SF2A 2017
C. Reylé, P. Di Matteo, F. Herpin, É. Lagadec, A. Lançon, Z. Meliani, F. Royer (eds)

MODELING OF EXOPLANETS INTERIORS IN THE FRAMEWORK OF FUTURE SPACE MISSIONS

B. Brugger[1], O. Mousis[1] and M. Deleuil[1]

Abstract. Probing the interior of exoplanets with known masses and radii is possible via the use of models of internal structure. Here we present a model able to handle various planetary compositions, from terrestrial bodies to ocean worlds or carbon-rich planets, and its application to the case of CoRoT-7b. Using the elemental abundances of an exoplanets host star, we significantly reduce the degeneracy limiting such models. This further constrains the type and state of material present at the surface, and helps estimating the composition of a secondary atmosphere that could form in these conditions through potential outgassing. Upcoming space missions dedicated to exoplanet characterization, such as PLATO, will provide accurate fundamental parameters of Earth-like planets orbiting in the habitable zone, for which our model is well adapted.

Keywords: Earth — planets and satellites: composition — planets and satellites: interiors — planets and satellites: individual (CoRoT-7b)

1 Introduction

Despite the huge diversity of detected exoplanets, in terms of orbital and physical properties, our knowledge regarding their composition remains limited. Overcoming this limitation is essential, namely to better understand the formation of the planetary systems we discover (but also our solar system), or to investigate the potential habitability of these extrasolar worlds. Beyond the simple approximation given by an exoplanet's mean density (inferred from its measured fundamental parameters), models of planetary interiors are able to probe the composition of such bodies, based on our knowledge of the interior of the Earth and other solar system bodies (Valencia et al. 2006; Sotin et al. 2007; Seager et al. 2007; Zeng & Seager 2008; Dorn et al. 2015). Such models are however inherently limited by the existence of degeneracies on the investigated compositions, as two planetary bodies of the same size and mass may have different compositions.

The interior model described and applied here aims at breaking this degeneracy by using additional parameters of the studied exoplanets. This model has been developed to handle solid planetary compositions, as all terrestrial planets of the solar system, with possible addition of water in solid and/or liquid phase (Brugger et al. 2017, *submitted*). By making the assumption that the bulk Fe/Si and Mg/Si ratios of a planet are similar to that of its host star, we are able to significantly reduce the degeneracy on the planet's composition, and in particular on the metallic core size. To illustrate this, we apply our model to the well-known Super-Earth CoRoT-7b. We do not investigate here the possibility that this planet is surrounded by a thick gaseous atmosphere.

2 Model and parameters

2.1 Planetary interiors model

Our approach is based on the work by Sotin et al. (2007): a planet in our model can be made from three main layers, namely a metallic core, a silicate mantle, and a hydrosphere. Following our knowledge about the Earth's interior, as well as other solar system bodies, the silicate mantle and the hydrosphere may be divided into two sublayers each. Therefore, we can simulate a planet made of up to five concentric and fully differentiated layers

[1] Aix Marseille Univ, CNRS, LAM, Laboratoire d'Astrophysique de Marseille, Marseille, France (e-mail: `bastien.brugger@lam.fr`)

(see Figure 1). The masses of the three main layers (in terms of fraction of the total planet mass) allow to set the composition of a planet, since the boundaries between two sublayers are directly computed by phase change laws of the corresponding material. By mass conservation, the core and water mass fractions only (hereafter CMF and WMF, respectively) allow to fix the composition. The compositional parameter space of a planet is then completely described by the variations of the CMF and WMF, which can be represented by a ternary diagram, as on Figure 2. Via the use of an equation of state adapted to high-pressures (the Vinet EoS), we are able to provide more accurate radius estimations compared to previous studies. Further details about our approach, as well as about other compositional parameters, can be found in Brugger et al. (2016) and Brugger et al. (2017, *submitted*).

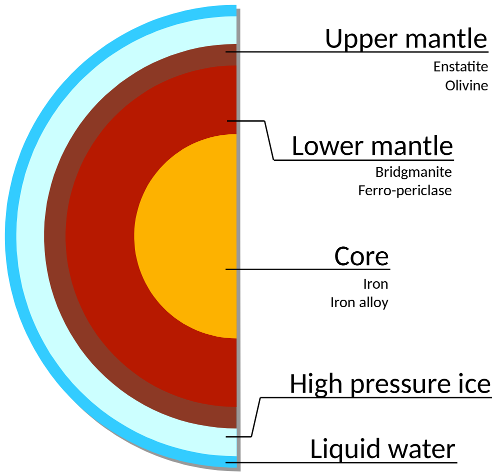

Fig. 1. Schematic view of the different concentric layers that compose our interior model: metallic core, lower and upper silicate mantles, high-pressure water ice, and liquid water. Depending on the mass of the water layers, the upper mantle or the high pressure ice layer may be absent.

2.2 Physical limitations on planetary compositions

Valencia et al. (2007) suggested two physical limitations to be placed on the composition of studied exoplanets, both taken from solar system formation conditions. From this, they exclude values of the CMF and WMF that are over 65% and 77%, respectively. In our work, we lower the limit on the WMF to 50%, based on the composition of large icy satellites in our solar system (Brugger et al. 2016). However these considerations are only valid if we assume that all studied exoplanets formed in the same conditions as in our solar system, which is an important limitation. Placing constraints on the composition of exoplanets from the chemical abundances of their host star is more adapted, since these abundances rule the composition of the protoplanetary disk from which these planets formed. Using a model of planet formation, Thiabaud et al. (2015) indeed showed that the Fe/Si and Mg/Si ratios of a star are retrieved in the planets that formed around it. With this assumption, and by incorporating the bulk Fe/Si ratio of a planet into our code, we show that this parameter can be linked to the CMF and WMF of the planet (see Figure 2). This significantly reduces the set of compositions compatible with the planet's fundamental parameters.

