Structure and Composition of Transiting super-Earths

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PLANETARY EVOLUTION AND LIFE

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Introduction

Over the last two decades, astronomers have discovered about thirty super-Earth-sized (1-10 $M_\oplus$) objects orbiting stars other than the Sun. In the recent years, modeling the interior structure has become a major task to characterize and classify these bodies. Two outstanding examples are CoRoT-7b and Kepler-10b, for which planetary radius *and* total mass have been measured. Both planets are in particular interesting due to their presumably terrestrial-type bulk composition.

Here, we apply our model approach to investigate the internal structure, thermal state, and bulk composition of transiting super-Earth-sized exoplanets. Particularly by taking CoRoT-7b and Kepler-10b as type-examples, we aim to determine the physical state of the deep interiors of rocky planets.

Model

Model Assumptions

Planets are considered…

- as spherically symmetric and fully differentiated
- in perfect mechanical equilibrium and thermal steady state

Model Constraints

- Mean density obtained by transit and radial velocity measurements
- Cosmochemistry

Structural Equations and Thermal Model

- Mass, *m*

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

- Pressure, *P*

$$\frac{dP}{dr} = -\rho g$$

- Gravity, *g*

$$\frac{dg}{dr} = 4\pi G\rho - 2\frac{g}{r}$$

- Density, *ρ*

$$\rho(r) = f_{EoS}(P(r), T(r))$$

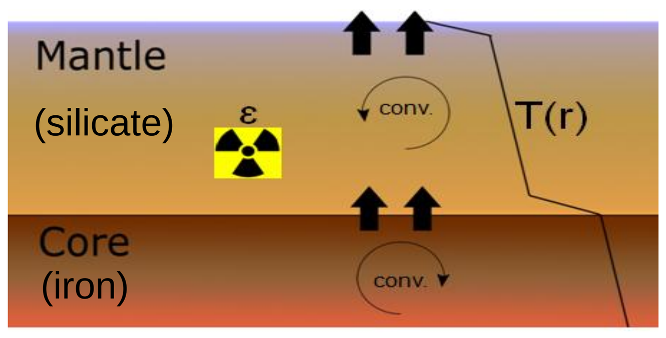

Fig. 1: Schematic representation of the model. A mixing length formulation [1] is used to calculate self-consistently the effective heat transport within the mantle.

- Heat flux, *q*

$$\frac{dq}{dr} = \epsilon\rho - 2\frac{q}{r}$$

- Temperature (mantle), *T*

$$\frac{dT}{dr} = -\frac{q}{Nu_r k_c}$$

- Temperature (core), *T*

$$\frac{dT}{dr} = -\frac{\gamma}{\Phi} g T$$

r: radius
G: gravitational constant
Nu_r: local Nusselt number
k_c: thermal conductivity
γ: Grueneisen gamma
Φ: seismic parameter obtained from an EoS

Planet (model)	CoRoT-7b (C1)	CoRoT-7b (C2)	CoRoT-7b (C3)	Kepler-10b (K1)	Earth	Ref.
Mass M_p [$M_\oplus$]	5.2±0.8	5.2±0.8	6.9±1.4	$4.56_{-1.29}^{+1.17}$	1.	A,B,C
Radius R_p [$R_\oplus$]	1.58±0.10	1.58±0.10	1.58±0.10	$1.416_{-0.036}^{+0.033}$	1.	A,C
Density (average) ρ_{avg} [g cm^{-3}]	7.2±1.8	7.2±1.8	9.6±2.7	$8.8_{-2.9}^{+2.1}$	5.515	A,B,C
Temperature (surface) T_s [K]	1300	1300	1300	1300	300	assumed
Heat production rate ε [pW kg^{-1}]	7.39	36.9	7.39	7.39	7.39	assumed
Pressure (surface) P_s [hPa]	0.	0.	0.	0.	1010	assumed

***Tab. 1:** Input parameters obtained from either observational measurements or reasonable assumptions.*

Conclusions

It is concluded that CoRoT-7b and Kepler-10b are most likely dry and rocky planets with a terrestrial bulk composition. For the given planetary radius (1.58 $R_\oplus$) and total mass (5.2 $M_\oplus$), CoRoT-7b is expected to harbor an iron core of 35 wt.-%, which is similar to the Earth's (32.6 wt.-%). Assuming a planetary mass of 6.9 $M_\oplus$, calculations suggest a much larger iron core of 60 wt.-%. Furthermore, it is shown that radiogenic heating has a negligible effect on planetary structures. This finding implies that the interior structure of CoRoT-7b is independent of the internal heating rate. For Kepler-10b, our model yields a relatively high iron core mass fraction of 59.5 wt.-% in comparison to the Earth's, but similar massive as the second CoRoT-7b scenario. All other transiting exoplanets with measured properties (M_p and R_p) resemble hot gaseous planets due to their low mean densities.

