Atmospheric Escape From TOI-700 d: Venus versus Earth Analogs

Chuanfei Dong[1,2],
Meng Jin[3,4], Manasvi Lingam[5,6]

[1] Department of Astrophysical Sciences, Princeton University; dcfy@princeton.edu
[2] Princeton Plasma Physics Laboratory, Princeton University
[3] SETI Institute
[4] Lockheed Martin Solar and Astrophysics Lab (LMSAL)
[5] Department of Aerospace, Physics and Space Sciences, Florida Tech
[6] Institute for Theory and Computation, Harvard University

Outline

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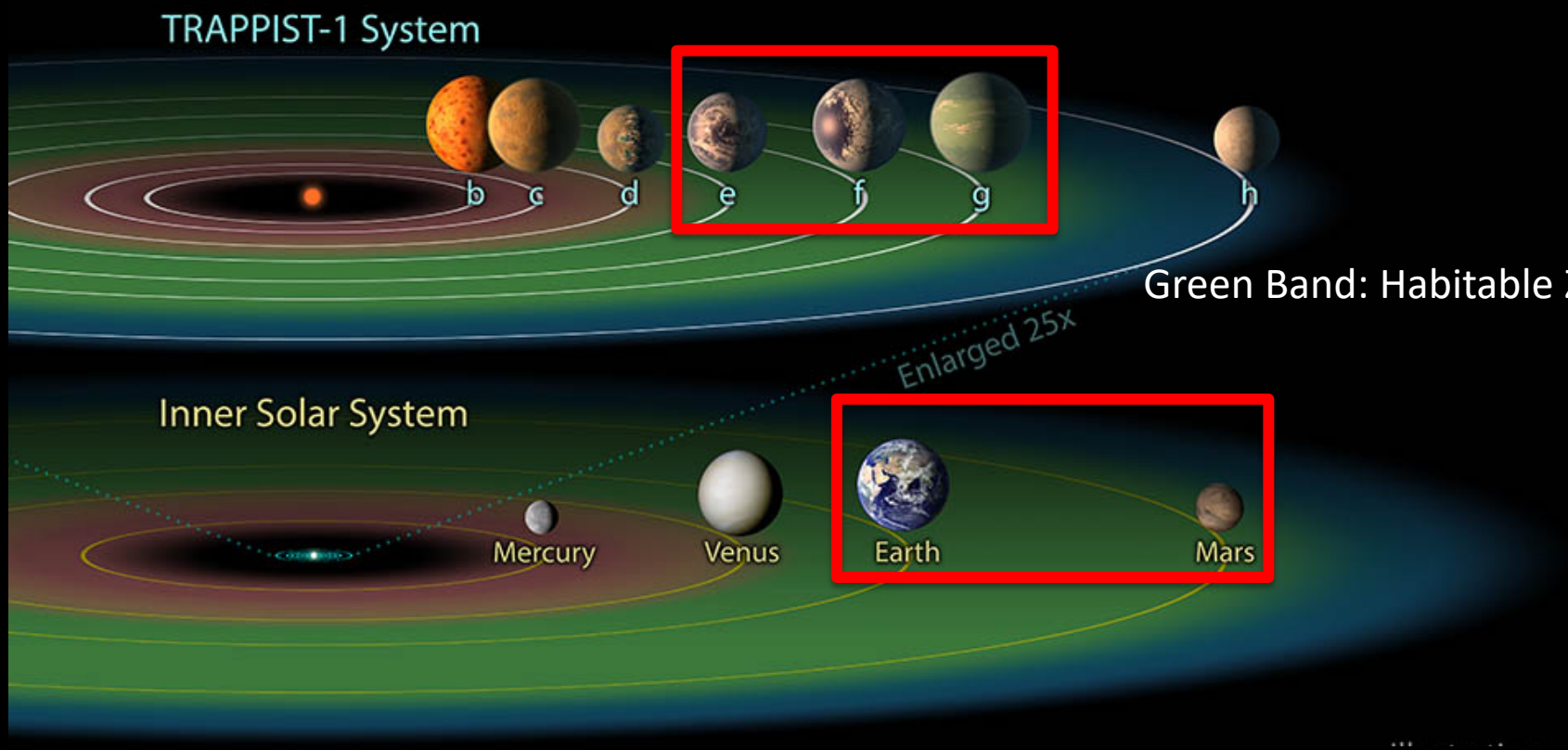
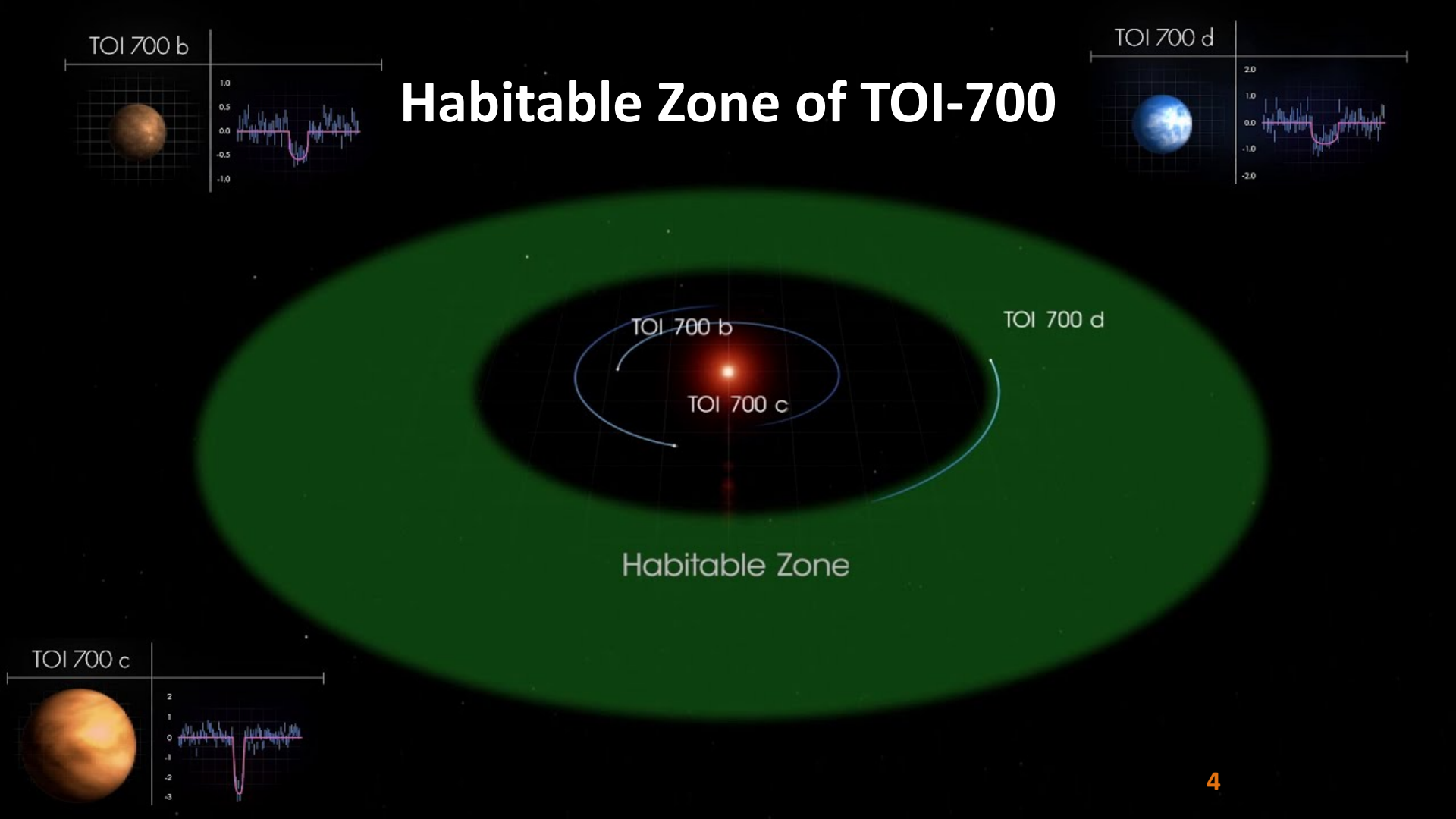
- Model Description and Results
  - Alfvén Wave Solar Model (AWSoM)
  - 3-D BATS-R-US Multifluid Magnetohydrodynamic (MHD) Model
  - Stellar Wind Interaction with TOI-700 d
  - Comparison between Venus and Earth Analogs
- Conclusion

