# Thermal effects on the bulk density of rocky planets: the Earth-like composition band

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## ABSTRACT

The diversity of masses and radii of terrestrial exoplanets is commonly attributed to a difference in bulk composition. In the mass-radius plane, terrestrial planets typically lie around the Earth-like iso-composition curve computed from theoretical planet interior structure models. This thought is reinforced by the fact that theoretical interior models predict a mere 1% change in radius when temperature gradients are taken into account. However, there is growing evidence that terrestrial planets had their interiors, core and mantle, fully molten at young ages. Unlike thermal expansion, phase transition between the liquid and solid state is accompanied by a greater change in density. We show that fully molten interiors can be up to 15% less dense than their solidified analogs. This result has important implications for the evolution of atmospheres and hydrospheres on terrestrial planets, and their habitability.

## METHODS: interior of same composition, but different physical state

The main objective of this study is to quantify the difference in radius of a planet between its fully molten and fully solid stages. The timescale of the cooling and solidification processes is beyond the scope of this study. As such, we developed a time-agnostic interior model where **the bulk composition of the planet is always that of the Earth, but the interior is parametrized by the physical state of each layer (liquid or solid) and the surface temperature of the planet (Tsurf)**. The different stages of planet solidification considered here are shown in Figure 1, with the goal of producing mass-radius iso-composition curves for each state.

