Atmospheric Escape from Rocky M-Dwarf Planets Orbiting within the Habitable Zone

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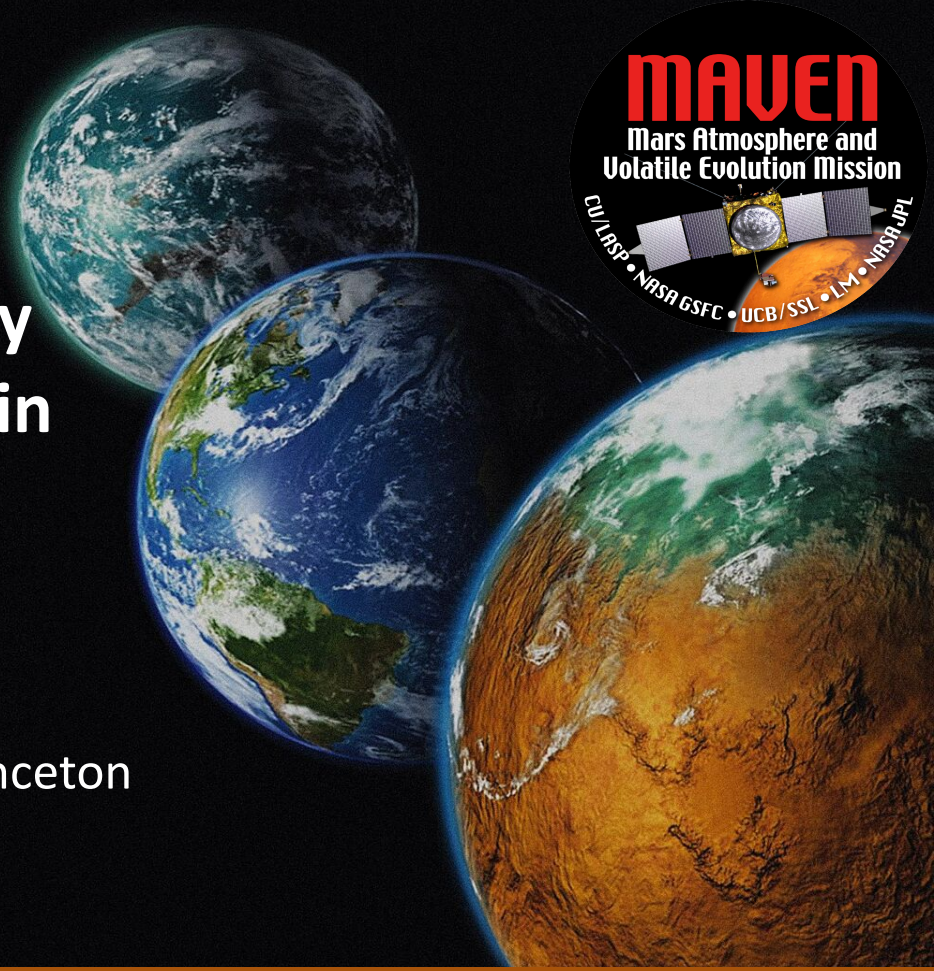

