Squeeze the atmosphere into magma: sub-Neptune mass-radius relation revised by atmosphere-magma interactions

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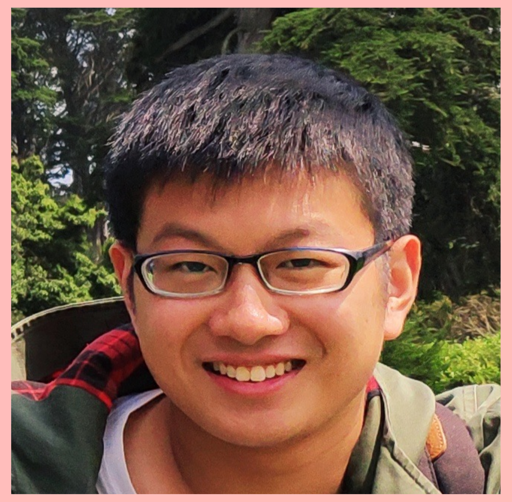
Abstract

The Kepler mission revealed that sub-Neptunes are about as common as stars, which defied our pre-existing notion of planet demographics. The prevailing view for sub-Neptunes was that they are mostly core by mass and atmosphere by volume (Lopez & Fortney, 2014). However, current formation models do not consider dissolution at the atmosphere-core interface. The temperature and pressure at the magma-atmosphere interface can rise to >3000 K and ~5-30 GPa (Lee et al., 2014; Piso et al., 2015), high enough for dissolution of hydrogen gas into the magma (Chachan & Stevenson, 2018). The dissolution of atmosphere into the magma may explain the drop-off in exoplanet abundance at 3 times Earth radius (Kite et al., 2019), but the puff-up of the magma due to gas dissolution has not previously been included. We propose a simple model to calculate sub-Neptune mass-radius relation, including, for the first time, the puff-up effect. Key assumptions include: (1) nonlinear solubility of gas in magma is constrained by limited laboratory data (Hirschmann et al, 2012); (2) the Fe/core mass fraction is Earth-like, and He/gas mass fraction is Solar-like; (3) ideal mixing between the dissolved gas and magma; (4) the dissolved gas is well mixed within the magma-layer. The EoS used are an Mg_2SiO_4 for the magma (Stewart et al., 2020); the H/He EoS (Chabrier et al., 2019); and a simple model for Fe (Seager et al., 2007). The model is integrated from the radiative-convective boundary and iterated until atmosphere-magma solubility equilibrium. We have varied the core mass, atmospheric mass and equilibrium temperature in the atmosphere. Our preliminary results are shown in Figures. The critical point for the puff-up of the core due to the dissolved gas corresponds to ~1% solubility at the magma-atmosphere boundary (Fig. 1). The puff-up effect can be important up to 0.3 Earth radius (Fig. 2), much larger than the radius error bars for a single planet in the CKS survey with Gaia DR2 data (Fulton & Petigura, 2018). In future, we will add additional constraints on gas/core mass fraction (Lee, 2019), forward-model the relationship between mass and photospheric radius, and generate predictions for exoplanet masses and radii that can be used to help interpret data from ESA's PLATO and NASA's TESS.



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

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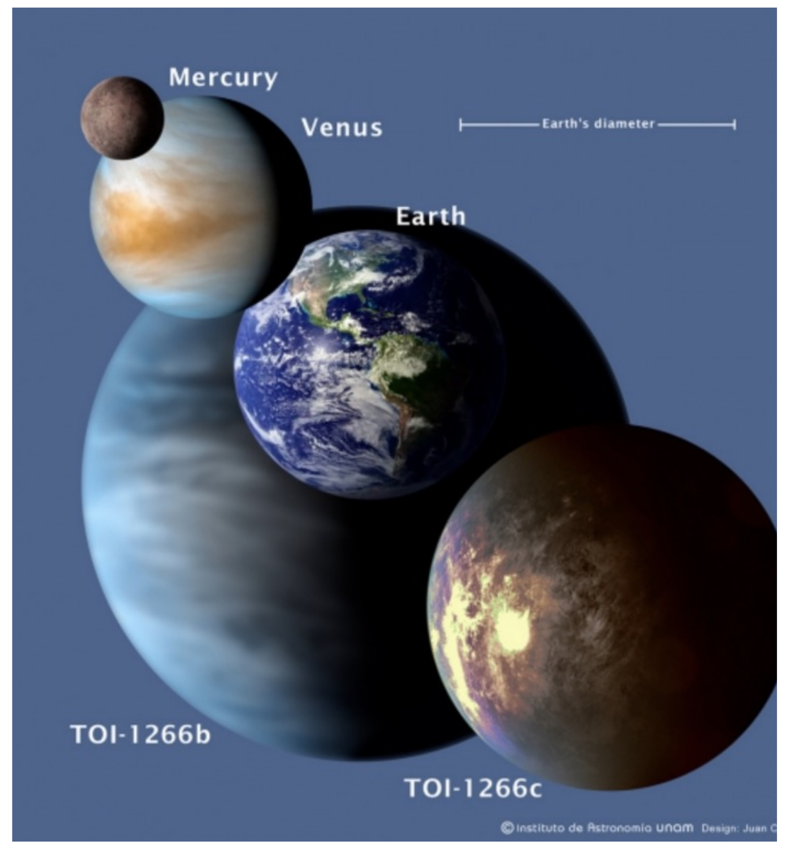
1 Motivation

