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Thermal Evolution and Habitability of Super-Earths

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Abstract

The recent discovery of super-Earths has increased the interest to better understand the thermal state and the habitability of such worlds. The major question is if super-Earths are simply scaled-up versions of Earth or if they are actually very different from our home planet.

The planet's habitability, in especially the planet's ability to form an atmosphere, have a magnetic field and plate tectonics, is controlled by the planet's interior thermal evolution, which is ultimately determined by high-pressure and high-temperature solid state physics.

The pressure at the Earth's core-mantle boundary (CMB) is about 135 GPa, pressures at the base of the mantles of extra-terrestrial rocky planets – if these are at all differentiated into mantles and cores - may reach, however, Tera Pascals. These high pressures might lead to very different interior energy transport mechanisms in comparison to Earth - and hence super-Earths might significantly differ from Earth.

In this talk, we present newest results from high-pressure physics ([4]), which control the interior thermal properties of super-Earths, and show how the thermal evolution of those planets can be described by a 1D model ([5]). We demonstrate that the mantles of super-Earths can be partially stagnant or highly sluggish and hot, strongly depending on the planet's initial interior thermal state. We additionally find that the duration of volcanism and outgassing, as well as the ability to generate magnetic fields on super-Earths is reduced in comparison to less massive planets.

1. Introduction

Recent studies ([1, 4]) have highlighted the importance of pressure effects on the thermal and transport properties of mantle rock and the implications for super-Earth rheologies. [1] & [4] differ in their conclusion about the pressure dependence of mantle viscosity for super-Earths: [1] suggests an almost isoviscous mantle for super-Earths assuming interior temperatures as discussed in the literature (e.g., [2, 3, 6]) and hence supports the idea of the entirely convecting mantle. Contrary to this study, we find a strongly increasing viscosity along the same thermal profiles, as well as increasing thermal conductivities, and a decreasing thermal expansivity for more massive planets [4].

The discrepancy between [1] and [4] reflects the present lack of knowledge of the properties of mantle rock at high pressure. But it also motivates to study the thermal evolution of super-Earths for a variety of rheologies to obtain a more complete picture of what could actually be happening inside rocky exoplanets.

Here, we model the interior thermal evolution of super-Earths with a pressure- and temperature-dependent mantle viscosity, and compare it to the thermal evolution of a planet with a purely temperature-dependent mantle viscosity. We additionally discuss impacts on the habitability of those worlds, i.e., magnetic field generation and outgassing.

2. Model

When mantle viscosities are strongly (but to a plausible degree) pressure-dependent stagnant zones, which we term CMB-lids, can emerge. We hence develop a parameterized 1D convection model, based on boundary layer stability analysis, which self-consistently considers a potential CMB-lid. We also compare the results of the parameterized model with those of a 2D spherical convection model to test the chosen 1D approximation, and find good agreement. For the model details please consult [5].

3. Results

In the following our main findings are summarized:

- The initial thermal state of super-Earths is crucial. In particular the initial lower mantle and CMB temperatures influence strongly the dynamics and thermal evolution – the so-called thermostat effect is not effective assuming a strongly pressure-dependent viscosity. Hence steady-state calculations might not be representative to make conclusions on the thermal state of super-Earths if viscosities are pressure-dependent, as suggested by [4, 5].

- With increasing planetary mass the likelihood that the lower mantle is partially stagnant increases - full mantle convection becomes less likely for more massive planets and heat in the deep interior of super-Earths is transported by conduction rather than by convection.
- CMB-lids become smaller and can be absent with increasing initial lower mantle and CMB temperatures or for less massive planets (as for Earth).
- For initially molten planets, our results suggest no CMB-lids but a hot lower mantle and core as well as sluggish lower mantle convection.
- For a large pressure-dependence of the viscosity, the cooling of the lowermost mantle and the core due to plate tectonics approaches the cooling due to stagnant lid convection – in strong contrast to a solely temperature-dependent viscosity.
- For the viscosities suggested by [4] the core does not effectively cool, which reduces the necessary driving to support a thermal dynamo.
- The duration of melt production and volcanism decreases with both increasing planetary mass and growing pressure dependence of the viscosity. This observation can be explained by the increase of gravity, which enlarges the radial gradient of the melting curve, the decreasing peak upper mantle temperatures for more massive planets, as well as by the strong increase of the upper stagnant lid thickness for super-Earths with increasing pressure dependence of the viscosity. This might strongly limit the outgassing capabilities of super-Earths.
- Super-Earths might be more diverse and complex than expected, and any results crucially depend on yet unverified assumptions, i.e., on the initial thermal profile and the viscosity law.

4. Summary and Conclusions

We have developed a 1D thermal evolution model that is capable of handling strongly pressure-dependent viscosities and apply it to study the thermal evolution and habitability of super-Earths for a variety of viscosity models. We find that super-Earths are likely to distinctively differ from Earth. CMB-lids may exist and restrict full mantle convection to less massive planets. Even if CMB-lids are not present (as for initially molten planets), lower mantle convection is sluggish and the lower mantle and core remain hot throughout 13 Gyr. In both cases, core cooling is strongly reduced, which limits thermally driven dynamos. Additionally, the duration of volcanic activity decreases with planetary mass, limiting the outgassing capability for super-Earths. Massive rocky exoplanets seem hence to be by far no scaled-up versions of Earth.

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