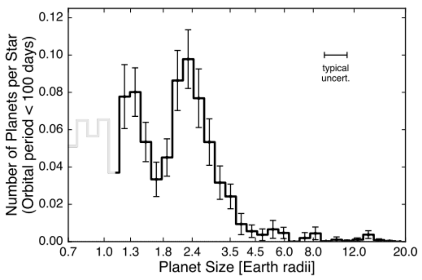
Chemical evolution of sub-Neptunes



SUMMARY.

This METEOR project will teach you about interior modeling of planets, evolution modeling as well as atmospheric loss. You will improve the calculation of sub-Neptune evolutions and explore their evolution tracks. We aim to understand how sub-Neptunes atmospheres change chemically as we approach those sub-Neptunes in the radius valley (see Figure).

OBJECTIVES

- *What will student learn?: learn about sub-Neptune population, their atmosphere diversity and how we anticipate their evolution over time, learn about fractionated mass-loss*
- *What will students learn to do?: run numerical simulations, use python, use Fortran-wrapped codes, interface existing codes*

INSTITUTE

ETH Zurich, Departement of Physics, Honggerberg Zurich, Switzerland

- ETH Zurich
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THEORY

Sub-Neptunes cool and contract over time. After formation, they can host deep magma oceans that can easily last over Gyrs. Magma oceans inherently interact with gases from overlying envelopes. There are chemical interactions and compositional coupling (i.e., the dissolution of gases). The extent of those chemical reactions are unknown, but we can map out end-members of assuming either no chemistry or full global chemical equilibrium states. As sub-Neptunes cool, their equilibrium states also shift and thus they chemically evolve. At the same time, sub-Neptunes are shaped by photoevaporative mass loss, which can preferentially remove light atoms. In this project all three major processes will be combined: thermal and chemical evolution and fractionated mass loss to space. Our group has developed models to account for all aspects individually. The combination of some of the processes are already done (Steinmeyer et al. 2026, Valatsou et al. 2026).The combination of all three processes and the exploration of resulting diversity of sub-Neptunes is at the heart of this project.

APPLICATIONS

You will explore the diversity of sub-Neptunes as they approach the radius valley. Existing models predict a clear trend of higher oxidation states of atmospheres (Cherubim et al. 2025), however they generally do not account for interior-atmosphere coupling and the replenishment of volatiles from the deep interior. Here, you will combine interior-atmosphere coupled models with fractionated mass loss models in an evolution framework. All individual components are readily developed, however not all aspects are fully coupled in the framework. You will first couple mass loss to the thermo-chemical-evolution framework and than explore how atmosphere composition of sub-Neptunes changes as they approach the radius valley and eventually become super-Earths.

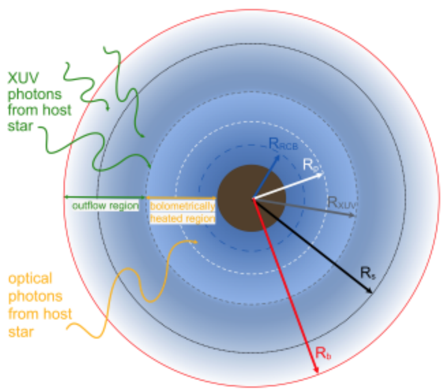

Illustration of BOREAS - the fractionated mass loss model from Valatsou et al. (2026), recently expanded to C-H-N-O-S species.

MAIN PROGRESSION STEPS

- Week 1: literate study
- Weeks 2-8: project & report writing
- Weeks 9: finishing report & talk

EVALUATION

Your work will be evaluated based on your progress during the project, your written report to present and summarize your results, and the final oral defense, in which you give a talk about your project and answer questions to the audience.

- Practice grade [60%]
  - Report (50%): writing structure, clarity of thought, and presentation of results
  - Project (50%): initiative, progress, analysis
- Defense grade [40%]
  - Oral and slides quality
  - Context
  - Project / Personal work
  - Answers to questions

BIBLIOGRAPHY & RESOURCES

- Group website
- Prof. Dorn website

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