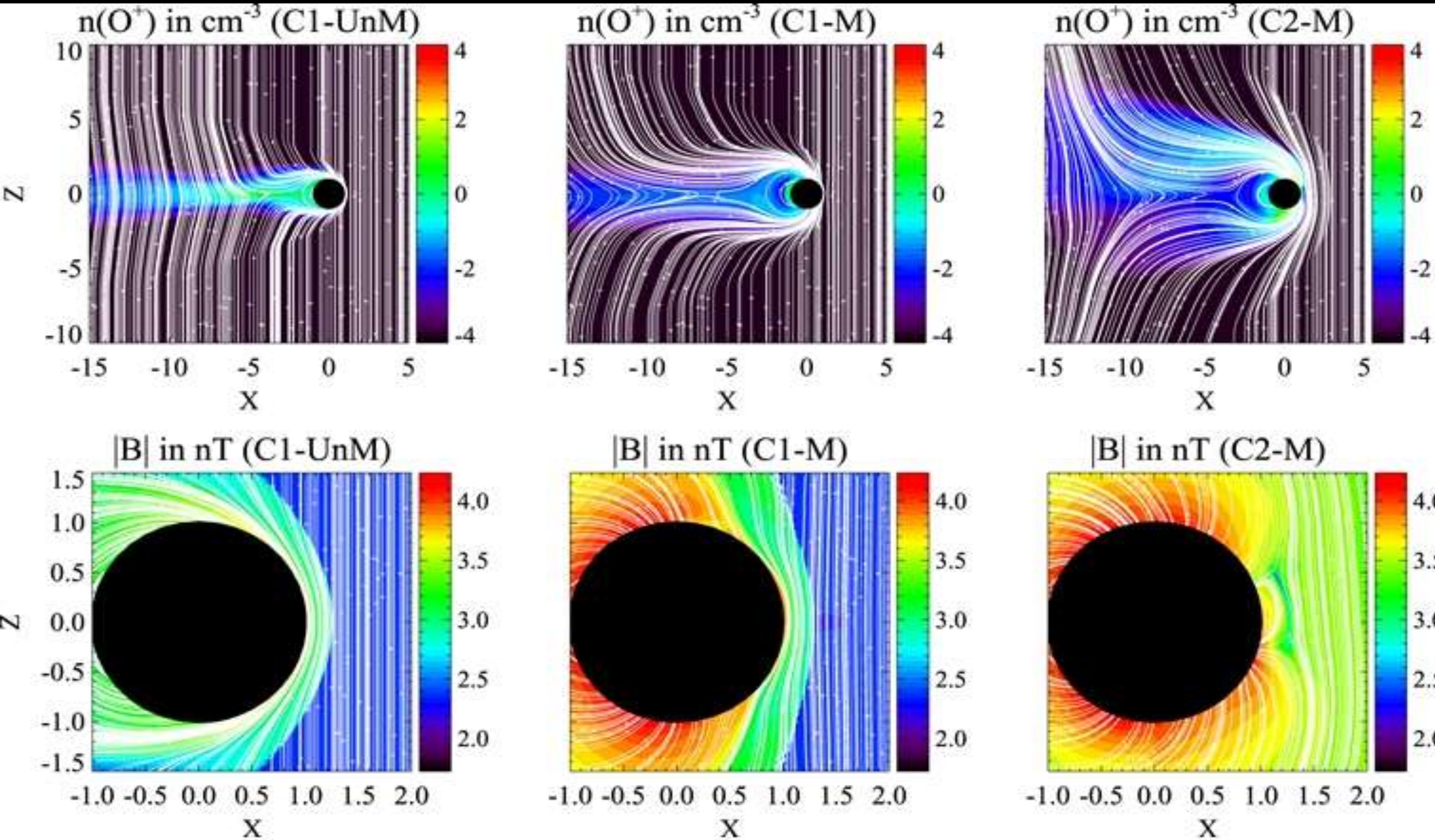
After Table 2 of Dong et al., 2017b, *ApJL*; Garraffo et al., 2016, *ApJL*

- Case 1 (C1) corresponds to the maximum P_{dyn} and P_{tot} over one orbital period of PCb. Case 2 (C2) corresponds to minimum P_{dyn} and P_{tot}, but with the maximum P_{mag}.
- Dynamic pressure $P_{dyn} = m_p n_{sw} v_{sw}^2$ (m_p is proton mass),
- Magnetic pressure $P_{mag} = B^2/(2\mu 0)$ and
- Total pressure $P_{tot} = P_{dyn} + P_{mag}$.

O⁺ Ion Density and Magnetic Field Strength

PCb's dipole moment ~ one-third of the Earth

Unmagnetized Case 1 Magnetized Case 1 Magnetized Case 2



Dong et al., 2017b, *ApJL*

Ion Escape Rates in Different Cases

The atmosphere depletion could occur over O(10^8) and O(10^9) years for C1-M and C2-M, respectively.

Ion Escape Rates in s^{-1}

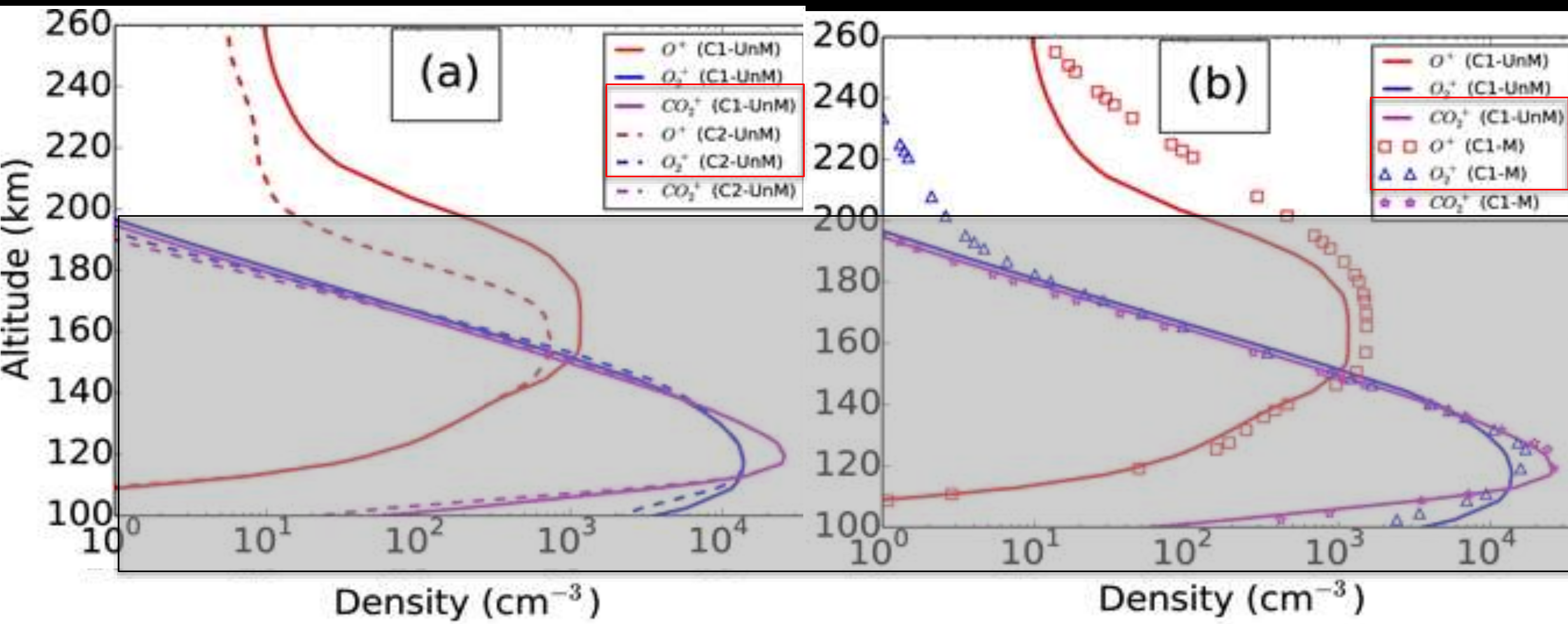
	O^+	O_2^+	CO_2^+	Total
PCb with 1 bar Surface Pressure				
C1-UnM[a]	1.8×10^{27}	2.4×10^{26}	3.3×10^{26}	2.4×10^{27}
C2-UnM	1.1×10^{27}	9.5×10^{25}	8.2×10^{25}	1.3×10^{27}
C1-M[b]	7.3×10^{26}	5.4×10^{26}	5.8×10^{26}	1.8×10^{27}
C2-M	5.9×10^{25}	8.7×10^{25}	5.3×10^{25}	2.0×10^{26}
PCb with 93 bar Surface Pressure[c]				
$C1\text{-}UnM_{93}$	3.7×10^{27}	4.1×10^{24}	1.4×10^{23}	3.7×10^{27}

