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Coupled chemistry and structure of hydrogen-silane-water sub-Neptune atmospheres

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Scan for arXiv link:

Full paper: Misener et al. (2023), *MNRAS*, in review, arxiv: 2303.09653

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Motivation

- Sub-Neptunes are thought to consist of Earth-like interiors surrounded by hydrogen atmospheres
- Substantial silicate vapor is expected at the base of sub-Neptune atmospheres [1]
- This silicate vapor can alter the structure of sub-Neptune envelopes by inhibiting deep convection [2,3]
- **What are the effects of chemical equilibrium between the outgassed oxidized silicate and the reducing background hydrogen?**
- **Are there detectable signals of typical interior composition, vital for characterizing formation and habitability, in sub-Neptune atmospheres?**

Main Takeaways

- Under chemical equilibrium between melt and atmosphere, **silane** (SiH_4) and **water vapor** (H_2O) **are the dominant secondary species** throughout most of the envelope
- Reaction of silicate melt with hydrogen atmosphere **pulls more silicon out of the interior** than captured in previous models (e.g. [2])
  - Results in **larger non-convective region**
- Abundances decrease with decreasing temperature (i.e. increasing altitude)
- Signatures of interior-atmosphere interactions **potentially observable in upper atmosphere**
  - SiO/SiH_4 balance reverses to favor SiO at high altitudes due to decreasing H_2