- 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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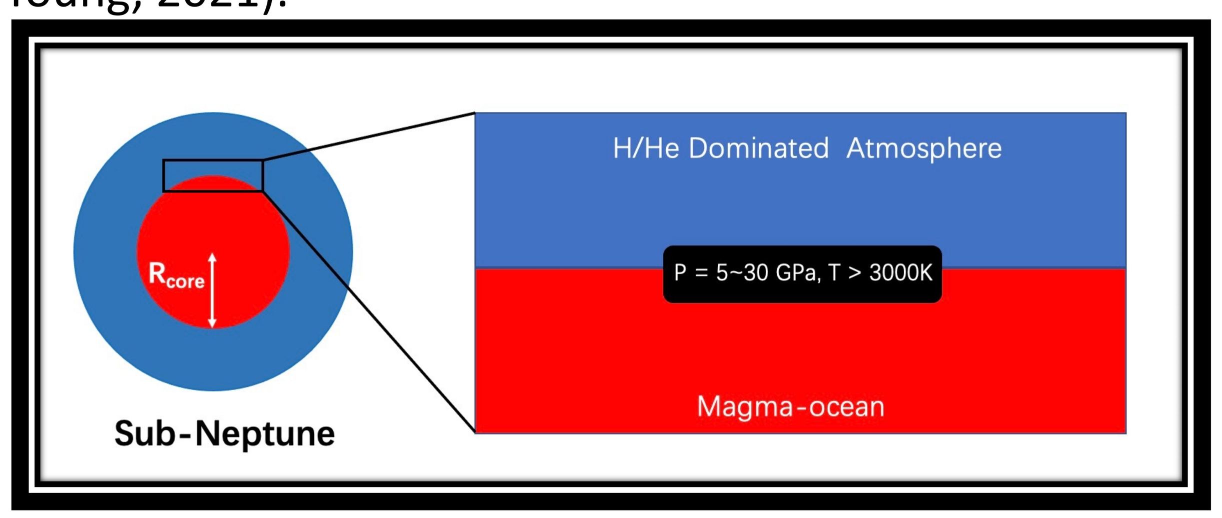


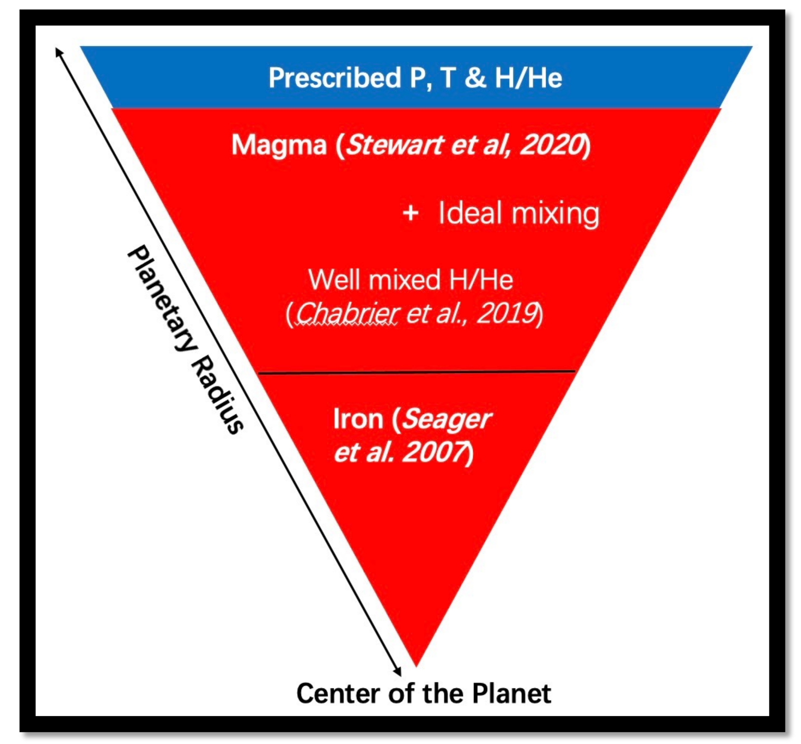
- Kite et al. (2019) found the decrease of planetary abundance at 3$R_\oplus$ can be explained by accounting for Hydrogen dissolved into magma, but only the change of atmospheric volume was calculated.
- **Question: how does R_{core} change when the core is inflated by the dissolved atmosphere?**