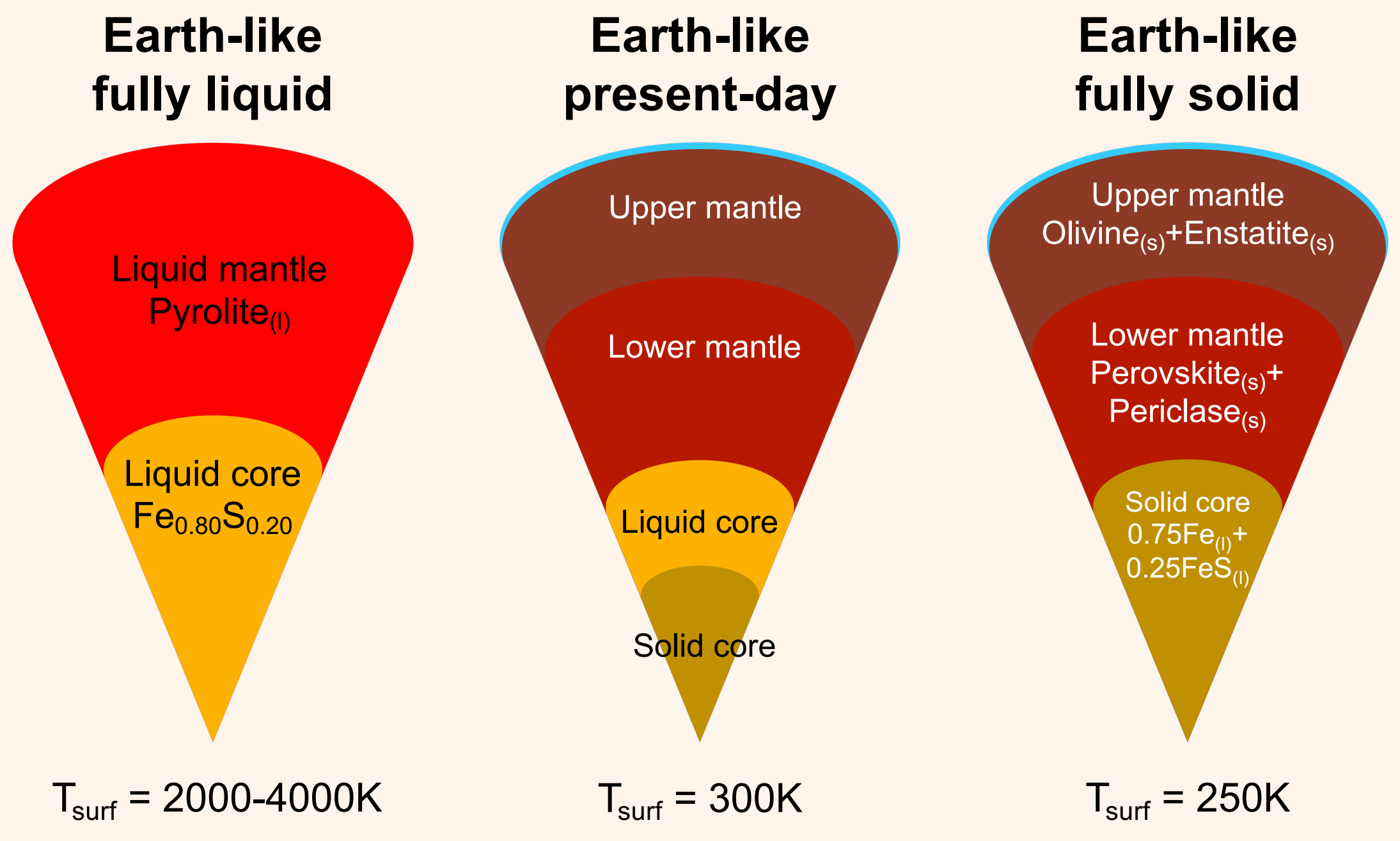


***Figure 1.*** *Visual representation of the different interior structures considered in this study, including the composition of each layer and the corresponding surface temperatures used for modeling the interiors.*

Our interior model is based on the Marseille Super-Earth Interior (MSEI) and Irradiated Ocean Planets (IOP) models [1,2]. We added the possibility of a molten liquid mantle on top of the upper mantle and separated the iron core into its solid and liquid components. We neglect liquid water on the surface due to its negligible thickness (~1.5 km) and do not account for the presence of a high mean molecular weight atmosphere or crust.

We calibrated our model on the Preliminary Reference Earth Model (PREM) [3] by adjusting the Fe to FeS ratio in the solid core and the Fe to S ratio in the liquid core, using existing equations of state (EOS) in the literature. We find a 0.3% difference in radius due to the absence of a crust in our model (24.4 km).

For the molten mantle, instead of using the properties of pure compounds like $MgSiO_3$ or $Mg_2SiO4$, we use the properties of pyrolite, a compound with the same bulk composition as the Earth's mantle, with a molar composition of $NaCa_2Al_3Fe_4Mg_{30}Si_{24}O_{89}$. There is no satisfactory EOS for pyrolite available in the literature, so we used data from simulations [4] and fitted it to a temperature-dependent EOS adapted to liquid compounds [5]. The data and the fit are shown in Figure 2.