Have the potential for habitability

Table 2 of Dong et al. (2017b) *ApJL*

Ionospheric Profiles along Substellar Lines

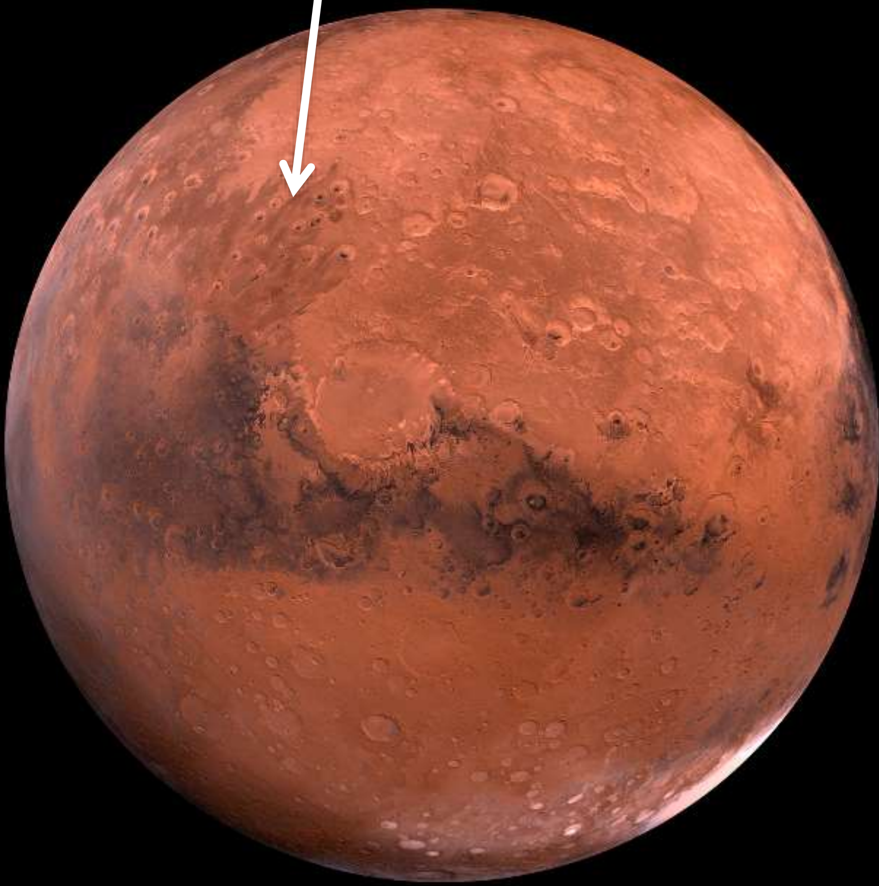
Two Unmagnetized Cases | Unmagnetized v.s. Magnetized



- ❑ The ionoshperic profiles are mostly unaffected by the stellar wind conditions at ≤200 km.

Is Proxima Centauri b Habitable?

If unmagnetized



If magnetized, **possible**

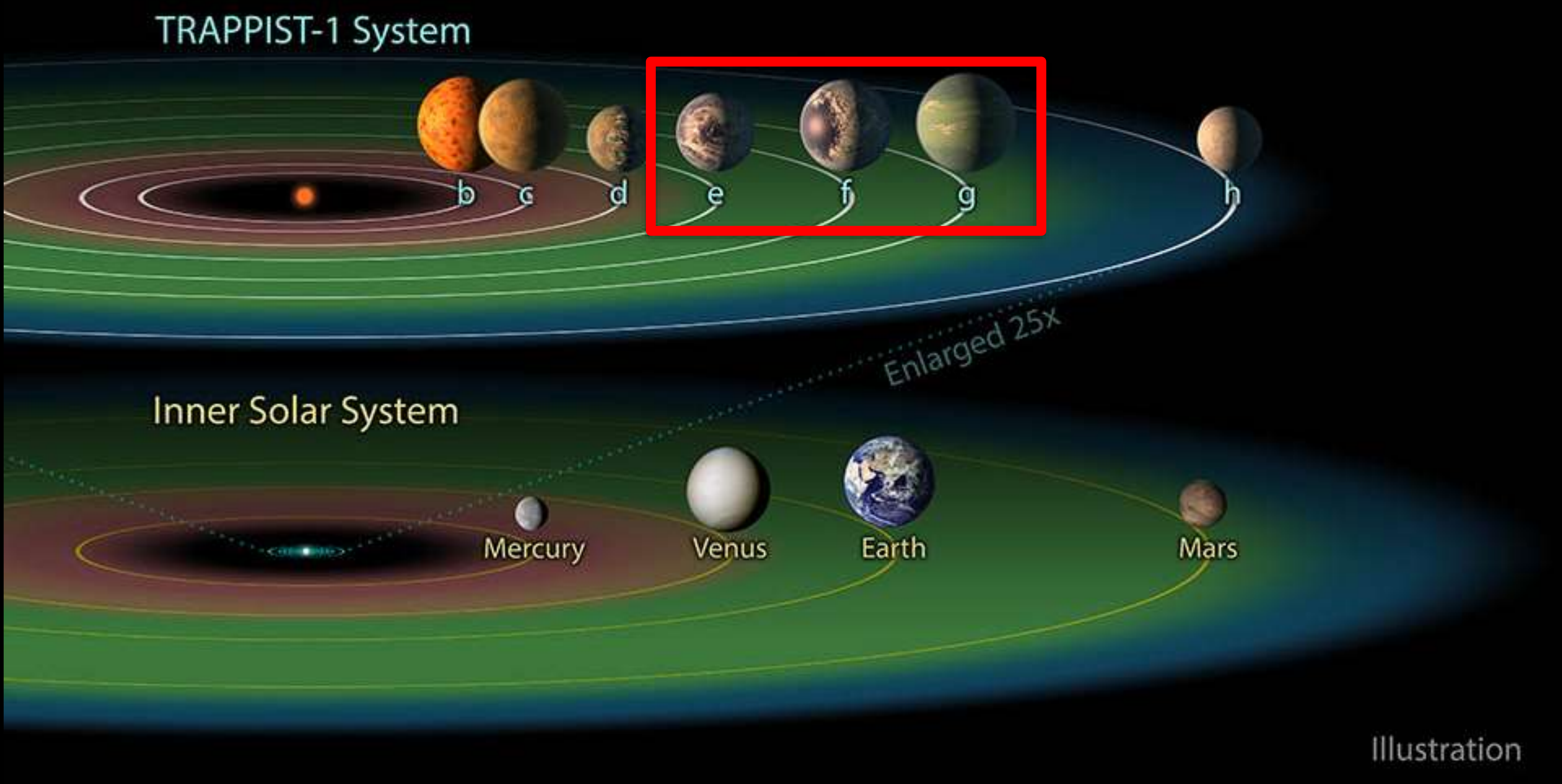
Topic Three

Atmospheric escape from the TRAPPIST-1 planets and implications for habitability

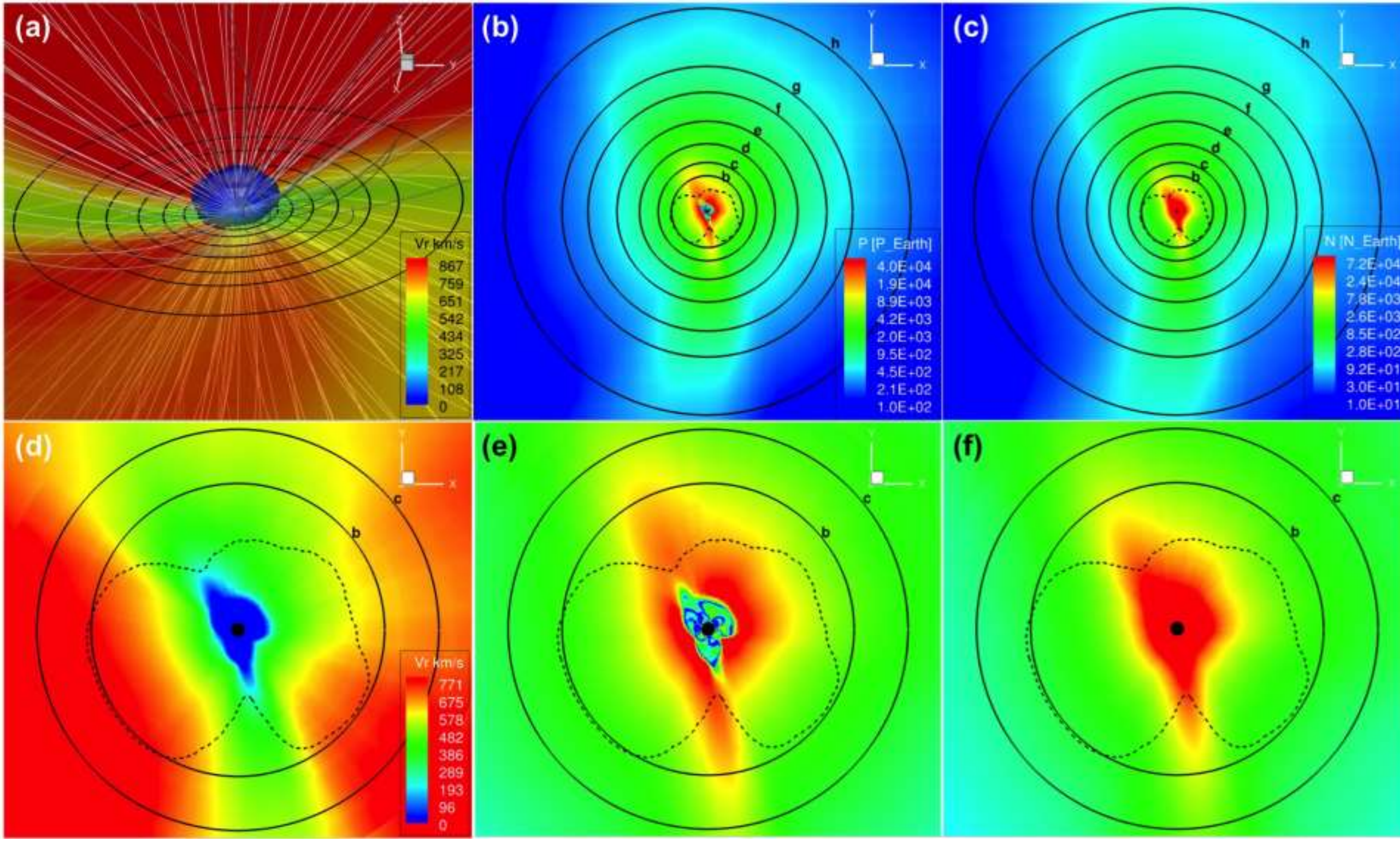
News story: www.theguardian.com
www.forbes.com