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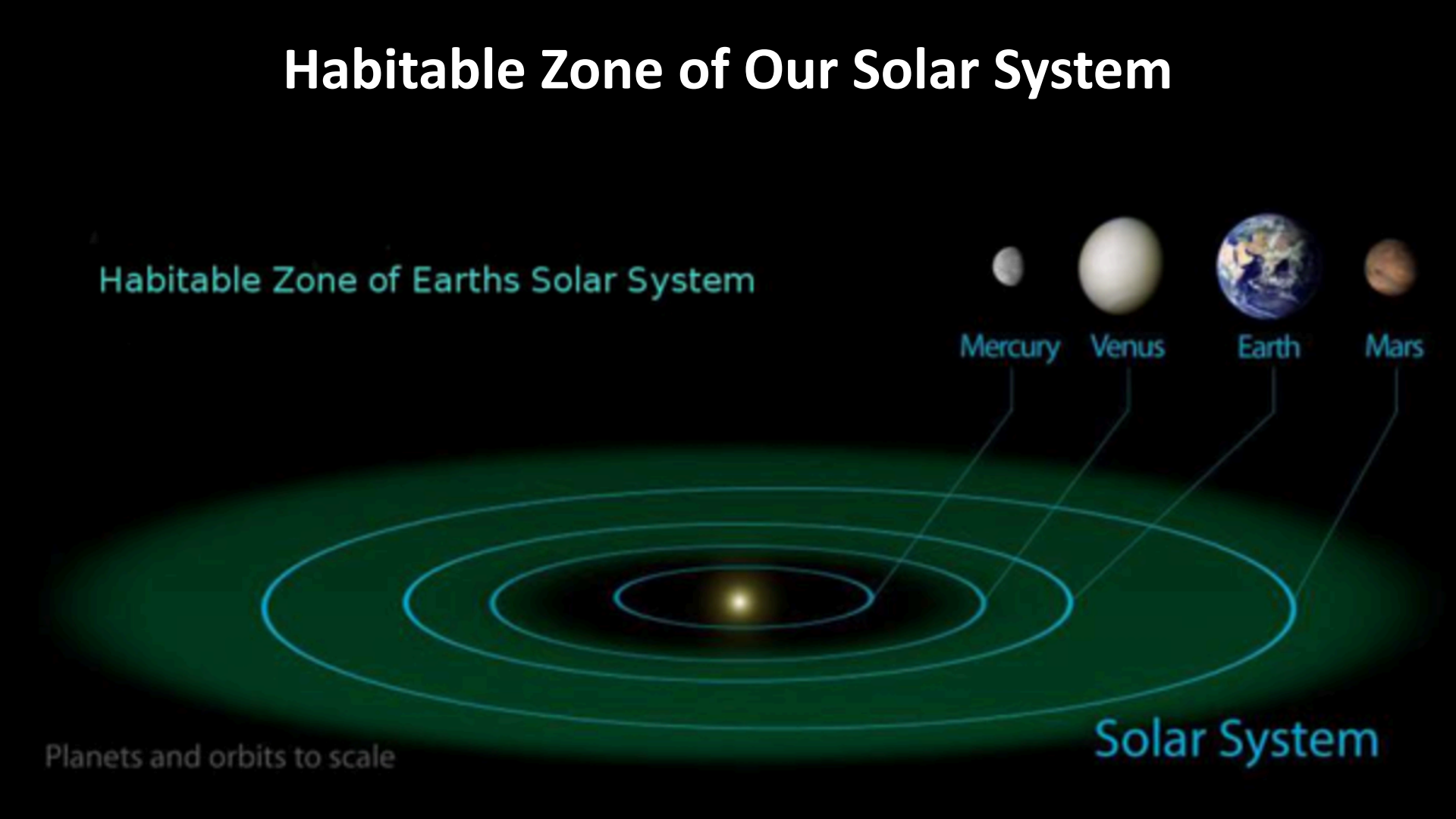
