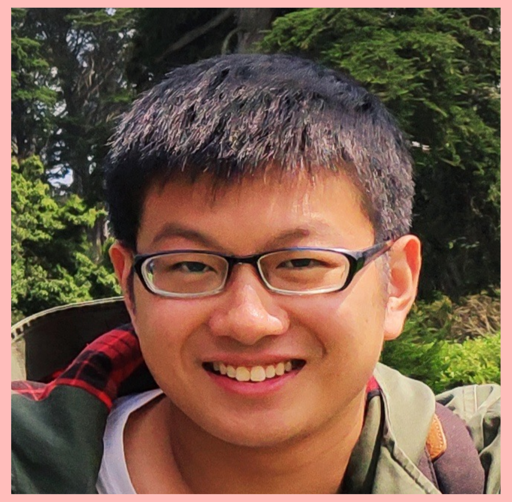

Squeeze the Atmosphere into Magma: How does Atmosphere-Magma Interaction Impact the Sub-Neptune Mass-Radius Relationship?

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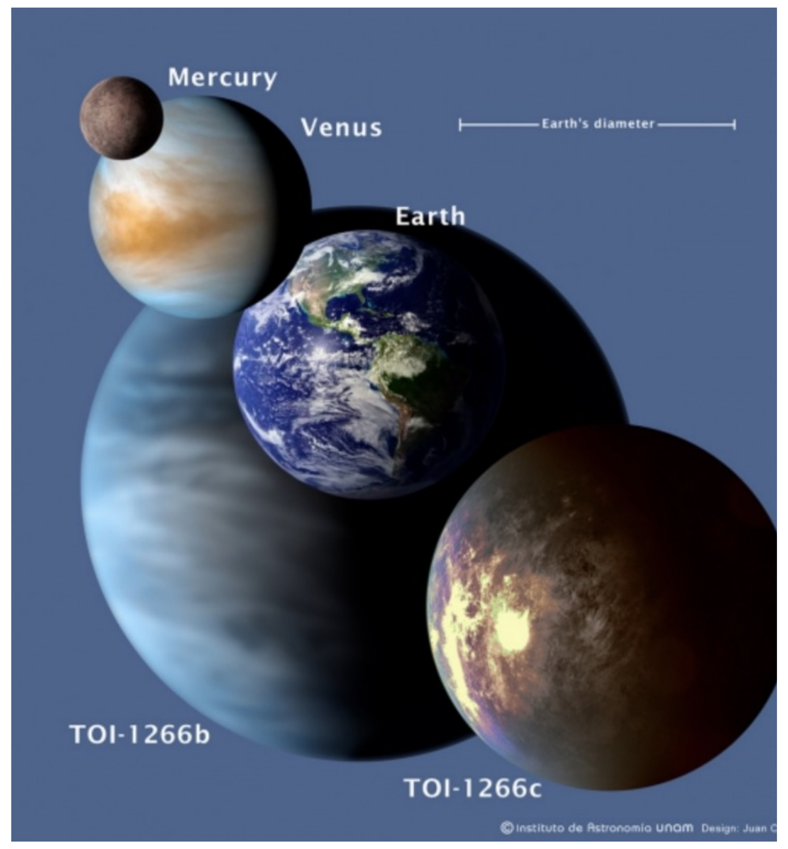
1 Motivation

- Sub-Neptune exoplanets (size between the Earth and Neptune) appears to be the most common type of planet in the universe (Fulton et al., 2017). Yet their formation and evolution history remains an outstanding question (Bean et al., 2021).
- Traditional evolution models for sub-Neptunes (e.g., Lopez & Fortney, 2014) assume no interaction between the core and atmosphere.
- However, the thick atmosphere of sub-Neptunes implies high pressure and temperature at the atmosphere-core boundary, which implies a long-lived magma ocean interacting with atmosphere (Chachan & Stevenson, 2018; Kite et al., 2020; Schlichting & Young, 2021).



