Characterisation of the interior structures and atmospheres of multiplanetary systems

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Introduction

Transit photometry missions such as CHEOPS and radial velocity follow-up telescopes are providing the density of low-mass planets ($M < 20\ M_\oplus$). These include both **super-Earths** and volatile-rich **sub-Neptunes**, which might be composed of a Fe core, a silicate mantle and a volatile layer. Together with H and He, water is the second most abundant volatile, whose density depends strongly on the planetary conditions and its phase. Therefore, interior structure models of low-mass planets need to take into account the dependency of density on the phases of water and the planetary surface conditions, which are defined by their atmosphere, if present. In this work, **we present an interior structure model where the interior and the atmosphere are coupled self-consistently**, that includes all possible water phases in low-mass planets - **supercritical, steam, liquid and ice**. We apply this model to a sample of multiplanetary systems within a Bayesian Markov-chain Monte Carlo (MCMC) framework. We obtain the probability distributions of their compositional and atmospheric parameters, which enables us to **compare their core mass fractions and volatile mass fractions in a homogeneous analysis.**

Interior-atmosphere model

We use a 1D interior structure model with an Fe-rich core, a silicate mantle and a water layer. For planets with liquid and ice surface conditions, we include liquid and ice Ih-VII in our water layer, whereas for close-in planets we implement a supercritical water layer with a steam atmosphere on top. The surface temperature and thickness of the steam atmosphere is computed with a **1D, radiative-convective (RC) atmosphere model**. The atmosphere model estimates the surface temperature at which the atmosphere is in RC equilibrium via the computation of the outgoing longwave radiation (OLR) and the Bond albedo (A_B). The atmosphere is coupled with the interior in a self-consistent algorithm (Fig. 1). In all water phases, we employ Equations of State (EOSs) that are based on experimental and theoretical data and are valid within the pressure and temperature ranges they are applied to. In addition, **we adopt a Markov-chain Monte Carlo (MCMC) Bayesian framework** to obtain the planetary core mass fraction (CMF), water mass fraction (WMF), surface pressure and temperature, and other atmospheric properties such as the atmospheric mass M_{atm}. We use as data the planetary radii, masses and Fe/Si mole ratio derived from their estimated host stellar abundances.

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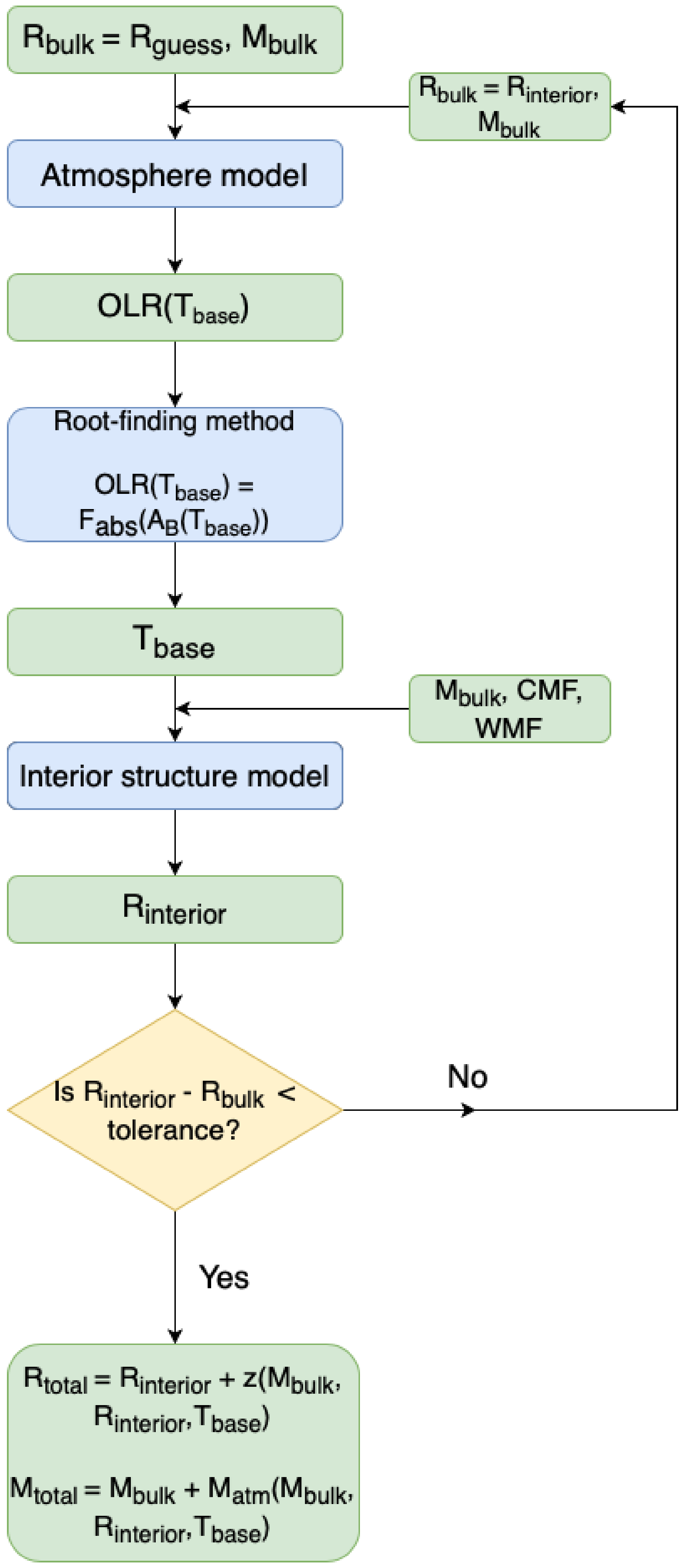