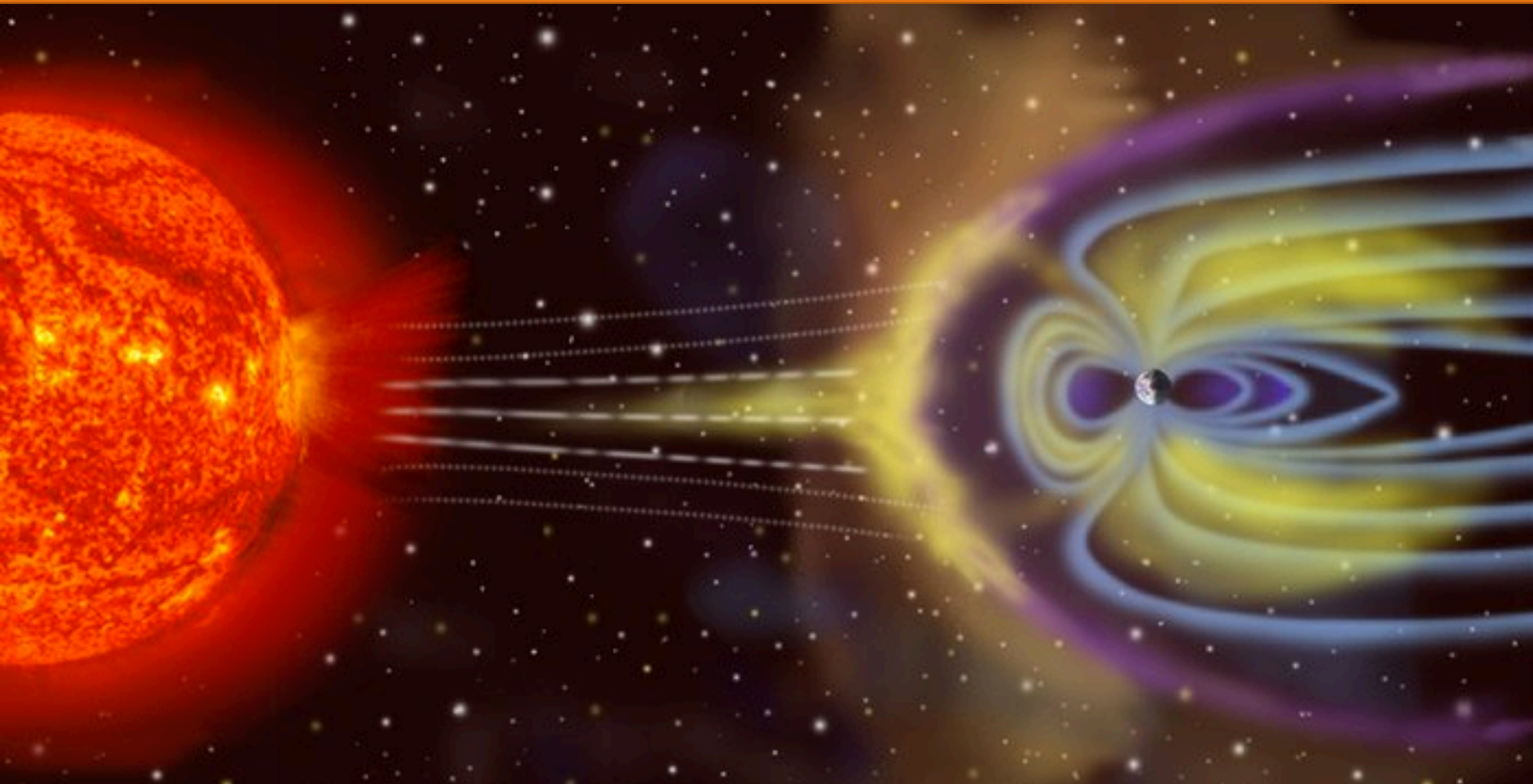
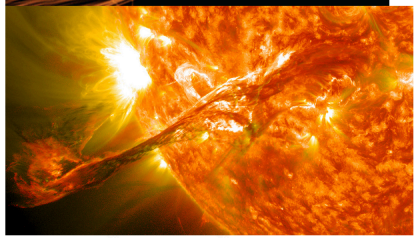
Habitable Zone of Our Solar System

