Study of atmospheric ion escape from exoplanet TOI-700 d based on global multi-species MHD simulations

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Background

- One of the most important factors for habitability is the presence of an atmosphere, which escape away to space through various processes (Figure 1).
- M dwarfs are more X-ray and EUV active than G dwarfs (Figure 2).
- TOI-700 d was discovered by TESS in the HZ around an inactive M dwarf.
- **The effect of XUV flux on the escape rate from TOI-700 d is still unknown.**

$\log_{10}$(O^+ density) [cm^{-3}]

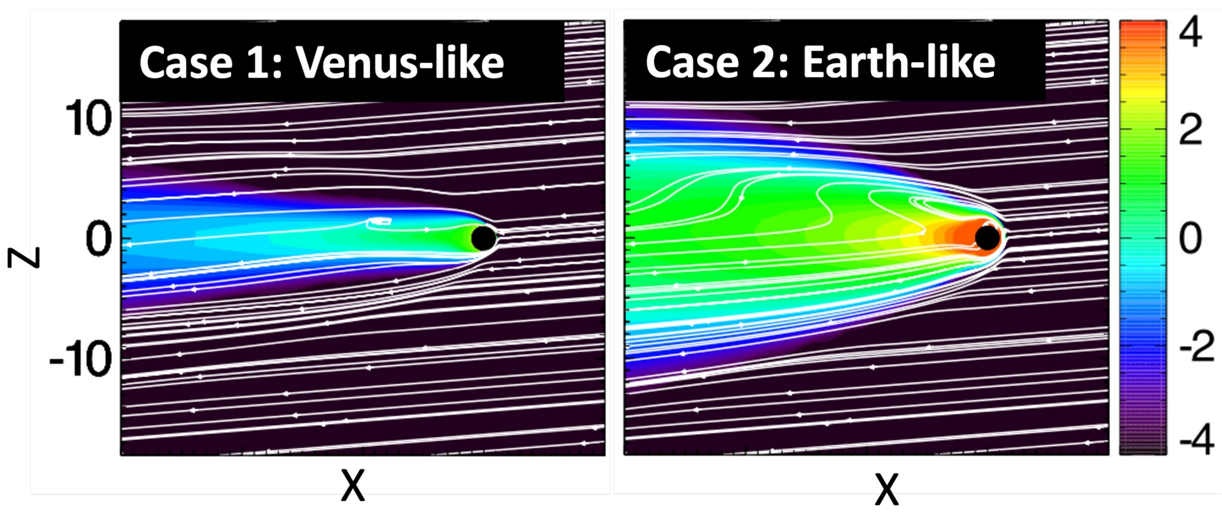

Figure 1. Results of the global MHD simulation for atmospheric escape from exoplanets (Dong+, 2020).

XUV = X-ray (0.1-10 nm) and EUV (10-100 nm)

