

CETIM-Earth: Modeling Thermospheric Structure and Atmospheric Escape from Exo-Earths for the Habitable Earths Observatory

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CETIM-Earth

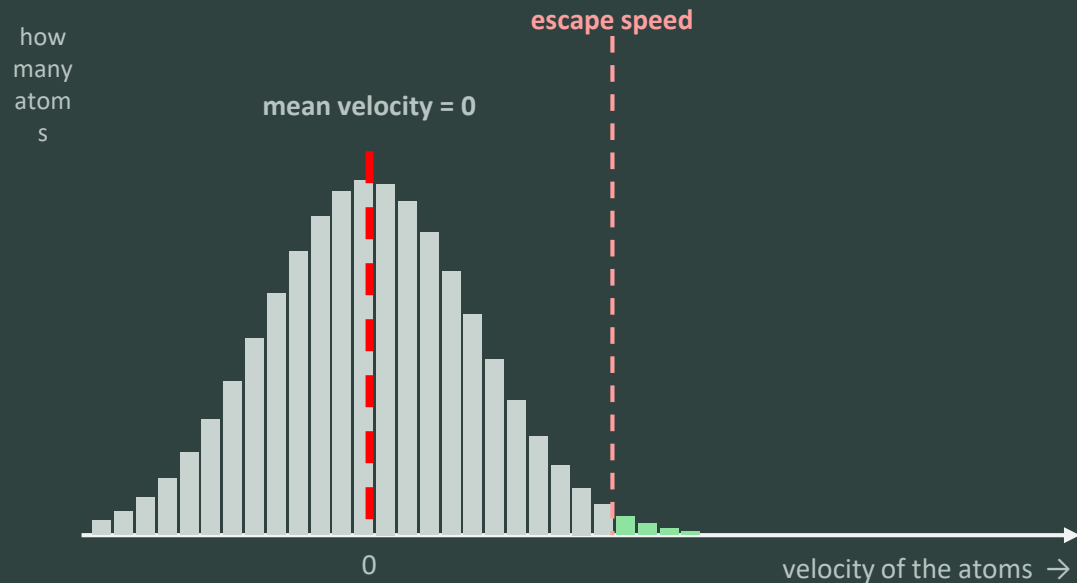
- CETIM-Earth: Coupled Escape and Thermosphere-Ionosphere Model – Earth
- Can be used to study Earth in the solar system and exo-Earths in any stellar system. Exo-Earth here refers to terrestrial planets with Earth-like chemistry and composition ($\text{N}_2 - \text{O}_2$ dominated atmosphere).
- The size and distance of the planet from the host star can be modified to run CETIM-Earth.
- CETIM-Earth takes in stellar spectra from 0 – 300 nm to study the effect of XUV radiation on upper atmospheric escape from terrestrial planets with Earth-like composition.
- The lower boundary in the model starts from 80 km.
- Most salient features of Earth's upper atmosphere can be reproduced by CETIM-Earth.

CETIM-Earth vs Previous Models

Characteristic	CETIM-Earth	Tian (2008)	Kompot (Johnstone, 2018)	Nakayama (2022)
Species (neutrals + ions)	17 (11 neutrals, 5 ions, e^-)	32 (13 ions)	63 (30 ions)	63 (30 ions)
Reactions within CETIM's species set*	114	53 of 154	93 of 481	93 of 481
Reverse reactions (within CETIM set)	23 pairs	0	1 pair	1 pair
Cooling	CO ₂ 15 μm , NO 5.3 μm ; multi-level non-LTE line cooling O, O ⁺ , N, N ⁺ (J-resolved fine structure for atoms, T-dependent collision strengths)	CO ₂ 15 μm , NO 5.3 μm ; O 63 μm only (Bates LTE $\times$ opacity factor $\times$ 0.5)	CO ₂ 15 μm , NO 5.3 μm , H ₂ O; O 63 + 147 μm (Bates LTE, optically thin)	CO ₂ , NO, H ₂ O; line cooling O, O ⁺ , N, N ⁺ , H, C, C ⁺ (collision strengths fixed at 10 ⁴ K, simplified fine structure for atoms, escape probability)
Photoabsorption cross sections	Updated N ₂ ; rest PHIDRATES	Low-resolution bins	PHIDRATES	PHIDRATES
Diffusion	Ion and neutral diffusion	Neutral diffusion; ambipolar diffusion for O ⁺ , N ⁺ , H ⁺ only	Neutral diffusion: ions treated as neutrals	Ion and neutral diffusion
Upper boundary	Kinetic modified-Jeans flux boundary (Volkov 2011) at $\text{Kn} \approx 1$ with sliding upper boundary between Jeans and hydrodynamic determined self-consistently	Exobase; Jeans effusion velocity per species, No particle drift.	Exobase; Jeans mass-loss velocity (subsonic) or free outflow (supersonic); any one is selected by user for a given run.	Exobase; density-weighted Jeans effusion velocity
Ion escape at the top	Yes: ambipolar potential (zero-current balance) lowers ion λ ; O ⁺ reaches free effusion at $\gtrsim 256\times$ (switchable; whole-planet $\Rightarrow$ upper limit)	O ⁺ , N ⁺ , H ⁺ effuse at their own λ ; no potential	None	None — ions bound at full λ