Traditional Habitable Zones



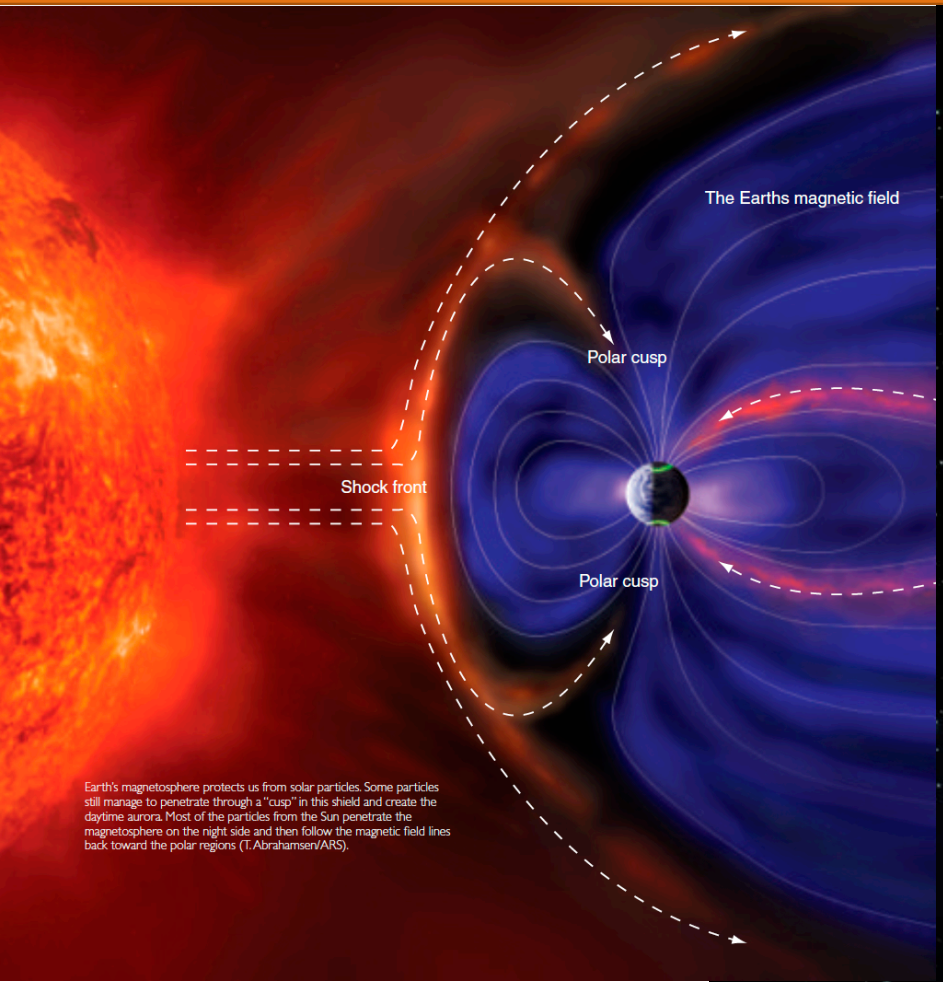
Habitable Zone of TOI-700



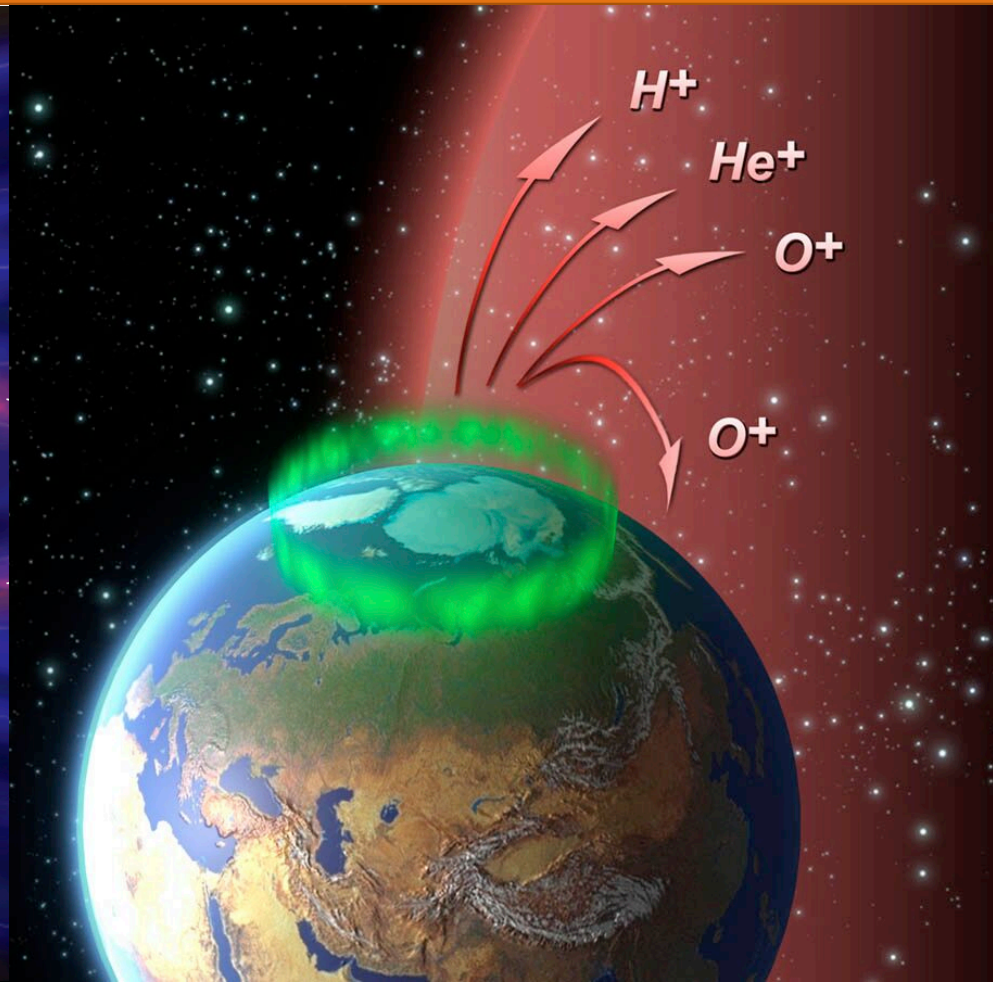
Space Weather: Stellar Wind and Activity

Stellar flare-CME events have been observed (Argiroffi et al., 2019, Nat Astro)!

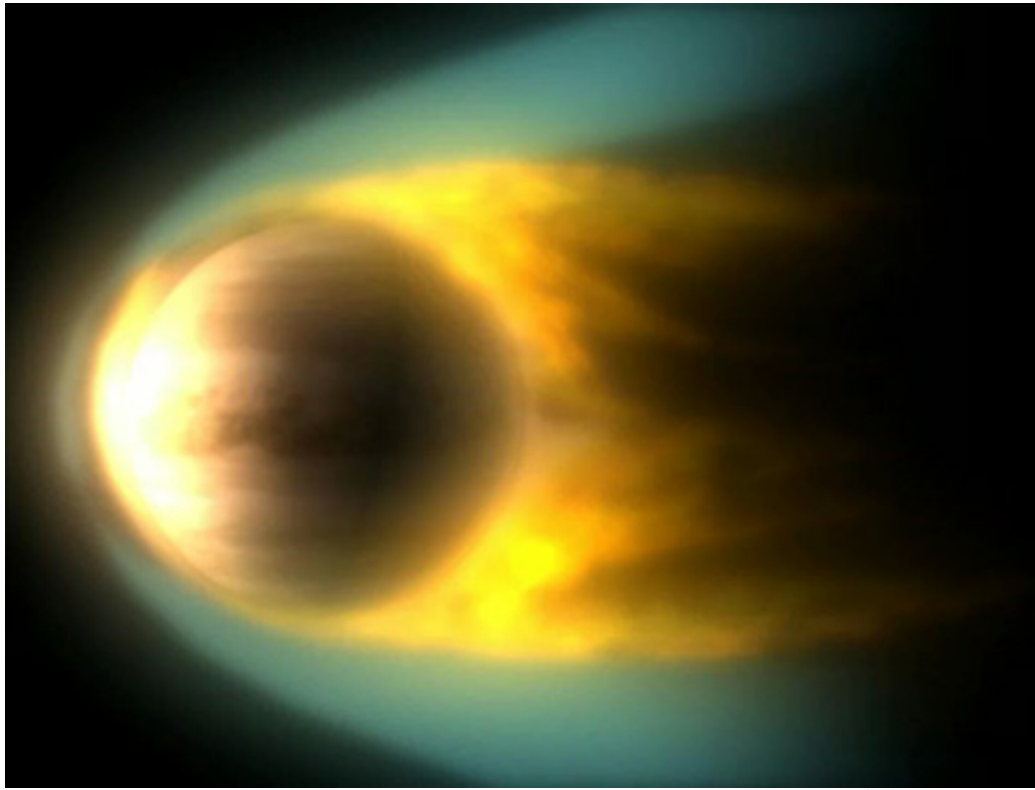
Atmospheric Ion Loss from Magnetized Earth



Earth's magnetosphere protects us from solar particles. Some particles still manage to penetrate through a "cusp" in this shield and create the daytime aurora. Most of the particles from the Sun penetrate the magnetosphere on the night side and then follow the magnetic field lines back toward the polar regions (T. Abrahamsen/ARS).

