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Interior dynamics of super-Earth 55 Cnc e constrained by general circulation models

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Abstract

Close-in Super-Earths experience efficient heating by stellar irradiation and tidal heating that may drive long-lived, partially molten interiors with a tectonic regime largely unknown from the Solar System planets. Here, we use constraints from general circulation models (GCMs) fitted to transit phase curves in order to infer the potential interior dynamics of super-Earth 55 Cancri e using a numerical geodynamic model of mantle flow. In particular, we investigate differences in heat transport and convective style between the day- and night-sides. Using solid-state convection models we find that plumes emerging from the thermal boundary layer at the core-mantle boundary tend to migrate towards the day side. The surface temperature on both the day and night side of the planet is sufficiently hot to mitigate the formation of an upper thermal boundary layer such that downwellings are not observed. In this regard, the dynamics of close-in super-Earths are markedly different from Earth which has a dominant mode of convection driven by the upper thermal boundary layer (i.e., subduction). In models that include melting processes, we investigate the distribution of regions with high melt production and the formation of a surface magma ocean. These regions are likely to have pronounced outgassing and are therefore important to investigate the possible exchange of volatiles between mantle and atmosphere.

1. Introduction

Many super-Earths have been detected in the past few years. Because of their large masses relative to Earth (up to ≈ 10 Earth masses) they also have an extended pressure range up to a few TPa. The pressure dependence of viscosity could lead to a lower mantle that has a very sluggish convection regime [3]. We therefore aim to investigate if and under which conditions a super-Earth is convective, particularly given the potentially important role of melting processes that have thus far not been considered in the literature.

Many of these super-Earths are close-in and tidally locked: they feature a day-side that always faces the host star and are thus subject to intense insolation. The thermal phase curve of 55 Cancri e, one of the best studied super-Earths, reveals a hotspot shift (offset of the maximum temperature from the substellar point) and a large day-night temperature contrast [1]. Recent general circulation models (GCMs) aiming to explain these observations determine the spatial variability of the surface temperature of 55 Cnc e for different atmospheric masses and compositions [2].

We aim to constrain the interior dynamics of 55 Cnc e by using the thermal profiles determined by the GCMs. We connect the atmospheric models to the nature and style of convection in the planet's mantle. We use the resulting longitudinal temperature profiles as a boundary conditions for the surface temperature of our mantle convection models. We also investigate how the type of convection depends on the temperature and hence viscosity at the CMB, because although these parameters are difficult to constrain they have a strong influence on the vigour of convection.

2. Methods

The geodynamic model is devised to be relatively simple due to uncertainties in the interior composition and structure of 55 Cnc e (and super-Earths in general). Hence we preclude a detailed treatment of thermophysical parameters or rheology. Rather, we focus on several end-member models inspired by the GCM results to map the variety of interior regimes relevant to understand the present-state and evolution of 55 Cnc e.

Mantle convection is modelled using the code StagYY [4] in a two-dimensional spherical annulus geometry. We employ the infinite Prandtl number approximation and the effect of dynamic pressure on temperature is neglected. Hence the effects of compressibility are modelled by employing the truncated anelastic liquid approximation (TALA) where a reference state density profile is assumed.

A temperature- and pressure-dependent Arrhenius-type viscosity law is used and tracers are used to track melting processes in the model. We present models with and without melt processes, such that we can isolate the role of melt in determining the convective state of super-Earths.

3. Results and Discussion

Our simulations without melt (reference cases) show that upwellings tend to form around the whole CMB and then preferentially migrate towards the dayside where they eventually might merge together. This may be facilitated by a hotter mantle temperature on the dayside which leads to a lower viscosity and hence less viscous resistance for a rising plume to overcome. Increasing the CMB temperature leads to more upwellings and a higher reference mantle viscosity leads to broader upwellings. Hotter surface temperature leads to higher mantle temperature and therefore hinders the formation of upwellings. It also hinders the formation of an upper thermal boundary layer and no downwellings are observed.

Figure 1 shows the temperature field of 55 Cnc e after approximately 5.35 Gyrs of runtime. Most of the upwellings congregate on the day side (left) whilst plumes that are forming on the night side are beginning to migrate to the day side.

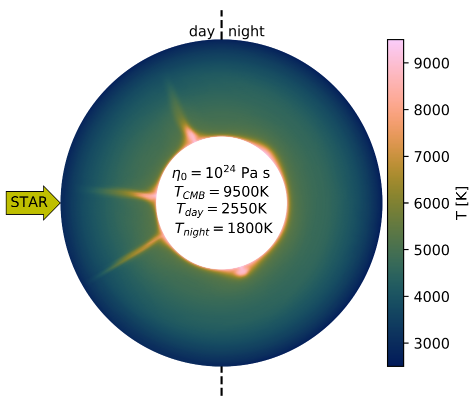

Figure 1: Temperature field for 55 Cnc e using a reference viscosity $\eta_0 = 10^{24}$ Pa s ($\eta_0 = \eta(T = 1200\ \mathrm{K}, P = 0)$), CMB temperature $T_{\mathrm{CMB}} = 9500$ K, dayside temperature $T_{\mathrm{day}} = 2550$ K and nightside temperature $T_{\mathrm{night}} = 1800$ K.

4. Summary and Conclusions

Our reference models of 55 Cnc e that exclude melt show that the interior dynamics are mostly dominated by the hot lower thermal boundary layer rather than the cold upper boundary layer. The surface temperature of 55 Cnc e is very hot (even on the nightside) which leads to a very high mantle temperature. Relatively small temperature drops across the thermal boundary layers at the surface and core-mantle boundary can hinder the formation of both downwellings and upwellings.

The high mantle temperature, driven by intense insolation at the surface, also means that there might be regions in the mantle that are molten. We therefore investigate the distribution of regions with high melt production and the formation of a surface magma ocean using solid-state convection models that additionally facilitate melting processes. These regions are important in terms of outgassing and therefore may constrain the exchange of volatiles between the mantle and the atmosphere. We thus compare the style of convection for models with and without melt.

With the ever-growing number of close-in super-Earths detected by current and near-future space missions, such as TESS, CHEOPS, PLATO and ARIEL, inferences on the interplay between interior and atmospheric dynamics will enable a deeper understanding of the nature of rocky exoplanets.

Acknowledgements

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