TRAPPIST-1 System

Green band: habitable zone

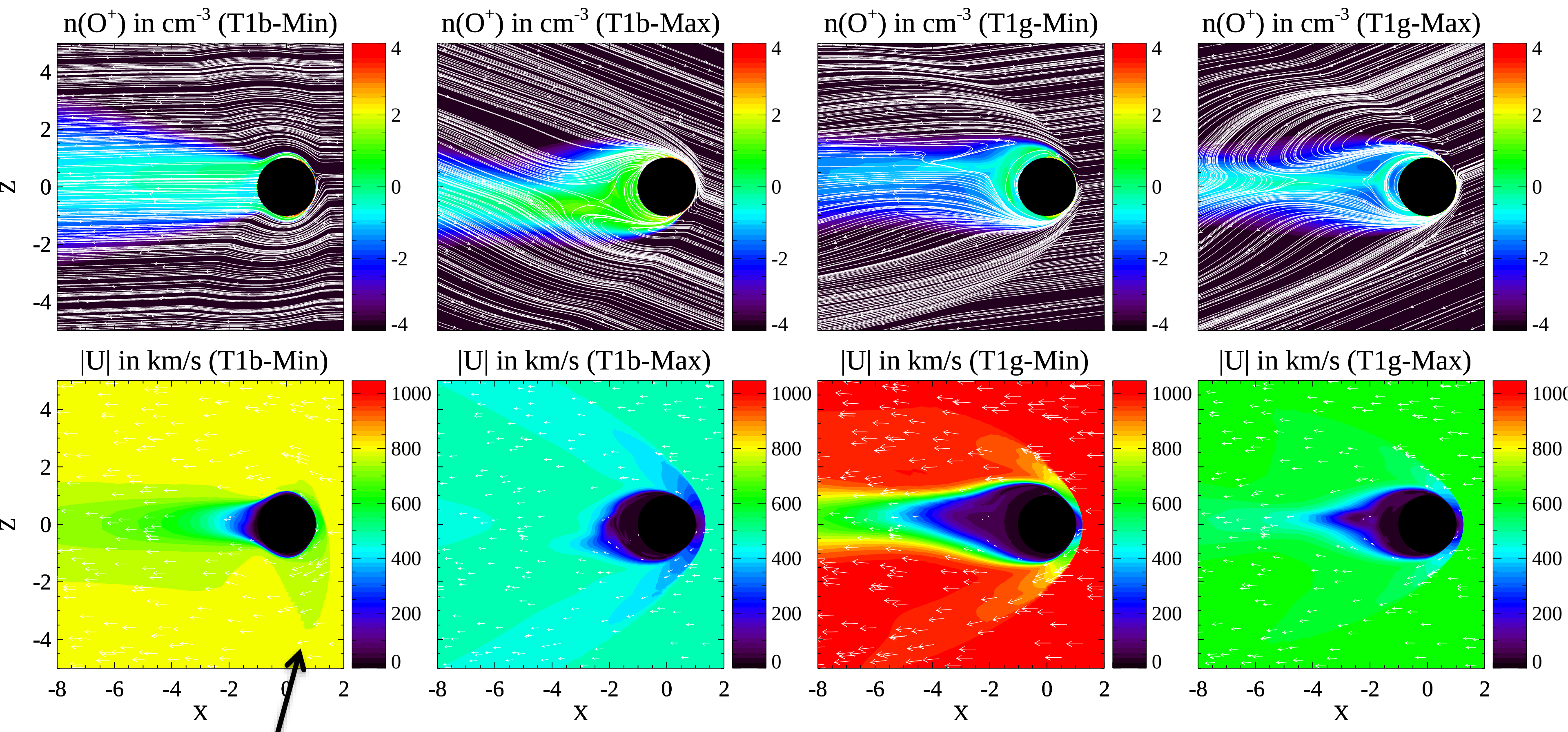


TRAPPIST-1 stellar wind



Dong et al., 2018a, *Proc Natl Acad Sci*

TRAPPIST-1b and TRAPPIST-1g



No shock due to sub-magnetosonic nature!

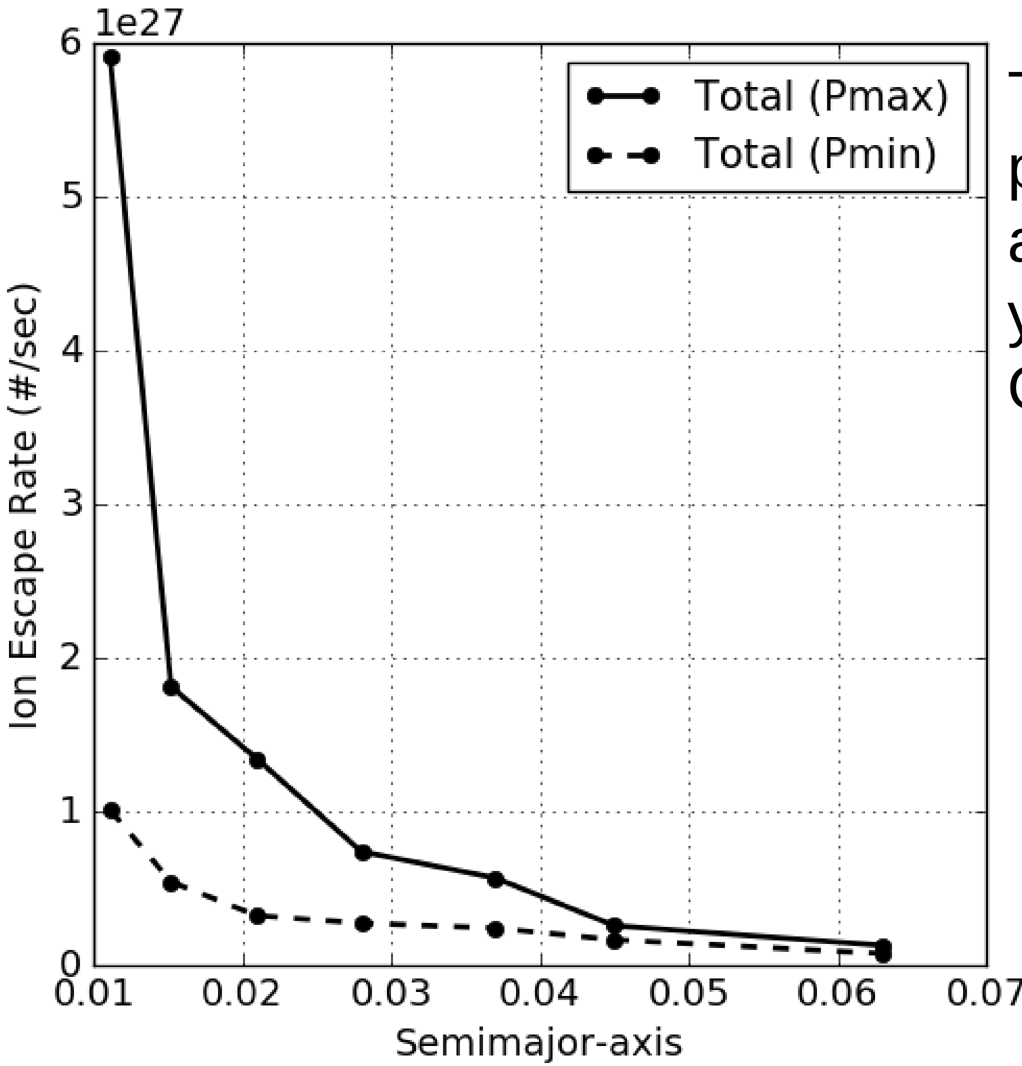
Dong et al., 2018a, *Proc Natl Acad Sci*