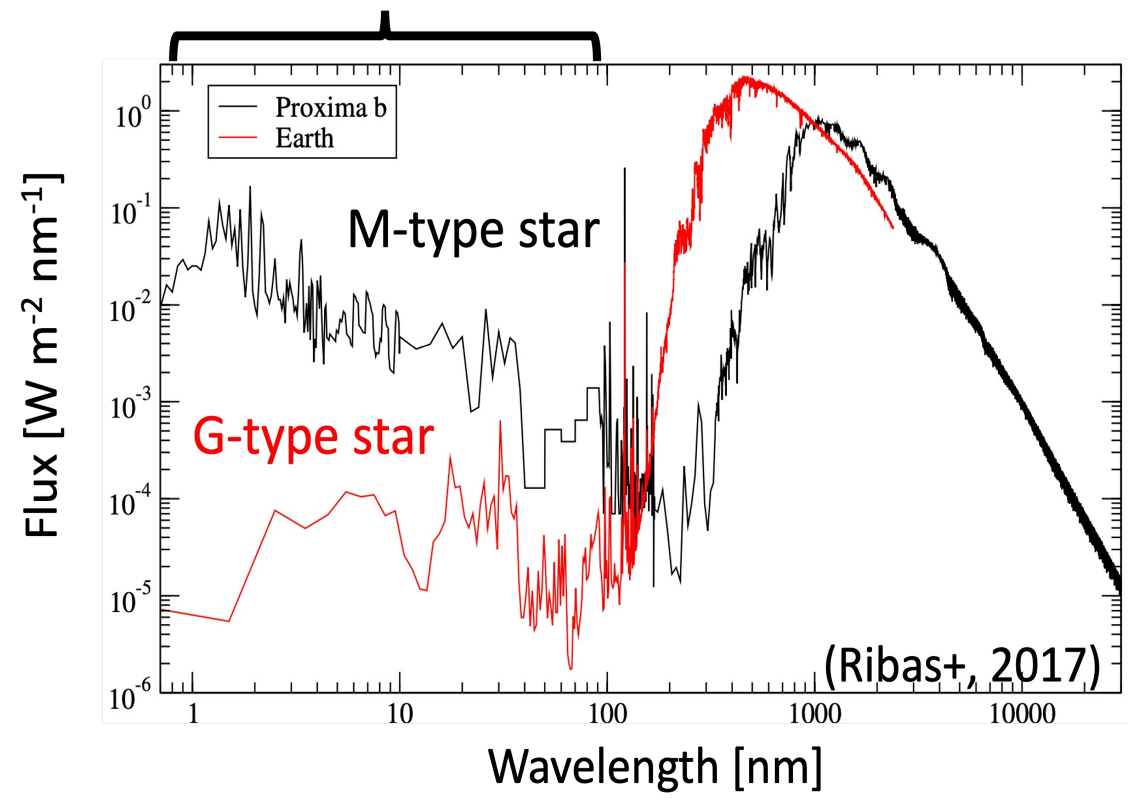

Figure 2. XUV radiation from M-dwarf.

Methods - Global multi-species MHD model

- Multi-species MHD model, **REPPU-Planets** (Terada+, 2009; Sakata+, 2020, 2022)
  - ✓ MHD equations which include the continuity equation, the conservation equation for the momentum and energy density, and additional continuity equations for 11 ion species ($O^+, O_2^+, CO_2^+, NO^+, CO^+, N_2^+, N^+, C^+, He^+, H^+, Ar^+$)
- Global model
  - ✓ From ionosphere to magnetosphere (110 km alt. < r < 10 R_p)
  - ✓ Considering chemical reactions (photoionization, electron impact ionization, charge exchange, ion neutral reactions, dissociative recombination) and collisional process between ion-electron, ion-neutral, and electron-neutral
  - ✓ Triangle unstructured mesh generated from a dodecahedron, 192 nonuniform grids in the radial direction and 1922 uniform grids in the horizontal direction (Δr=6-1200 km)