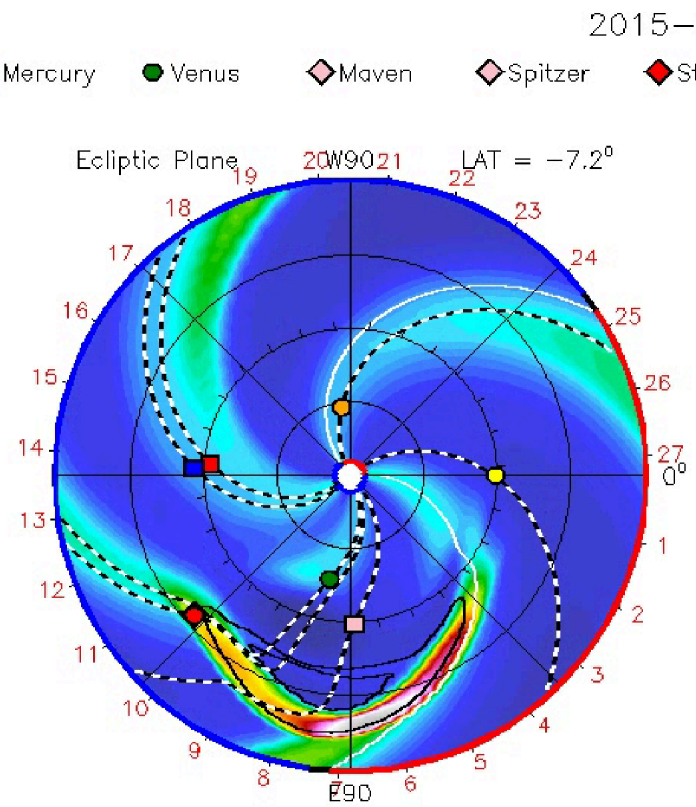


Space Weather: Stellar Wind and Activity



The 2015 March 8th Interplanetary Coronal Mass Ejection (ICME) sideswiped Mars

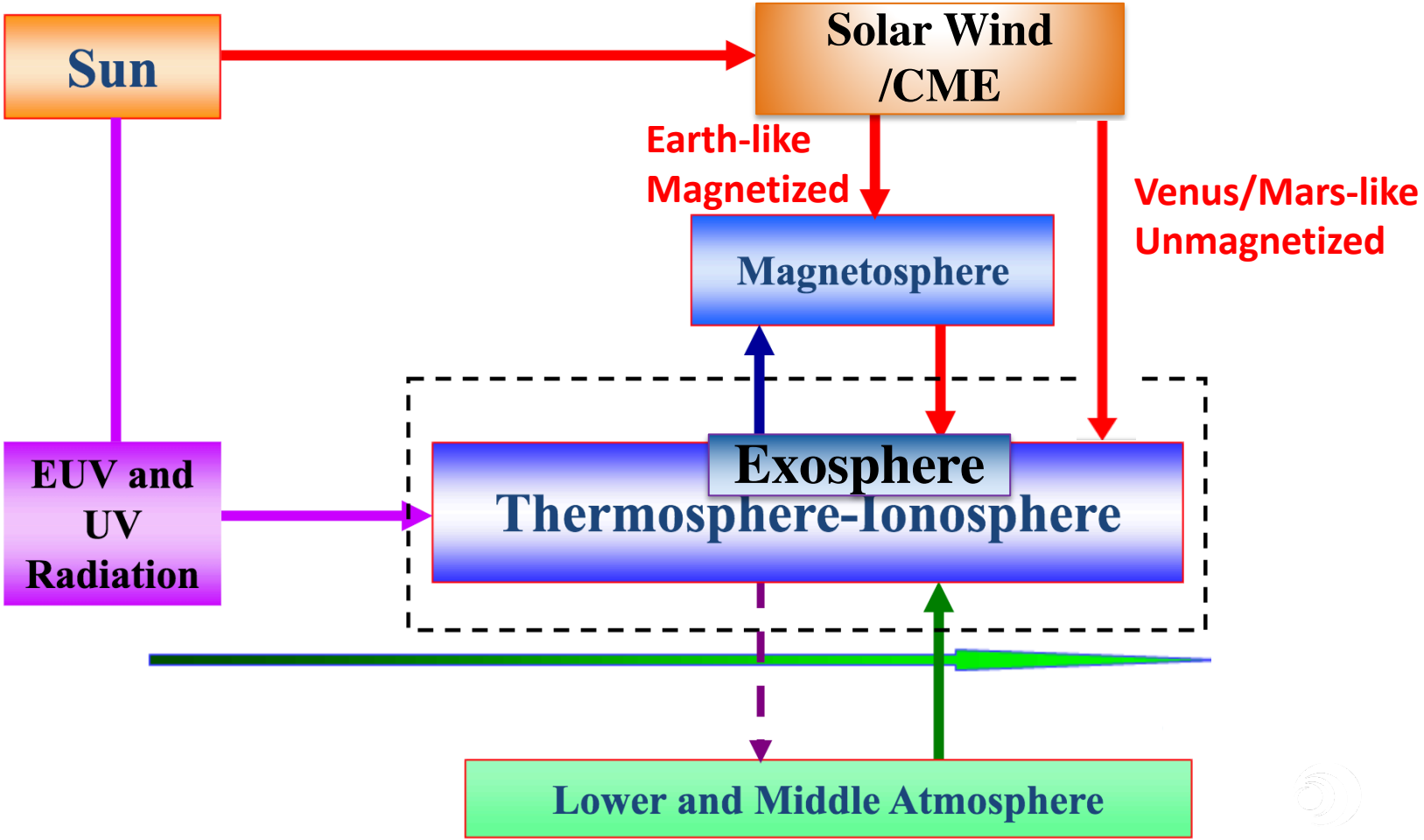




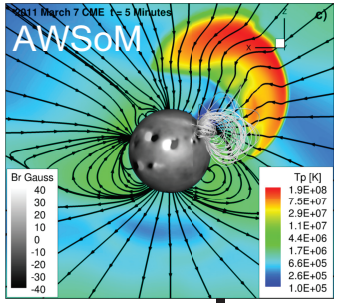
Non-thermal atmospheric ion escape rate increased by more than one order of magnitude!

Jakosky et al., 2015, Science
Bougher et al., 2015, Science
Curry et al., 2015, GRL
Dong et al., 2015, GRL
Luhamnn et al. 2017, JGR
Ma et al., 2017, JGR

How Does the Sun/Star Affect a Planet?



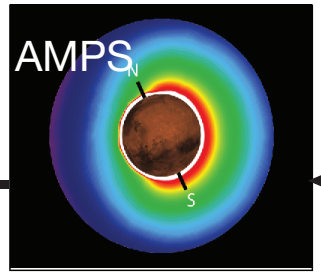
Model Coupling and Model Validation/Application in the Solar System – Unmagnetized Mars as an Example



Stellar Wind MHD model

$\vec{B}_{sw}$, $\vec{U}_{sw}$, n_{sw}, T_{sw}

Planetary Magnetosphere MHD model



neutral exosphere Monte Carlo model

Domain: 100km-6R_M

$[O_{hot}]$

$[O],[CO_2],[CO],[N_2],[O_2^+],[e^-],T_e,T_i,T_n,U_n,V_n,W_n$

For model coupling details, please refer to:

Dong et al., 2015 JGR (Current Mars)

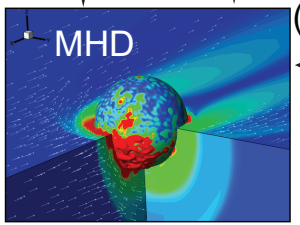
Dong et al., 2015 GRL (Solar Storms)

Dong et al., 2018 JGR (Current Mars)

Dong et al., 2018 ApJL (Ancient Mars)

neutral atmosphere fluid model (including lower, middle, and upper atmosphere)