Ion escape rates of TRAPPIST-1 planets

	O^+	O_2^+	CO_2^+	Total
Maximum total pressure				
Trappist-1b	5.56×10^{27}	2.09×10^{26}	1.52×10^{26}	5.92×10^{27}
Trappist-1c	1.54×10^{27}	1.38×10^{26}	1.32×10^{26}	1.81×10^{27}
Trappist-1d	1.29×10^{27}	3.80×10^{25}	1.14×10^{25}	1.34×10^{27}
Trappist-1e	7.01×10^{26}	2.83×10^{25}	1.10×10^{25}	7.40×10^{26}
Trappist-1f	5.23×10^{26}	3.37×10^{25}	1.19×10^{25}	5.68×10^{26}
Trappist-1g	2.17×10^{26}	2.71×10^{25}	1.32×10^{25}	2.58×10^{26}
Trappist-1h	1.06×10^{26}	1.65×10^{25}	6.98×10^{24}	1.29×10^{26}
Minimum total pressure				
Trappist-1b	9.33×10^{26}	4.99×10^{25}	2.92×10^{25}	1.01×10^{27}
Trappist-1c	4.23×10^{26}	9.22×10^{25}	2.76×10^{25}	5.42×10^{26}
Trappist-1d	2.81×10^{26}	3.07×10^{25}	1.04×10^{25}	3.23×10^{26}
Trappist-1e	2.20×10^{26}	4.19×10^{25}	1.25×10^{25}	2.74×10^{26}
Trappist-1f	1.88×10^{26}	4.30×10^{25}	1.10×10^{25}	2.42×10^{26}
Trappist-1g	9.33×10^{25}	5.85×10^{25}	1.38×10^{25}	1.66×10^{26}
Trappist-1h	4.52×10^{25}	2.69×10^{25}	4.39×10^{24}	7.66×10^{25}

Dong et al., 2018a, *Proc Natl Acad Sci*

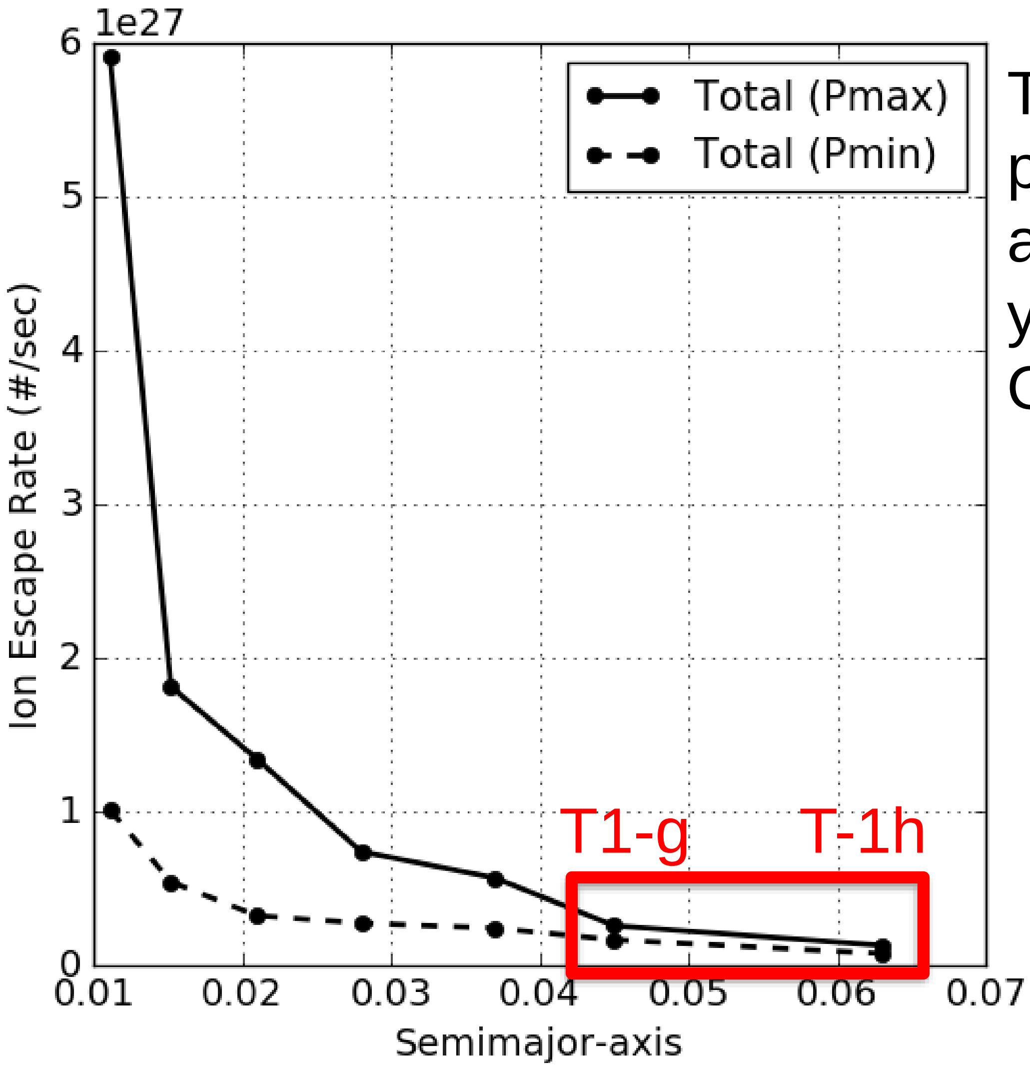
Ion escape rates of TRAPPIST-1 planets



The timescales over which these planets can retain their atmospheres range from $O(10^8)$ years for TRAPPIST-1b to $O(10^{10})$ years for TRAPPIST-1h.