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.

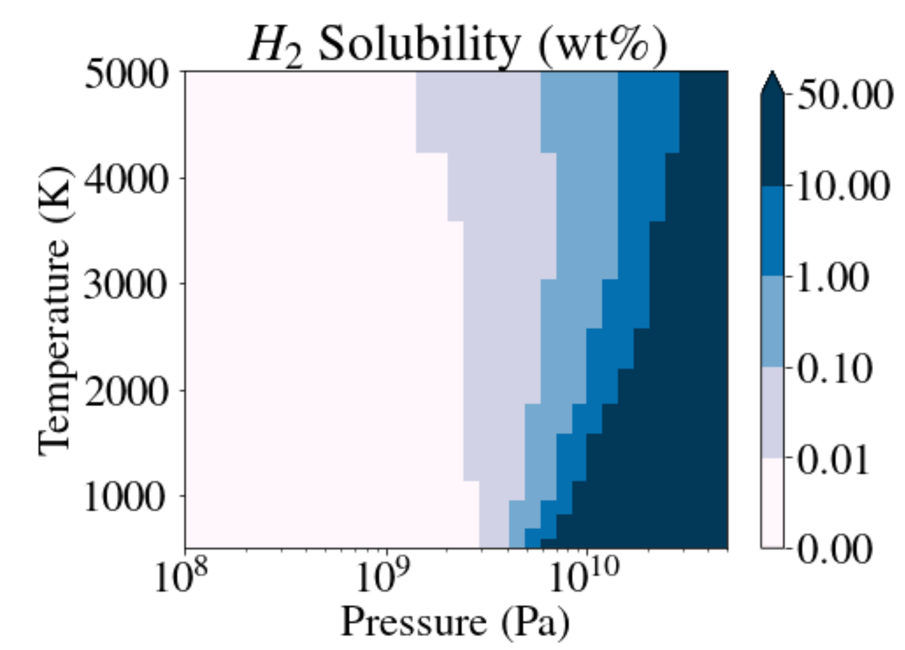


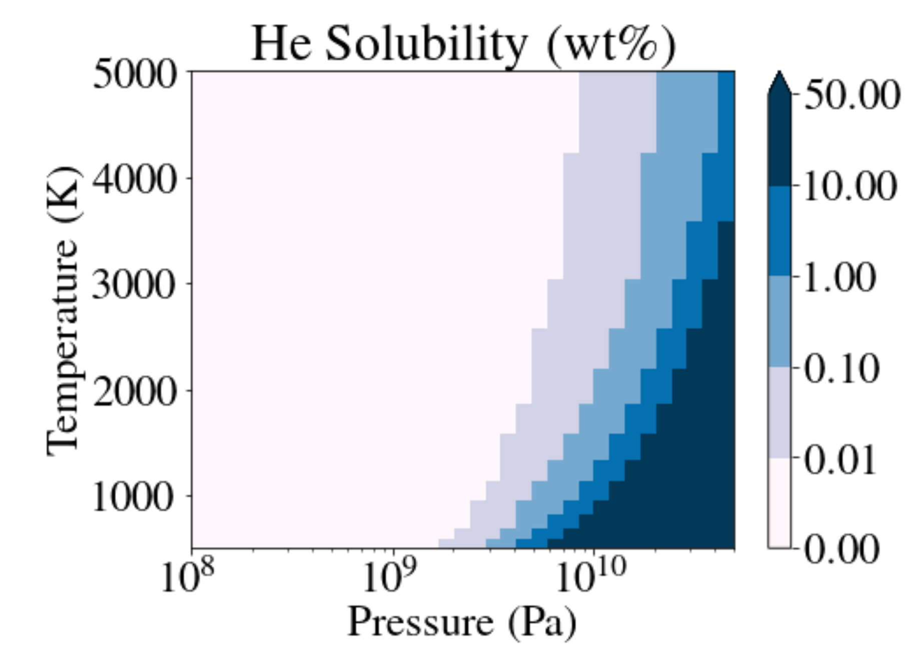
3 Hydrogen and Helium Solubilities Explode with Increasing Pressure

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

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.