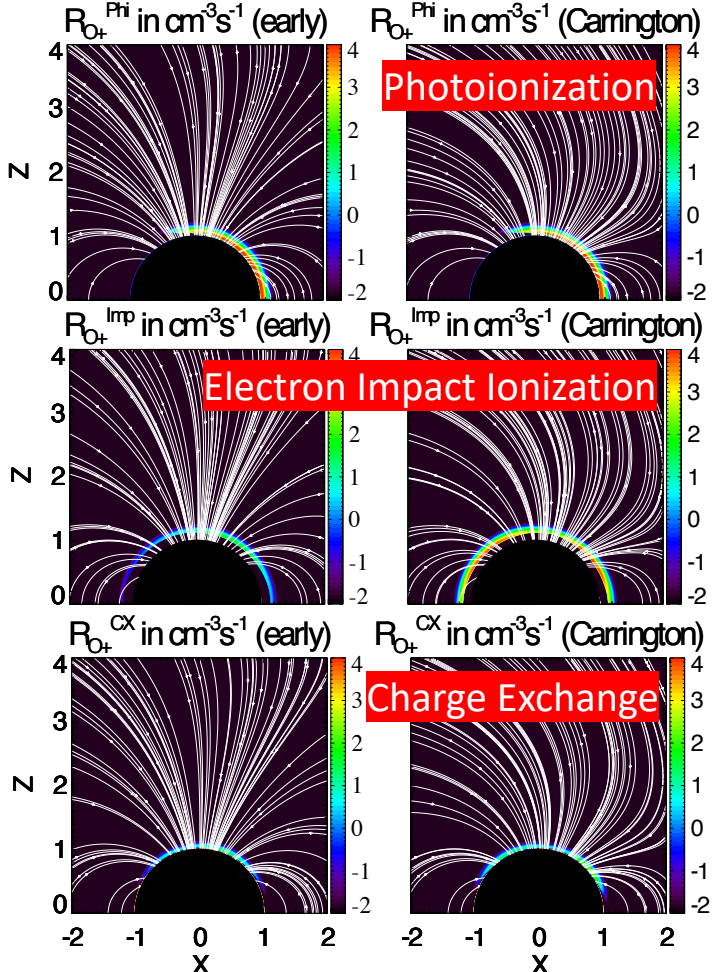
$[O],[CO_2],T_n$, Ionization frequencies ($CO_2 \rightarrow CO_2^+, O \rightarrow O^+, CO_2 \rightarrow O^+$)

