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Is the Super-Earth 55 Cancri e still a carbon-rich planet?

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Abstract

The Super-Earth 55 Cancri e forms one of the best cases for the study of planetary interiors, as its physical properties are known with an unrivaled precision. Using the latest estimates of these parameters, we investigate the composition and internal structure of 55 Cancri e as a solid silicate-rich planet and confirm that the planet is not dense enough to be purely rocky. A water-rich composition presents limitations, especially given the planet's surface conditions. The measured mass and radius of 55 Cancri e can however be reconciled by considering a composition based on carbon materials. As the latest measurements tend to discuss the likelihood of such an extremely carbon-rich composition, we think that 55 Cancri e constitutes a strong test case for the investigation of hybrid compositions containing both silicates and carbon molecules.

1. Introduction

Probing the composition of exoplanets is possible through the use of planetary interiors models, who allow to constrain the internal structure of these bodies. A precision of a few percent is required on the fundamental parameters (mass and radius) of an exoplanet to precisely derive its composition. The Super-Earth 55 Cancri e (hereafter 55 Cnc e) meets these requirements, as it orbits a bright and close solar-type star, 55 Cancri [1, 2]. The use of precise interferometric measurements and improved stellar models provided an error under 6% on the planet's mass, and 4.5% on its radius [3].

Here we perform a detailed study of 55 Cnc e's interior with these parameters, that is a mass of $8.631 \pm 0.495\ M_{\oplus}$ and a radius of $2.031^{+0.091}_{-0.088}\ R_{\oplus}$ [3]. We first explore the case of a terrestrial planet (i.e. fully rocky) with a possible water envelope. A theoretical kind of planets is then considered, formed from different materials than those that predominate in the solar system, that is carbon-based molecules. We then discuss the legitimacy of the compositional parameters derived for 55 Cnc e in both cases.

2. Interior model and parameters

Our model is presented in [4], it computes the radius of a planet from its known mass and assuming a composition. A planet described by this model is constituted by three concentric and fully differentiated main layers: a core, a mantle, and an envelope. Depending on the kind of planet we consider, these layers are formed from different materials. For terrestrial planets, our model takes the Earth as a reference and these layers are made of metals (iron and iron alloy), silicate rocks, and water, respectively. The two latter layers may be divided into two sublayers each because of phase changes of the corresponding materials. The two mantle sublayers contain different silicate rocks, whereas the water envelope divides into a liquid water layer on top of a high-pressure ice layer. In the case of a carbon-rich planet, the core is also made of iron metals. The mantle is solely composed of silicon carbide SiC, surrounded by a pure carbon envelope. The carbon envelope may divide into graphite and diamond sublayers.

The composition of a planet is thus fixed by the mass of the three main layers, therefore we define two parameters in our model: the core mass fraction (CMF) and envelope mass fraction (EMF), that are varied in the 0 to 1 range. We exclude from our simulations planets that harbor a thick gaseous atmosphere. However, to allow the presence of liquid water at the surface of simulated terrestrial planets, we consider the surface conditions to be close to those of the Earth (1 bar pressure and 288 K temperature).

3. Results

We perform a simulation of the interior of 55 Cnc e for every composition allowed by the variations of the CMF and EMF. The parameter space formed that way is represented as a ternary diagram (see Figure 1). Here we present the results obtained for a terrestrial planet of a mass of 8.63 $M_{\oplus}$. Two parameters allow to reduce the explored set of compositions and place constraints on the values of the CMF and EMF. The first parameter is the planet's radius, whose range estimated by [3] is plotted on Figure 1. The compositions located between the isoradius curves that show the 1σ values are those compatible with both a mass of 8.63 $M_\oplus$ and a radius between 1.943 and 2.122 $R_\oplus$. To lower the important degeneracy that appears, a second parameter is taken into account, namely the Fe/Si bulk ratio of the planet, which is assumed to be identical to the stellar value. Here we take Fe/Si = 0.903 ± 0.287, derived from [5]. The grey area on the ternary diagram shows the 1σ values of the Fe/Si ratio. From these constraints, we derive the allowed ranges for 55 Cnc e's CMF and EMF when considering terrestrial materials: 10–30% for the CMF, and 10–50% for the EMF (i.e. water mass fraction). With such a structure, 55 Cnc e cannot be fully rocky like the Earth. A significant water amount is needed to explain the planet's radius and Fe/Si ratio.

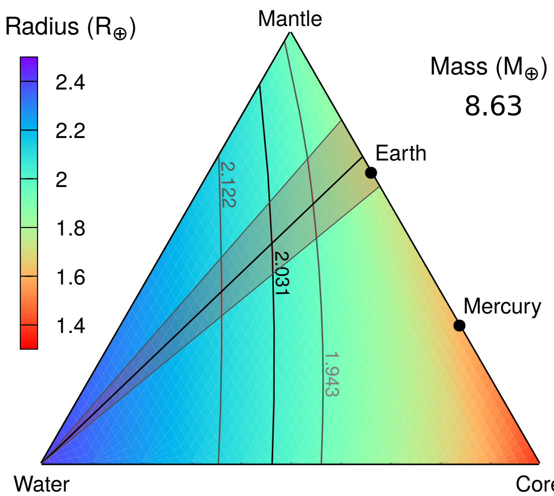

Figure 1: Ternary diagram displaying the compositional parameter space of a 8.63 $M_\oplus$ 55 Cnc e. A colored map of the planet radii is shown, with isoradius curves denoting the central and 1σ values from [3]. The darkened area delimits which compositions are compatible with the stellar Fe/Si ratio from [5].

We use the same methodology in the case of a carbon-rich planet, and explore the ternary diagram of metallic core, SiC mantle, and pure carbon envelope. With the constraint from the planet's radius, we obtain a range of 0–35% for the CMF, and 0–90% for the EMF. These results show that the measurement of the radius strongly constrains the CMF in the case of carbon-rich planets, compared to the EMF.

4. Discussion

We investigated the composition of the Super-Earth 55 Cnc e using updated stellar parameters. Assuming terrestrial materials imposes the planet to be an ocean world (at least 10% of water in mass). A fully rocky composition is excluded by the measured radius and stellar Fe/Si ratio. Following recent studies suggesting that 55 Cnc e is carbon-rich [6, 7], we explored the impact of such an enrichment on the planet. The modeling shows that the mass and radius of 55 Cnc e can be explained by a small metallic core surrounded by a mantle and an envelope of carbon materials. Although recent estimates of stellar abundances suggest that the planetary system is less enriched in carbon than previously reported [5], the planet has likely a hybrid composition with both oxygen and carbon-based molecules. Further studies have to be carried out to determine the structure of materials that would form in such conditions.

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