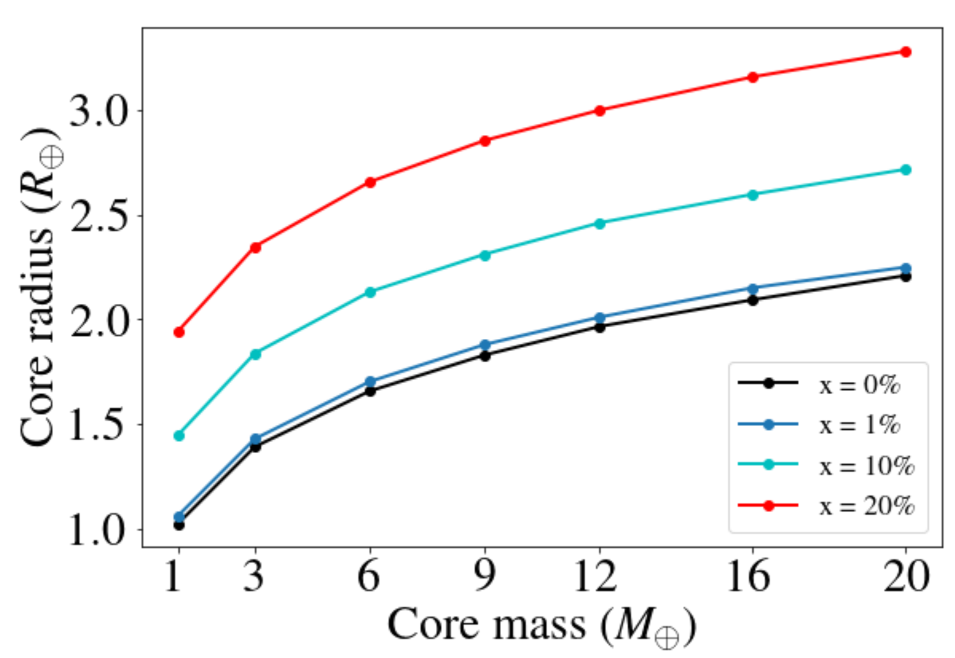


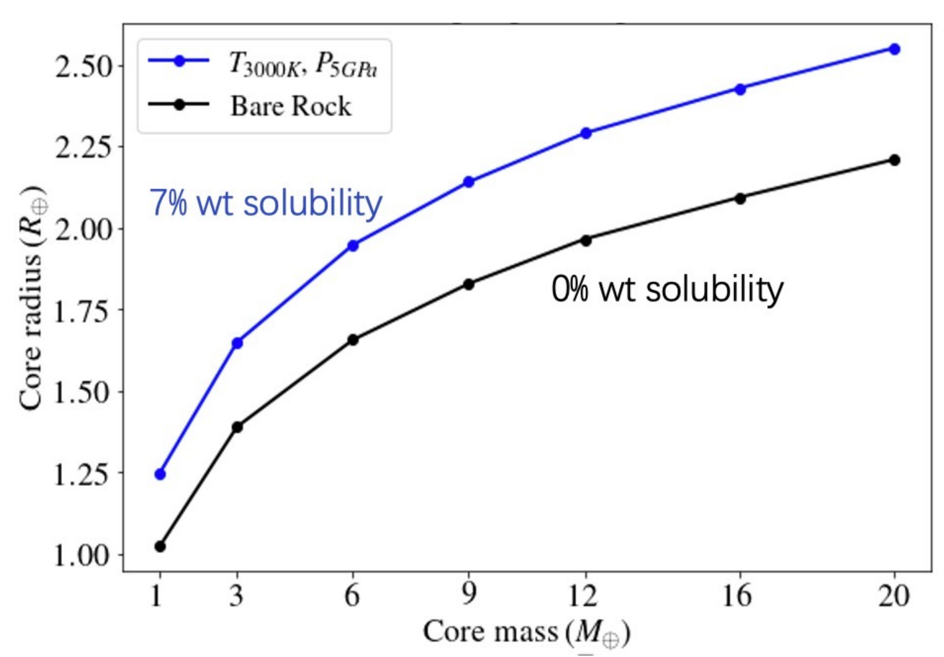
4 Dissolved Gas Inflates the Core Even for Sub-Neptunes with Thin Atmospheres

- 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}**.