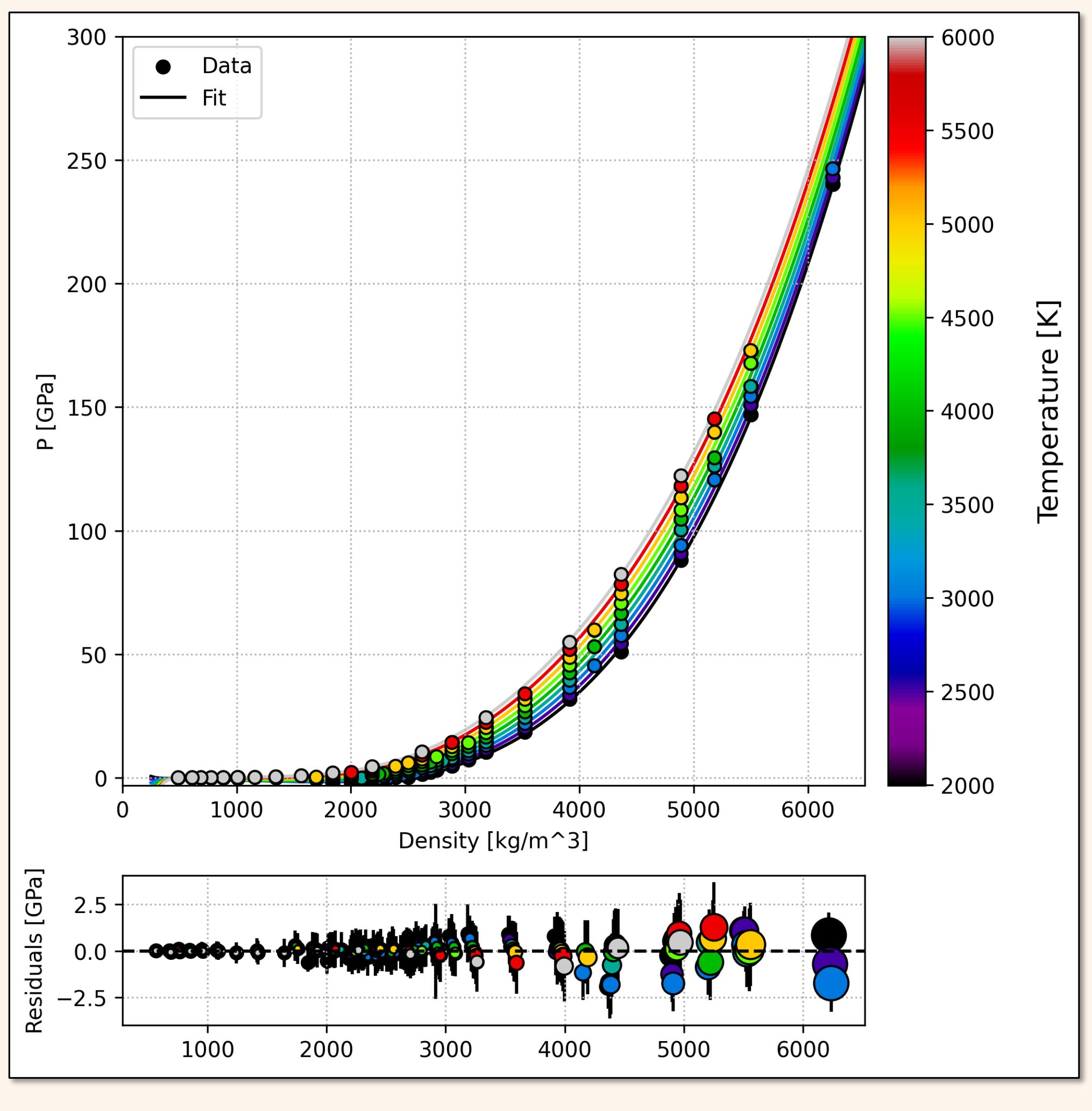


***Figure 2.*** *Top panel: Data from [3] and the fit using the RTpress EOS [4]. Bottom panel: Residuals of the fit. The fitted EOS accurately reproduces the data over a wide range of pressures (0-250 GPa) and temperatures (2000-6000 K).*

