



Introduction

Exoplanet characterization is one of the main foci of current exoplanetary science. For super-Earths and sub-Neptunes, we mostly rely on mass and radius measurements, which allow us to derive the mean density of the body and give a rough estimate of the bulk composition of the planet. However, the determination of planetary interiors is a very challenging task. In addition to the uncertainty in the observed fundamental parameters, theoretical models are limited owing to the degeneracy in determining the planetary composition.

Goal: We aim to study several aspects that affect the internal characterization of super-Earths and sub-Neptunes: observational uncertainties, location on the M-R diagram, impact of additional constraints such as bulk abundances or irradiation, and model assumptions.

Methods

Structure model

We use the structure model presented in Dorn et al. (2017), which assumes a pure iron core, silicate mantle, pure water layer, and an atmosphere. Unlike Earth's core, we do not consider the presence of light elements in the core. The silicate mantle is assumed to be made of oxides $\text{Na}_2\text{O}-\text{CaO}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$, and the gas layer of H, He, C and O, which are fundamental for the formation of key atmospheric molecules as H_2 , CO, CO_2 and CH_4 .

Bayesian inference based on nested sampling scheme

For the interior characterization we used the Bayesian inference analysis based on a nested sampling scheme using the PyMultiNest package (Buchner et al. 2014). In short, the algorithm samples some number of live points randomly from the prior, and the likelihood is evaluated at each of these points. At each iteration the point with the lowest likelihood is replaced by a new point sampled from the region of prior with likelihood, keeping the number of live points constant. This process is continued until Bayesian evidence reaches some specified value.

Table 1: Summary of model parameters, priors and observational constraints.

Model Param.	Priors	Obs.Constraints
M_{Core}	$\mathcal{U}(0, M)$	Total Mass
M_{Mantle}	$\mathcal{U}(0, M)$	Total Radius
M_{Water}	$\mathcal{U}(0, M)$	Bulk Fe/Si
$M_{\text{H-He}}$	$\mathcal{U}(0, M)$	Bulk Mg/Si
$\text{Fe/Si}_{\text{Mantle}}$	const. or $\mathcal{U}(0, 2\text{Fe/Si}_{\odot})$	
$\text{Mg/Si}_{\text{Mantle}}$	const. or $\mathcal{U}(0, 2\text{Mg/Si}_{\odot})$	
$\text{Al/Si}_{\text{Mantle}}$	const.	
$\text{Ca/Si}_{\text{Mantle}}$	const.	
$\text{Na/Si}_{\text{Mantle}}$	const.	
Z	const.	
L	const.	
T_{irr}	const.	

Dependence of internal structure determination on observational uncertainties

We study the internal structure of a sample of 20 synthetic planets with different masses and radii up to $25M_{\oplus}$ and $3.5R_{\oplus}$, which are chosen to represent the properties of the exoplanet catalog presented in Otegi et al. (2019), a catalog based on robust, reliable, and precise mass and radius measurements for transiting exoplanets.

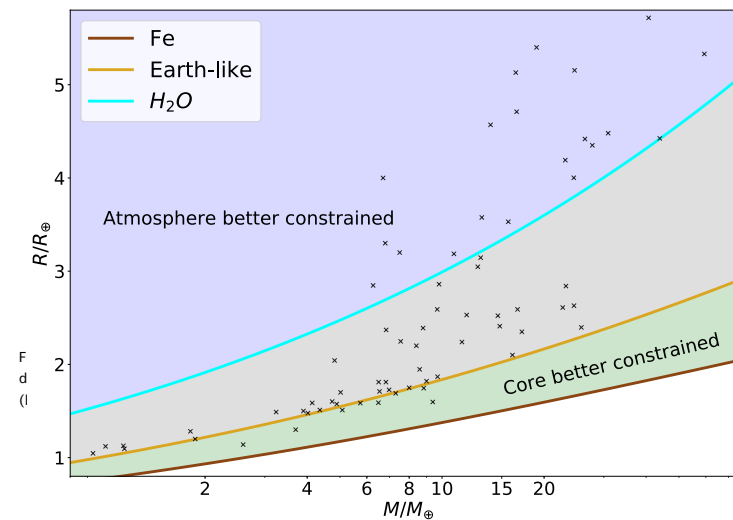


Figure 1: Mass-Radius diagram with composition lines of pure-iron (brown), Earth-like planet (light brown), and pure water (blue). Different colours indicate regions in which the a decrease in observational uncertainties lead to a better constrained core (green), better constrained atmosphere (blue) or not significant improvement of any model parameter (grey).