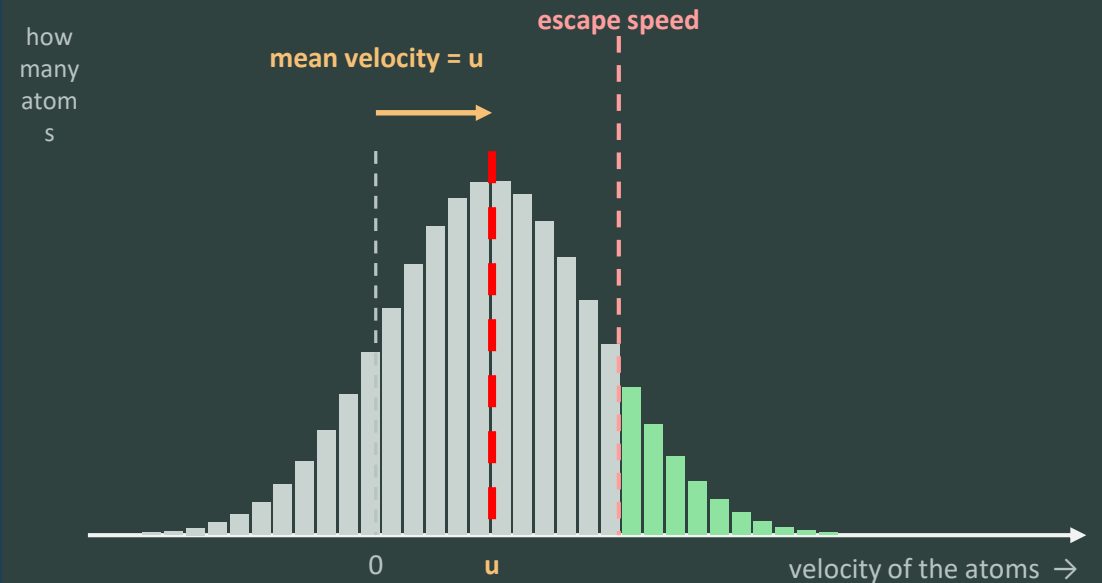
Adding a Drift to Particles (Volkov, 2011)

1. Gas at rest (classical Jeans escape)



Only the **green shaded portion** is faster than the escape speed — a tiny leak.

2. Gas already flowing outward (Volkov)



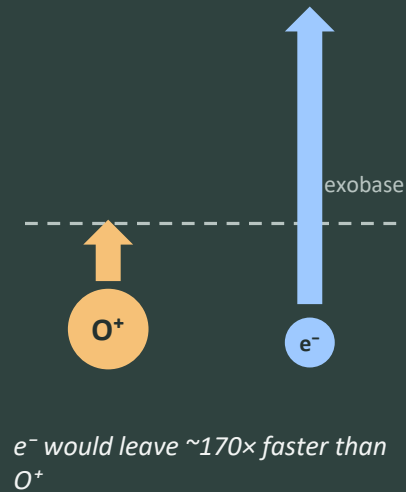
The same bell shifted by u : **a much bigger share** is past the escape speed.