Dong et al., 2018a, *Proc Natl Acad Sci*

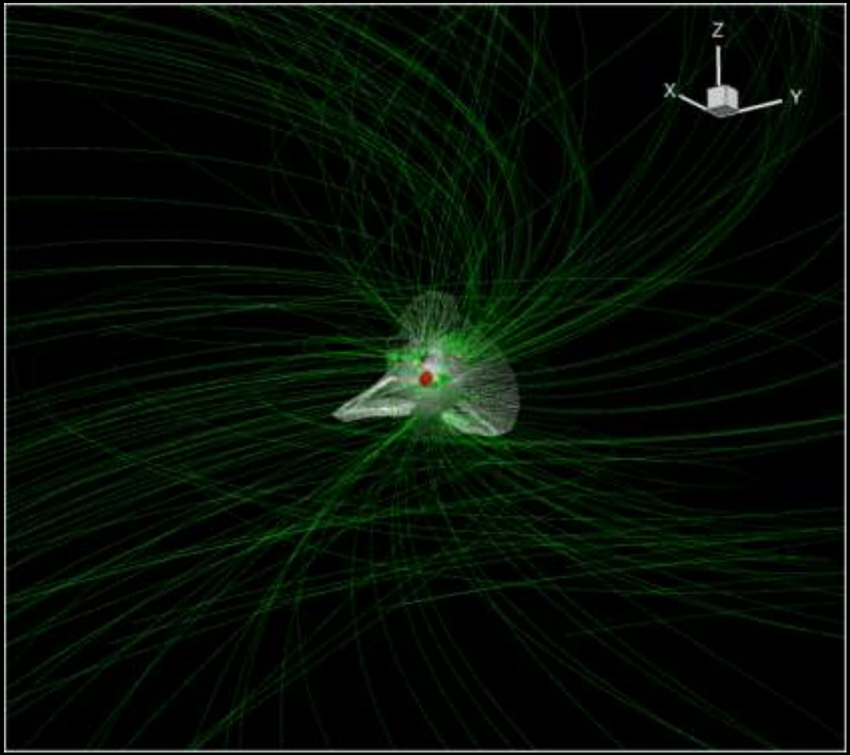
Ion escape rates of TRAPPIST-1 planets

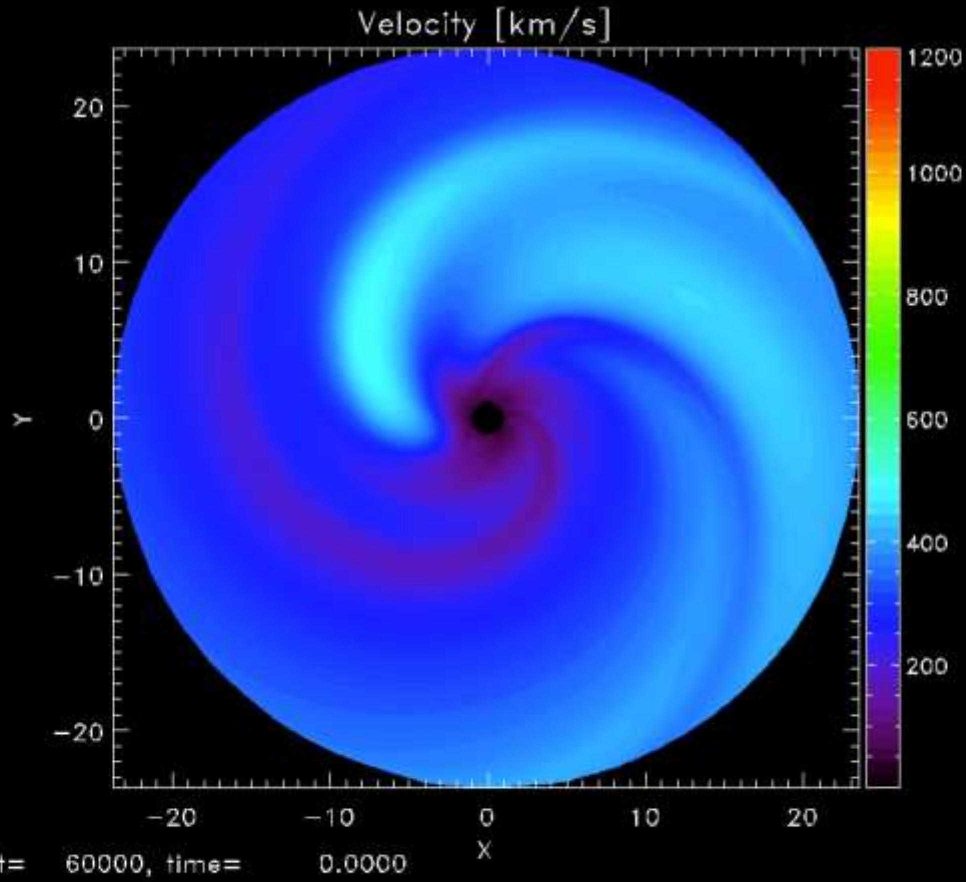


The timescales over which these planets can retain their atmospheres range from O(10^8) years for TRAPPIST-1b to O(10^{10}) years for TRAPPIST-1h.

Dong et al., 2018a, *Proc Natl Acad Sci*

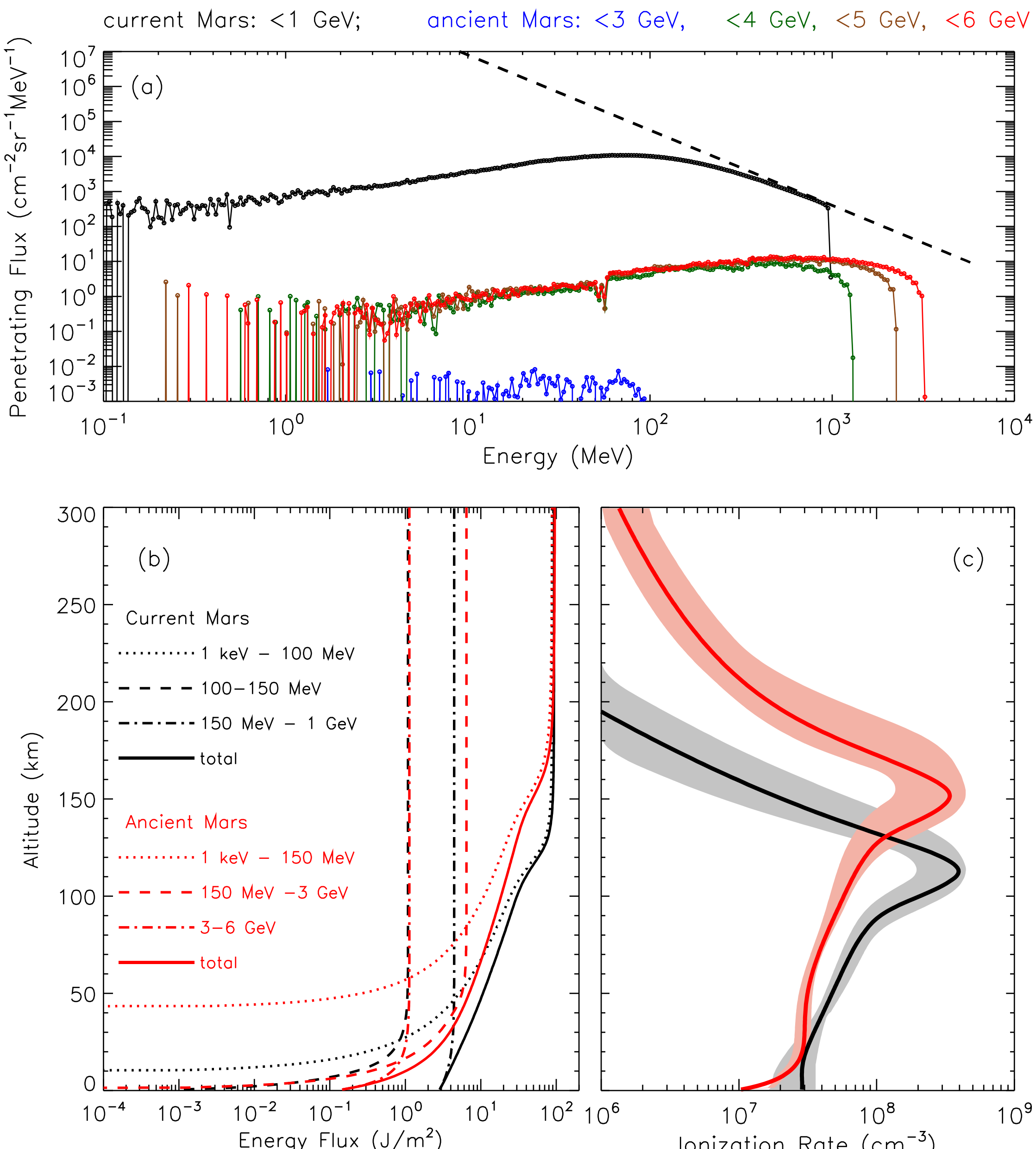
A Stellar CME





- **This simulation is to demonstrate the influence of Young Sun-like star's fast rotational rate on the CME propagation.**
- **With a tighter Parker spiral, the CME could impact a larger longitudinal region and the CME propagation is non-radial.**

Role of Stellar Energetic Particles on Prebiotic Chemistry



N_2 → N and N^+ (by SEPs)

$$N^+ + O_2 \rightarrow NO^+ + O$$
$$N + O_2 \rightarrow NO + O$$
$$N + O_3 \rightarrow NO + O_2$$
$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO + CH \rightarrow HCN + O,$$

CH_4

Hydrogen cyanide (HCN) is critical for the prebiotic synthesis.