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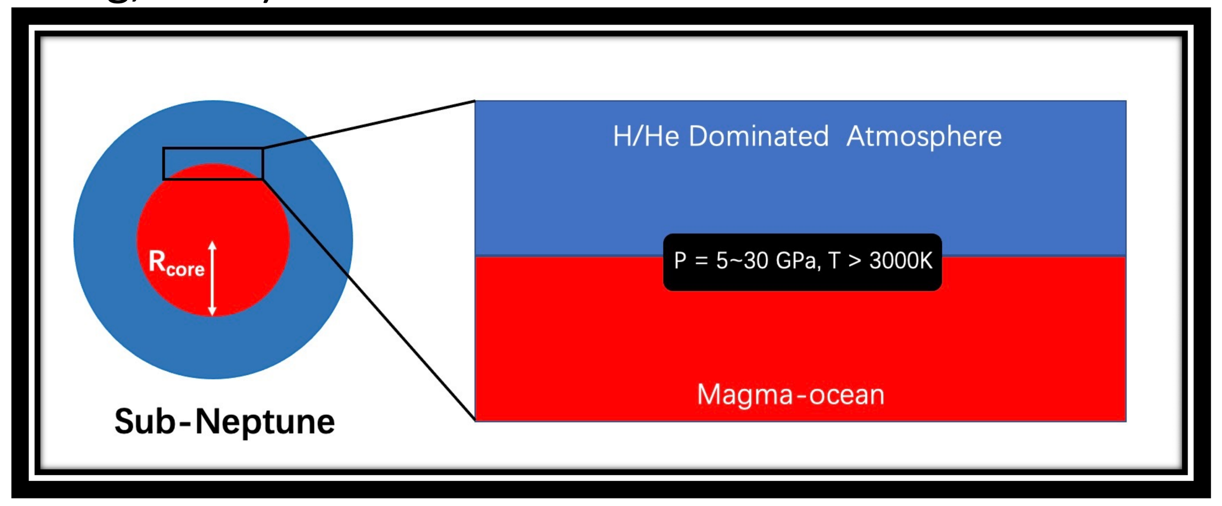


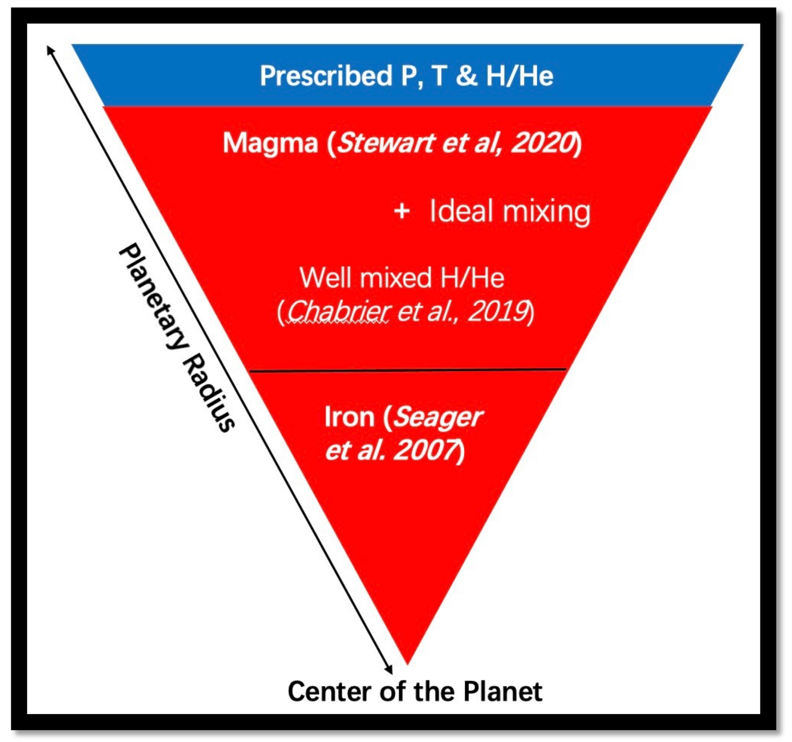
- Kite et al. (2019) found the decrease of planetary abundance at $3R_\oplus$ can be explained by accounting for Hydrogen dissolved into magma, but only the change of atmospheric volume was calculated.
- **Question: how does R_{core} change when the core is inflated by the dissolved atmosphere?**

2 A Simple Model to Calculate R_{core}

- Given the upper boundary and an initial R_{guess}, the model integrates inwards to solve for the mass and pressure at each layer.

$$\frac{dm(r)}{dr} = 4\pi r^2 \rho(r) \quad \frac{dP}{dr} = -\frac{Gm(r)\rho(r)}{r^2}$$

- After the integration, the model iterates with new R_{guess} until the error of residual/lacked mass is small.

