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The part of the core in thermal evolution of super-Earths

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Abstract

Standard planet evolution models of super-Earths assume that the terrestrial part (hereafter core) is cooling as fast as the envelope. But several works show that core heat transport may be much slower [1]. Slow core cooling by conduction and/or high-viscosity convection, leads to a cooling timescale of billions of years, which overlaps with the regime of super-Earth observation data. In addition, it can become dependent on initial conditions.

We calculate the thermal evolution of the core simultaneously with the evolution of the envelope. We find that planet formation history and core thermal evolution can have a substantial and long term effect on planet radius and cannot be neglected in evolutionary calculations of super-Earth planets. We present the contribution of this effects to the mass-radius relation of super-Earth, and the implications on the interpretation of observation data.

1. Introduction

Although we don't have such planets in our own solar system, super-Earths are the most abundant class of planets known to date in our galaxy. Those planets exhibit a great diversity in their mass-radius relation. Most studies attempt to relate this diversity to composition, but the thermal evolution of the planet can play a key role in this diversity. In contrast to other planet types, in super-Earths the core is the dominant energy reservoir, while the gaseous envelope, which is very sensitive to thermal conditions, determines the planet's radius. Thus, the cooling rate of the core, which contains great uncertainties, affects the radius of the planet in time.

2. Model

We employ a complete center-to-surface 1D evolutionary model of super-Earth planets, in which the solid core and a gaseous envelope share the same structure grid. The energy transport is by convection, conduction or radiation, depends on the local conditions and composition in each layer, as described in [3]. We use a realistic equation of state and proper opacity tables [2], and solve the structure and evolution equations for the entire planet in an adaptive grid with variable time step.

3. Results

We find that the influence of the core thermal evolution on the envelope radius can be substantial (tens of percent) and depends strongly on thermal parameters, as shown in table 1.

Parameter (range)	Radius (%)
Initial envelope radius (0.1-1 $R_{\rm Hill}$)	5%
Core composition (rock/ice)	5%
Radioactive heating (0-$E_\oplus$)	10%
Core heat transport rate (conv-cond)	40%
Initial core temperatures (0.05-0.2 $E_{\rm acc}$)	25%
Age (1-10 Gyr)	50%
Envelope mass (1-10% of M_p)	100%
Atmospheric opacity (ESN – ESN/10)	20%

Table 1: Ranges of thermal evolution parameters that were examined (left) and their effect on the planet radius (right) for super-Earth planet masses.

The effect of the heat transport rate within the core on the radius evolution is significant. In figure 1 we present two planets which are identical in structure, composition and initial conditions. The heat transport within the core in one planet is by large-scale convection (green), as used in standard models [4], and in the second planet is by slow convection and conduction (black) as recent works suggest [5]. For the slow core cooling case the luminosity of the core (dashed dotted) determines the planet luminosity (solid) on Gyr timescale. As a result, the radius of this planet is larger, over long period of time.

The temperature profile evolution for the two cases is shown in figure 2. The less efficient heat transport in the slow cooling core, as well as in the core-envelope boundary, result in much hotter core -than the standard model- on Gyrs timescale.

The influence of the different thermal properties (see table 1) on the mass-radius relation of super-Earth is presented in firgure 3. As shown, such a model can explain the few observed super-puffs planets with much less gas content than is usually assumed.

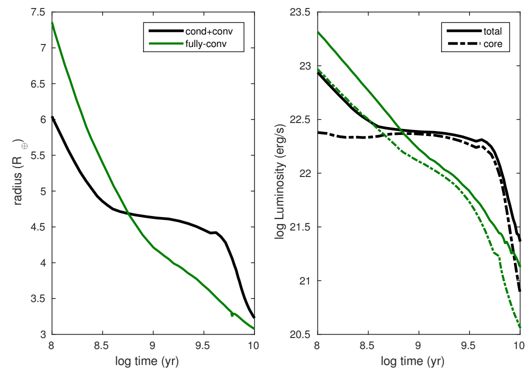

Figure 1: Radius (left) and luminosity (right) evolution of 5 $M_{\oplus}$ planets with 10% of the mass in H+He envelope. The heat transport within the core is by large-scale convection (green) and by slow convection and conduction (black).

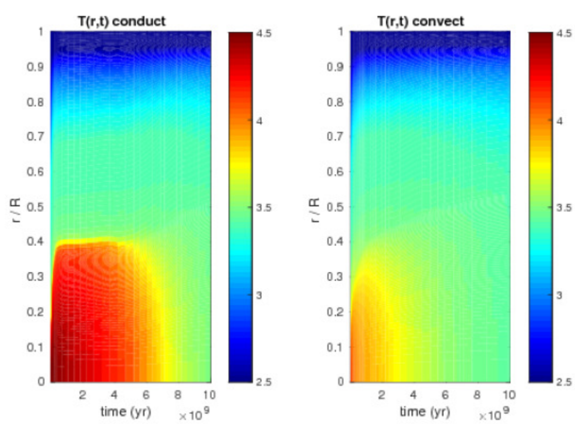

Figure 2: Temperature profile evolution for the two cases of figure 1: slow (left) and fast (right) heat transport in the core. The temperature (color) in log scale is presented as function of radius (y-axis) and time (x-axis).

4. Conclusions

1. Super-Earths are more sensitive to thermal processes (formation and evolution) than other planetary types, because of the high core to envelope ratio.
2. The mean density diversity of super-Earths is not determined only by composition (*i.e.*, hydrogen and helium fraction), but can also be driven by different thermal conditions and evolution, as shown in figure 3.
3. The uncertainties in thermal parameters should be considered when inferring the composition from observed mass-radius pairs of super-Earths.

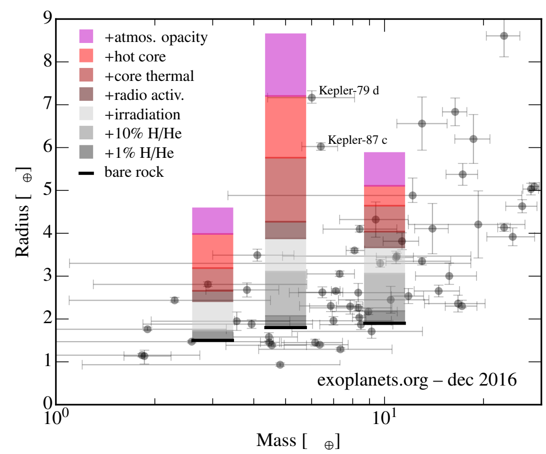

Figure 3: Cumulative contributions of structure and thermal evolution properties (see table 1) on the mass-radius relation of super-Earth planets. Each colored block indicates the maximum change in radius obtained from a single effect within 1-10 Gyr timescale.

References

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