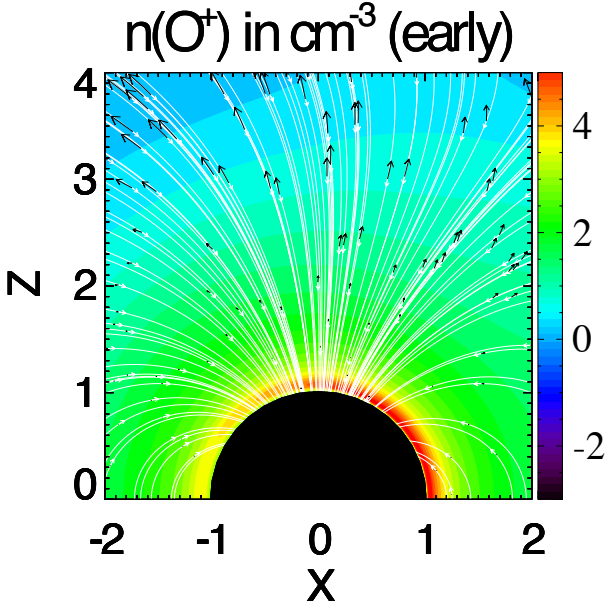


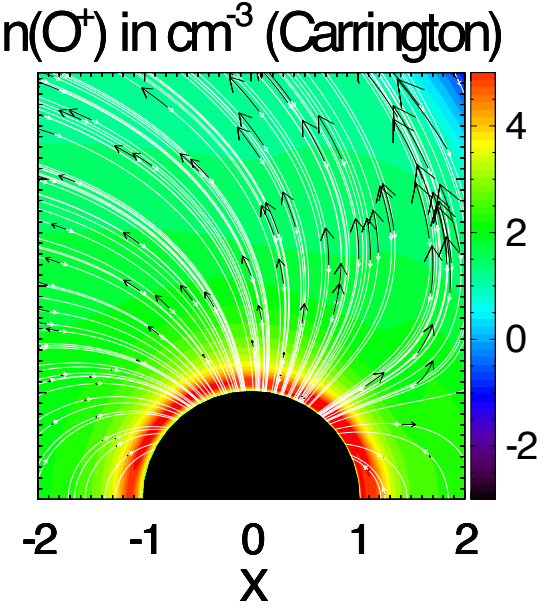
Domain: 100km-up to ~100R_M

Domain: Ground-to-exobase

Atmospheric O^+ Ion Loss from a Magnetized Earth-Like Exoplanet







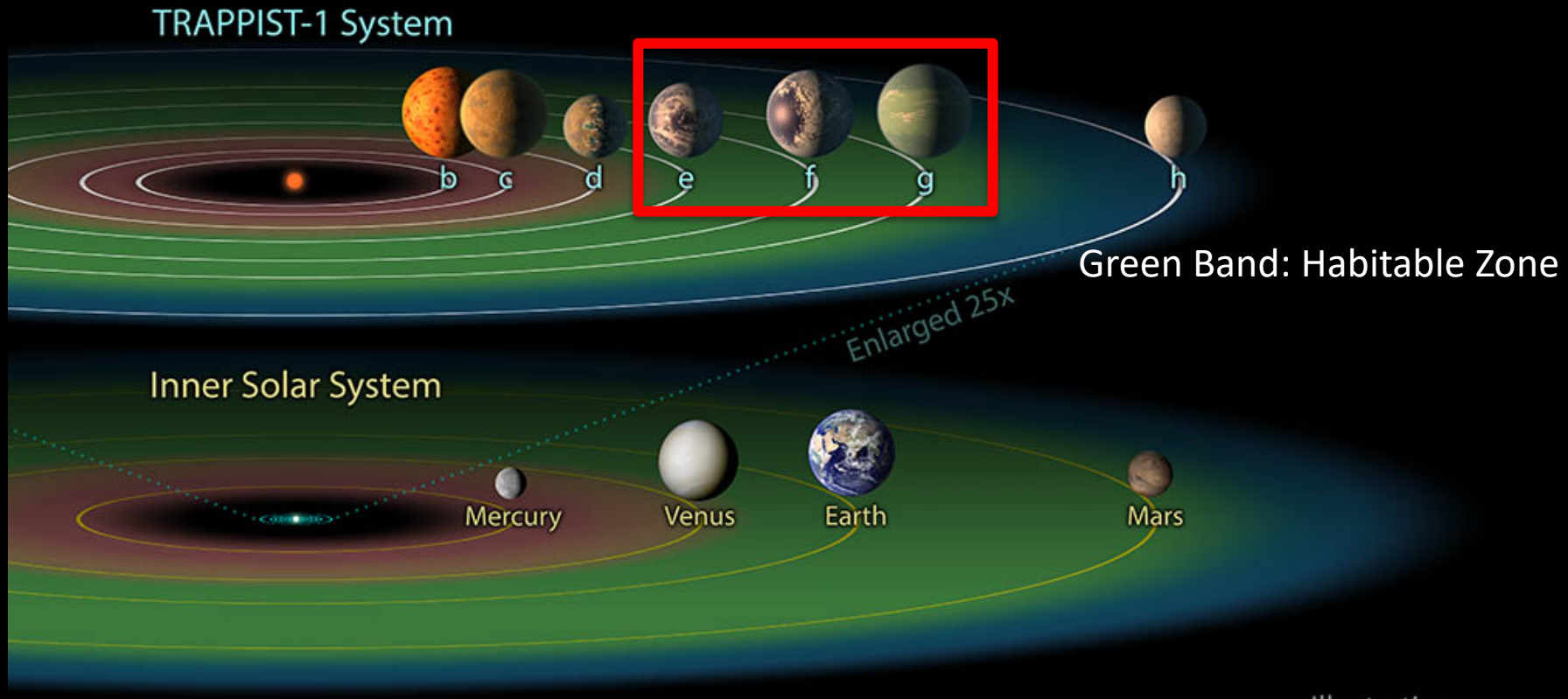
Ancient (4.02 Gyr) solar wind parameters at 1 au (Boesswetter et al. 2010).