Acknowledgement

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Results

Mass-Radius Relationships and Transiting super-Earth-sized Exoplanets

- Relationship between planetary mass and radius can be used to infer the bulk composition of an exoplanet

Kepler-10b:

- Kepler-10b is a rocky planet under the assumption of a high surface temperature due to its close proximity
- As endmember scenarios an Earth-like bulk composition corresponding to an iron core of 32.6 wt.-% and a Mercury-like (70 wt.-% iron core) planet are barely possible
- A coreless silicate planet and a pure iron sphere can be ruled out

CoRoT-7b:

- Taking a high surface temperature into account, CoRoT-7b is a dry and rocky planet
- Depending strongly on the actual planetary mass, a pure silicate planet is as possible as a Mercury-like body with a relatively high iron content

GJ 1214b, Kepler-11b, and Kepler-11f

- Low densities imply planets with extended atmospheres and a bulk composition similar to the gas giants within the solar system

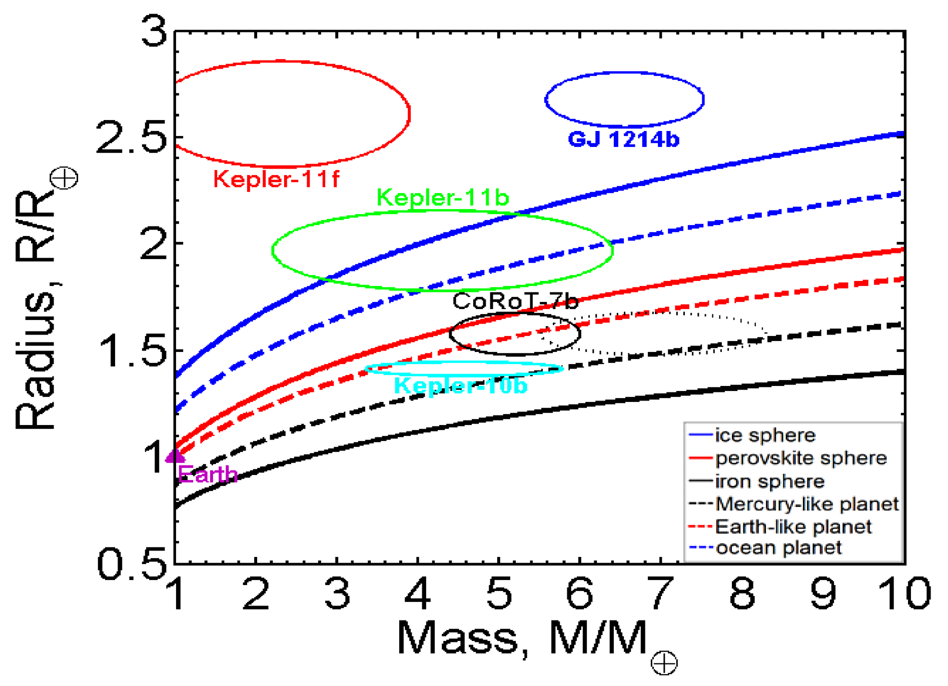

Fig. 2: Mass-radius relationships for differentiated exoplanets (dashed lines) and homogeneous, self-compressible spheres of water, silicate, and iron (solid lines). The triangle denotes the position of the Earth for orientation. The relative positions of transiting super-Earth-sized exoplanets with a measured mass and radius are indicated by solid ellipses of different colors. Whereas another possible solution [B] for the CoRoT-7b exoplanet is shown as dotted ellipse. The size of an ellipse corresponds to observational uncertainties. To determine the bulk composition of Earth-sized objects, highly precise instruments are needed, e.g. PLATO.

