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Characterising the interior structures and atmospheres of transiting super-Earths and sub-Neptunes

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Introduction

Low-mass planets such as **super-Earths** and **sub-Neptunes** 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 a **self-consistent interior-atmosphere model**, that includes all possible water phases in low-mass planets. We apply this model to several multi-planetary systems to explore their compositional trends.

Interior-atmosphere model

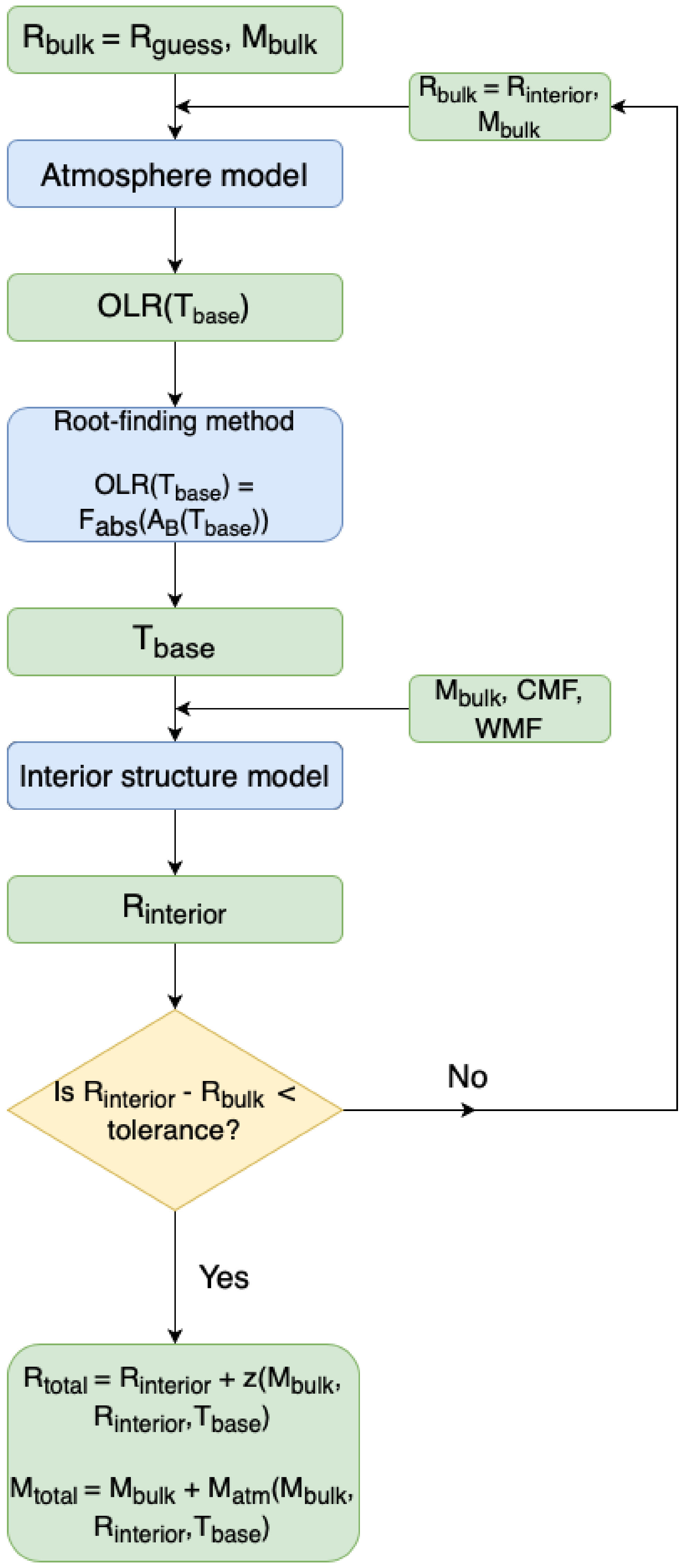
① We use a 1D interior structure model with a Fe-rich core, a silicate mantle and a water layer. For planets with liquid and ice surface conditions, we include **liquid and ice Ih-VII** in our water layer, whereas for highly-irradiated planets we implement a **supercritical** water layer with a **steam atmosphere** on top.

② 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.

③ 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).

④ 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}, with their associated uncertainties.

⑤ We use as input data the **planetary radii, masses and Fe/Si mole ratio** derived from their estimated host stellar abundances.



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

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

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.

Results

① The water mass fraction shows a global trend with incident flux, which consists of an **increasing gradient** for the inner planets, **followed by a plateau of constant water content** for the outer planets (Fig.2)

② Highly-irradiated planets, such as TOI-220 b, can present **WMFs up to 60%**, (Fig.3), while the outer planets might present **H/He atmospheres** since their densities are significantly lower than those of a planet with a water-dominated atmosphere (Fig. 4).

③ This trend might result from the combination of **planetary formation in ice-rich regions** of the protoplanetary disk, followed by a later inward **migration** in the case of the outer planets, while the increasing water mass fraction trend for the inner planets could be shaped by **atmospheric escape**.