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

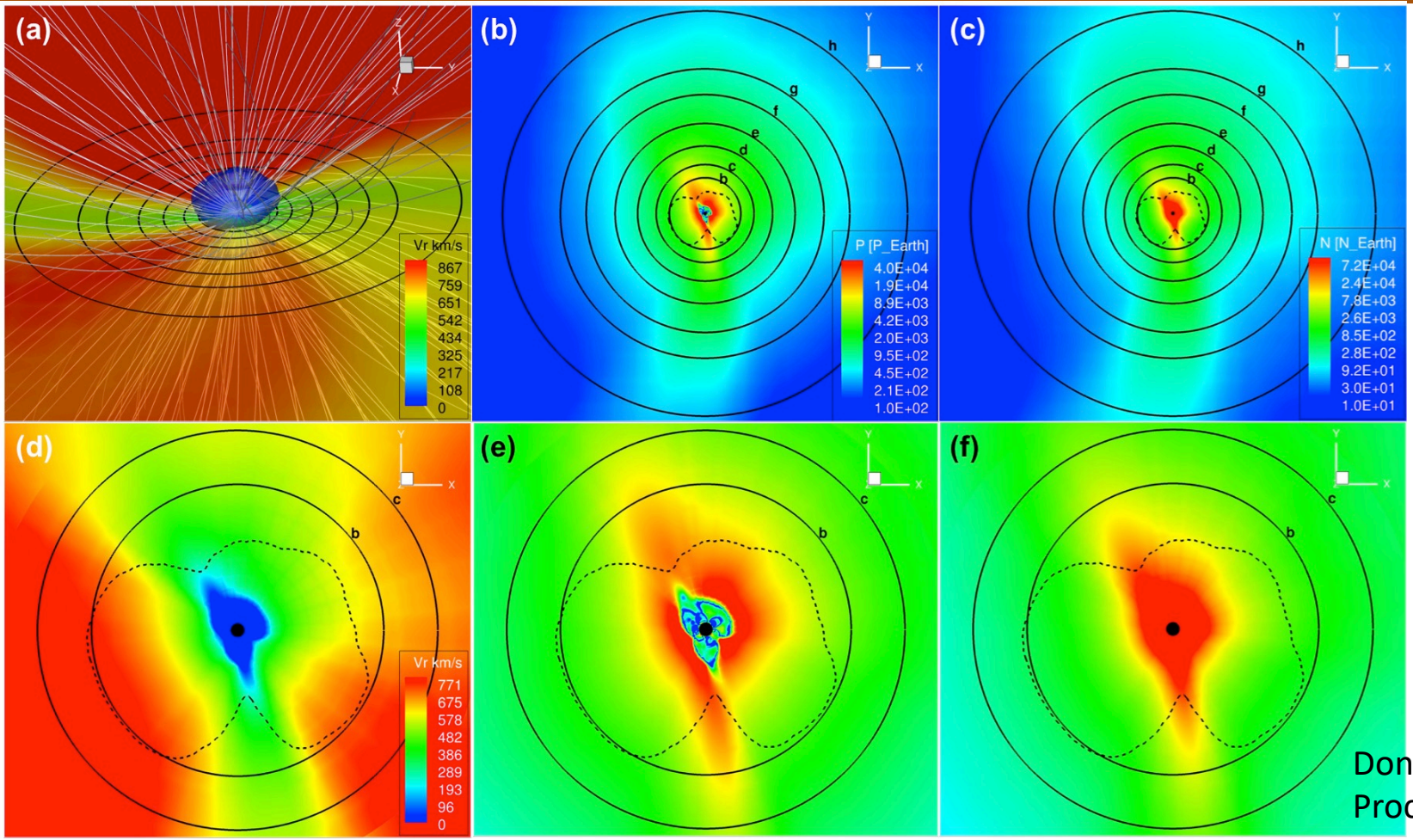
Dong et al., 2017, 2019, ApJL

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

Three TRAPPIST-1 Planets in the Close-in Habitable Zone with Strong Stellar Wind Erosion

