Residual H/He Atmospheres of Super-Earths

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Main Takeaways

Motivation

- Previous work has shown core-powered mass loss can reproduce the observed dichotomy of super-Earths and sub-Neptunes (e.g., Ginzburg et al. (2016), Gupta & Schlichting (2019), Berger et al. (2020))
  - But what is the **long-term imprint of this mass loss process on super-Earth atmospheres**?

Mechanism

- As core-powered mass loss unbinds overlying atmospheres, super-Earth cores can cool more quickly
- These planets' cooling timescales eventually become shorter than their mass loss timescales, **allowing super-Earths to keep small residual H/He envelopes**

Results

- The mass of these retained envelopes increases with planet mass and semi-major axis
- **The retained atmospheric mass fraction, f_{ret}, ranges from $<10^{-8}$ to 1% of the planet's total mass** and is of order 10^{-3} for a 5 Earth mass planet at $T_{eq} = 1000$ K

Importance

- Retaining such quantities of H/He **reduces the atmosphere's mean molecular weight** compared to an outgassed secondary atmosphere
  - This signature could be **observable today or in the near future** via transmission spectroscopy (e.g., Benneke & Seager (2012), Fortney et al. (2013), Greene et al. (2016))
- Large amounts of retained H/He after core-powered mass loss would affect the early geochemistry and rock-atmosphere interactions of this common class of planet (e.g., Wordsworth et al. (2018), Doyle et al. (2019), Seager et al. (2020))
  - It therefore affects their potential habitability
- Such tenuous atmospheres may be susceptible to further processing, e.g. by long-term photo-evaporation
- TESS and related missions have found and continue to find excellent candidates to test these predictions