Lingam and Dong et al., 2018b, *ApJ*

Summary

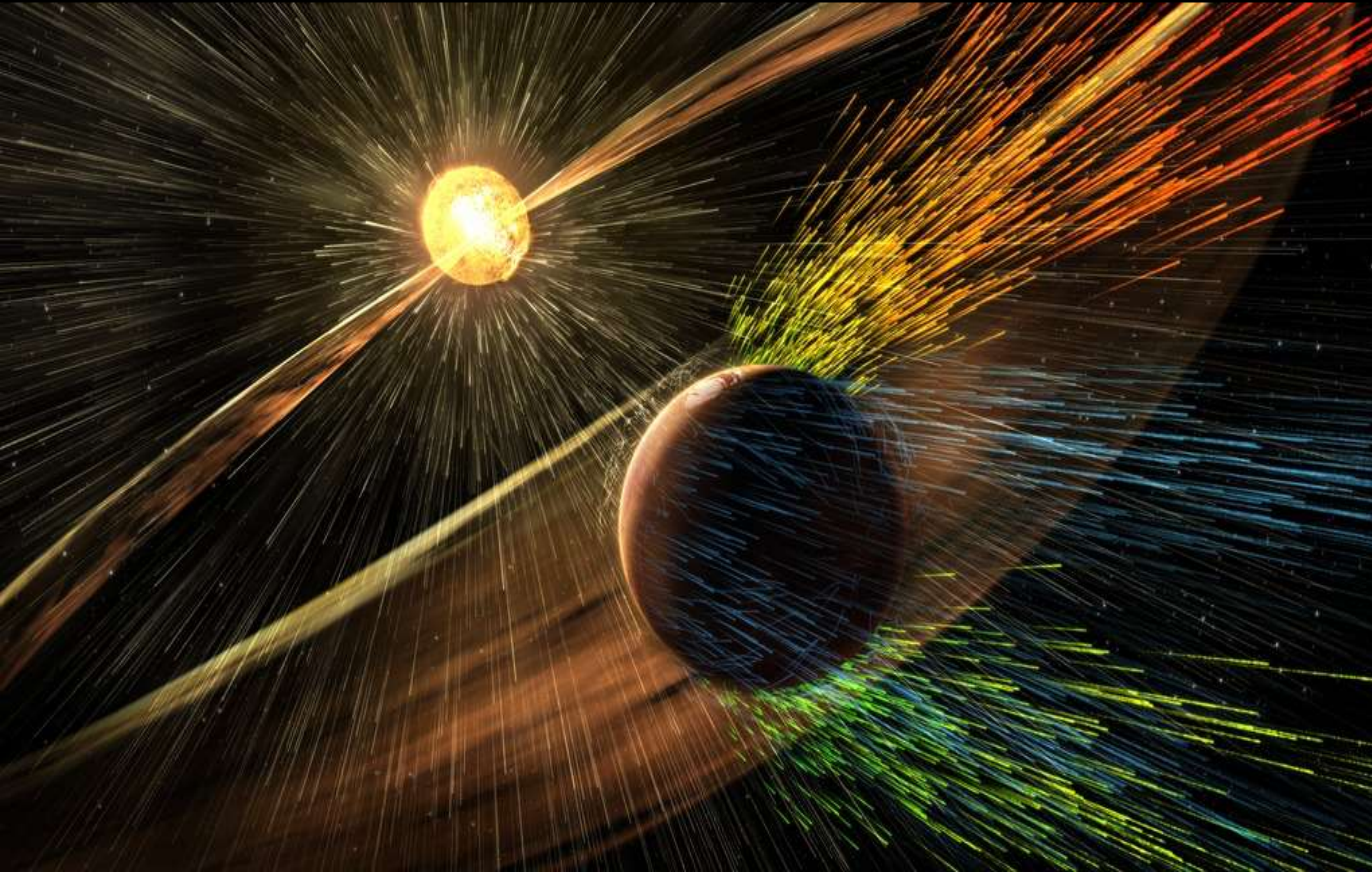
Exoplanetary space weather and stellar wind-induced atmospheric loss need to be taken into account for planetary habitability!

(1) For water worlds orbiting Sun-like stars, we find that Earth-like oceans (with a total mass of ~ 10^{24} g) will not be evaporated over Gyr timescales as the ion escape rates are far too low (by 3-4 orders of magnitude). In contrast, for exoplanets in the close-in HZ of M-dwarfs, the situation may be very different (next study).

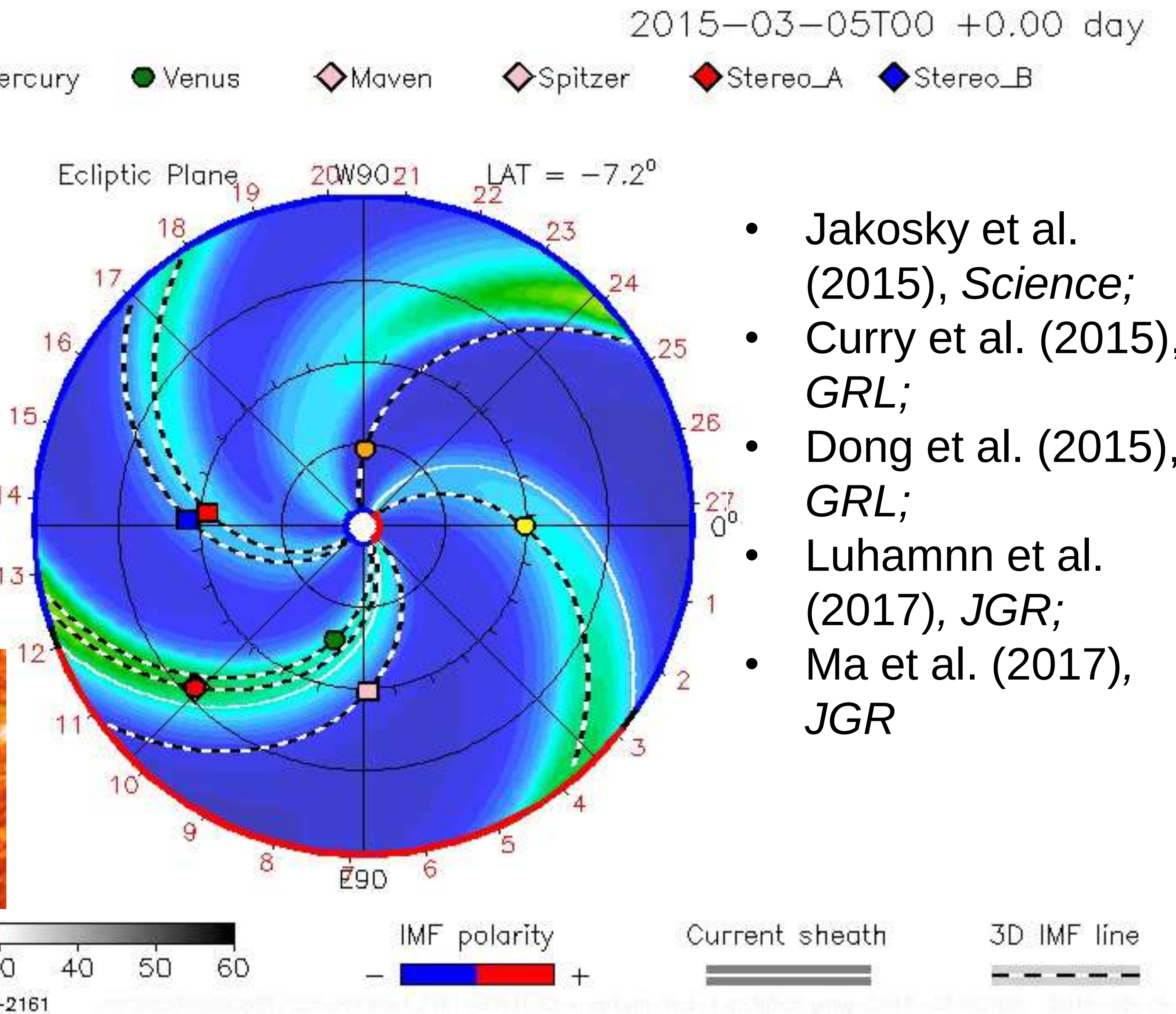
(3) PCb has the potential for habitability only if it is magnetized (i.e., has global magnetic field).

(4) TRAPPIST-1g will represent the best chance for a planet in the HZ of this planetary system to support a stable atmosphere over long periods.

Thanks for Your Attention!



The March 8th ICME event



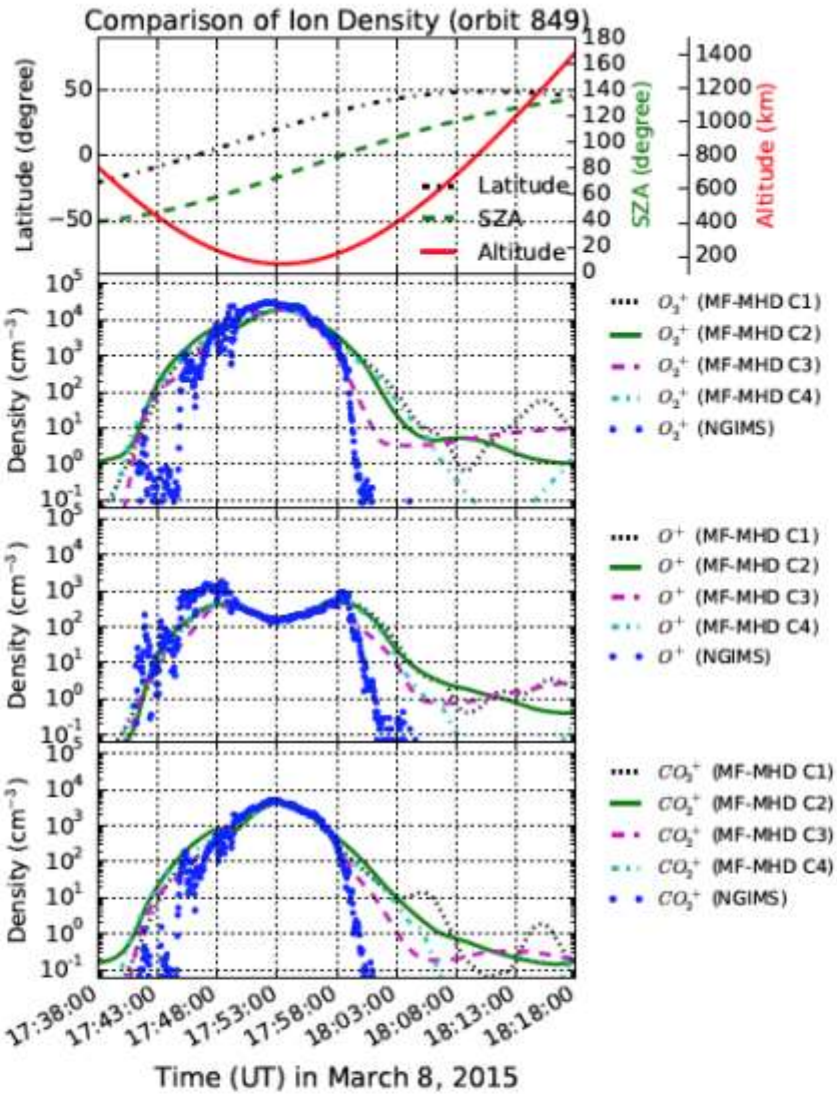
- Jakosky et al. (2015), *Science;*
- Curry et al. (2015), *GRL;*
- Dong et al. (2015), *GRL;*
- Luhamnn et al. (2017), *JGR;*
- Ma et al. (2017), *JGR*