Atmospheric structure and composition methods

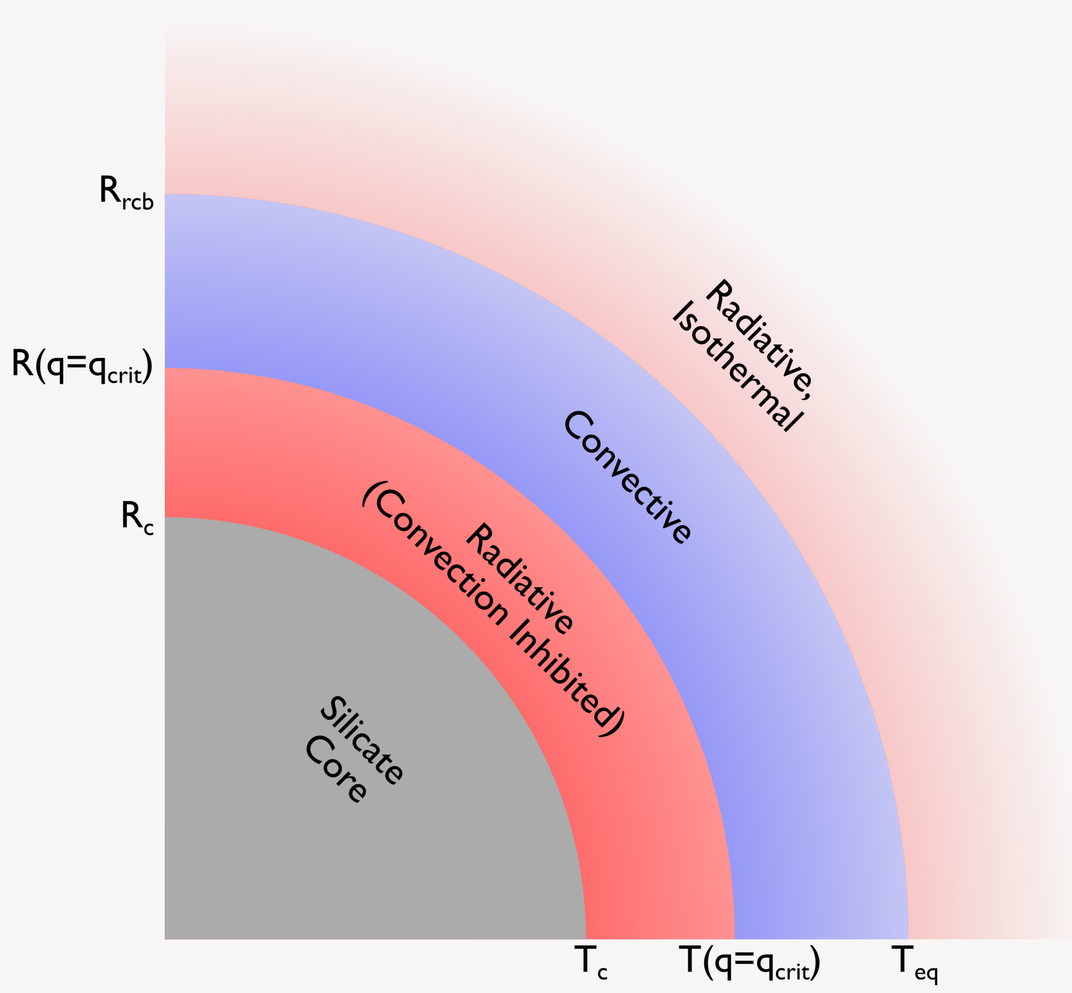

Figure 1: Sub-Neptune structure. The silicate interior (gray) is overlain by a hydrogen-dominated atmosphere, which is divided into non-convective (red) and convective (blue) regions. The inner non-convective region is caused by the silicate vapor.

$$SiO_{2\,(liq.)} \rightleftharpoons SiO_{(g)} + 0.5\,O_{2\,(g)}$$

$$H_{2\,(g)} + 0.5\,O_{2\,(g)} \rightleftharpoons H_2O_{(g)}$$

$$3\,H_{2\,(g)} + SiO_{(g)} \rightleftharpoons SiH_{4\,(g)} + H_2O_{(g)}$$

- Fiducial planet is a typical sub-Neptune
  - Mass: 4 M_E, equilibrium temperature: 1000 K, hydrogen mass: 2.5% of the core mass, 5000 K at core-atmosphere interface (appropriate for young sub-Neptune [4])
- **Allow chemical equilibrium between melt and gaseous species at all levels of atmosphere,** described by three reactions above
- Structure:
  - Radiative, isothermal outer region
  - Convective, adiabatic interior until mass mixing ratio q exceeds critical value that inhibits convection [5]: $q_{crit} = \frac{1}{\left(1-\frac{\mu_H}{\mu_{sv}}\right)\frac{\partial \ln P_{svp}}{\partial \ln T}}$
  - If convection becomes inhibited, energy transported by radiation and conduction