Super-Earth atmosphere evolution

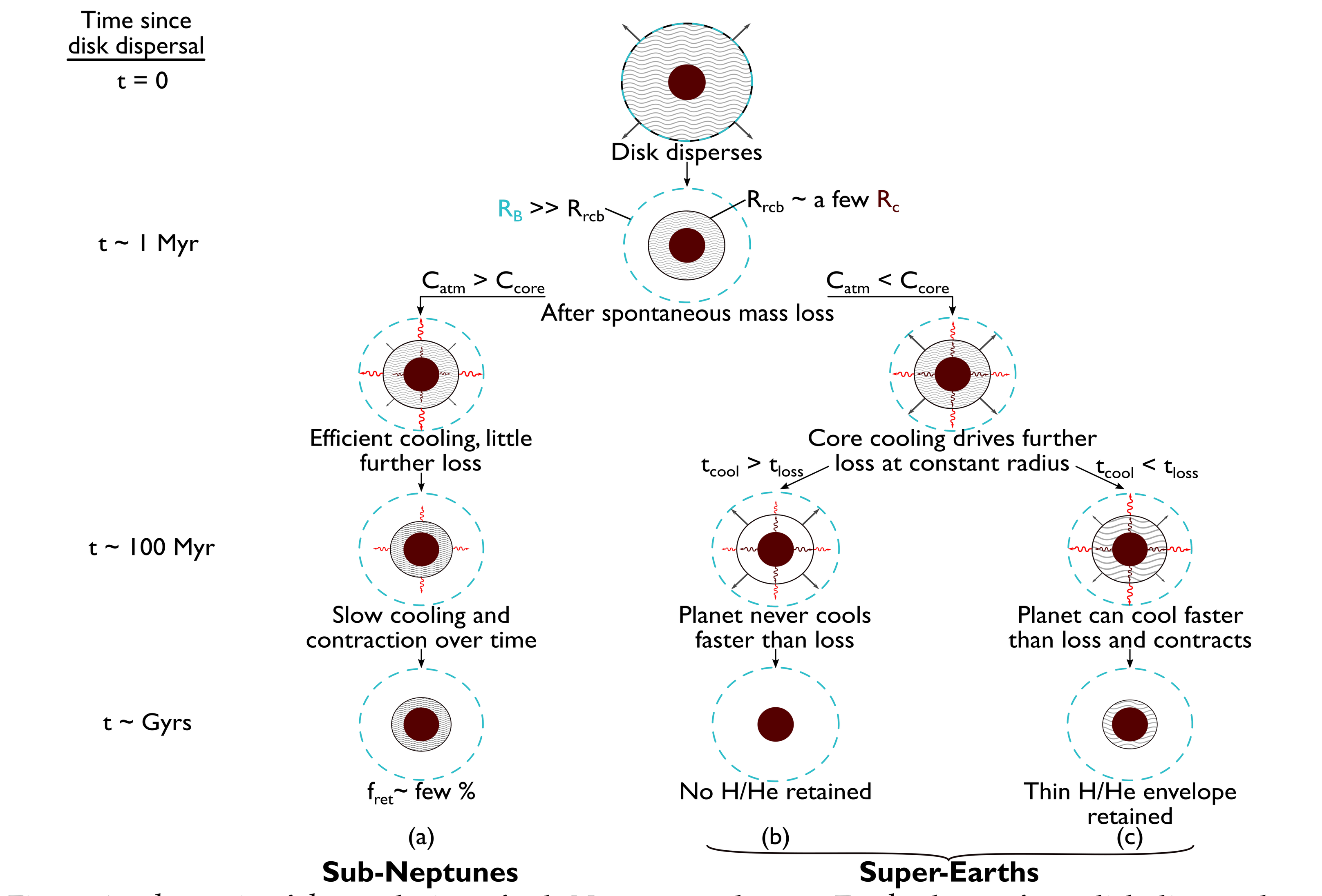

Figure 1: schematic of the evolution of sub-Neptune and super-Earth planets from disk dispersal.

- After spontaneous mass loss, if planet maintains atmosphere with larger heat capacity than its core, atmosphere will cool and contract, cutting off atmospheric mass loss → sub-Neptune (Fig. 1a)
- If core has larger heat capacity than atmosphere, $C_{core} > C_{atm}$, its cooling will inhibit contraction, leading to continued mass loss → super-Earth
  - If planet can never cool more quickly than it loses mass → atmosphere entirely stripped (Fig. 1b)
  - If it can cool more quickly, atmosphere resumes contraction and mass loss ceases → thin H/He atmosphere saved (Fig. 1c, Fig. 2)

How are super-Earth atmospheres retained?

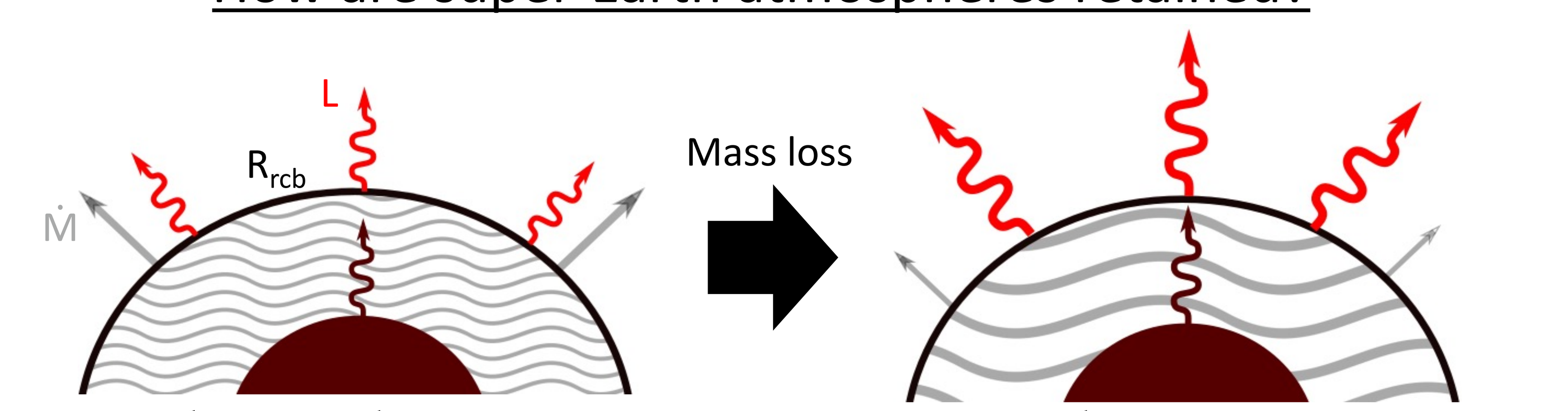

Figure 2: schematic of the end of core-powered mass loss, allowing the preservation of low-mass primordial envelopes.