Outflow makes the escaping tail bigger, and more escape drives more outflow — so CETIM solves the two together at the top of the model.

Ambipolar Potential At the Upper Boundary

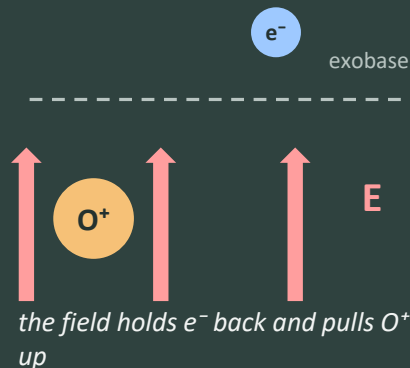
1. Electrons are 30,000× lighter

light e^- : long arrow
heavy O^+ : barely moves



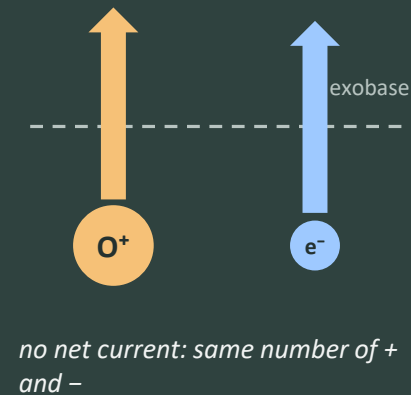
2. Charge separates $\rightarrow$ electric field