Results: SiH_4 as the dominant outgassed Si-bearing species

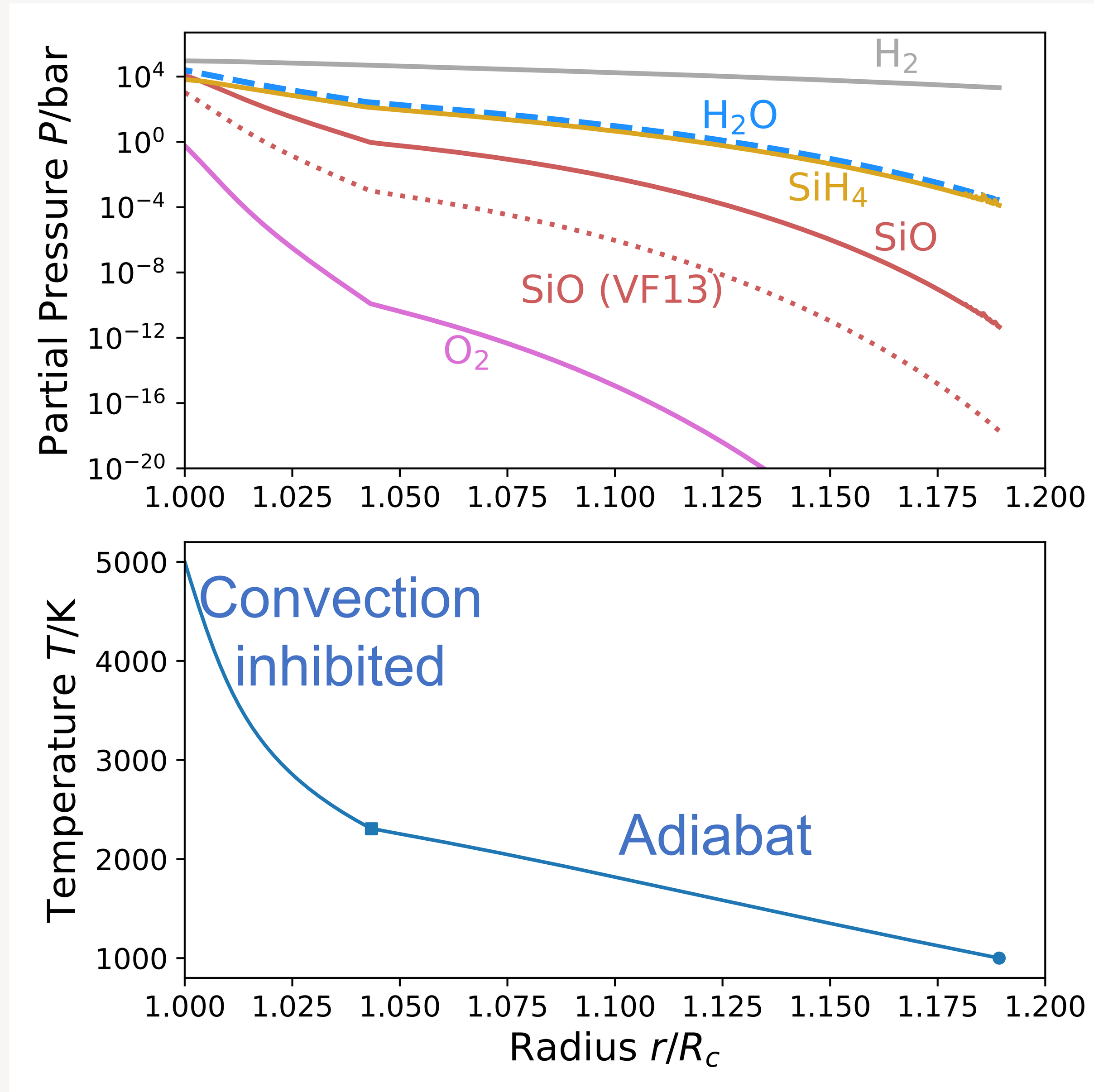

Figure 2: Results of coupled atmospheric structure and chemistry calculations for fiducial planet, in region interior to outer radiative-convective boundary. Top: partial pressures of considered species as functions of radius. Bottom: temperature profile.

- Partial pressures of species considered shown in Fig. 2, top
  - **SiH_4 dominates over SiO throughout most of atmosphere** – SiO overtakes at very base
  - **H_2O most abundant product of magma ocean-atmosphere interaction** (see also [6] for application to Earth's formation)
  - Significantly more Si pulled into atmosphere than found in previous models which do not consider reactions with H [2, 7]
- Convection inhibited to temperatures as low as 2400 K, **much lower than found previously**
  - Time taken to cool enough for convection to resume could take longer than previously estimated [2]