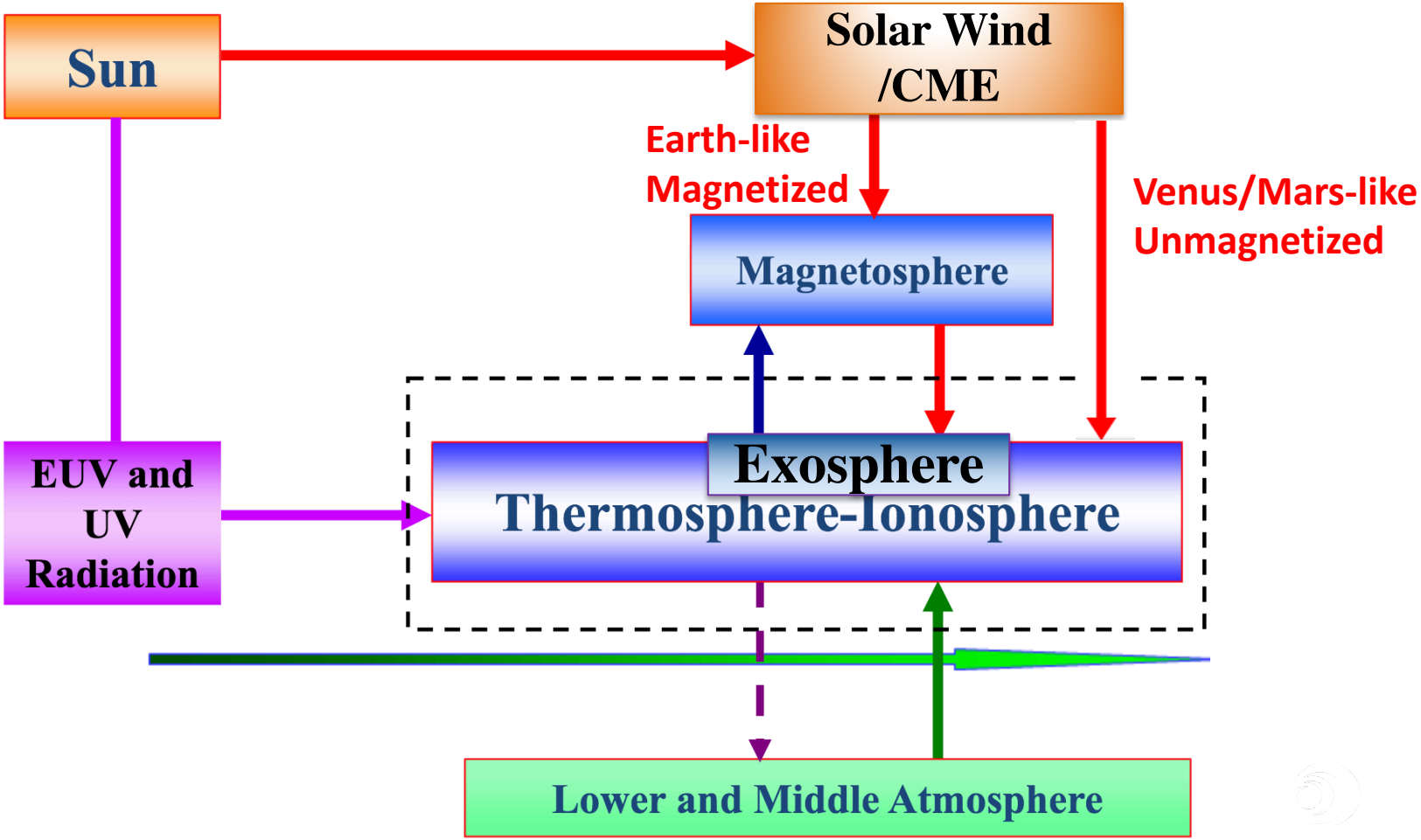


Atmospheric Ion Loss from Unmagnetized Venus

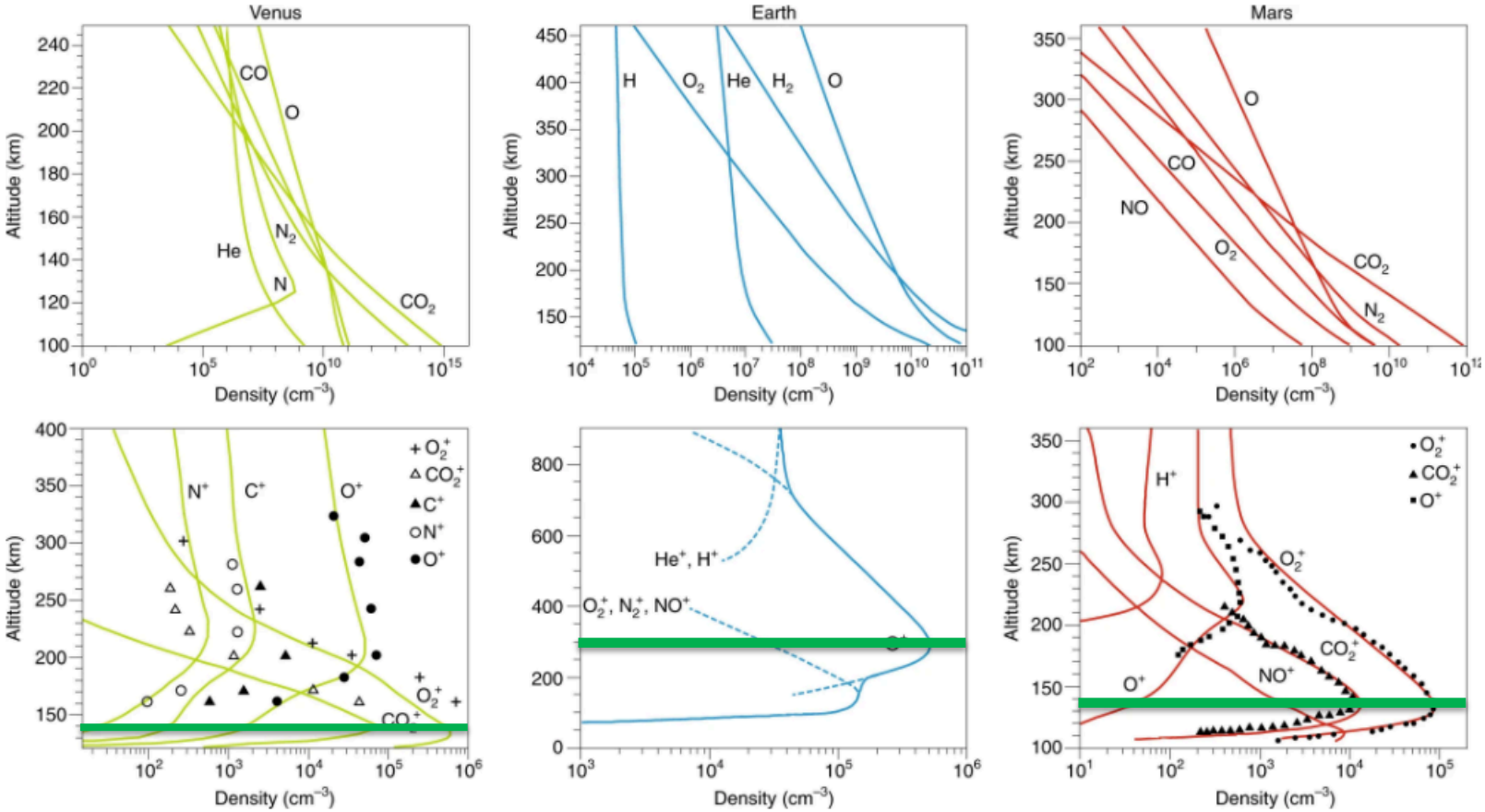


Analogy: Blow-Dry Your Hair

How Does the Sun/Star Affect the Planetary System?