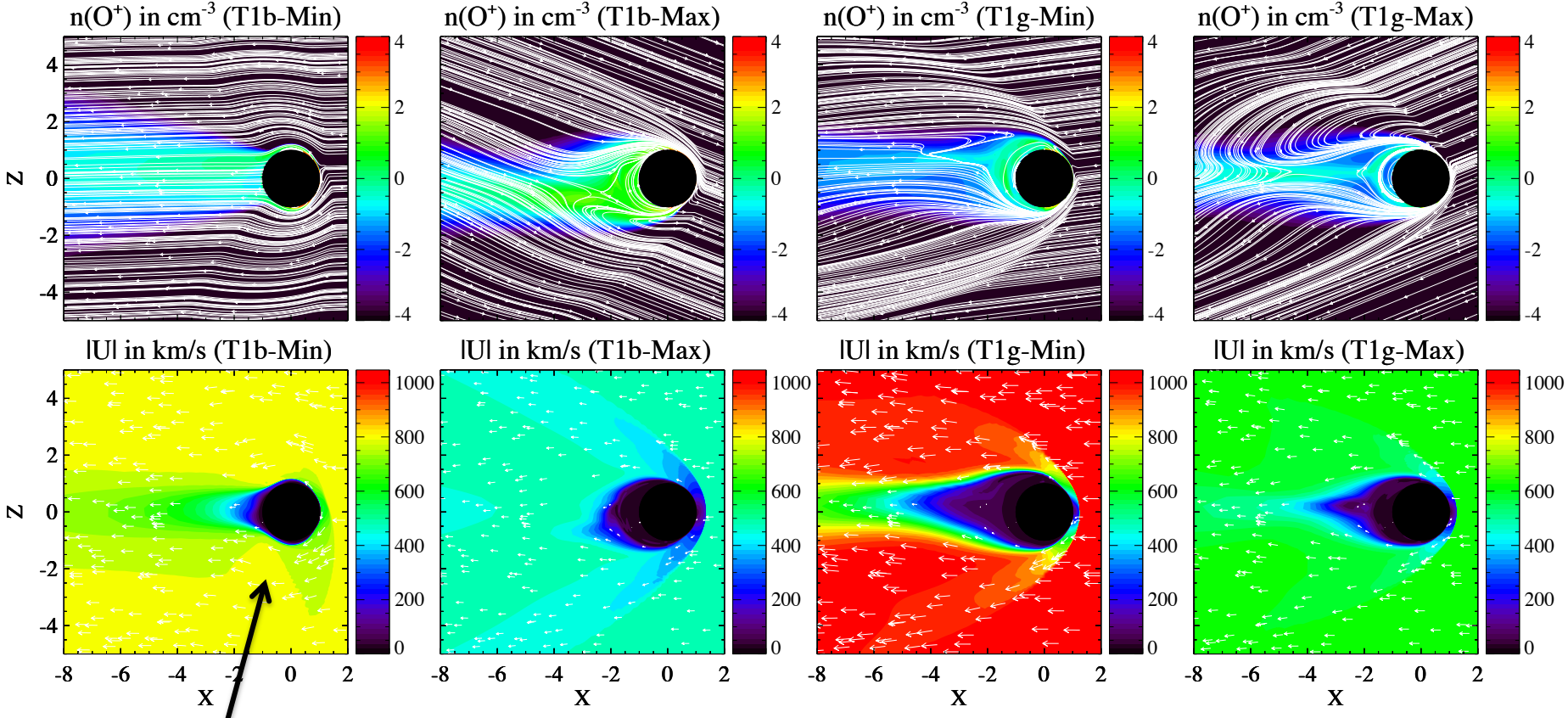


TRAPPIST-1 Stellar Wind Decreases Rapidly with Distances



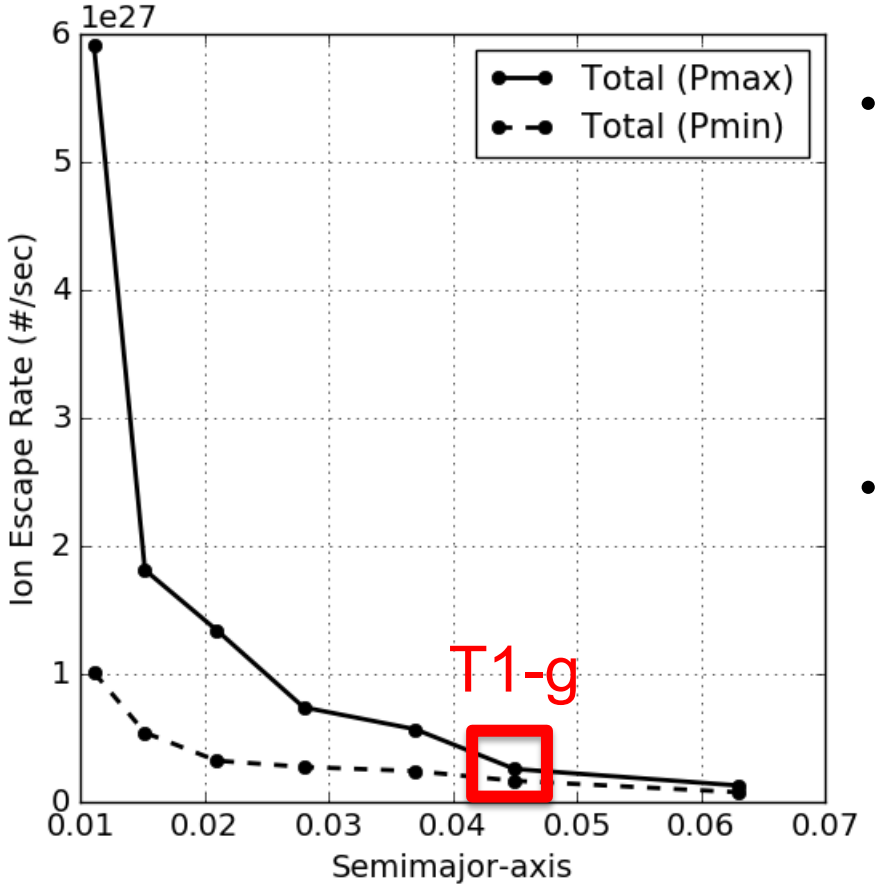
Dong et al., 2018,
Proc Natl Acad Sci

Stellar Wind Interaction with the TRAPPIST-1 Planets



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

Atmospheric Ion Escape Rates of the TRAPPIST-1 Planets due to the Stellar Wind Erosion



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

Dong et al., 2018, Proc Natl Acad Sci

Thank You for Your Attention and References

- C. Dong et al., Role of Planetary Obliquity in Regulating Atmospheric Escape: G-dwarf versus M-dwarf Earth-like Exoplanets, *ApJ Letters*, **882**, L16 (2019).
- C. Dong et al., Atmospheric escape from the TRAPPIST-1 planets and implications for habitability, *Proceedings of the National Academy of Sciences*, **115**, 260-265 (2018).
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- C. Dong et al., Solar wind interaction with the Martian upper atmosphere: Roles of the cold thermosphere and hot oxygen corona, *J. Geophys. Res.*, **123**, 6639-6654 (2018).
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- C. Dong et al., Solar wind interaction with the Martian upper atmosphere: Crustal field orientation, solar cycle and seasonal variations, *J. Geophys. Res.*, **120**, 7857-7872 (2015).