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Thermal evolution of sub-Neptunes: the role of the rocky core

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Abstract

Sub-Neptune planets are very common in our Galaxy and show a large diversity in their mass-radius relation. In sub-Neptunes most of the planet mass is in the rocky core, which is surrounded by a modest hydrogen-helium envelope. We study the long-term consequences of the core cooling on the planet mass-radius relation. We consider the role of various core energy sources resulting from core formation, iron differentiation, rock solidification, core contraction, and radioactive decay. We follow the core formation phase, which sets the initial conditions, the magma ocean phase, characterized by rapid heat transport, and the solid-state phase, where cooling is inefficient. We find that for typical sub-Neptune planets ($2-10\,M_\oplus$) with envelope mass of $0.5\%-10\%$, the magma ocean phase lasts several gigayears, much longer than for terrestrial planets. The magma ocean phase effectively erases any signs of the initial core thermodynamic state. After solidification, the reduced heat flux from the rocky core causes a significant drop in the rocky core surface temperature, but its effect on the planet radius is limited. The overall long-term radius uncertainty by core effects is usually about 5%, and not more than 15%. Therefore, the inferred envelope mass from mass-radius relation is mostly proportional to the envelope (H/He) mass fraction.

1. The model

1. Complete center-to-surface (core + envelope) thermal evolution and contraction on one structure grid [3, 4]. Heat transport by convection, radiation and conduction in all planetary layers.

2. Core-envelope boundary (CEB) heat flow is calculated by the local conditions.

3. Equation of state (EOS) of H, He [1], ice and rock [2]. Radiative (envelope) and conductive (core) opacity.

4. Three phases of the core evolution (see Fig. 1): (1) Formation - the core is hot due to conversion of binding (accretion) energy to heat; (2) Magma ocean - vigorous (liquid) core convection and efficient cooling; (3) Solid state - we consider either an entirely conductive core (3a), or a convective core with a conductive core surface (3b).

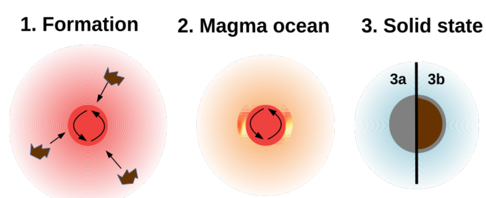

Figure 1: The three phases of the core evolution in our mode).

Core energy sources [4]:
Formation: the core binding (accretion) energy, $E_{\rm binding} = 3GM^2/5R$. Fraction that is left in the core after formation is unknown. We take $0.05-0.5\,E_{\rm binding}$ to remain in the core as heat. **Differentiation:** the iron differentiate and sink to the center of the planet during the early evolution. The released gravitational energy further heats the interior. We assume Earth-like iron-to-rock ratio. **Radioactive heating:** we apply the radiogenic luminosity to the rocky material (core layers). We examine a range between $0.5-2.5$ times the Earth ratio, as is expected in solar analogue stars. **Rock solidification:** as the planet cools the core changes from liquid to solid. The solidification process releases latent heat, which is added to

the energy of each solidified layer. **Core contraction:** under the high pressures in sub-Neptune interiors core compression heats the core. Core contraction is naturally included in the model, since the rocky core is part of the structure matrix, and pressure-temperature-density relation are derived from our rock EOS.

2. Main findings

1. Core cooling can significantly enhance the radius of the planet only if it operates on a timescale similar to the observed age [3].
2. Most of the observed sub-Neptune planets are in the magma ocean phase (molten surface). We find that the duration of the magma ocean phase for planets with envelope masses between 0.01 - 1 Earth masses lies between 1 and 7 Gyrs (see Fig. 2).
3. The magma ocean phase effectively erases any signs of the initial core thermodynamic state. For this reason, the heat of formation and iron differentiation does not influence the radius evolution for more than several 10^7 years.
4. After core solidification, the reduced heat flux from the rocky core causes a significant drop in the rocky core surface temperature, but its effect on the planet radius is limited, no larger than 6% (see Fig. 3).
5. Radioactive decay is the most significant energy source to affect the planet radius, and the latent heat from solidification is the second.
6. The overall contribution from the thermal state of the core to the planet radius is rather limited (up to 15%). Therefore, the inferred envelope mass from mass-radius relation is mostly proportional to the envelope (H/He) mass fraction.

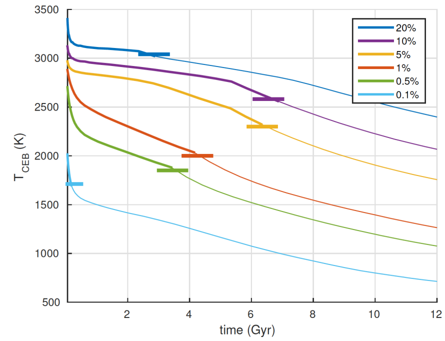

Figure 2: Core envelope boundary (CEB) temperature of 4.5 Earth masses cores with different envelope masses (mass percentages). The horizontal lines indicate the CEB solidification temperature. The magma ocean phase appears in thicker lines.

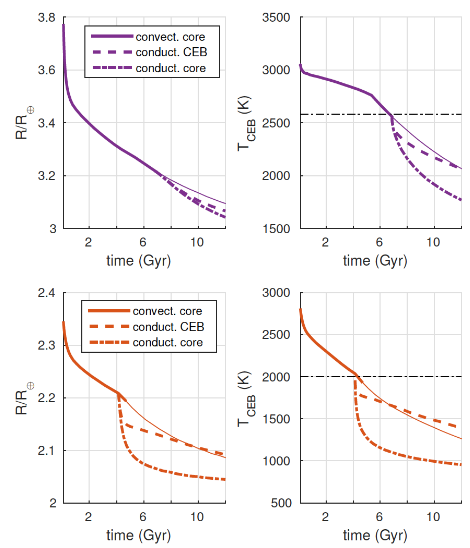

Figure 3: Radius and CEB temperature for a 4.5 Earth masses core with 10% envelope mass (purple) and 0.1% envelope mass (red). The solid curve is for efficient core cooling (magma ocean). The evolution with a conductive CEB layer (dashed) and with a conductive core (dashed-dotted) are shown after the CEB reaches the solidification temperature (horizontal dashed).

References

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