Observability

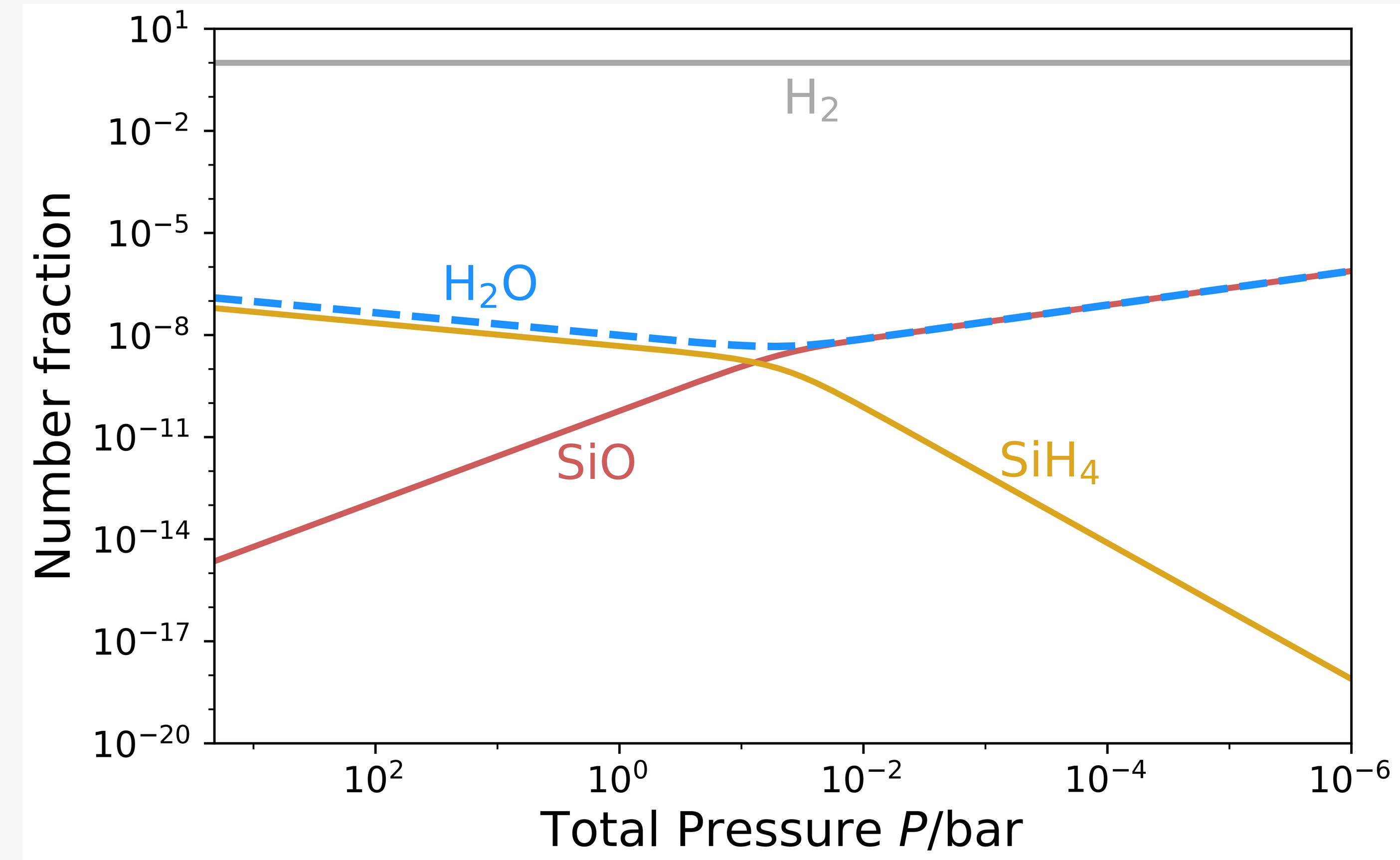

Figure 3: Number fraction of species considered in outer isothermal region as functions of total pressure.

- Switch between SiO and SiH_4 as favored Si-bearing species occurs near 1 bar in fiducial planet
- **Predicted abundances testable with JWST**
- Abundances and elemental ratios are non-solar
  - Observations would probe whether composition is primordial or set by equilibrium with interior

Future directions

- More realistic melt species, especially Mg
  - **Can elemental ratios in atmosphere probe interior composition?**
- Sub-Neptune parameter space survey
  - **Which sub-Neptunes are most amenable to detection of the products of interior-atmosphere interactions?**
- Combination with mass loss and thermal evolution
  - **How does mantle outgassing affect planetary evolution?**

References

[1] Schlichting & Young 2022, PSJ, 3, 127
[2] Misener & Schlichting 2022, MNRAS, 514 (4):6025
[3] Markham et al. 2022, A&A, 665, A12
[4] Ginzburg et al. 2016, ApJ, 825, 29
[5] Guillot 1995, Science, 269, 1697
[6] Young et al. 2023, Nature, 616, 306
[7] Visscher & Fegley, 2013, ApJ, 767, L1