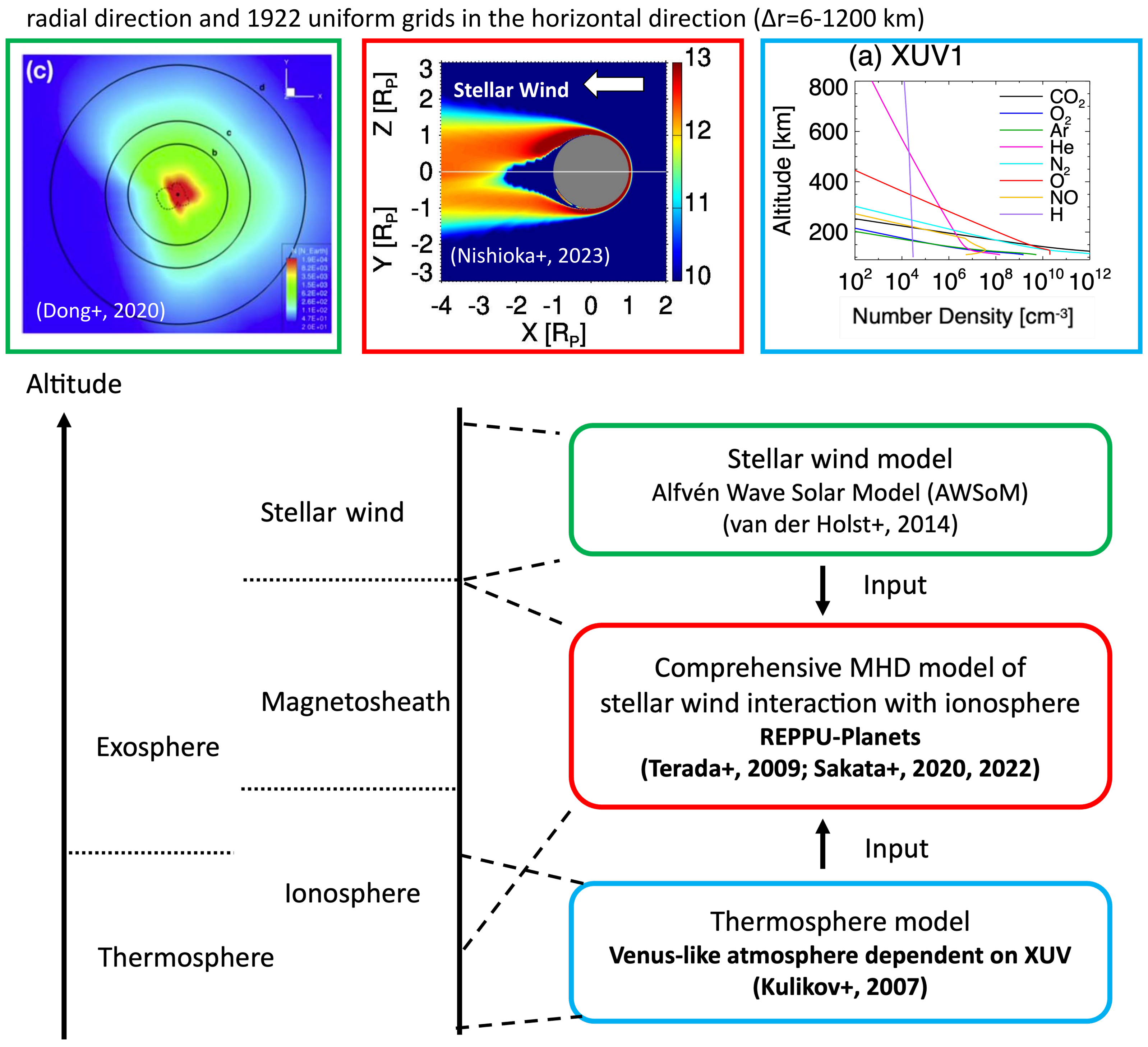

Figure 3. Schematic diagram of models in this study

Methods - Parameter settings

- Simulations are conducted under different conditions for the interplanetary magnetic field (IMF) orientation, the planetary intrinsic magnetic field, and the XUV radiation.
- The XUV flux is set between 1 and 50 times the current Earth (referred to as XUV1, XUV50 and so on hereafter).
- The IMF is assumed to be a Parker spiral of close-in exoplanet (~4°) or Earth (~45°)
- The planetary intrinsic magnetic field is assumed to be a dipole field and strength of the dipole magnetic field is set to 0 nT or 100 nT or 1,000 nT at the equatorial surface .

Density	450 cm^{-3}
Velocity	470 km/s
Temperature	1.3×10^6 K
IMF strength	12 nT
XUV flux	1 to 50
IMF angle (θ^b)	4°, 45°
Strength of planetary intrinsic magnetic field ($B_{eq}{}^c$)	0 nT, 100 nT, 1,000 nT

Table 1. Simulation Settings

Results

- As XUV increases, the ionotail is thicker and the tailward flux is stronger because stronger XUV flux results in an expanded thermosphere-exosphere (Figure 4).
- In the case of θ = 4°, the pileup of the magnetic field is smaller because the magnetic field lines and flow are mostly parallel (Figure 5).
- XUV must be smaller than 30 times of Earth to retain atmosphere for a long time (> 2Gyr) in unmagnetized cases (blue line in Figure 6).
- The strong intrinsic magnetic field of B_{eq} = 1000 nT suppresses the ion escape.

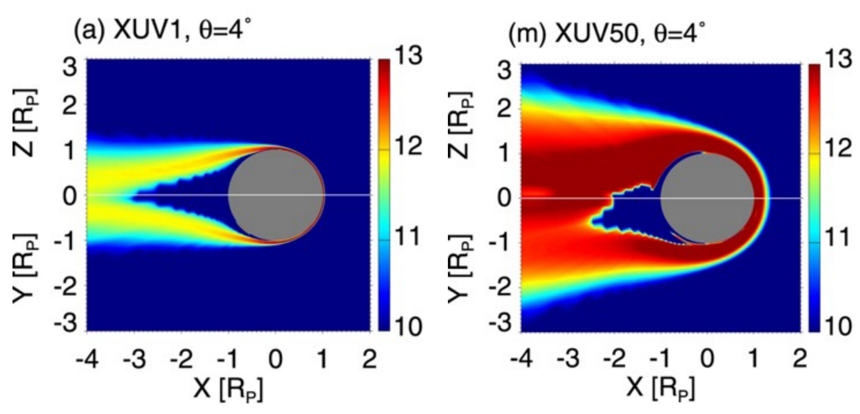

Figure 4. $\log_{10}$(Tailward Flux) [m^{-2} s^{-1}] in the x-z (upper half) and x-y (lower half) planes

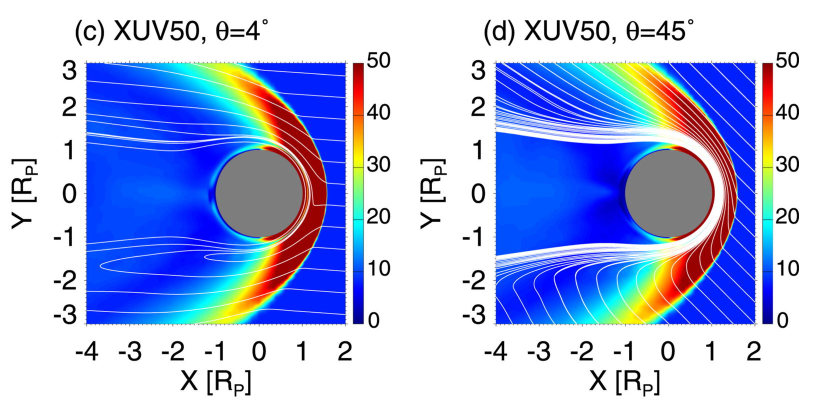

Figure 5. Thermal pressure with magnetic field lines (nT)