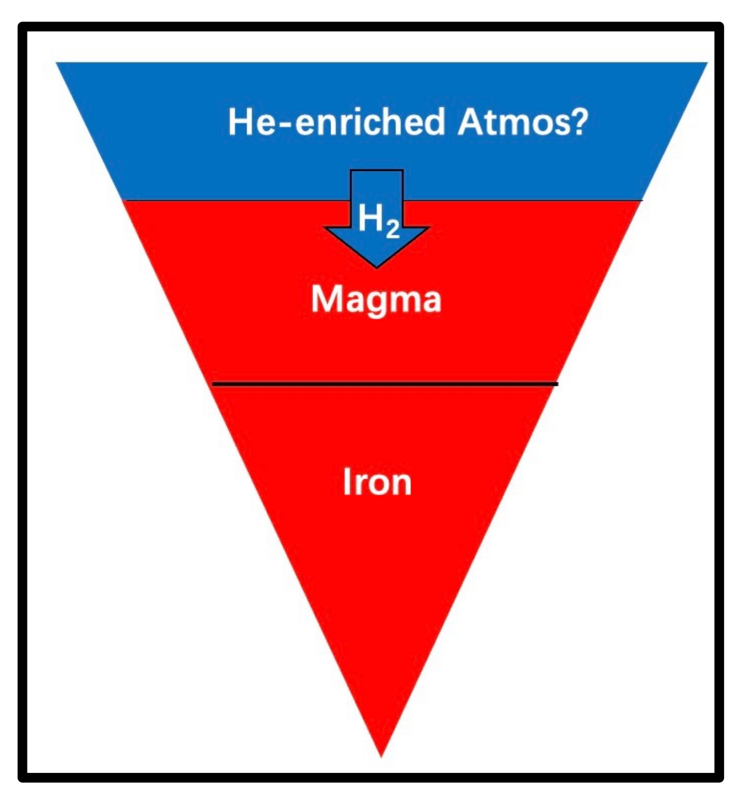
5 Ongoing Work: Helium is Enriched in Atmosphere in Core-Atmos Coupled Model

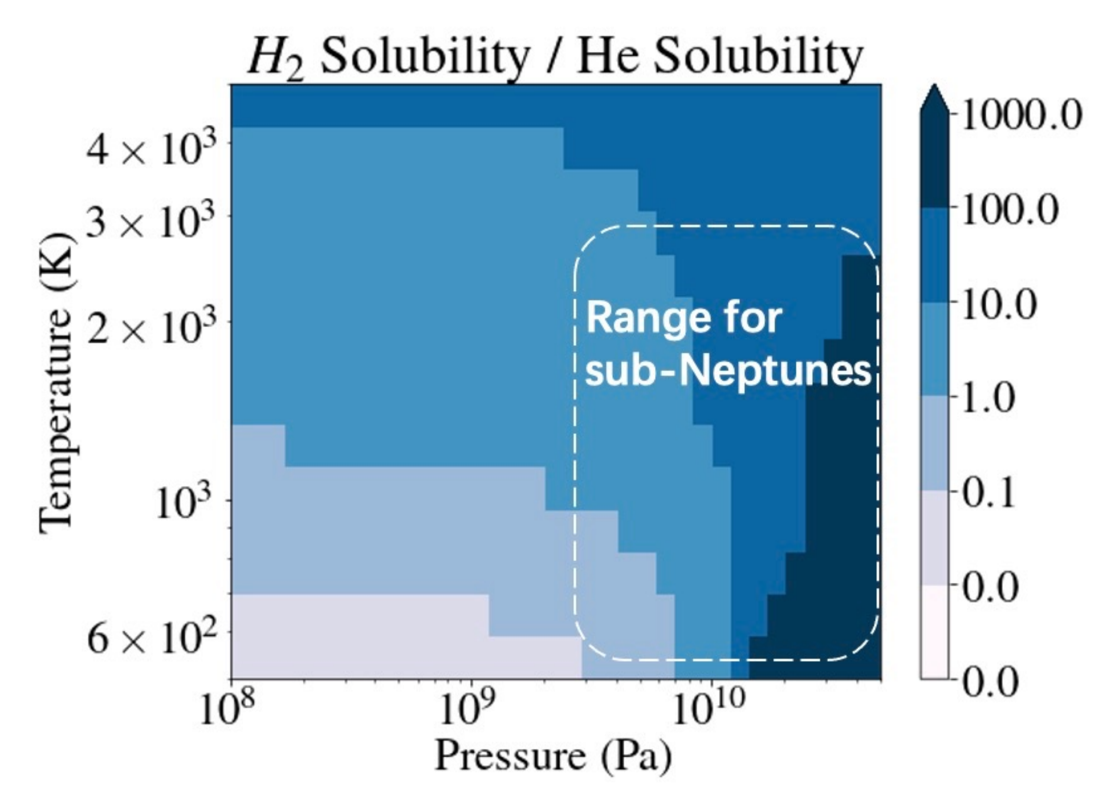
- From a core-only model to core-atmosphere coupled model.
- Hydrogen solubility > Helium solubility.