$R_{bulk} = R_{guess}, M_{bulk}$

$R_{bulk} = R_{interior}, M_{bulk}$

Atmosphere model

OLR(T_{base})

Root-finding method

OLR(T_{base}) = F_{abs}(A_B(T_{base}))

T_{base}

M_{bulk}, CMF, WMF

Interior structure model

$R_{interior}$

Is $R_{interior}$ - R_{bulk} < tolerance?

No

Yes

$R_{total} = R_{interior} + z(M_{bulk}, R_{interior}, T_{base})$

$M_{total} = M_{bulk} + M_{atm}(M_{bulk}, R_{interior}, T_{base})$

Figure 1:Interior-atmosphere coupling algorithm. T_{base} is the temperature at the bottom of the steam atmosphere. z denotes the atmospheric thickness. R_{bulk} and M_{bulk} correspond to the planet bulk radius and mass, respectively. R_{guess} refers to the initial guess of the bulk radius, while $R_{interior}$ is the output bulk radius of the interior structure model in each iteration. See [1] for more details.

Compositional trends in multiplanetary systems

We select a sample of several multiplanetary systems with 5 or more planets with mass, radius and host stellar abundances data available. We assume their host star Fe/Si value in each system. These systems are TRAPPIST-1, K2-138, TOI-178, Kepler-11, Kepler-102 and Kepler-80.