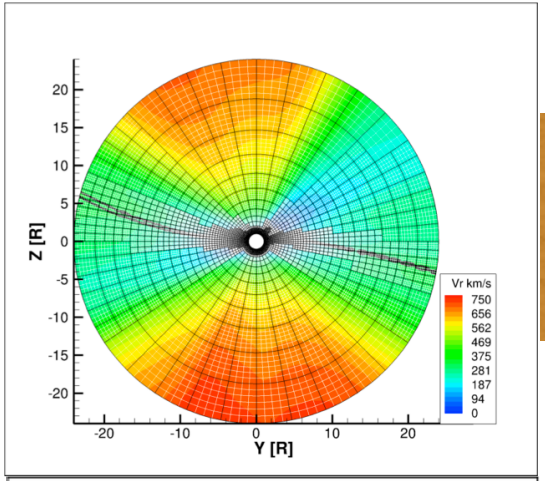


Thermosphere and Ionosphere (Venus, Earth, and Mars)

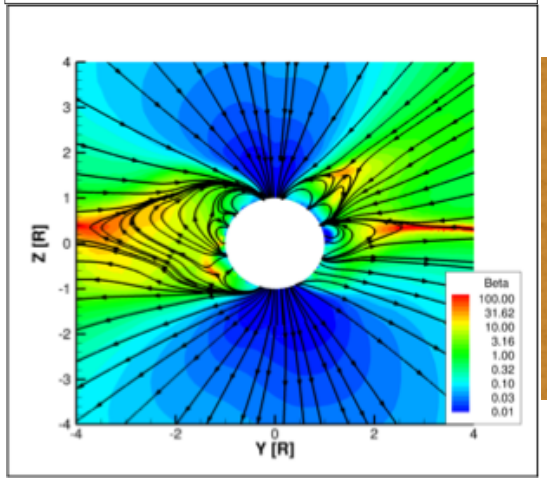


Mendillo et al., 2018

Alfven Wave Solar Model (AWSoM) [van der Holst et al. 2014]



Velocity

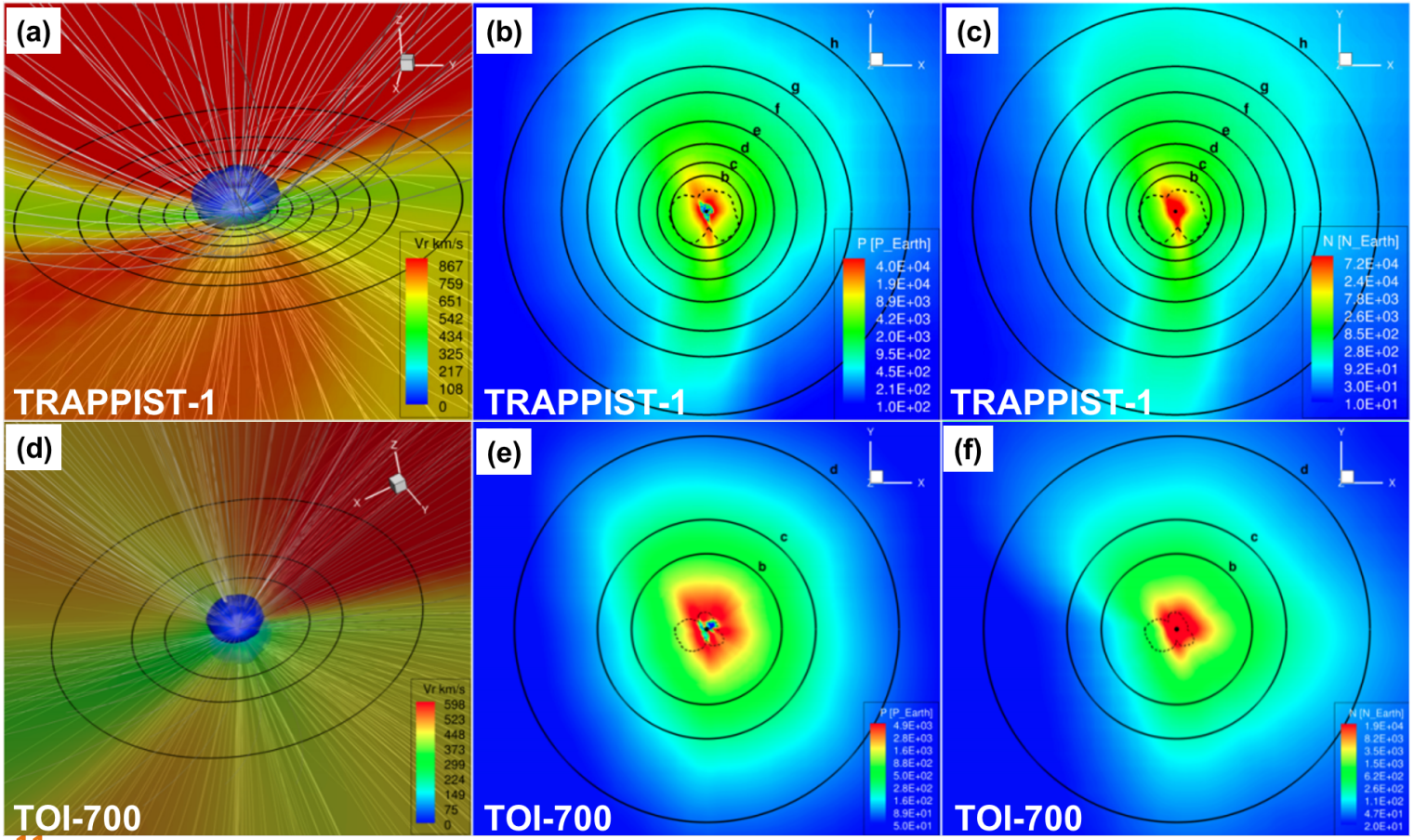


Plasma Beta

Alfvén Wave Solar Model (AWSoM)

- **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).