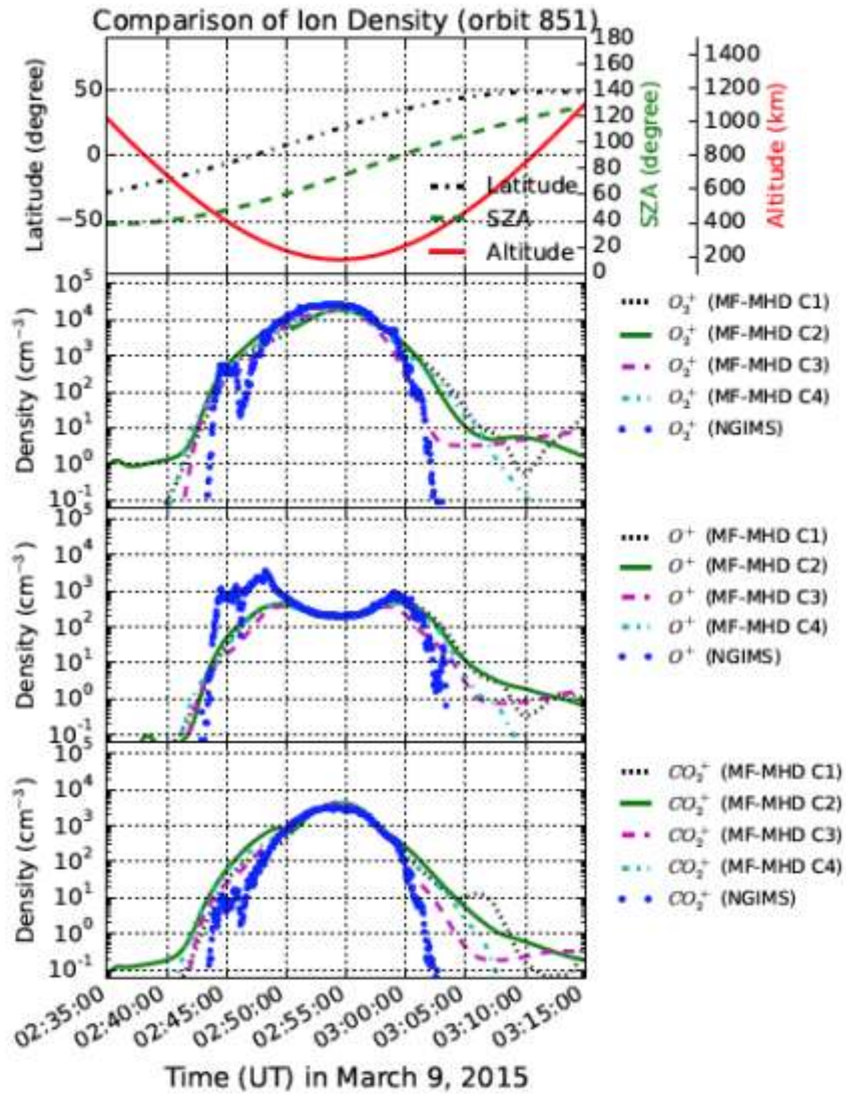
Variation in Ion Escape Rate

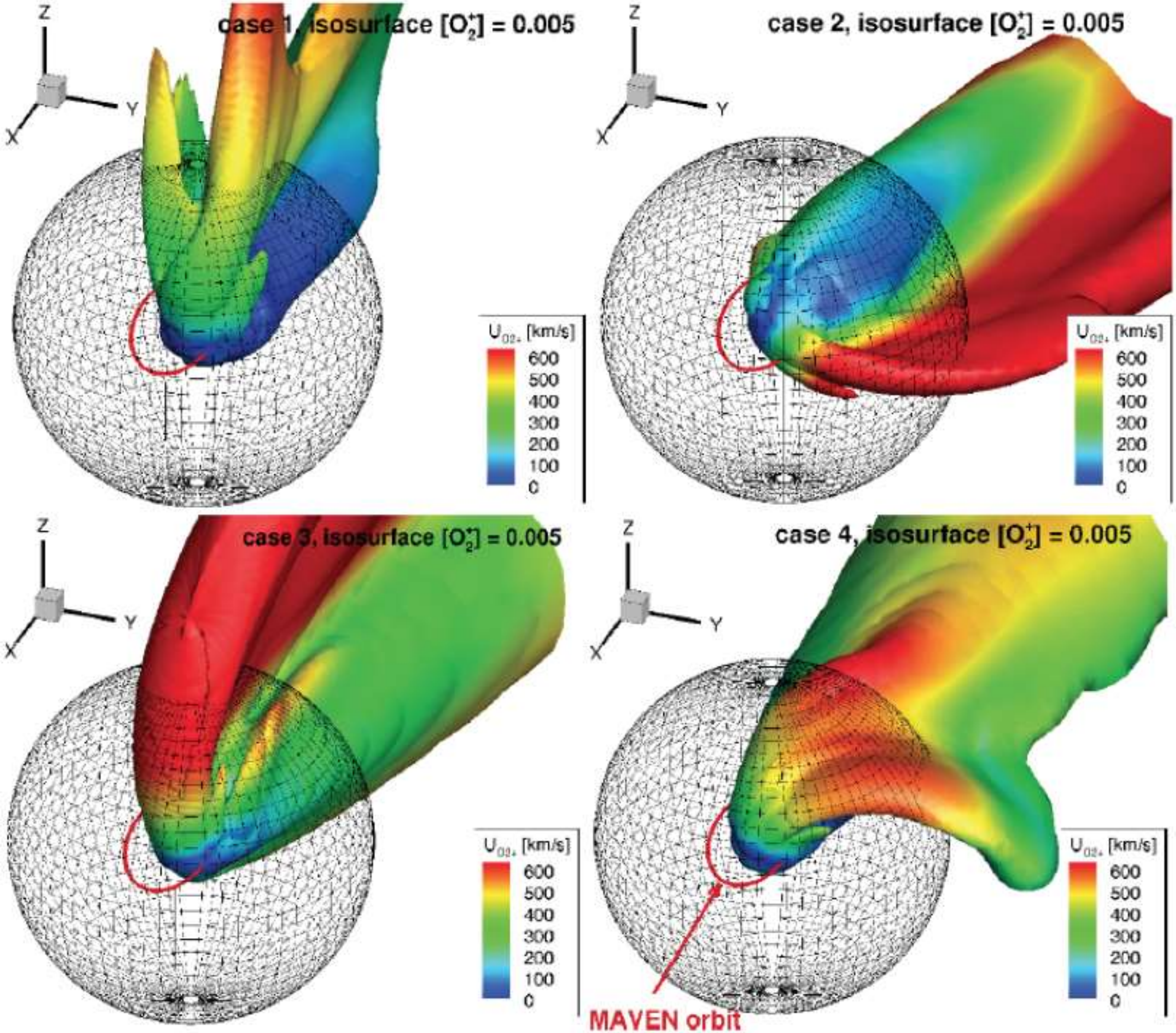
Escape Rate: (x 10^{24} s^{-1})	Case 1 (pre-ICME phase)	Case 2 (early sheath phase)	Case 3 (late sheath phase)	Case 4 (ejecta phase)
Total ion escape rate	2.05	5.62	22.5	8.10
O^+ escape rate	0.60	0.72	1.92	0.92
O_2^+ escape rate	1.28	4.40	18.7	6.37
CO_2^+ escape rate	0.17	0.51	1.88	0.81

- *ICMEs are important for understanding how a more active, early Sun may have removed much of Mars' atmosphere!*