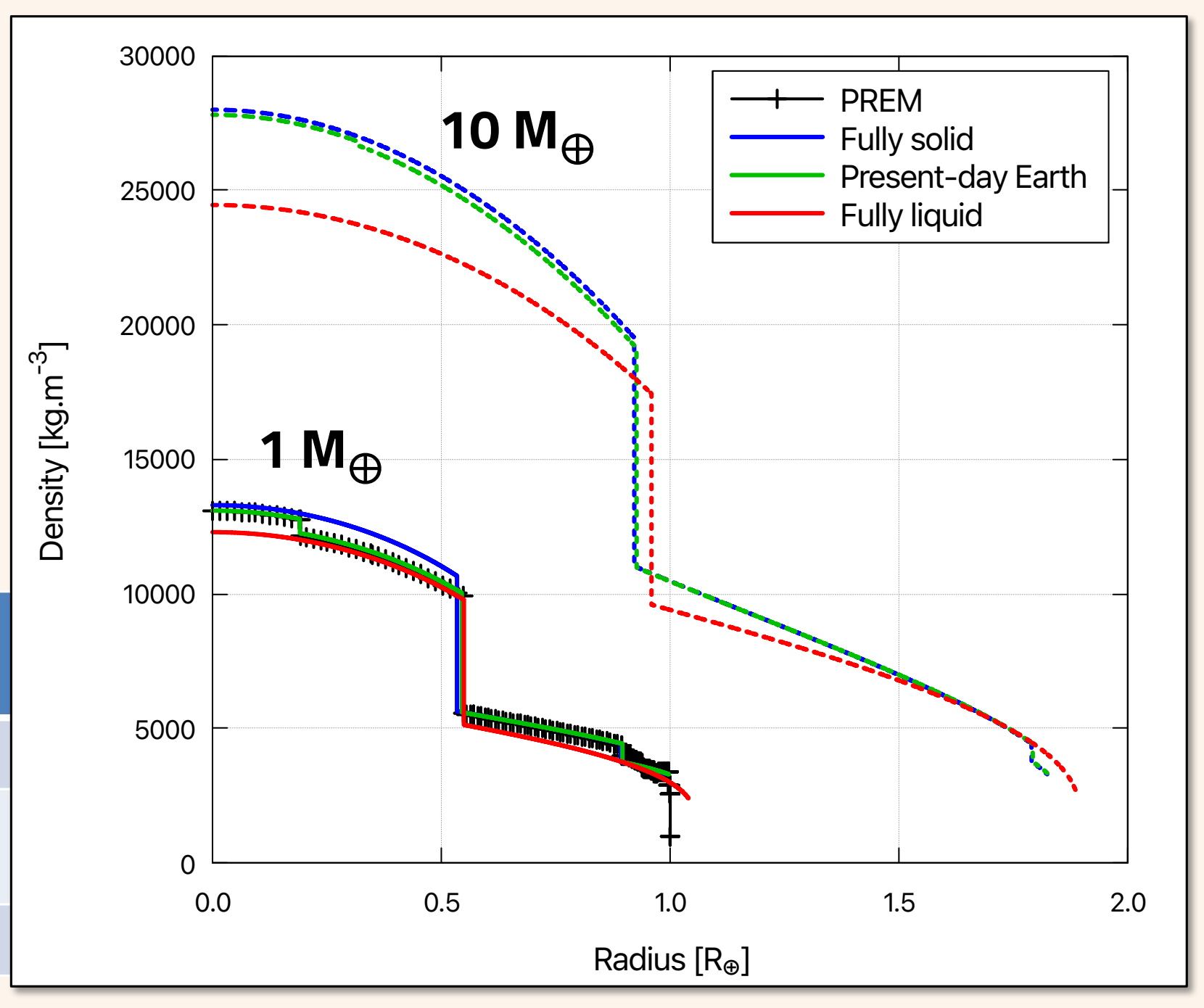
## RESULTS: the Earth-like composition is a band, not a line

Figure 3 shows the density profiles of interiors computed by our model in three cases: fully solid, present-day Earth-like, and fully liquid interiors, for planetary masses of 1 $M_\oplus$ and 10 $M_\oplus$. The corresponding radii are given in Table 1.
Our present-day Earth-like model at 1 $M_\oplus$ reproduces well the density profile of the PREM in all layers. The computed radius is ~20 km lower than that of Earth due to the absence of Earth's crust in our model (24.4 km) [3].
The complete solidification of the iron-rich core has a negligible effect on the planet's radius, marginally impacting the overall planet structure. Conversely, a fully liquid core increases the radius by approximately 1%, and a fully liquid mantle is about 2% more extended than its solid counterpart. For $T_{surf}$ = 2000 K, planets with fully liquid interiors have radii that are roughly 3% larger than the present-day Earth-like structure.