– above, + below
 $\rightarrow$ upward electric field E

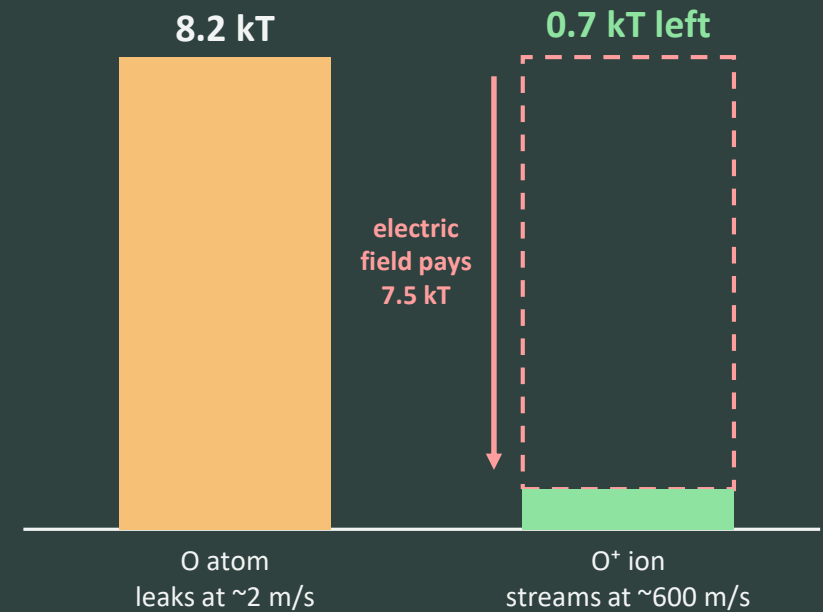


3. They leave together

equal arrows: the pair streams out as one

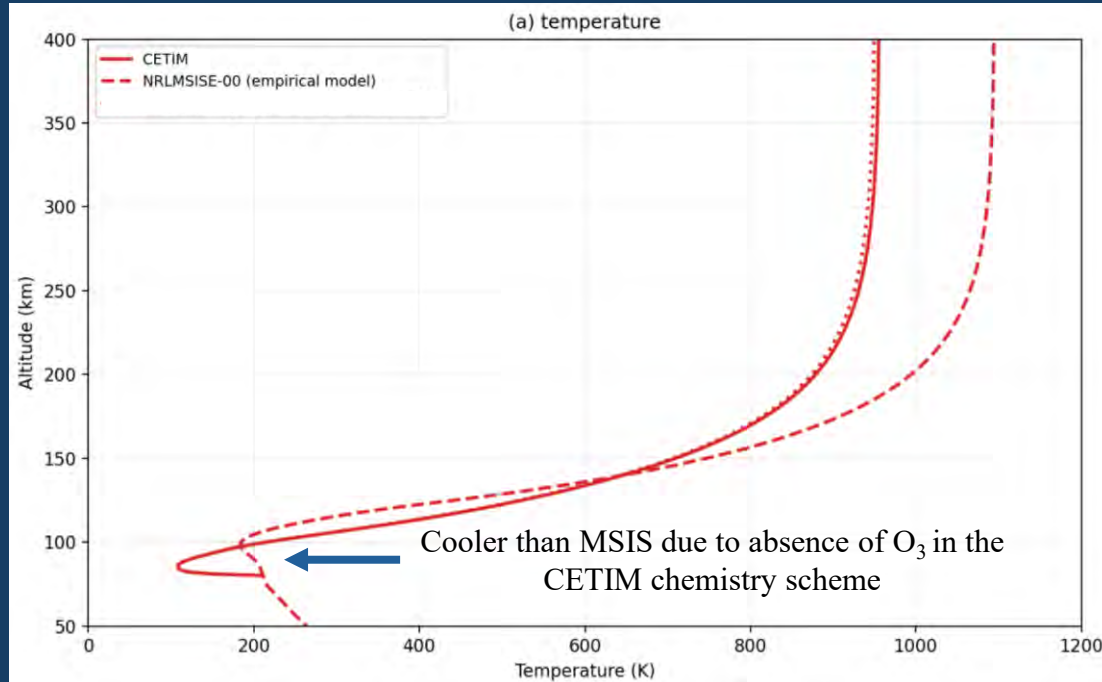
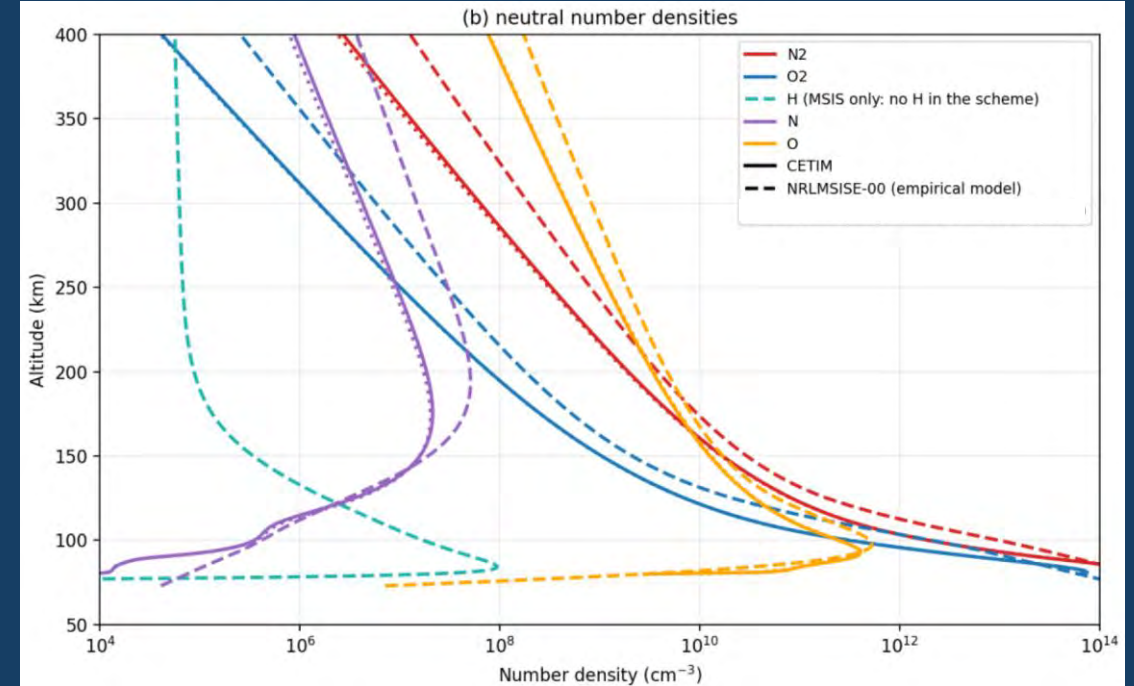


Energy needed to escape Earth's gravity
(in units of kT, at the 256× solar XUV)



Ions and electrons cannot separate, so the electrons' eagerness to leave turns into an electric field that lifts the heavy ions. At 256× the field pays 7.5 of the 8.2 kT an O^+ needs to escape — **the ions are nearly free; the neutrals are not.** Previous models have no such field, so their ions stay as bound as their neutral counterparts.