Detailed Interior Structure and Present Thermal State of CoRoT-7b and Kepler-10b

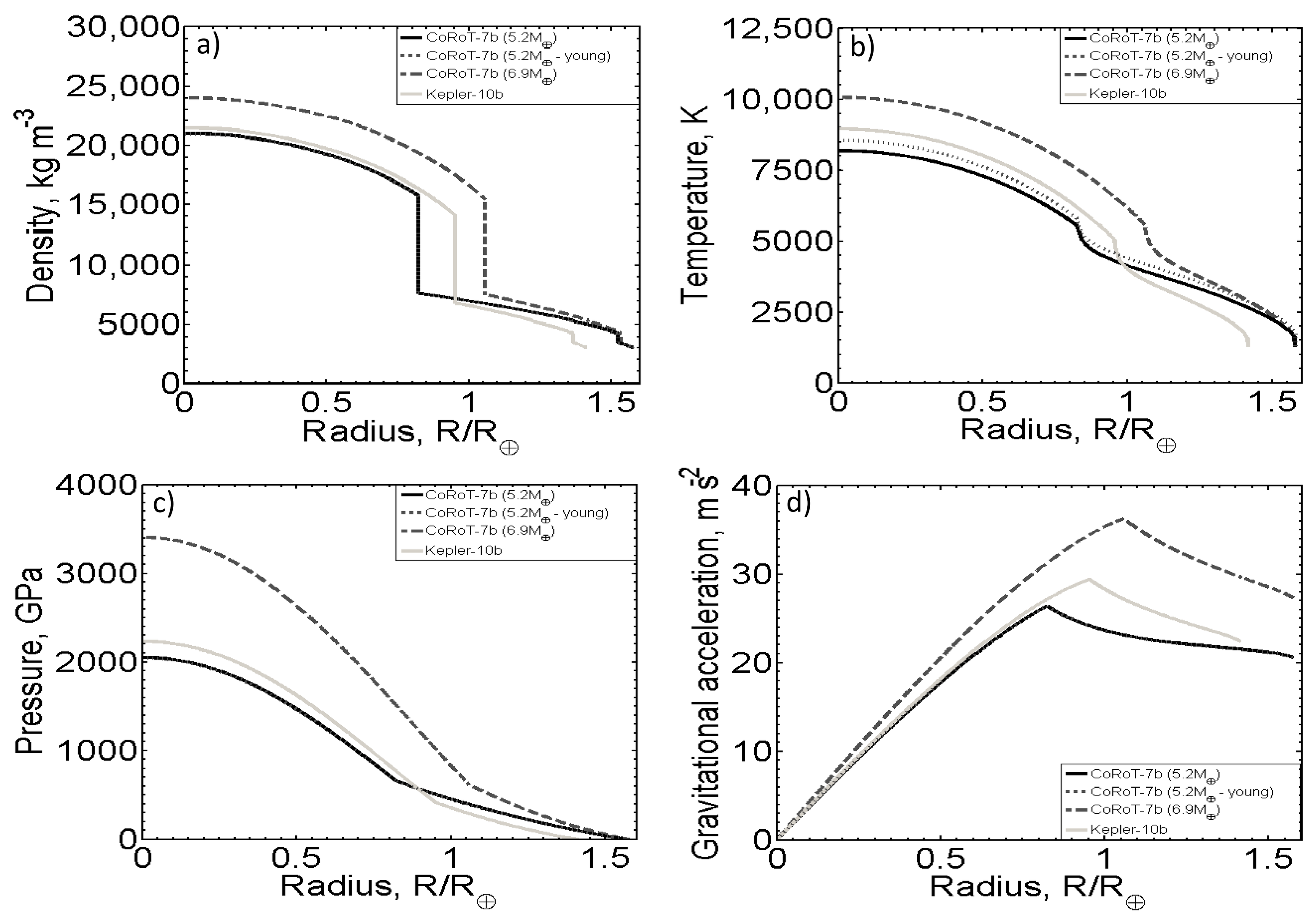

Fig. 3: Depth-dependent interior structure models of CoRoT-7b and Kepler-10b: From upper left to lower right, the panels illustrate the calculated distribution of (a) density, (b) temperature, (c) hydrostatic pressure, and (d) acceleration of gravity, respectively.

- Three CoRoT-7b and one Kepler-10b cases have been considered fitting the measured radius and mass
- Model C2 corresponds to a young CoRoT-7b with a high radiogenic heat production rate
- It can be seen that the heating rate only has minor effects on the interior structure

***Tab. 2:** Modeling results for CoRoT-7b and Kepler -10b. Values of the Earth are given for comparison.*

Planet (model)	CoRoT-7b (C1)	CoRoT-7b (C2)	CoRoT-7b (C3)	Kepler-10b (K1)	Earth (ref.)
Core mass fraction cmb [wt.-%]	35	35	60	59.5	32.6 (D)
Mantle thickness D_m [km]	4820	4820	3330	2950	2890 (D)
Temperature (cmb) T_{cmb} [K]	5550	5800	5580	5060	3740 (D)
Temperature (center) T_c [K]	8190	8560	10,100	8960	5030 (D)
Heat flux (surface) q_s [mW m^{-2}]	129	599	123	106	65 (E)
Heat flux (cmb) q_{cmb} [mW m^{-2}]	40.5	42.4	58.6	57.2	20 (F)
Pressure (cmb) P_{cmb} [GPa]	656	654	615	410	136 (G)
Pressure (center) P_c [GPa]	2050	2050	3410	2230	364 (G)
Gravity (surface) g_s [m s^{-2}]	20.6	20.5	27.3	22.4	9.83 (G)

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