Calculated Stellar Wind Profiles from TRAPPIST-1 and TOI-700



Dong et al., 2018, PNAS; Dong et al., 2020, ApJL

3-D BATS-R-US Multifluid MHD Model
(Earth: Dong et al., 2019; Venus: Dong et al., 2020)

- Four ion fluids: H^+, O_2^+, O^+, $CO_2^{+;}$ two background neutrals: CO_2, O; and eight photochemical reactions.
- Spherical grids:
  - Radial resolution varies from 5 km in the ionosphere to 3000 km far from the planet.
  - Angular resolution is 2.5^0
  - 10 million cells
- Inner Boundary Conditions
  - Inner boundary at 100 km
  - $[O_2^+]$, $[O^+]$ and $[CO_2^+]$ are in photochemical equilibrium (SZA and optical depth considered)
  - Absorbing boundary condition for U and B
- Chemical reactions
  - Photoionization
  - Charge exchange
  - Electron impact ionization
  - Electron Recombination

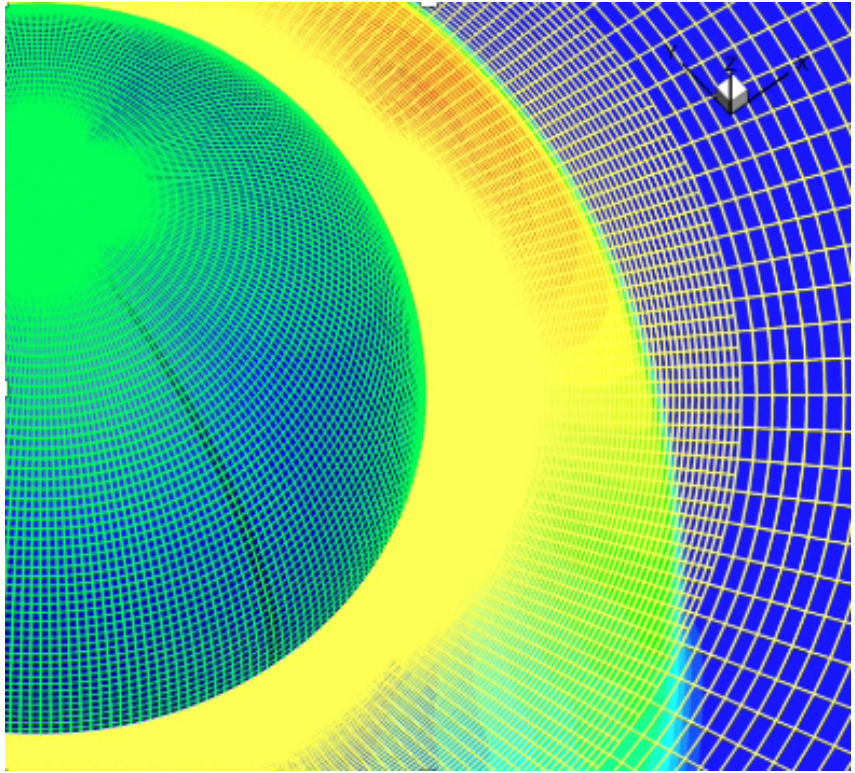
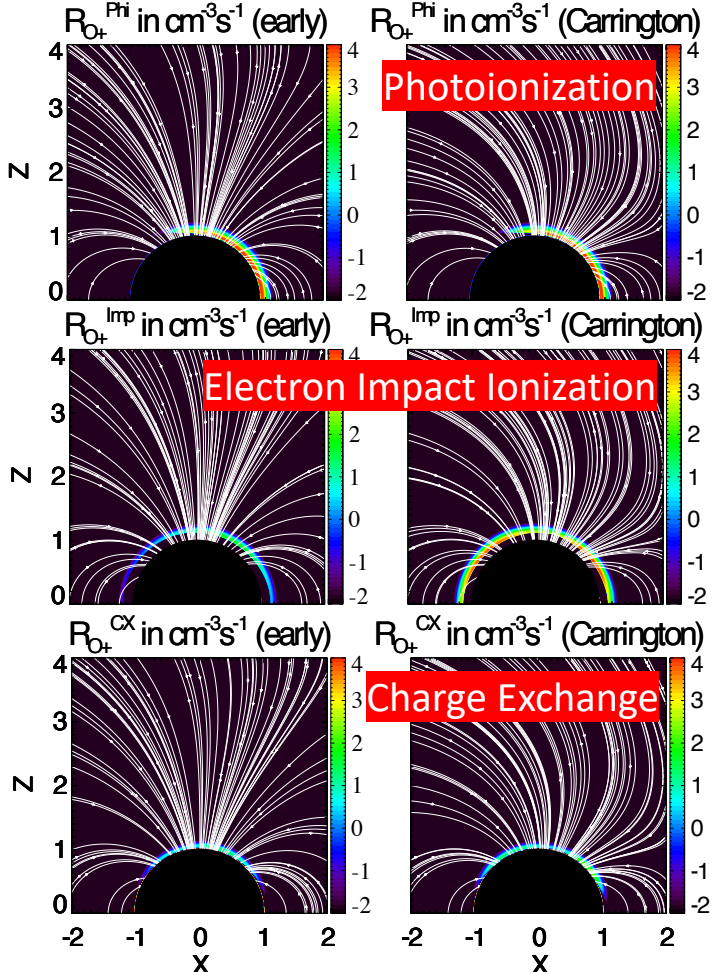
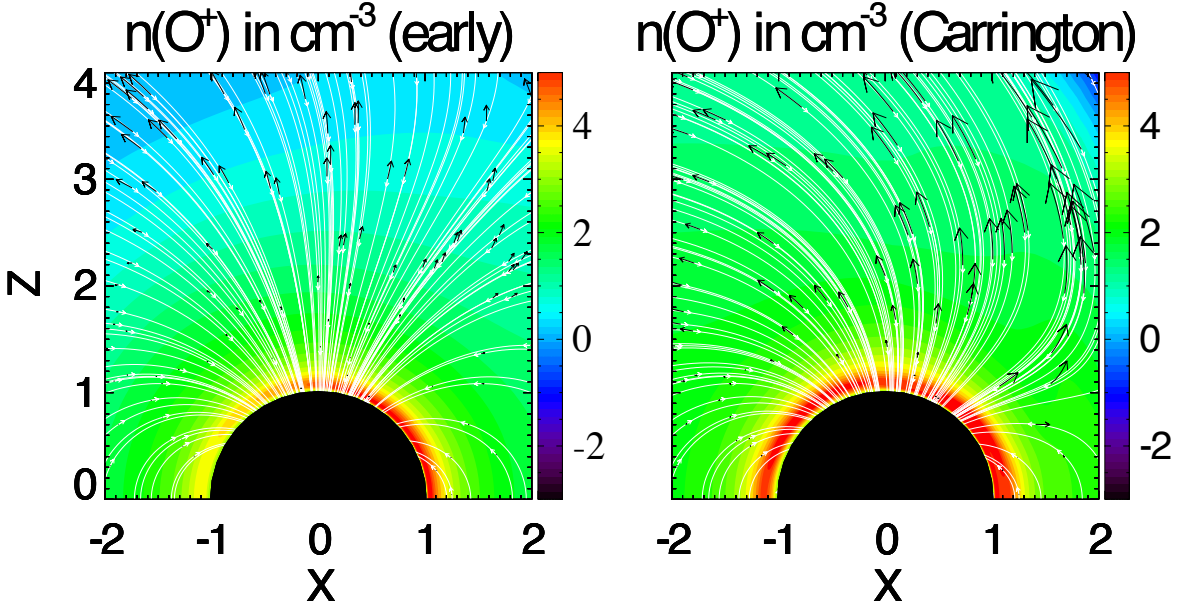