Ionospheric Ion Density
Model vs NGIMS Ion Data





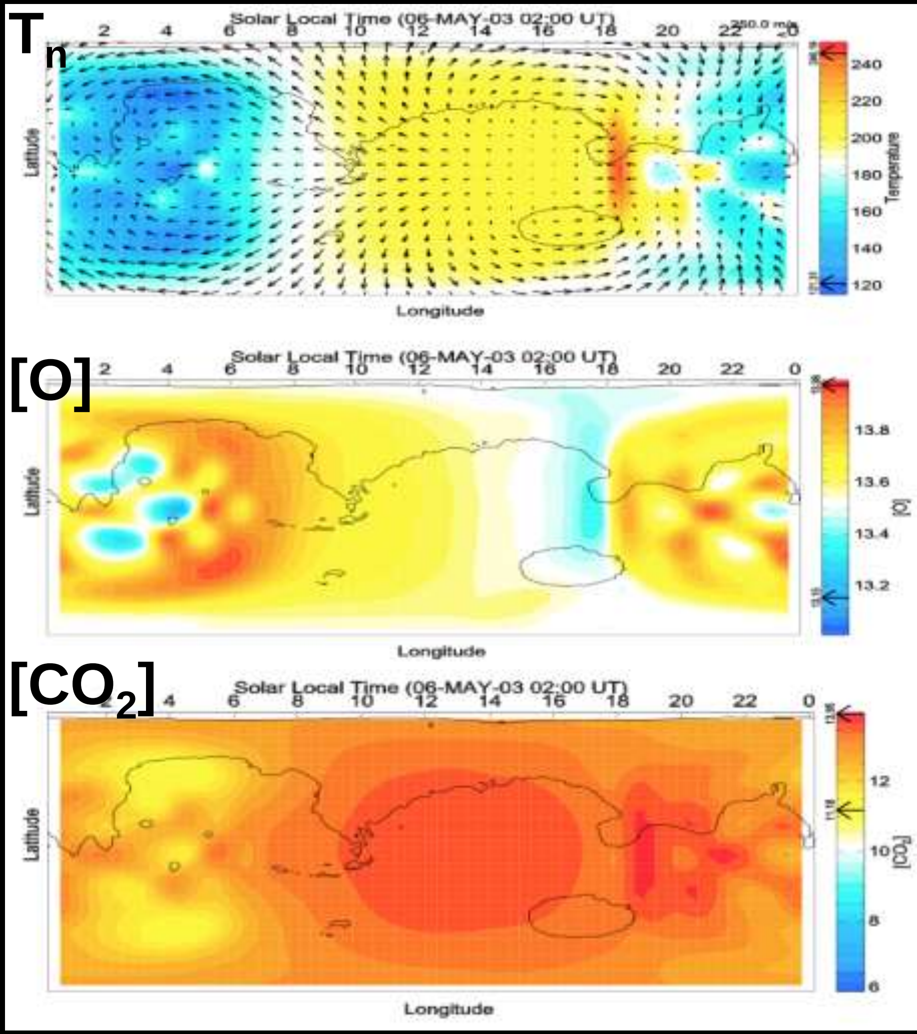


case 1, isosurface [O_2^+] = 0.005
case 2, isosurface [O_2^+] = 0.005
case 3, isosurface [O_2^+] = 0.005
case 4, isosurface [O_2^+] = 0.005
Z
Y
X
U_{O2+} [km/s]
600
500
400
300
200
100
0
MAVEN orbit

3-D Mars Global Ionosphere Thermosphere Model (M-GITM) [Bougher et al. 2015, *JGR*]

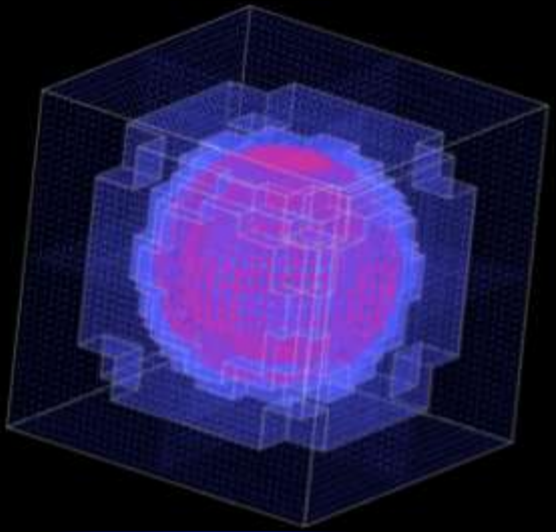
- ❑ Altitude Range 0-250 km
  - typical 2.5 km vertical resolution
  - no hydrostatic assumption
- ❑ Flexible horizontal resolution
  - 5x5º latitude-longitude grid
- ❑ Neutrals fields:
  - T, U, V, W (T, winds)
  - O, CO_2, CO, N_2, Ar, O_2 (major)
  - $N(^4S)$, NO, etc. (minor)
- ❑ PCE Ions: CO_2^+, O^+, O_2^+, N_2^+, NO^+
  - Sources and losses explicitly calculated
- ❑ Lower Atmosphere Physics
  - patterned after NASA Ames MGCM
- ❑ Upper Atmosphere Physics
  - patterned after Michigan MTGCM

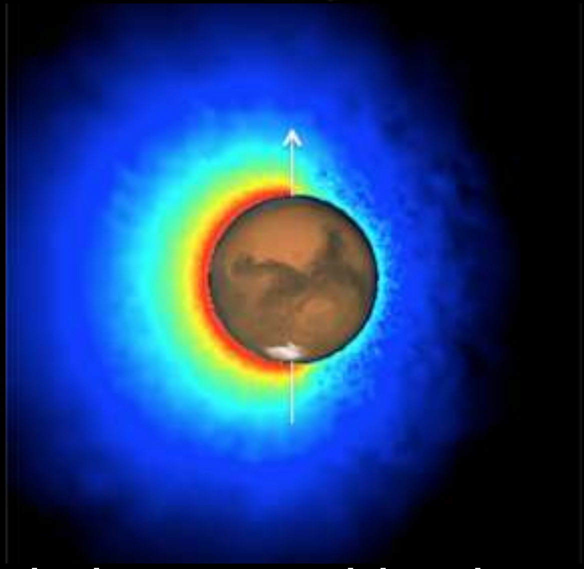
M-GITM Outputs at ~200 km:



3-D Mars Adaptive Mesh Particle Simulator (M-AMPS) [Lee et al. 2015, *JGR*]

- **DSMC (Direct Simulation Monte Carlo) method**
  - Approximates the Boltzmann equation and is valid for all gas flow regimes in the Martian atmosphere
- **Adaptive Block Mesh Refinement (AMR)**
  - Accurate and less expensive computation by using the optimum (local) spacing
  - Cut-cell method – reduces computational resource and time
- **Model Details**
  - Upper boundary at ~5 Mars radii
  - Interaction with background atmosphere is simulated in 3-D
  - Transitional domain: No hard exobase. Production & collisions near the regions where k_n =1 are simulated





dissociative recombination:
$O_2^+ + e^-$ --> $O^* + O^*$

Ion escape rates of TRAPPIST-1 planets

	O^+	O_2^+	CO_2^+	Total
	Maximum total pressure			
Trappist-1b	5.56×10^{27}	2.09×10^{26}	1.52×10^{26}	5.92×10^{27}
Trappist-1c	1.54×10^{27}	1.38×10^{26}	1.32×10^{26}	1.81×10^{27}
Trappist-1d	1.29×10^{27}	3.80×10^{25}	1.14×10^{25}	1.34×10^{27}
Trappist-1e	7.01×10^{26}	2.83×10^{25}	1.10×10^{25}	7.40×10^{26}
Trappist-1f	5.23×10^{26}	3.37×10^{25}	1.19×10^{25}	5.68×10^{26}
Trappist-1g	2.17×10^{26}	2.71×10^{25}	1.32×10^{25}	2.58×10^{26}
Trappist-1h	1.06×10^{26}	1.65×10^{25}	6.98×10^{24}	1.29×10^{26}
	Minimum total pressure			
Trappist-1b	9.33×10^{26}	4.99×10^{25}	2.92×10^{25}	1.01×10^{27}
Trappist-1c	4.23×10^{26}	9.22×10^{25}	2.76×10^{25}	5.42×10^{26}
Trappist-1d	2.81×10^{26}	3.07×10^{25}	1.04×10^{25}	3.23×10^{26}
Trappist-1e	2.20×10^{26}	4.19×10^{25}	1.25×10^{25}	2.74×10^{26}
Trappist-1f	1.88×10^{26}	4.30×10^{25}	1.10×10^{25}	2.42×10^{26}
Trappist-1g	9.33×10^{25}	5.85×10^{25}	1.38×10^{25}	1.66×10^{26}
Trappist-1h	4.52×10^{25}	2.69×10^{25}	4.39×10^{24}	7.66×10^{25}

Dong et al., 2018, *Proc Natl Acad Sci*