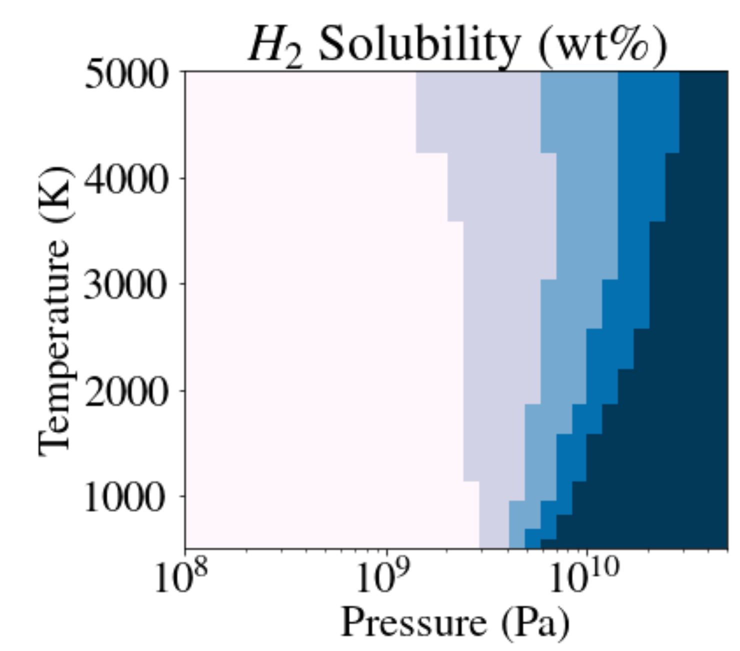


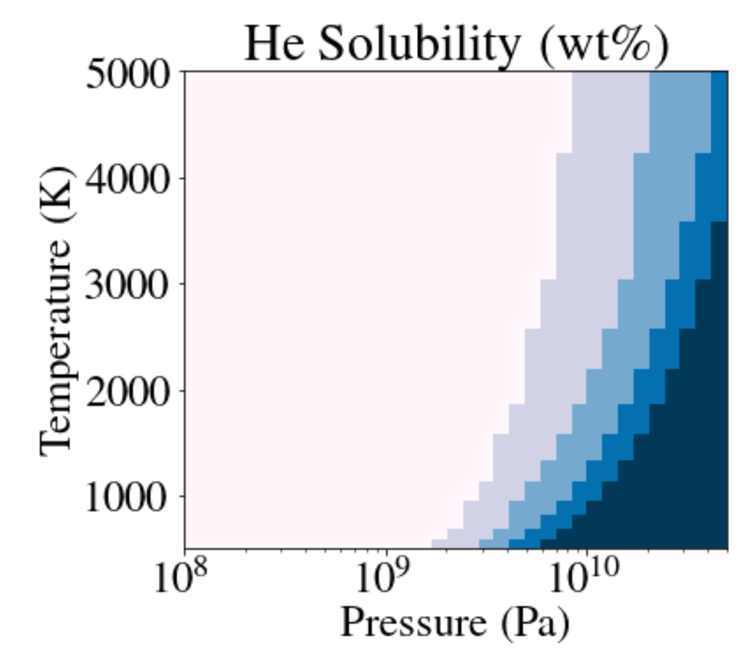
3 Hydrogen and Helium Solubilities Explode with Increasing Pressure

$$x_i = A_i f_i \exp(-T_i/T)$$

x_i: solubility (mass fraction) of gas species i
A_i: the constant to fit data (e.g., Lux, 1987; Paonita, 2005; Chachan & Stevenson,2018)
f_i: fugacity of gas species i (controlled by the EOS)
T: temperature

- Hydrogen and Helium solubilities are significant (blue colors) when **P > 3 GPa**.
- The solubility of Hydrogen can be much higher than Helium for large P.