Illustration of the grid system used in the calculation.

Atmospheric O^+ Ion Source and Loss (Earth/Earth-like Exoplanets)





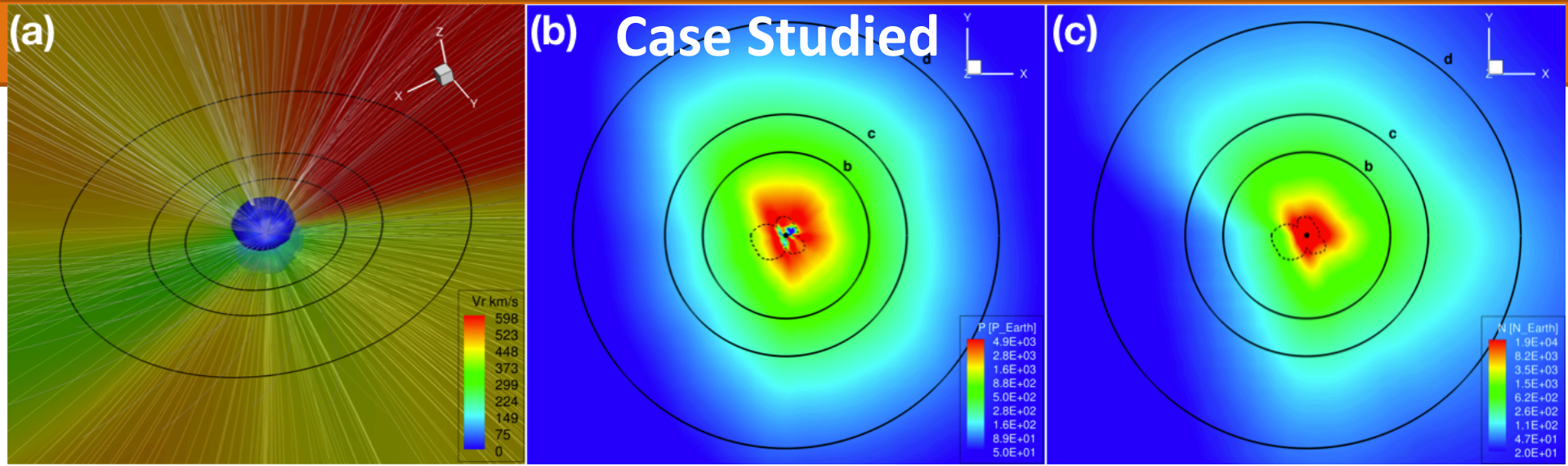
Ancient (4.02 Gyr) solar wind parameters at 1 au (Boesswetter et al. 2010).

An extreme "Carrington-type" space weather event (Ngwira et al. 2014)

Joule/Ohmic heating included:

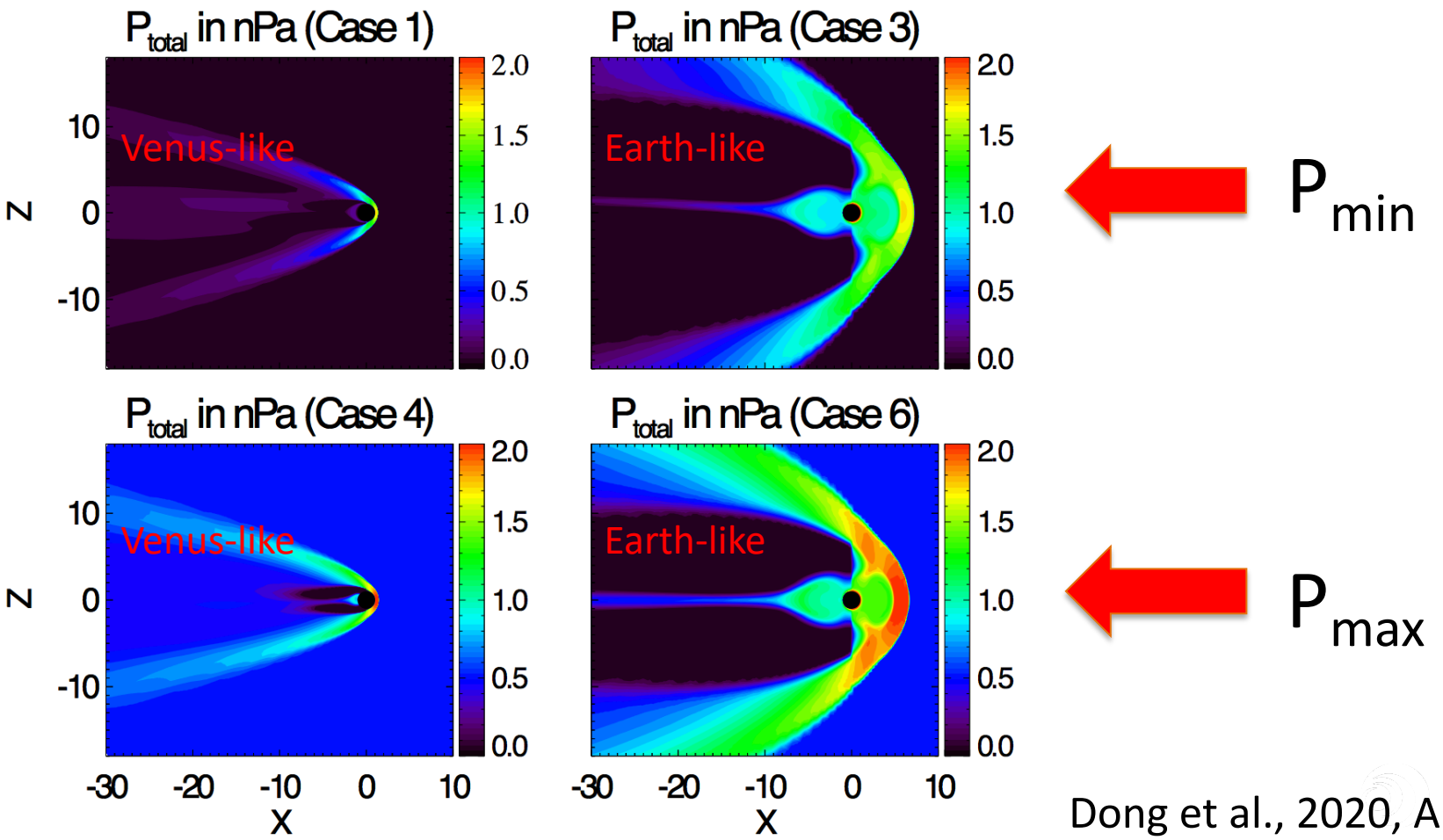
$$\sum_{t=\mathrm{O},\mathrm{O}^+} \frac{\rho_e \nu_{et}}{m_e + m_t}\left[\frac{2}{3} m_t (\boldsymbol{u}_t - \boldsymbol{u}_e)^2\right] \propto \frac{\boldsymbol{J}^2}{\sigma_e} = \boldsymbol{J}\cdot\boldsymbol{E}$$