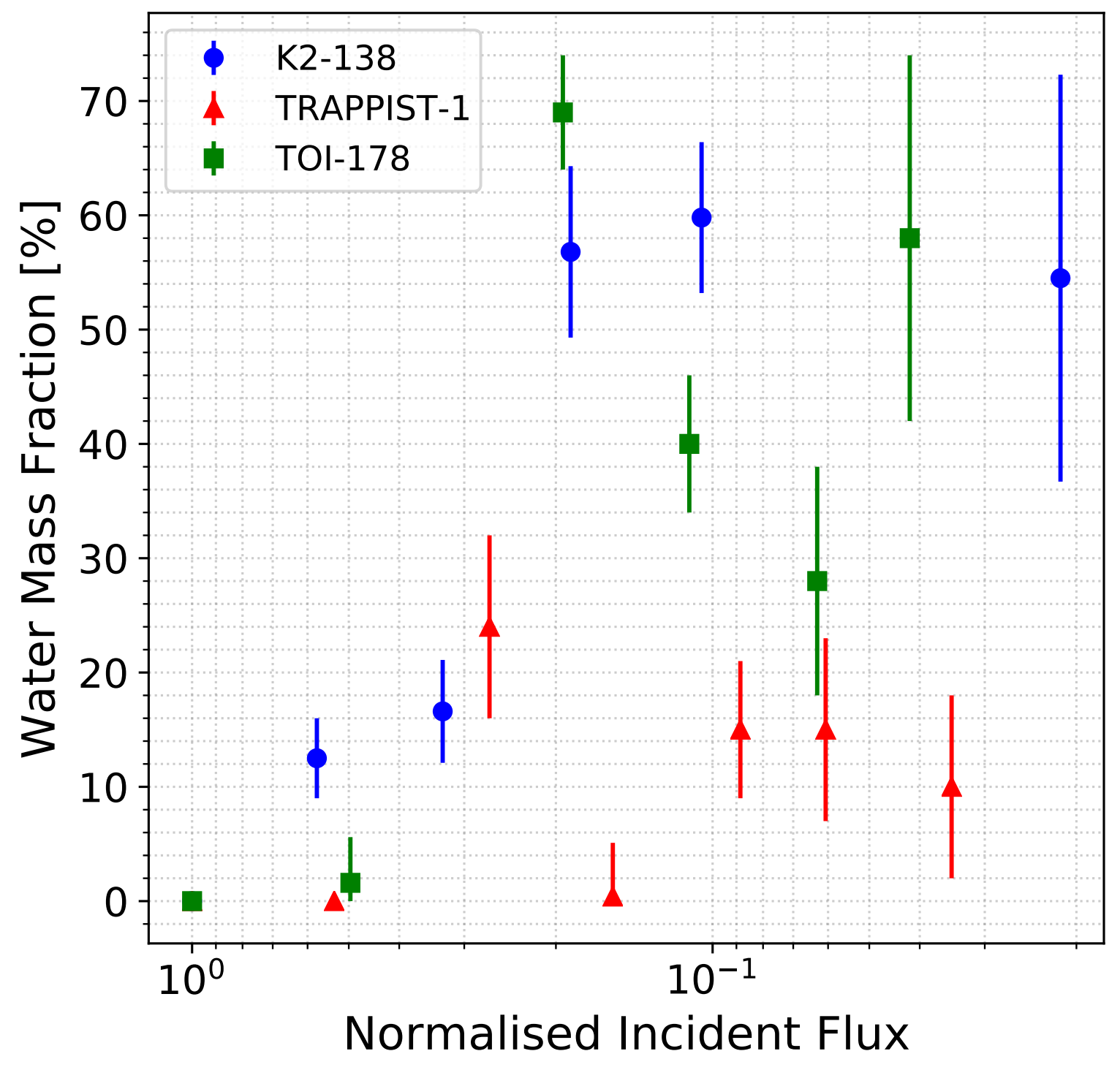


Figure 2:Water mass fraction as a function of received flux, normalised to the flux of the innermost planet for the TRAPPIST-1, K2-138 and TOI-178 multiplanetary systems.