3 Results and discussion

CoRoT-7b is a well-known exoplanet, representative of the Super-Earth family, with a mass and radius of $3.72 \pm 0.42\ M_\oplus$ and $1.47 \pm 0.03\ R_\oplus$, respectively (Barros et al. 2014; Haywood et al. 2014). Its composition and interior have been studied by Valencia et al. (2010), who concluded that the planet was not compatible with an Earth-like composition, and that it should present a significant depletion in iron in order to remain rocky. Here, we apply our model to CoRoT-7b, with the use of the planet's Fe/Si ratio, estimated from the host-star abundances to be 0.826 ± 0.419 (Brugger et al. 2017, submitted). With these parameters, we investigate the composition of CoRoT-7b in the entire ternary diagram, assuming that the surface conditions of the planet are

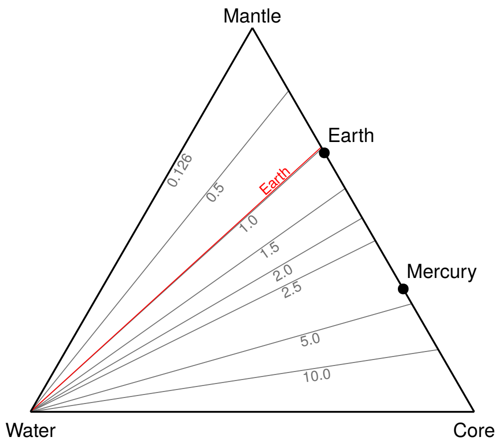

Fig. 2. Isolines of constant planetary Fe/Si ratio in the ternary diagram. The Earth's value is shown in red.

Earth-like. Our results are shown on Figure 3. From the mass and radius of CoRoT-7b, we constrain its CMF in the 0–50% range, showing that this data is compatible with an Earth-like composition (32.5% CMF). By incorporating the Fe/Si ratio of this planet, this range is significantly reduced, to 13–37%, which still includes an Earth-like composition. The WMF of CoRoT-7b, on the other hand, can be estimated to be 31% at maximum from the same data, and is not significantly modified by the incorporation of the Fe/Si ratio. This latter result is however strongly overestimated given the planet's high equilibrium temperature, since water on the surface of CoRoT-7b would rather be in the vapor (or supercritical) phase.

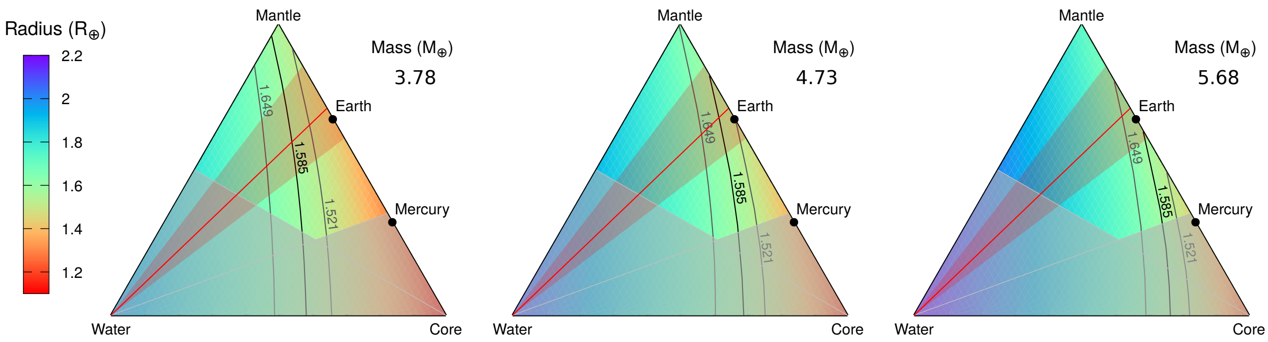

Fig. 3. Ternary diagrams displaying the investigated compositional parameter space of a cold water-rich CoRoT-7b for the minimum, central, and maximum masses inferred by Haywood et al. (2014), using 1σ uncertainties. Also shown are the isoradius curves denoting the planet radius measured by Barros et al. (2014) with the 1σ extreme values. Two areas of the diagrams are excluded from the study, based on assumptions on the solar system's present properties (Brugger et al. 2017, submitted). The Fe/Si ratio assumed for CoRoT-7b, with its associated uncertainties, delimit a line and an area represented in red.

We showed here that our model is able to constrain the compositional parameter space of a given exoplanet from its mass and radius measurements only, and that this space can be even more restrained if we use the bulk Fe/Si ratio of the planet (taken equal to the stellar value, following planet formation models). In the case of CoRoT-7b, we show in particular that this planet is compatible with an Earth-like composition, unlike in previous studies, which strengthens its Super-Earth status. Our model is not yet adapted to the case of hot water-rich exoplanets that orbit close to their star, even if it still can be used to derive the maximum water amount of the planet. However, in the future, space missions as PLATO will be dedicated to the search of Earth-like candidates orbiting within their host star's habitable zone, where water can be stable in the liquid phase. Our model is thus well prepared to the study of such planetary interiors.

The project leading to this publication has received funding from Excellence Initiative of Aix-Marseille University - A*MIDEX, a French "Investissements d'Avenir" program. O.M. and M. D. also acknowledge support from CNES.

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