→ **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.**

References

1. Bean, J. L., Raymond, S. N., & Owen, J. E. (2021). The nature and origins of sub-Neptune size planets. *Journal of Geophysical Research: Planets*, *126*(1), e2020JE006639.
2. Chabrier, G., Mazevet, S., & Soubiran, F. (2019). A new equation of state for dense hydrogen–helium mixtures. *The Astrophysical Journal*, *872*(1), 51.
3. Chachan, Y., & Stevenson, D. J. (2018). On the role of dissolved gases in the atmosphere retention of low-mass low-density planets. *The Astrophysical Journal*, *854*(1), 21.
4. Fulton, B. J., Petigura, E. A., Howard, A. W., Isaacson, H., Marcy, G. W., Cargile, P. A., ... & Hirsch, L. A. (2017). The California-Kepler survey. III. A gap in the radius distribution of small planets. *The Astronomical Journal*, *154*(3), 109.
5. Hu, R., Seager, S., & Yung, Y. L. (2015). Helium atmospheres on warm Neptune-and sub-Neptune-sized exoplanets and applications to GJ 436b. *The Astrophysical Journal*, *807*(1), 8.
6. Kite, E. S., Fegley Jr, B., Schaefer, L., & Ford, E. B. (2019). Superabundance of exoplanet sub-Neptunes explained by fugacity crisis. *The Astrophysical Journal Letters*, *887*(2), L33.
7. Kite, E. S., Fegley Jr, B., Schaefer, L., & Ford, E. B. (2020). Atmosphere origins for exoplanet Sub-Neptunes. *The Astrophysical Journal*, *891*(2), 111.
8. Lopez, E. D., & Fortney, J. J. (2014). Understanding the mass-radius relation for sub-Neptunes: Radius as a proxy for composition. *The Astrophysical Journal*, *792*(1), 1.
9. Lux, G. (1987). The behavior of noble gases in silicate liquids: Solution, diffusion, bubbles and surface effects, with applications to natural samples. *Geochimica et Cosmochimica Acta*, *51*(6), 1549-1560.
10. Malsky, I., & Rogers, L. A. (2020). Coupled Thermal and Compositional Evolution of Photoevaporating Planet Envelopes. *The Astrophysical Journal*, *896*(1), 48.
11. Paonita, A. (2005). Noble gas solubility in silicate melts: a review of experimentation and theory, and implications regarding magma degassing processes. *Annals of Geophysics*, *48*(4-5).
12. Schlichting, H. E., & Young, E. D. (2021). Chemical equilibrium between Cores, Mantles, and Atmospheres of Super-Earths and Sub-Neptunes, and Implications for their Compositions, Interiors and Evolution. *arXiv preprint arXiv:2107.10405*.
13. Seager, S., Kuchner, M., Hier-Majumder, C. A., & Militzer, B. (2007). Mass-radius relationships for solid exoplanets. *The Astrophysical Journal*, *669*(2), 1279.
14. Stewart, S., Davies, E., Duncan, M., Lock, S., Root, S., Townsend, J., ... & Jacobsen, S. (2020, November). The shock physics of giant impacts: Key requirements for the equations of state. In *AIP Conference Proceedings* (Vol. 2272, No. 1, p. 080003). AIP Publishing LLC.

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