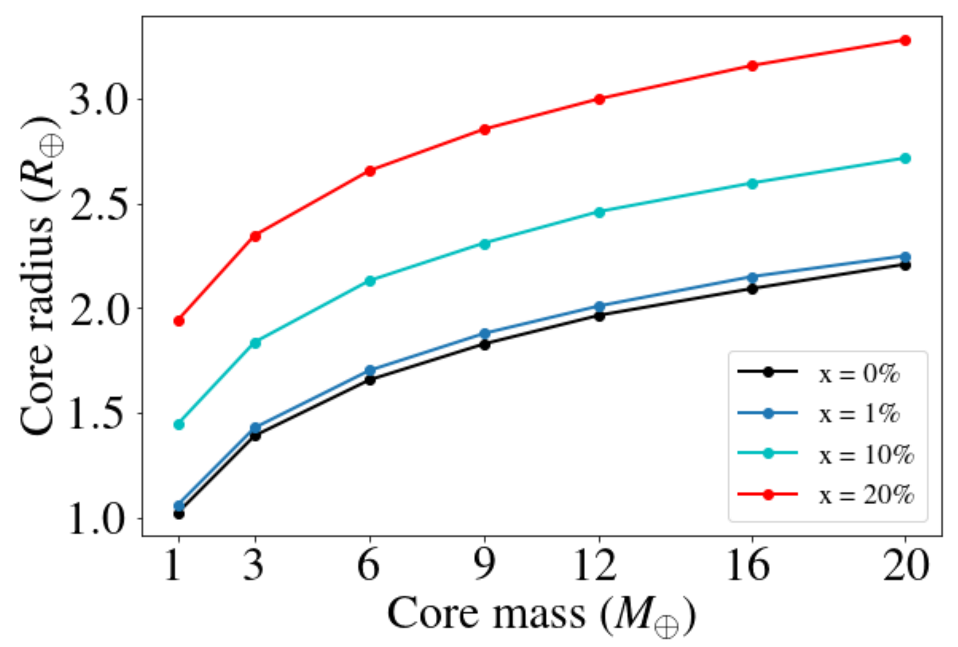


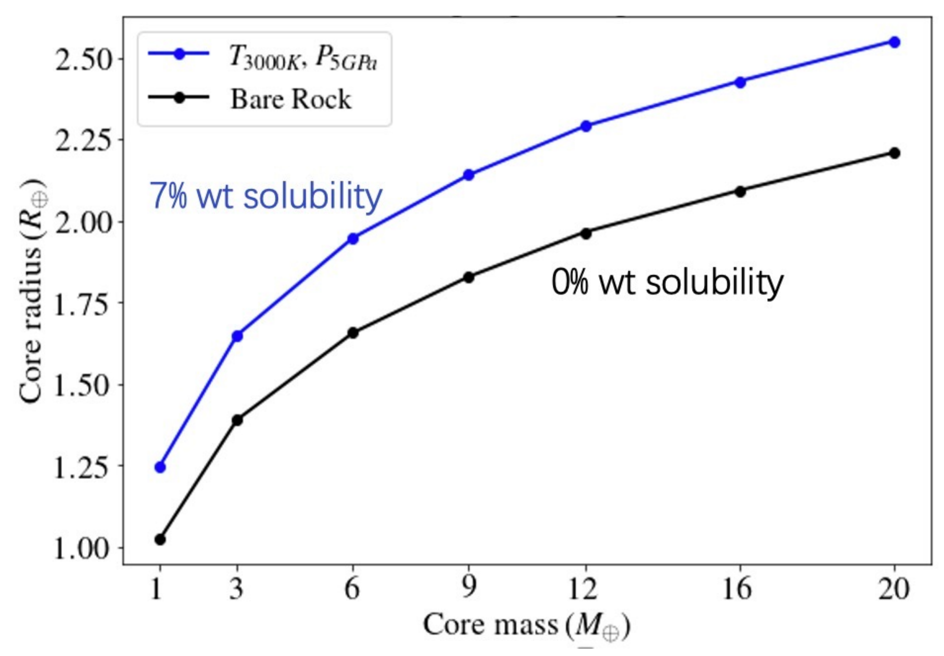
4 Dissolved Gas Inflates the Core Even for Sub-Neptunes with Thin Atmospheres

- The core is puffed up by the dissolved gas when solubility ***x* > 1%.**
- A thicker atmosphere means higher T and P at the core-atmosphere boundary.

→ The bottom-line for sub-Neptune planets is (T, P) = (3000 K, 5 GPa), which means **solubility ≈ 7%.**

