EPSC Abstracts
Vol. 11, EPSC2017-345-3, 2017
European Planetary Science Congress 2017

The Interior of Kepler-406b, a high-density solid exoplanet

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Abstract

Using an interior model developed to investigate the interior of solid terrestrial planets, we provide precise constraints on the possible compositions and internal structures of Kepler-406b, which is a high-density exoplanet (ρ = 11.82 ± 2.70 g/cm^3). We find that, to account for its measured mass and radius, Kepler-406b has to possess a massive metallic core corresponding to at least 52% of the planet's mass. Solar system formation conditions set an upper limit to this fraction at 65%, however a limit more adapted to the Kepler-406 system needs to be brought from measurements of the elemental abundances of this host star.

1. Introduction

Diversity is the main characteristic that appears with the increasing number of detected exoplanets. Exotic worlds have been discovered, in terms of orbital and physical parameters, compared to the planets of our solar system. These parameters have been estimated for 49 planets within 22 planetary systems observed with the *Kepler* mission, most of them being small-mass exoplanets within the terrestrial to icy giant regime (masses under ∼20 $M_\oplus$) [1] . Detections of planets with extreme mean densities have been reported, ranging from 0.90 ± 0.21 g/cm^3, to 11.82 ± 2.70 g/cm^3.

Such extreme values of mean density raise the question about the composition of these exoplanets, which can be probed using models of planetary interiors. Here we perform the detailed study of one exoplanet among those with extreme densities detected by [1], namely Kepler-406b. This planet has a measured mass of 6.35 ± 1.4 $M_\oplus$, and a radius of 1.43 ± 0.03 $R_\oplus$, yielding a density of 11.82 ± 2.70 g/cm^3 (which is above the density of pure iron at ambient conditions, 8.34 g/cm^3 [2]). Using an interior model of solid exoplanet, we derive constraints on the possible compositions and internal structures of Kepler-406b that are compatible with these measurements.

2. Interior model and parameters

A planet described by our model (see [3] for details) is constituted by three concentric and fully differentiated main layers: a metallic core, a silicate mantle, and a water envelope. 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.

Because the composition of a planet is fixed by the mass of the three main layers, we define two parameters in our model: the core mass fraction (CMF) and the water envelope mass fraction (WMF), that are varied in the 0–1 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). The physical and orbital parameters of Kepler-406b and its host star Kepler-406 are summarized in Table 1.

Table 1: Physical and orbital properties of Kepler-406b and its host star Kepler-406 [1].

Parameter	Unit	Value
Planet parameters		
Orbital period	day	2.42629
Planet mass	$M_\oplus$	6.35 ± 1.4
Planet radius	$R_\oplus$	1.43 ± 0.03
Planet density	g/cm^3	11.82 ± 2.70
Stellar parameters		
Effective temperature	K	5538 ± 75
Star mass	$M_\odot$	1.07 ± 0.06
Star radius	$R_\odot$	1.07 ± 0.02

3. Results

We perform a simulation of the interior of Kepler-406b for every compositions allowed by the variations of the

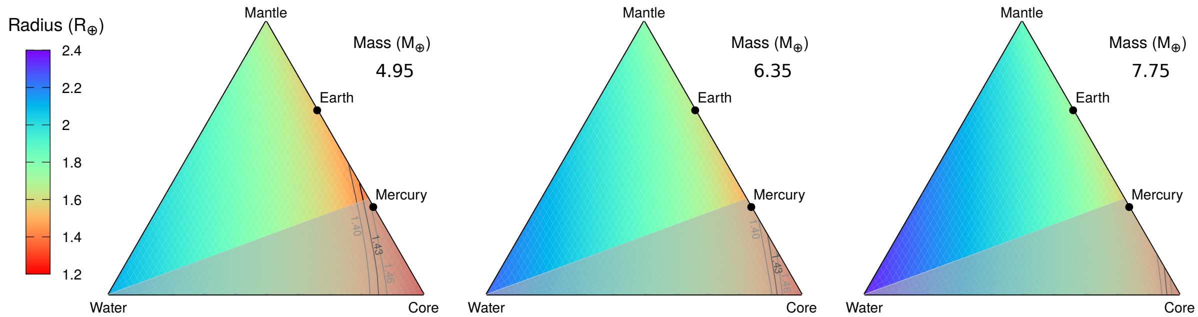

Figure 1: Ternary diagrams displaying the compositional parameter space explored for Kepler-406b, for three values of the planet mass: the minimum, central, and maximum values inferred by [1] using 1σ uncertainties. Also shown are the isoradius curves denoting the measured planet radius with its 1σ extreme values [1]. The shaded region covers compositions incompatible with solar system formation conditions.

CMF and WMF. The parameter space thus formed is represented by a ternary diagram (as those displayed in Figure 1). We explore the planet composition from its measured mass and associated 1σ error, giving 4.95, 6.35, and 7.75 $M_\oplus$. The compositions located between the isoradius curves denoting the 1σ values on each ternary diagram of Figure 1 are those compatible with both a mass between 4.95 and 7.75 $M_\oplus$ and a radius between 1.40 and 1.46 $R_\oplus$. Our simulations show that Kepler-406b possesses a massive metallic core, with a CMF between 52% and 95%. In comparison, Mercury has a CMF of 68% [4]. Such high CMF values can be considered unlikely regarding the formation conditions of planets in the solar system. If one assumes that these planets have compositions derived from that of the protosolar nebula, CMF higher than 65% are then excluded [5]. The corresponding area on the ternary diagrams of Figure 1 is shaded. This assumption rules out an important part of the set of compositions derived for Kepler-406b, and the density measurement can only be explained if i) the planet's mass corresponds the lowest value of the investigated mass range and ii) the CMF is between 52% and 65%.

4. Discussion

We investigated the internal structure and composition of Kepler-406b, under the assumption that it is a terrestrial planet with possible addition of water. To account for its measured mass and radius, Kepler-406b has to possess a massive metallic core corresponding to at least 52% of the planet's mass. According to our study, this fraction may go up to 95%, which is incompatible with solar system formation conditions that exclude CMF values over 65%. Applying this assumption to a planetary system different from the solar system is questionable, since the formation conditions of Kepler-406b may have been different. This can be investigated by measuring the elemental abundances of the host star Kepler-406, and in particular its Fe/Si ratio, which is shown to be identical for the host star and for orbiting planets [6].

Acknowledgements

B.B. and O.M. acknowledge support from the A*MIDEX project (n° ANR-11-IDEX-0001-02) funded by the "Investissements d'Avenir" French Government program, managed by the French National Research Agency (ANR). O.M. and M.D. also acknowledges support from CNES.

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