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IMPLEMENTATION OF HIGH-PRESSURE PHASES OF WATER ICE IN THE MARSEILLE SUPER-EARTH INTERIOR MODEL

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Abstract. Measurements of the mass and radius of an exoplanet allow the body's mean density to be derived. This quantity gives a rough estimate of the planet's bulk composition, which ranges between those of the terrestrial planets and Jupiter. To better constrain the composition of exoplanets, interior models have been developed, based on our knowledge of the properties of the Earth and other Solar System bodies. We present an evolution of the Marseille super-Earth Interior model developed to assess the composition of solid planets. The Marseille super-Earth Interior model now includes a precise description of the various high-pressure phases of water ice, allowing one to precisely describe the interiors of solid icy planets with densities lower than that of the Earth and located far enough from the host star to harbor significant icy materials in their interiors. We illustrate the results achieved on one exoplanet example.

Keywords: planets and satellites: composition, planets and satellites: interiors

1 Interior model

The Marseille super-Earth interior (MSEI) model consists in a one-dimensional description of a planet made of fully differentiated concentric layers: core, silicate mantle, and hydrosphere. Their respective proportions are controlled by the Core Mass Fraction (CMF) and the Water Mass Fraction (WMF). The model iteratively solves the differential equations for gravitational acceleration, pressure, temperature and density inside the planet (Brugger et al. 2016, 2017). When the surface temperature of an exoplanet is below 250K, different phases of water ice could exist inside those planets, due to the augmentation of pressure and temperature. However, previously in the model, the treatment of the high-pressure ice was restricted to the use of the equation of state (EoS) of ice VII. Here, we implemented the EoS of additional phases of high-pressure water ice to provide a better description of the interiors of low-density Earth-like planets.

2 High-pressure ice phases

There exists a multitude of high-pressure phases of water ice. This is due to the change of crystal structure of the water ice when this one is progressively crushed under high-pressure. The objective is to incorporate four high-pressure ices into our model: ice II, ice III, ice V, and ice VI. They are likely to be present in the interior of planets due to their locations in the water-phase diagram. To implement those ices into the model, it is necessary to find their equation of state (EoS), their thermal parameters and the interfaces between them, which corresponds to their validity range in pressure and temperature. The different EoS forms are displayed in Tab. 1. The thermal parameters and the expressions of the interfaces were found in the literature (Choukroun & Grasset 2010; Dunaeva et al. 2010).

3 Case of Kepler-441b

Kepler-441b is a Super-Earth with a mass and radius of 3.88 ± 0.83 $M_\oplus$ and 1.60 ± 0.23 $R_\oplus$, respectively (Torres et al. 2015). Its equilibrium temperature is $\sim 206 \pm 20$ K and its low bulk density suggest the presence of high-pressure phases of water ice in its interior. The fractions of the various layers calculated in our model

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	Reference density kg.m^{-3}	Form of the EoS	Reference
Ice II	1169.8	V(P, T)	Leon et al. (2002)
Ice III	1139	V(P, T)	Tchijov et al. (2004)
Ice V	1235	V(P, T)	Tchijov et al. (2004)
Ice VI	1270	Second-order Birch-Murnaghan	Bezacier et al. (2014)

Table 1. Reference density, temperature and the form of equation of state used for each phase of water ice.

come from the Core Mass Fraction (CMF) and the Water Mass Fraction (WMF) determined as inputs. The different solutions of the parameters space are represented in a ternary diagram represented in the left panel of Fig. 1. The CMF and WMF are found to be 10.02 % and 9.87 % to derive a radius of 1.60 $R_\oplus$, respectively. These values also allow the model to determine the proportion of each layer in the interior of Kepler-441b (see right panel of Fig. 1).

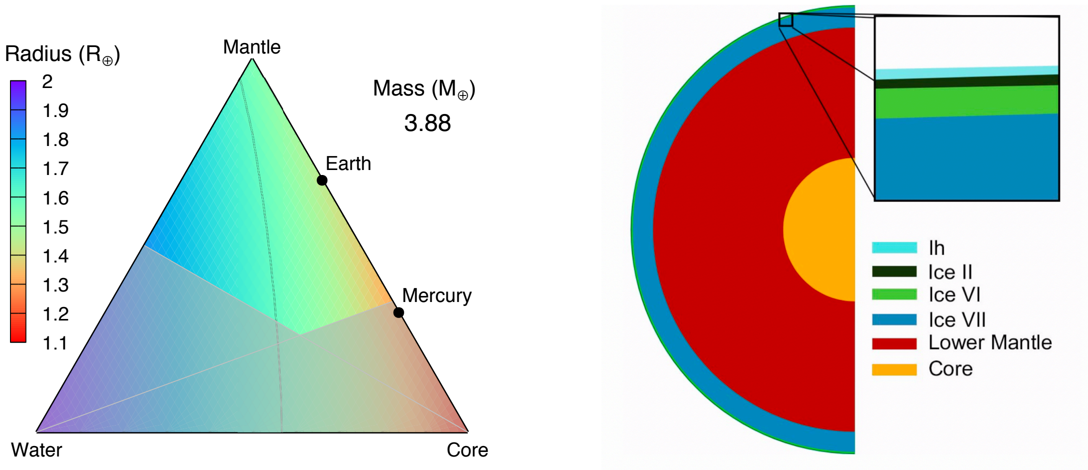

Fig. 1. Left: Ternary diagram displaying the investigated compositional parameter space for a mass $M_p = 3.88 M_\oplus$. The compositions of the Earth and Mercury are indicated for the sake of information. The shaded area corresponds to planet compositions that do not exist in our solar system. **Right:** Interior of Kepler-441b.

4 Conclusions

The implementation of the high-pressure phases of water ice to the MSEI model allows us to provide a better description of the interiors of icy worlds (exoplanets or exomoons) located far from their host stars. This update of the MSEI model will allow to derive the composition of exoplanets at large orbital distance from their host stars, as the upcoming PLATO mission will detect.

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