→ 7% solubility means **up to 0.3 $R_\oplus$ increase of the R_{core}.**





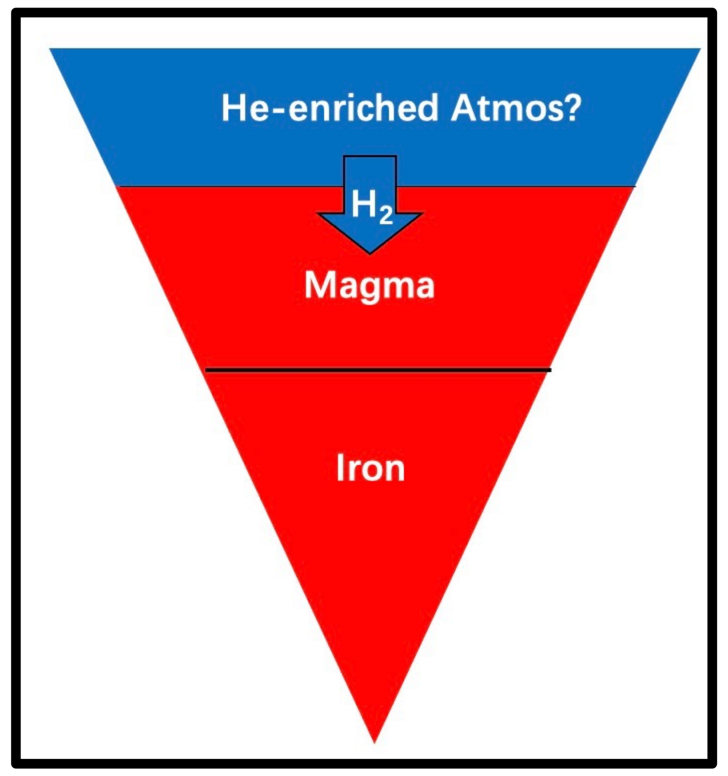
5 Ongoing Work: Helium is Enriched in Atmosphere in Core-Atmos Coupled Model

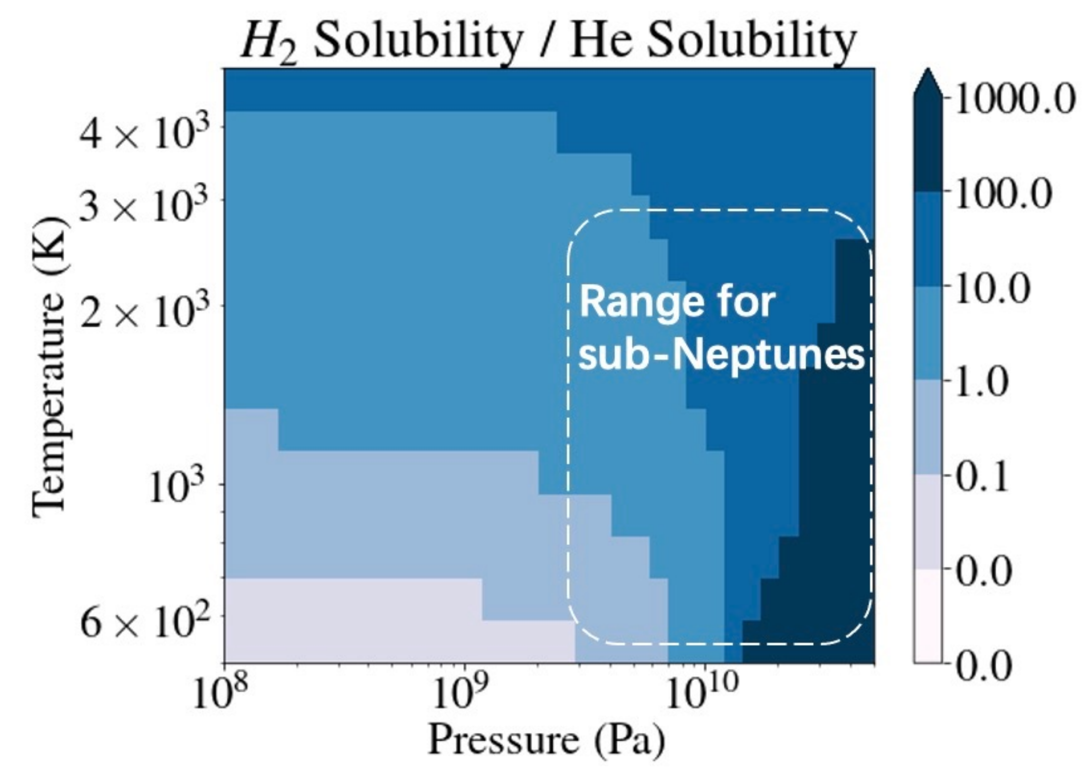
- From a core-only model to core-atmosphere coupled model.
- Hydrogen solubility > Helium solubility.

→ **Most H_2 in magma, but most He in atmosphere.**

→ **A new mechanism for He enrichment**, previously proposed to occur by factionary escape (Hu et al, 2015; Malsky and Rogers, 2020)

- Future work: forward modeling the planetary M-R relation, thus aiding the interpretation of future data from TESS, JWST (2021), and PLATO (2026)





6 Take-home Message

- **Planetary cores inflate by up to 0.3 $R_\oplus$ due to dissolved H_2.**
- **He enrichment in atmosphere.**

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