- Mass is lost at slowly changing radiative-convective boundary, R_{rcb} → density, $\rho \propto f$, decreases
- Radiative diffusion easier across R_{rcb} → luminosity, $L \propto 1/\rho$, increases
- Core thermal energy, E, independent of atmospheric mass fraction, f → cooling timescale, $t_{cool} = E/L \propto f$, decreases
- Mass loss rate, $\dot{M} \propto f$ → mass loss timescale, $t_{loss} = M_{atm}/\dot{M}$, independent of f
- Eventually $t_{cool} < t_{loss}$ → R_{rcb} quickly decreases as planet cools
- Mass loss rate exponentially sensitive to R_{rcb} → remaining atmosphere preserved

Results: Broad range of retained atmospheric masses

Analytic Results

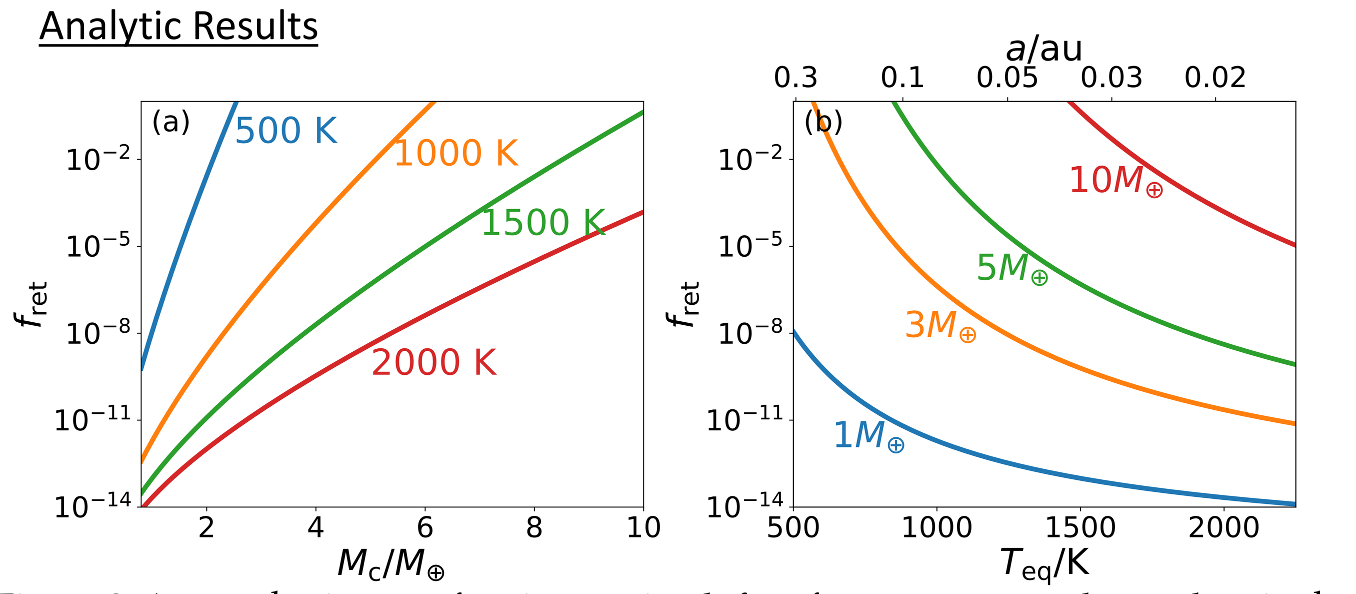

Figure 3: Atmospheric mass fraction retained, f_{ret}, after core-powered mass loss in the thin regime as a function of (a) core mass M_c and (b) equilibrium temperature T_{eq}.

- Retained atmospheric mass is f at which t_{cool} becomes shorter than t_{loss}
- Analytic form (plotted in Fig. 3):

$$f_{ret} \propto M_c^{3/2} T_{eq}^{-1/2} \exp\left[M_c^{3/4} T_{eq}^{-1}\right]$$

  - Higher mass and lower equilibrium temperature planets retain more massive primordial atmospheres
  - Assumes $R_{rcb}=2R_c$ when timescales become equal