***Figure 3.*** *Density profiles of interiors shown in Figure 1 for planetary masses of 1 $M_\oplus$ and 10 $M_\oplus$. The fully solid, Earth-like, and fully liquid cases have surface temperatures of 250 K, 300 K, and 2000 K, respectively. The density profile of the PREM is also shown for reference.*

***Table 1.*** *Computed radii for the cases shown in Figure 3.*

| Interior | Radius (1 $M_\oplus$) | Radius (10 $M_\oplus$) |
|---|---|---|
| Full solid | 0.993 $R_\oplus$ | 1.823 $R_\oplus$ |
| Present-day Earth-like | 0.997 $R_\oplus$ | 1.825 $R_\oplus$ |
| Full liquid | 1.031 $R_\oplus$ | 1.890 $R_\oplus$ |



We compare the results of our model to the exoplanet population by generating mass-radius relationships, shown in Figure 4. We compute mass-radius relationships of fully liquid interiors with surface temperatures of 2000, 3000, and 4000 K to account for the extremely hot surface temperatures of Ultra Short Period (USP) planets (e.g., the day-side temperature of $3771^{+669}_{-520}$ K on 55 Cnc e [6]). Our present-day Earth-like curve matches well with the curve from [7], with only a 2% deviation in radius at 20 $M_\oplus$.

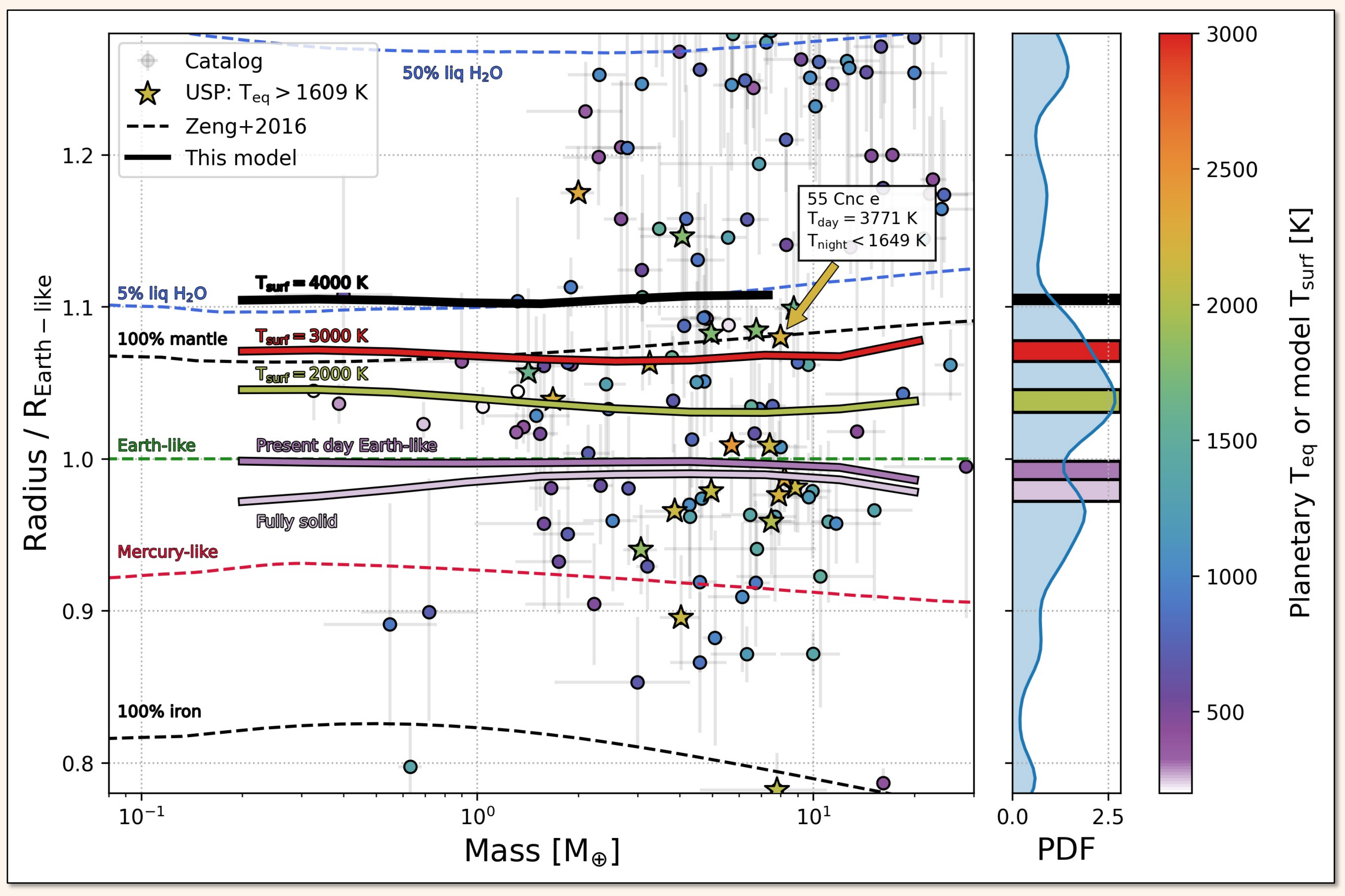
We highlight three main findings from this modeling:

