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Constraints on low mass Exoplanets Interiors from Stellar Abundances

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Abstract

Through models of planetary structure, we can now probe the interior and composition of the hundreds of exoplanets with known masses and radii. In addition to the still limited precision on the fundamental parameters of these bodies, models are limited by the existence of degeneracies when deriving a planet's composition. Here we present a model of internal structure developed to study the interior of planets up to $\sim$10 Earth masses. To break the degeneracy, the model takes into account the Fe/Si ratio of a simulated planet, assuming it is equal to that of the host star. This allows to precisely constrain the compositional parameters of the body, and shows the importance of measuring the elemental abundances of exoplanet-hosting stars.

1. Introduction

The huge diversity of detected exoplanets, in terms of physical and orbital parameters, has revealed that terrestrial and giant gaseous planets such as those in our system are not the only families of planetary bodies. In particular, Super-Earths and sub-Neptunes fill the gap that exists in the 1–10 $M_\oplus$ range in the solar system. Knowing their composition brings key constraints to understand the formation conditions of the various planet families. The mean density of a planet only gives a rough estimate on its composition. Models of planetary interiors overcome this limitation by precisely constraining the composition and internal structure of a planet.

Here we present an interior model able to handle compositions as various as those of small planets and large satellites of the solar system. It uses an equation of state adapted to high-pressure materials, and is designed to explore a large range of compositions for solid terrestrial planets. A degeneracy inherent to such models however remains on a planet's composition, independently from the precision on its fundamental parameters. We show that taking into account the bulk Fe/Si ratio of a planet, derived from stellar abundances, allows to break this degeneracy.

2. Interior model and parameters

All planets considered in our model are fully differentiated into three main layers: a metallic core, a silicate mantle, and a water envelope. The metallic core is composed of iron and iron alloy FeS. Depending on the pressure and temperature conditions, the mantle may be divided into two sublayers, that contain different phases of silicate rocks. Likewise, the water envelope can divide into a layer of high-pressure ice and a liquid water layer on top. The mass and size of these layers fix the composition of a planet, and they are linked through the model, which is able to reproduce the behavior of a given material. Moreover, the boundaries between two phases of the same material are computed from its phase change laws. Therefore, only the locations of the core-mantle and mantle-envelope boundaries are required to fix the composition of the planet. These variables are equivalent to the masses of the three main layers, and from mass conservation to the planet mass, the core mass fraction (CMF) and the water mass fraction (WMF). Therefore, in the following, the "composition" of an exoplanet refers to the pair (CMF,WMF).

The distribution of chemical species in the different layers and sublayers is described by another set of parameters [2], which do not have a significant influence on the computation of a planet's radius compared to the CMF and the WMF. Therefore, they are fixed to produce a distribution of materials which reflects that of the Earth [1]. For a given composition and planetary mass, the model computes the profiles of gravitational acceleration, pressure, temperature, and density inside the body, and computes the corresponding radius. In this work, we use the Vinet equation [3] as equation of state. It is more suited than other equations of state in describing the behavior of a given material, but also extrapolates better at large pressures [4].

3. Results

The parameter space formed by the variations of the CMF and the WMF can be represented as a ternary diagram (see Figure 1). For a given planet mass, each point on the diagram corresponds to a unique composition, and yields a planetary radius through the model. Isoradius curves can be drawn on the produced colormap, on which the planetary radius is constant. These curves show the degeneracy that exists when using a model of internal structure: a set of fixed planetary mass and radius can be explained by all the compositions located on the corresponding isoradius curve. To reduce this set of possible compositions, we fix limits on the CMF and WMF by considering formation conditions of the solar system. Reflecting the composition of the icy moons of Jupiter and Saturn, we place an upper limit of 50% on the WMF [1]. Similarly, the value of the Fe/Si ratio in the protosolar nebula allows to rule out compositions with a CMF larger than 65% [1]. The corresponding areas on the ternary diagram are shaded. However, these limitations are based on solar system conditions, which may not be relevant for a large part of known planetary systems, and other parameters better reduce the set of possible compositions.

The degeneracy on the composition can be broken by taking into account the bulk Fe/Si ratio of the planet. This planetary parameter cannot be measured, thus we assume its value to reflect the stellar ratio, a hypothesis that is verified by models of planetary formation [5]. As for the planet radius, the Fe/Si ratio of a planet can be computed for a given composition, and thus lines of constant Fe/Si ratio can be drawn on the ternary diagram. For a given set of planet mass, radius, and Fe/Si ratio, only one composition is possible.

4. Discussion

We have developed a model that allows to simulate the interior of planets with various compositions, from terrestrial (i.e. fully rocky) planets like the Earth or Mercury, to ocean planets that possess a massive envelope of water. Using the Vinet equation of state, our model is more adapted to describe planets with masses under $\sim$10 $M_\oplus$ compared to previous studies. The degeneracy that exists on a planet's composition for a given set of mass and radius is efficiently broken with the incorporation of the body's bulk Fe/Si ratio, and is independent from solar system conditions. As this parameter is directly derived from the stellar abundances, we hereby show the importance of precisely measuring the chemical composition of exoplanet-hosting stars.

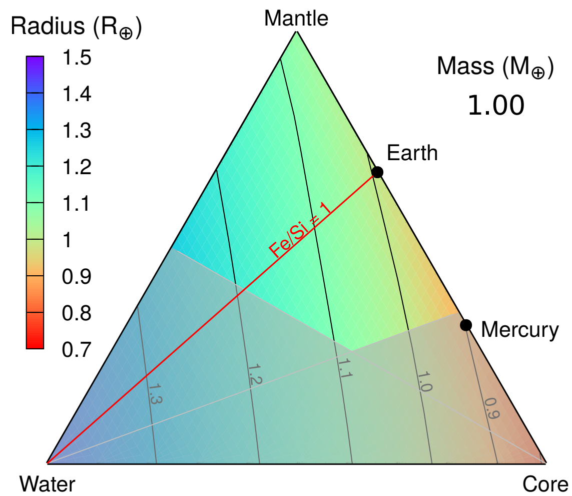

Figure 1: Ternary diagram displaying the compositional parameter space of a 1 $M_\oplus$ planet. A colored map of the planet radii is shown, with isoradius curves and a line of constant bulk Fe/Si ratio. The grey areas correspond to compositional limitations based on solar-system formation.

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