Numerical Results

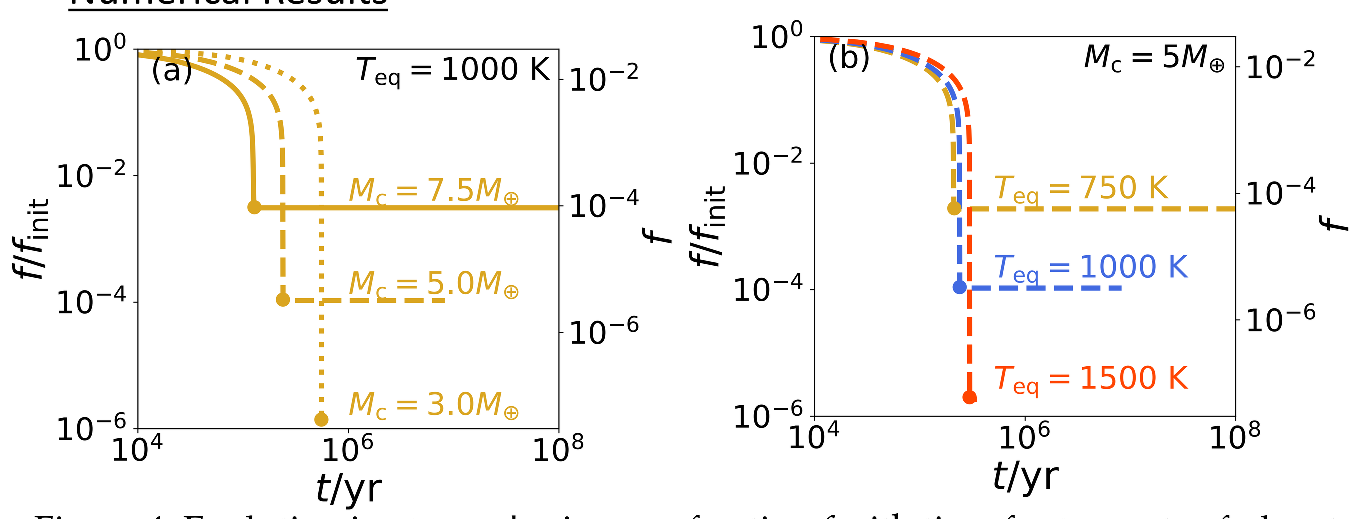

Figure 4: Evolution in atmospheric mass fraction f with time for two sets of planets: (a) with set T_{eq} and varying M_c and (b) with set M_c and varying T_{eq}. Dots mark time at which $t_{cool}=t_{loss}$

- Mass fraction retained varies orders of magnitude across super-Earth regime, from $<10^{-8}$ (negligible) to 10^{-2} (sub-Neptune)
  - Generally matches analytic trends
  - Exact values vary due to variation in R_{rcb} at which $t_{cool}=t_{loss}$

Dependence on f_{init}

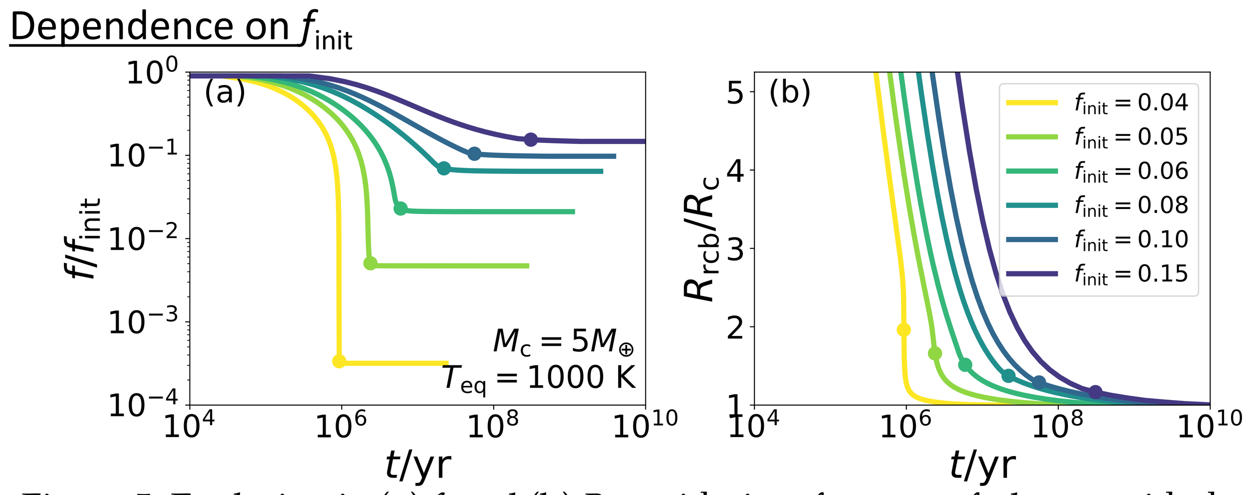

Figure 5: Evolution in (a) f and (b) R_{rcb} with time for a set of planets with the same M_c and T_{eq} but different initial atmospheric masses f_{init}

- Larger initial mass fraction decreases R_{rcb} after spontaneous mass loss, aiding atmospheric retention
  - Final atmospheric masses depend on assumptions for mass captured from protoplanetary disk