- **Earth-like composition models form a band** in the mass-radius plane, rather than a single line.
- **Fully molten interiors are degenerate** with iso-composition curves for pure mantle and even 5% liquid water interiors.
- There is a **dearth of exoplanets with a present-day Earth-like structure**.

These findings challenge the current paradigm of using radius as a proxy for composition. The large radius of exoplanet 55 Cnc e was previously interpreted as having a pure mantle interior (no iron-rich core). Instead, our model shows that 55 Cnc e could be an exoplanet with an Earth-like composition and a liquid magma ocean with a surface temperature of $T_{surf}$~3000 K. **With this model, the bulk densities of all super-Earths can be explained without any volatile atmosphere or envelope.**

The PDF of normalized radii (left panel of Fig. 4) presents a bimodality, with the two modes being on both sides of the present-day Earth-like composition curve. The high-radius mode can be attributed to a smaller iron core or the presence of a volatile atmosphere/envelope. However, a magma ocean could also significantly contribute to a terrestrial planet's large radius. The low-radius mode is not compatible with fully solid interiors and is better explained by a difference in composition. Alternatively, this could indicate a different physical process not yet understood, or our limited knowledge of equations of state at such high pressures and temperatures. Both possibilities question what the present-day Earth-like interior for super-Earths represents. However, the statistical robustness of the bimodality should also be tested.

***Figure 4.*** *Mass-radius curves produced by our model, showing the range of planetary radii accessible with an Earth-like composition, by modifying the temperature profile and physical state of the interior alone. Conventional mass-radius iso-composition curves from [7] are shown for comparison. The exoplanet catalog[1] is limited to a subsample of planets with mass errors smaller than 50%, in which we highlight Ultra Short Period (USP) planets, for which the equilibrium temperature is higher than the melting point of pyrolite at 1 bar (1609 K). All radii are normalized by the present-day Earth-like composition from [7]. The Probability Density Function (PDF) of normalized planetary radii is shown on the right panel, computed using a gaussian Kernel Density Estimation (KDE). The PDF highlights the bimodal nature of terrestrial planets.*



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[1]https://exoplanetarchive.ipac.caltech.edu/

## DISCUSSION: how to maintain a molten interior?

To infer how realistic is the scenario presented here, it is necessary to determine what processes can maintain a fully molten interior:

(a) The simplest way to maintain such hot interiors is by observing a planet immediately after its formation when the interior still retains energy from accretion. For Earth, this stage is thought to last between 1 and 100 Myr.
(b) If the equilibrium temperature is high, the interior may lose its energy more slowly, maintaining the magma ocean state of the planet for a longer period of time.
(c) The cooling of Earth's iron core is drastically limited by conduction at the core-mantle boundary. Similarly, an insulating crust on the surface of a planet can play a comparable role, as observed on Jupiter's moon Io.
(d) A thick atmosphere can produce a similar effect through its blanketing effect.
(e) Additionally, tidal heating can deposit extra energy into a planet's interior. Many exoplanets, including those in the TRAPPIST-1 system, are likely to experience tidal heating.