Validation Against Earth Models



- CETIM temperature seems to be cooler than MSIS. Reasons for this could be:
 - Differing solar F10.7 activity levels between MSIS and CETIM inputs.
 - Tunable knobs not at the proper value.
- As a result, the CETIM densities have a smaller scale height than the MSIS densities.

Testing the Model for XUV Range Tolerance

CETIM-Earth

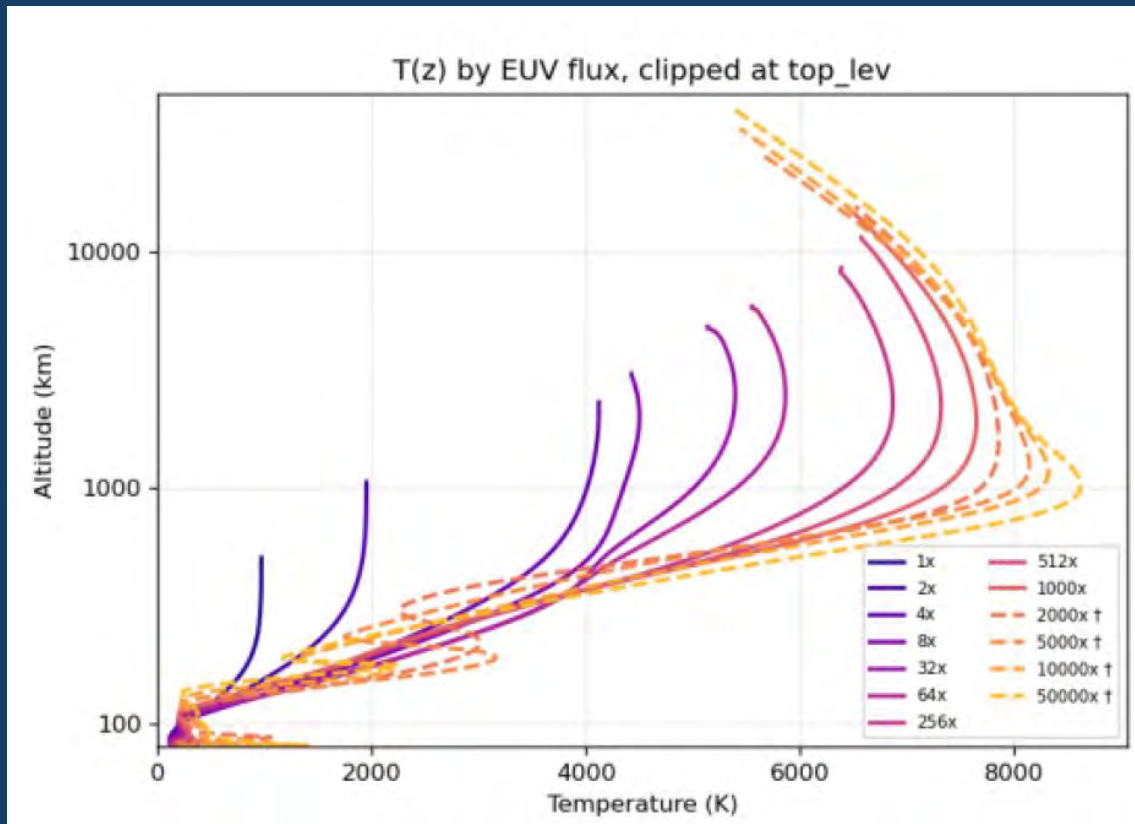
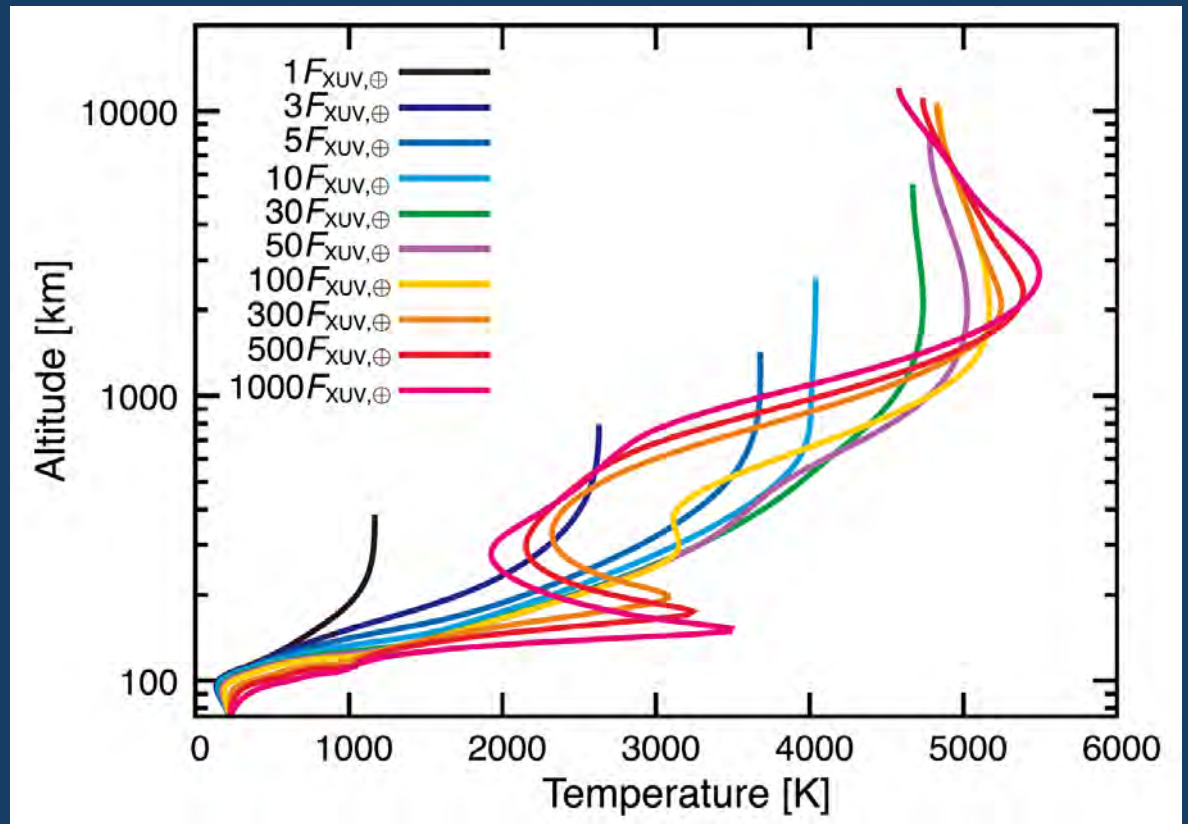
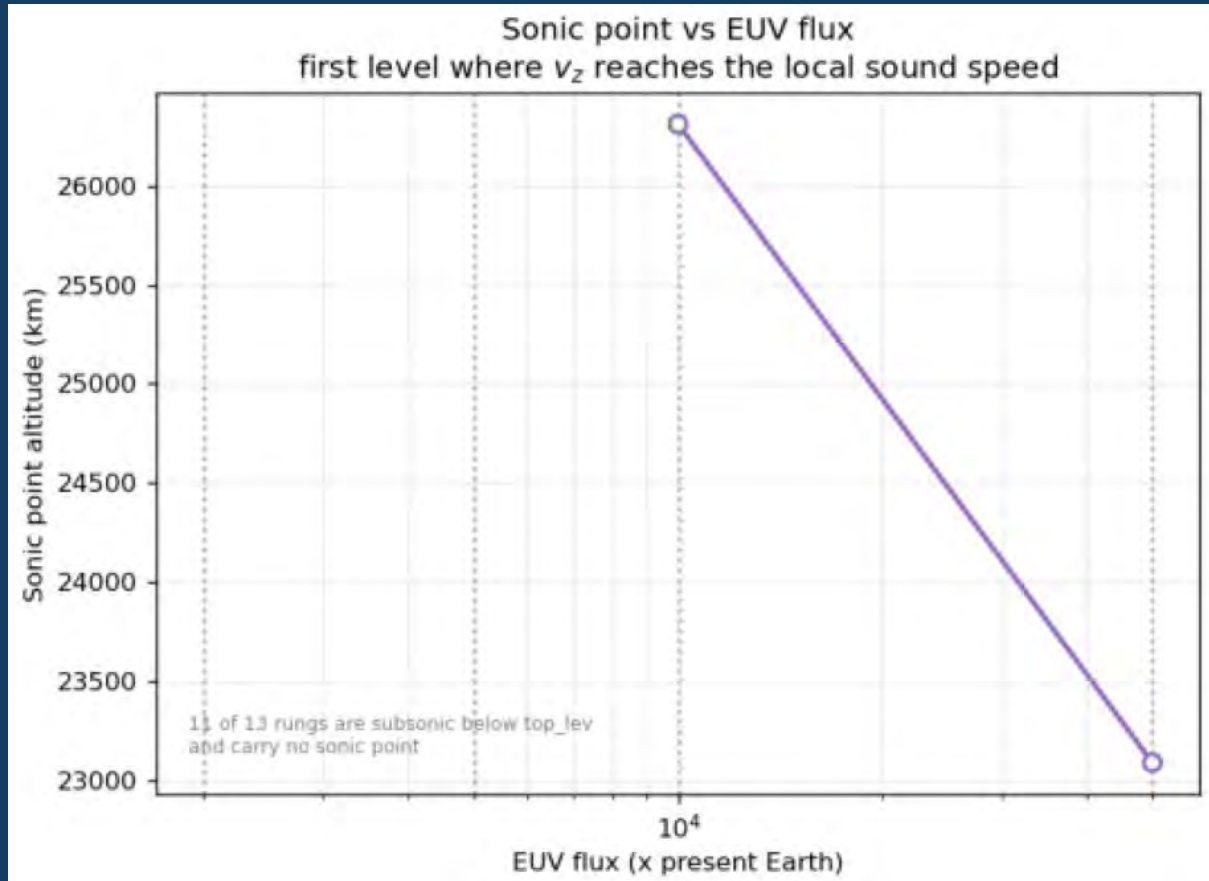