Observational implications

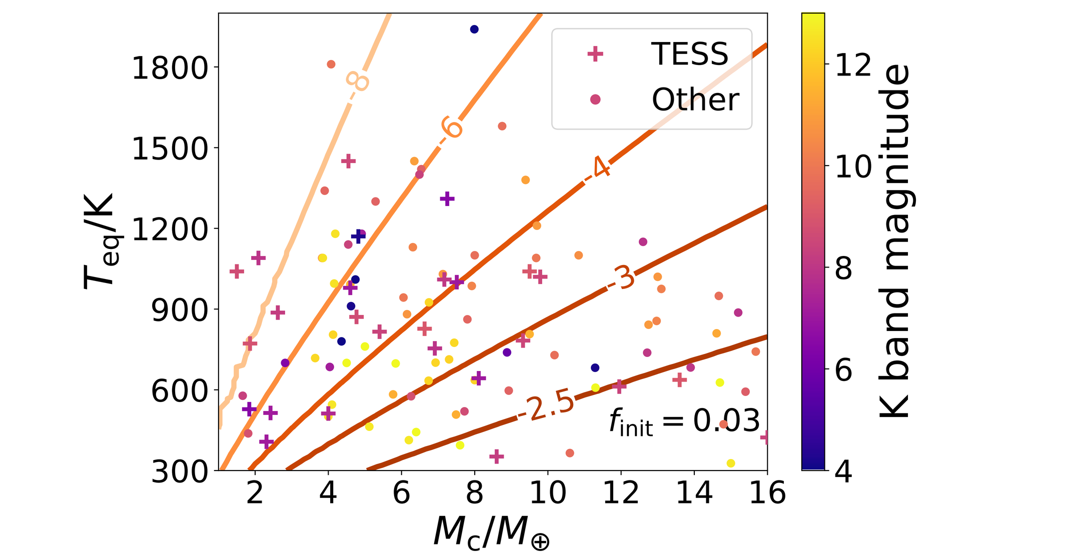

Figure 6: Contours of $\log_{10} f_{ret}$, in orange, for f_{init}=0.03. Super-imposed are planets with well-measured radii and masses. TESS planets are marked by crosses, those discovered by others are marked by dots. Planets are colored by their K band magnitude (planet data from Exoplanet Archive)

- Fig. 6 demonstrates many known planets, including TESS discoveries, could have retained substantial residual atmospheres after core-powered mass loss
- A number of these planets are amenable to further characterization with transmission spectroscopy
  - Such studies will be able to distinguish residual H/He atmospheres from those composed of heavier outgassed species

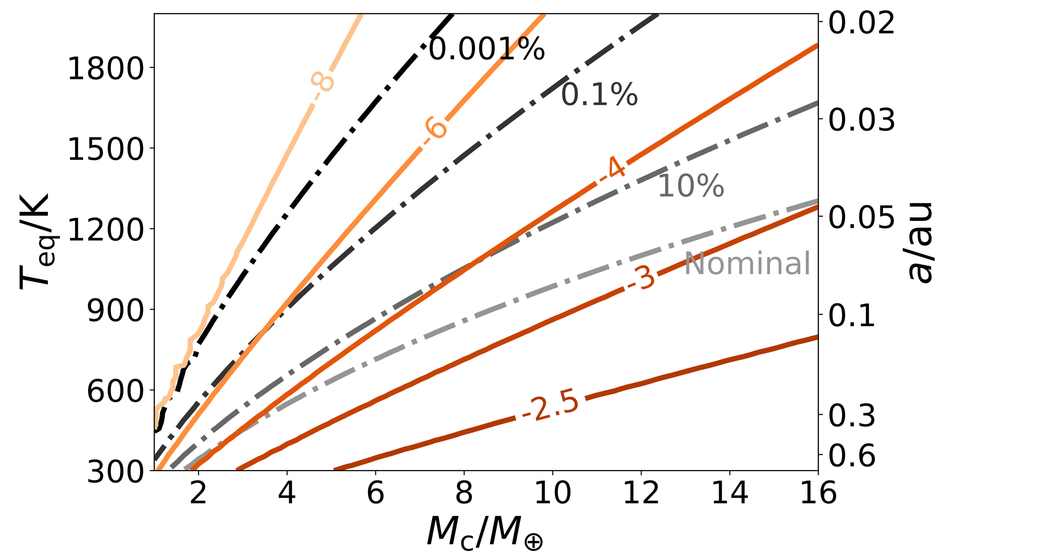

Figure 7: The same contours as in Fig. 6, but with susceptibility to photo-evaporation shown in gray dash-dotted lines. These lines are labeled with the percent of nominal photo-evaporative effectiveness necessary to preserve the retained atmospheres on Gyr timescales.

- These tenuous atmospheres are susceptible to photo-evaporation on Gyr timescales
  - If residual H/He atmospheres are observed, photo-evaporation must be less effective than current theories predict (Owen & Wu 2017)

References

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