We find that:

- A decrease in observational uncertainties for planets below the Earth-like composition line leads to a better determination of the core mass. Similarly, for planets above the pure-water composition line it leads to a better determination of the core mass.
- A decrease in observational uncertainties for planets between Earth-like and pure-water composition lines does not significantly improve the determination of any internal structure parameter.

Sensitivity of atmosphere-rich planets to irradiation

Our results depend on the assumed insolation. Figure 2 shows whether an improvement in observational uncertainties contributes to constrain the envelope mass depending on the planetary density and irradiation. We find that the atmospheric mass of strongly irradiated atmosphere-rich planets can be better determined than for weakly irradiated planets.

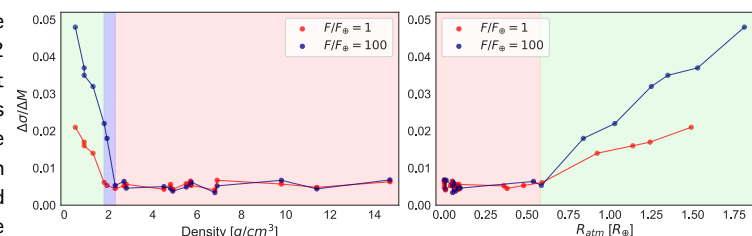


Figure 2: Atmospheric mass $\Delta\sigma/\Delta M$ for the synthetic planets vs. the bulk density (left) and median atmospheric thickness (right) for different irradiation. The light green and red regions represent the ranges in which decreasing the observational uncertainties lead and do not lead to better constraints on the atmospheric mass, respectively. The blue region represents the density range in which planets with an irradiation of 100 Earth fluxes have better constrained atmospheric mass with decreasing uncertainties and planets with an irradiation of one Earth flux do not.

Using stellar abundances as an additional constraint

We also explore how the results are affected when assuming that the stellar relative abundances reflect the planetary relative abundances. We use the bulk Fe/Si and Mg/Si as additional constraints, and introduce two additional model parameters: the Fe/Si and Mg/Si ratios in the mantle. The goal is to evaluate whether using the bulk abundances allows us to improve the estimation of the internal structure using a more detailed interior model.

We find that using the stellar Fe/Si and Mg/Si abundances as a proxy for the bulk planetary abundances does not always help to constrain the planetary internal parameters when adding two extra model parameters related to the mantle composition. This depends on the actual value of the measured stellar abundances and their uncertainties and on the data of planetary mass and radius.

Dependence of the radius on the temperature profile

Finally, we investigate how the assumed temperature profiles affect the inferred planetary radius and study what uncertainty in the temperature profile of a planet is required to match the observational uncertainty. We do not know a priori what composition gradients might exist in most planets, and here we artificially perturb the temperature profile from the adiabat and study how it affects the inferred planetary radius.

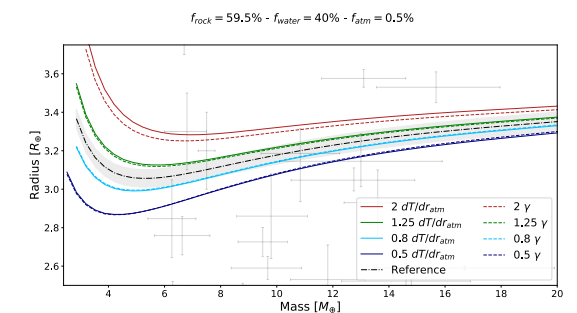


Figure 3: M-R relationships for a planet with fixed composition and the perturbations applied to the temperature profile. The gray envelope corresponds to a radius uncertainty of 3%.

We find that uncertainties of 20% in the temperature gradient can lead to radius uncertainties of 3%. This implies that theoretical uncertainties that are associated with the model assumptions could be larger than the observational uncertainties and therefore dominate the uncertainties in internal structure models.

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