Fig. 3 from Nakayama et al., 2022

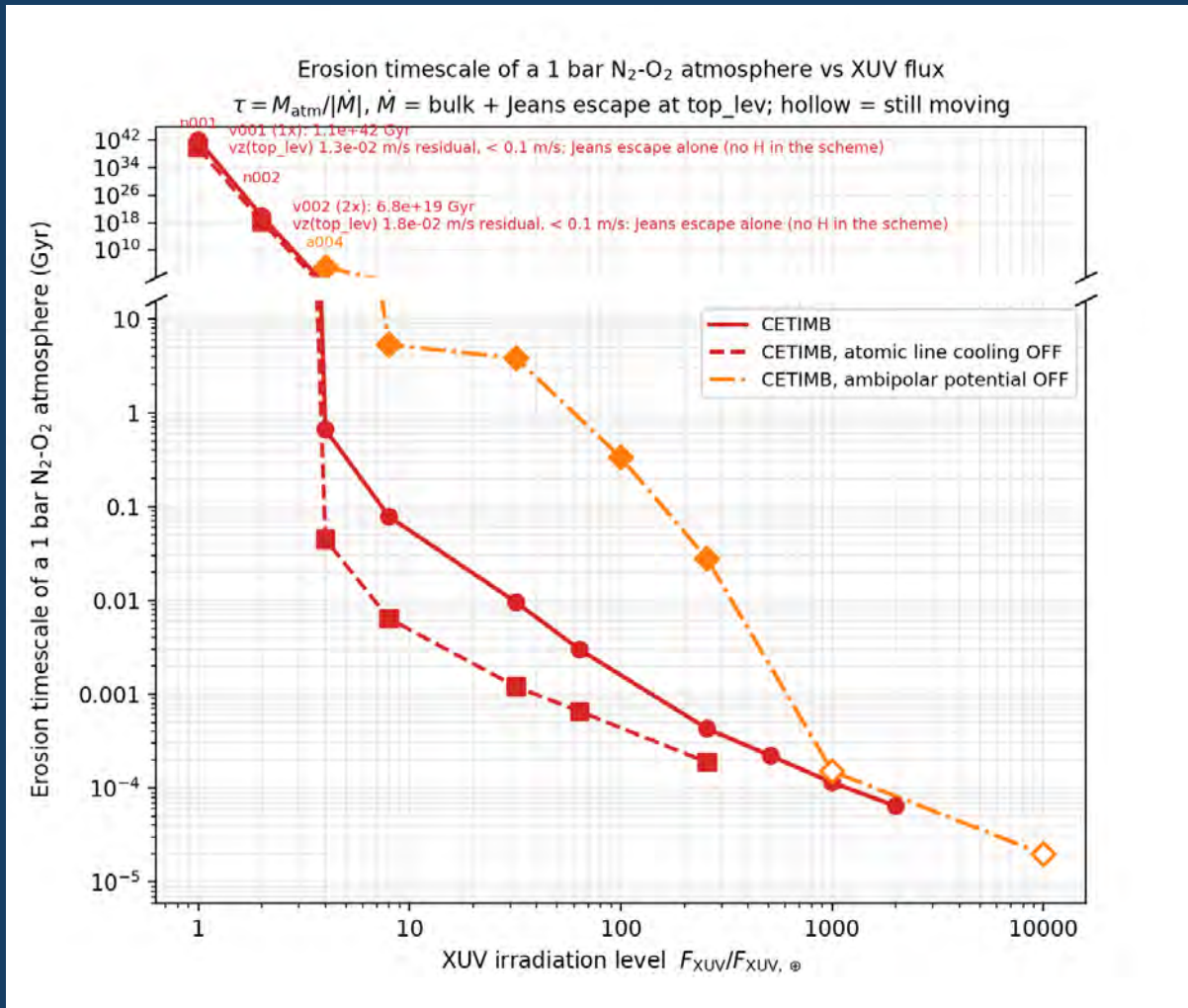


Tolerance to Hydrodynamic Escape



- It takes $> 5000\times$ solar EUV flux to trigger hydrodynamic escape
- Atomic line cooling is quite efficient in preventing the atmosphere from undergoing hydrodynamic escape [Nakayama et al., 2022].
- Other competing processes like drift velocity [Volkov, 2011] and ambipolar potential at the upper boundary may influence the escape rate which is currently being evaluated.
- At present the group is trying to understand the effect of the stellar XUV profile on the escape rate for $\text{N}_2\text{-O}_2$ dominated atmospheres.

Preliminary Observations



- Without atomic line cooling the escape rate is higher at the upper boundary, which corroborates the Nakayama et al., 2022 results. The exact escape rate as a function of XUV flux though, is still being evaluated.
- With ambipolar potential switched off at the upper boundary, the amount of escape is reduced when compared to the case where it is switched on.
- Both line cooling and ambipolar potential have non discernable effect at lower XUV flux levels.
- Their effect at higher XUV flux levels is still being evaluated.

Summary

- We have built the CETIM-Earth model which is an upper atmosphere model for $\text{N}_2\text{-O}_2$ dominated (Earth-like) atmospheres to study the effect of differing levels of stellar XUV radiation on atmospheric escape from the upper boundary.
- The model is quite stable and can run for varying levels of stellar XUV radiation, useful for studying HWO targets.
- Certain aspects, especially its validity against Earth-based models are still being tested.
- When running the model for different levels of solar XUV flux, we find that it takes XUV flux levels $>5000 \times$ to trigger hydrodynamic escape of the atmosphere.
- Two processes, ambipolar potential, and line cooling, may be competing against each other to facilitate escape from the upper boundary or the exobase of the planet.