Case Studied



Case #	P_{sw}	n_{sw} (cm^{-3})	v_{sw} (km s^{-1})	IMF (nT)	Planetary Type	Magnetic Field	O^+ Loss Rate (s^{-1})
Case 1					Venus-like	Off	1.93×10^{26}
Case 2	P_{min}	96.8	(-650.4, 47.4, -7.4)	(-46.7, 2.9, -3.7)	Earth-like	Off	1.18×10^{28}
Case 3					Earth-like	On	1.39×10^{27}
Case 4					Venus-like	Off	2.04×10^{26}
Case 5	P_{max}	451.6	(-471.2, 47.4, 4.3)	(9.2, 2.7, -7.0)	Earth-like	Off	1.61×10^{28}
Case 6					Earth-like	On	2.12×10^{27}

Pressure Balance during the Stellar Wind-Planet Interaction

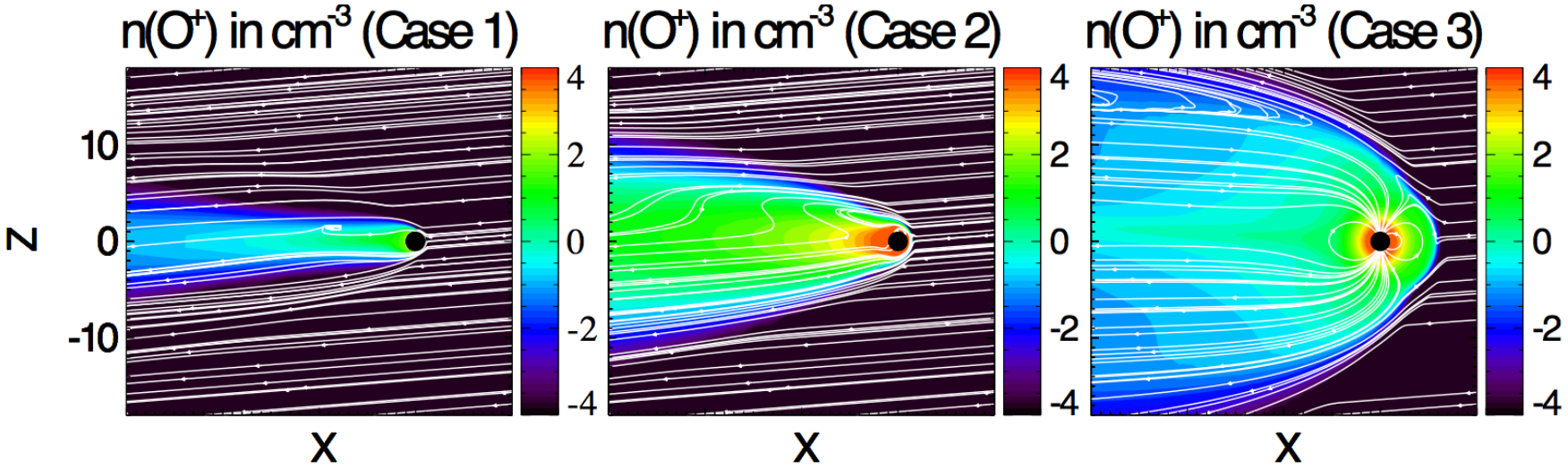


Dong et al., 2020, ApJL

Atmospheric Escape From TOI-700 d (an exoplanet): Venus versus Earth Analogs

Assuming Venus-like and Earth-like planets orbiting an M-type star instead of the Sun. In general, an M-type star has higher stellar radiation and stronger stellar wind pressure than our Sun, therefore, the ion escape rates are also larger than current Venus and Earth.

Unmagnetized Venus	Unmagnetized Earth	Magnetized Earth
2.10×10^{26} S^{-1}	1.18×10^{28} S^{-1}	1.39×10^{27} S^{-1}



Dong et al., 2020, ApJL

Conclusion

- We assess the feasibility of TOI-700 d to retain an atmosphere – one of the chief ingredients for surface habitability – over long timescales by employing state-of-the-art magnetohydrodynamic models to simulate the stellar wind and the associated rates of atmospheric escape.
- The simulations show that the unmagnetized TOI-700 d with a 1 bar Earth-like atmosphere could be stripped away rather quickly (< 1 gigayear), while the unmagnetized TOI-700 d with a 1 bar CO2-dominated atmosphere could persist for many billions of years; we find that the magnetized Earth-like case falls in between these two scenarios.
- Space weather and stellar wind-induced atmospheric loss need to be taken into account for planetary habitability!

Thanks for Your Attention and Questions!