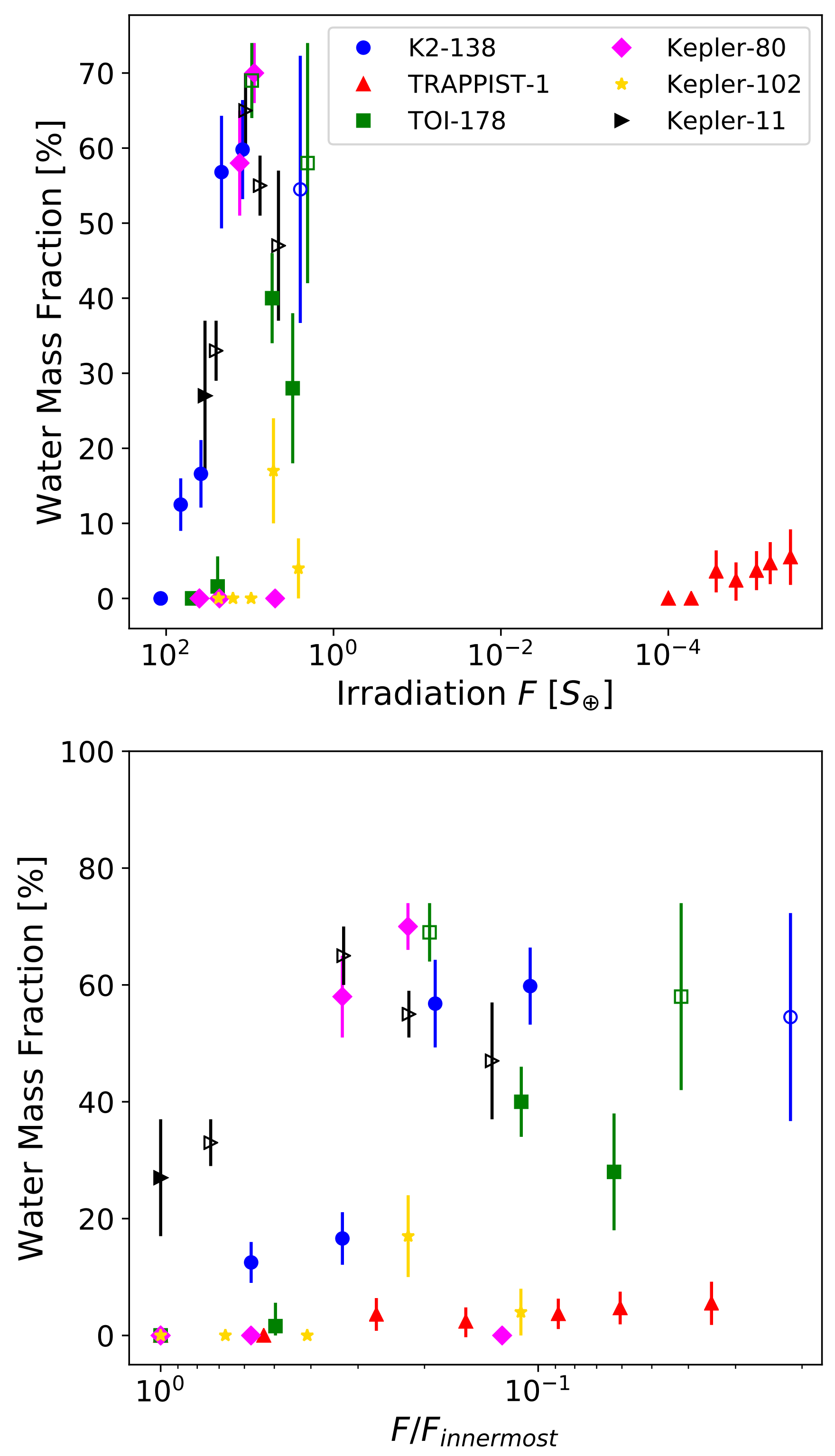

Figure 2:Upper panel: Volatile mass fraction trend as a function of stellar incident flux or irradiation in Earth irradiation units. Lower panel: volatile mass fraction trend as a function of incident flux normalised with respect to the inner, most irradiated planet in each system. Planets whose volatile layer is likely to be H/He-dominated instead of water-dominated are indicated in empty markers.

In the case of TRAPPIST-1 and K2-138, **the WMFs show a clear trend with distance from the host star that consists of an increasing gradient for the inner planets, followed by a constant WMF for the outer planets - a plateau**. The Kepler-102 system could potentially show the gradient and plateau trend given the uncertainties in WMF of its two outermost planets. The other multiplanetary systems seem to follow an increasing volatile mass fraction with increasing distance from the host star with some of their planets deviating from this trend.

We explore case-by-case these slight deviations and we find that they are due to atmospheres more extended than a water-dominated envelope. These extended envelopes can be explained by H/He atmospheres or Jeans and XUV atmospheric escape. To distinguish between the two cases, we estimate the atmospheric mass lost due to these two processes for each planet in the sample as described in [2].

Planet	$\Delta M_{Jeans,H2}$ [$M_\oplus$]
K2-138 b	0.13
TOI-178 d	0.16
Kepler-11 f	0.56
Kepler-80 g	140

Table 1:Mass loss due to Jeans H_2 atmospheric escape for the planets that present extended atmospheres with a non-negligible mass loss estimate.

The volatile mass fraction trend observed in TRAPPIST-1 and K2-138 could result from the combination of **planetary formation in the vicinity of the ice line**, which is an ice-rich region of the protoplanetary disk, **with later inward migration in the case of the outer planets. The increasing water mass fraction trend for the inner planets could be shaped by XUV atmospheric escape.**
We also observe that the density of the inner planets of Kepler-102 and Kepler-80 have very high CMFs that are not compatible with the host stellar Fe/Si mole ratio. This means that **the inner planets of these two systems could have undergone collisions that stripped away their mantles, mantle evaporation or formation in the vicinity of rocklines**, which are Fe-rich regions in the protoplanetary disk.

Conclusion

The modelling of the interior structure and composition of super-Earths and sub-Neptunes gives an insight into their formation and evolution history. **We present a homogeneous analysis of the composition of different systems**, which is necessary to overcome differences between interior models. This is particularly useful in multiplanetary systems, **to constrain their initial location in the protoplanetary disk, migration distances and the extent of atmospheric escape.**

References

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[2] A. Aguichine, O. Mousis, M. Deleuil, and E. Marcq, "Mass-Radius Relationships for Irradiated Ocean Planets," , vol. 914, p. 84, June 2021.