These processes, summarized in Figure 5, are not mutually exclusive. An insulating crust could help prevent the dissolution of a thick atmosphere into the magma ocean. In this case, the combination of a crust and atmosphere can efficiently trap the heat produced by tidal heating inside a planet. **These considerations are important for motivating further modeling and identifying observables that would reveal these hidden lava worlds**.

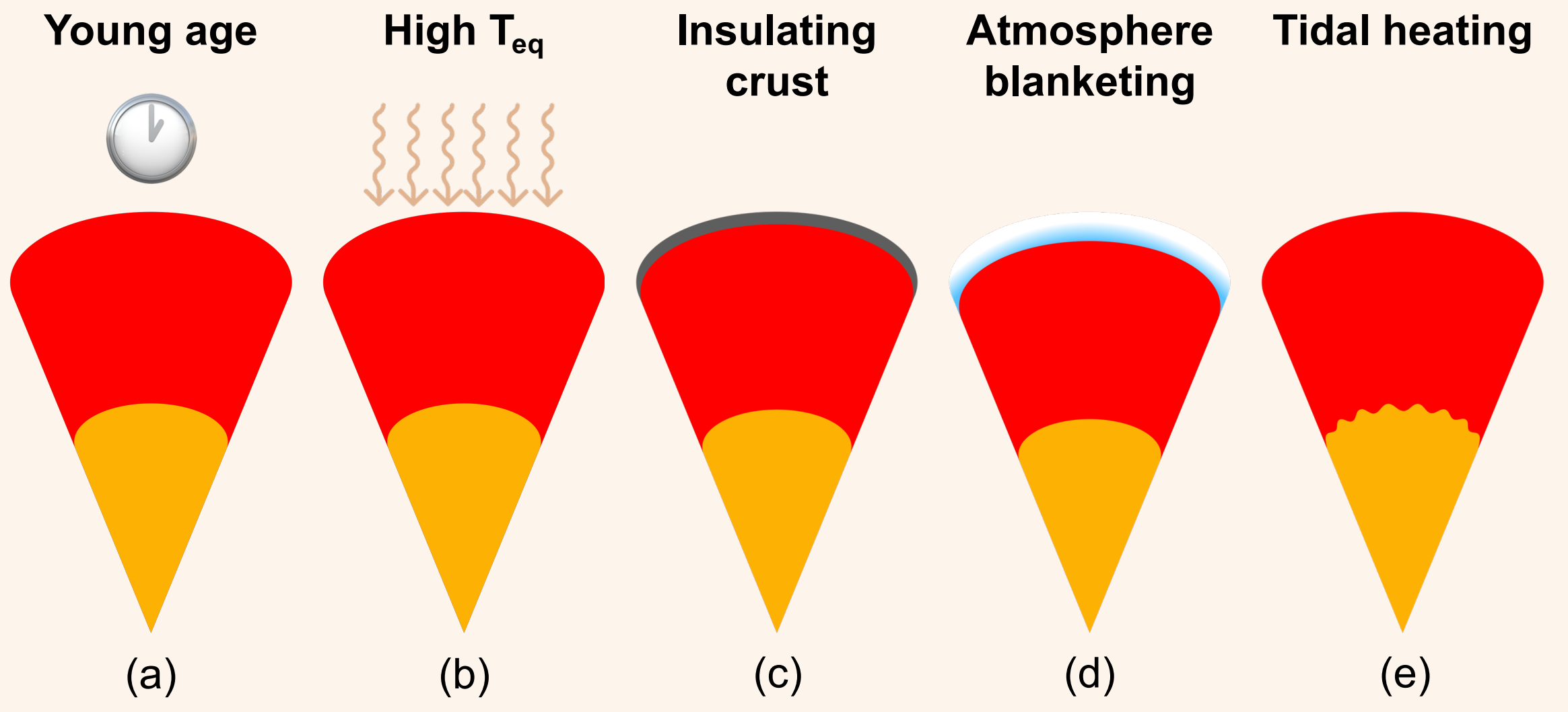

***Figure 5.*** *Physical processes that could maintain fully liquid interiors.*

## ACKNOWLEDGEMENTS

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