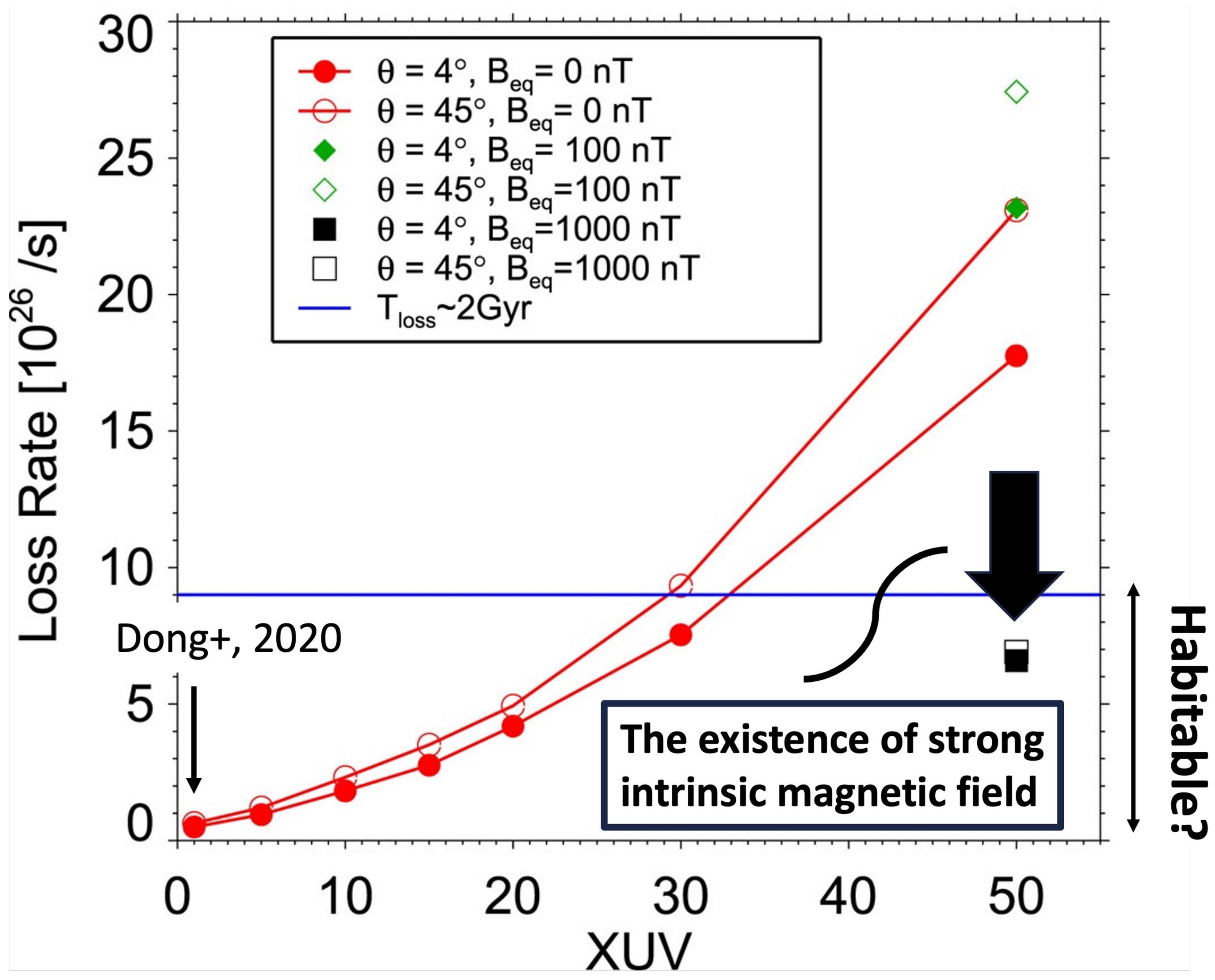

Figure 6. The dependence of escape rate on the XUV flux. The blue line shows the timescale of atmospheric loss is 2 Gyr.

Conclusions

- ✓ **Small Parker spiral angles suppress the ion escape due to weaker magnetic tension force of the pileup magnetic field.**
- ✓ **TOI-700 d can retain its atmosphere under strong intrinsic magnetic field (~1000 nT) or low-XUV environment (≲ 30x current Sun).**