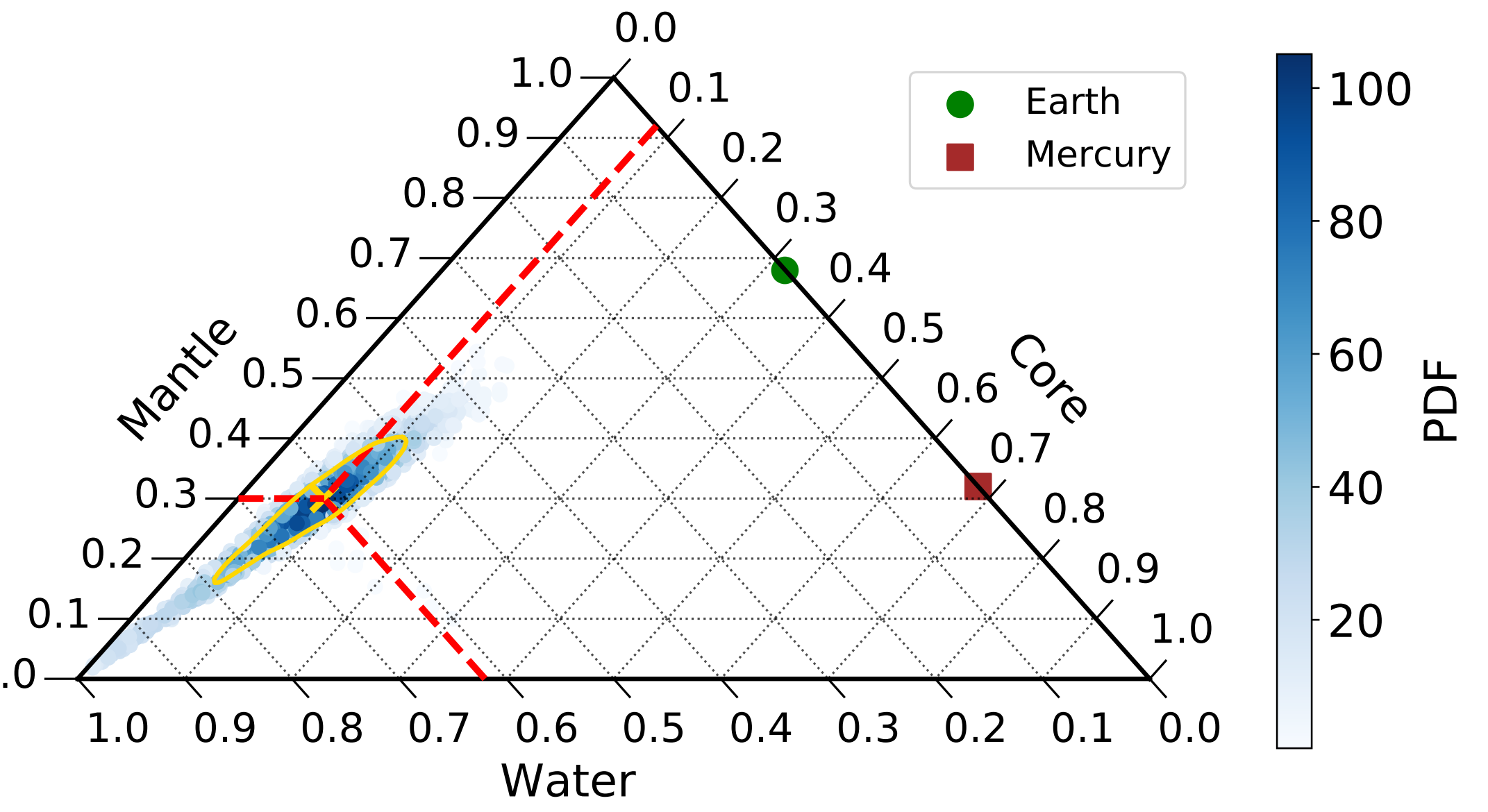


Figure 3:Sampled 2D marginal posterior distribution function for the CMF and WMF of TOI-220 b (blue region). The PDF mean and the 1 σ confidence interval is marked by the yellow cross and curve, respectively.

System	Planet	CMF	WMF	Significance
TOI-178	b	0.21±0.30	0	<1 σ
	c	0.30±0.02	$0.02^{+0.04}_{-0.02}$	<1 σ
	d	0.10±0.01	0.69±0.05	1.3 σ
	e	0.18±0.02	0.40±0.06	<1 σ
	f	0.22±0.03	0.28±0.10	<1 σ
	g	0.10±0.01	0.58±0.16	3.0 σ
Kepler-11	b	0.20±0.04	0.27±0.10	<1 σ
	c	0.18±0.01	0.33±0.04	1.7 σ
	d	0.10±0.02	0.65±0.05	2.4 σ
	e	0.12±0.01	0.55±0.04	4.4 σ
	f	0.14±0.06	0.47±0.10	1.9 σ
Kepler-102	b	$0.91^{+0.09}_{-0.16}$	0	<1 σ
	c	$0.95^{+0.05}_{-0.30}$	0	<1 σ
	d	0.80±0.14	0	<1 σ
	e	0.22±0.02	0.17±0.07	<1 σ
	f	0.27±0.09	0.04±0.04	<1 σ
TOI-220	b	0.08±0.03	0.62±0.10	<1 σ

Figure 4:Retrieved CMF and WMF of planets in the multi-planetary systems. Low significance levels indicate that the assumption of a water-dominated atmosphere is adequate for a particular planet.

Take-home message

① We present a **homogeneous analysis** of the **compositional trends** of several multiplanetary systems with a self-consistent interior-atmosphere model.

② **Multiplanetary systems** allow us to study both super-Earths and sub-Neptunes that have formed within the same protoplanetary disk simultaneously, making them suitable distant laboratories to explore the **diversity of small planets**, and their formation and evolution pathways.

References

[1] L. Acuña et al., "Characterisation of the hydrospheres of TRAPPIST-1 planets," *A&A*, vol. 647, p. A53, 2021.

[2] S. Hoyer et al., "TOI-220 b: a warm sub-Neptune discovered by TESS," *MNRAS*, vol. 505, pp. 3361–3379, 05 2021.

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