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Tidally-induced melting in extrasolar Earths

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1 Introduction

The number of detected planets with mass and/or radius comparable to the Earth is now increasing. A large fraction of detected Earth-sized planets orbits at close distance from their stars ($P_{\mathrm{orb}} < 20\,\mathrm{days}$) [1]. Tidal interaction has likely played a major role in the evolution of these planets, especially during the early stage before the planets reached their final rotational state. Dissipation of tidal energy in the interiors during this early stage as well as in planets on eccentric orbits may strongly affect their thermal budget. Particularly for potentially habitable planets around low mass stars, it is crucial to understand how tidal friction may have affected their thermal and climate evolution, and whether it prevented the occurrence of stable and temperate surface conditions. In a previous study Behounkova et al. [2], we determined the conditions under which tidally-induced thermal runaways may occur for Earth-sized planets in 1:1 and 3:2 spin-orbit resonances around stars with mass varying between 0.1 and 1 solar mass. Here, we extend this analysis by taking into account the effect of melt production and transport. The objective is to quantify the extent and duration of large-scale melting events for planets entering thermal runaways regime, for a variety of initial conditions and orbital configurations.

2 Model

In order to investigate the effect of the tidal heating on the interior evolution and possible melt production, we perform numerical simulations in a three-dimensional spherical geometry using the numerical tool ANTIGONE [3, 2], solving simultaneously heat production by tidal friction and heat transfer by thermal convection. Compared to previous versions, the compression effect in the thermal equation was introduced and extended Boussinesq approximation is used. Due to large internal heating induced by tides, the temperature can reach the solidus [4, 5]. Therefore, internal melting and a simple model of instantaneous melt extraction has also been incorporated.

3. Results

Here, we present preliminary results for the model described above. For the example displayed in Figures 1 and 2, we investigate thermal evolution of strongly tidally heated exo-Earth assuming constant orbital parameters (1:1 spin-orbit resonance, $e = 0.005$, $P_{\mathrm{orb}} = 2\,\mathrm{days}$). The viscosity contrast and Rayleigh number has been chosen in order to mimic an efficiency of heat transfer comparable to the Earth. For simplicity, we consider a uniform surface temperature. Surface temperature variations due to stellar insolation and geothermal flux will be considered in a second step.

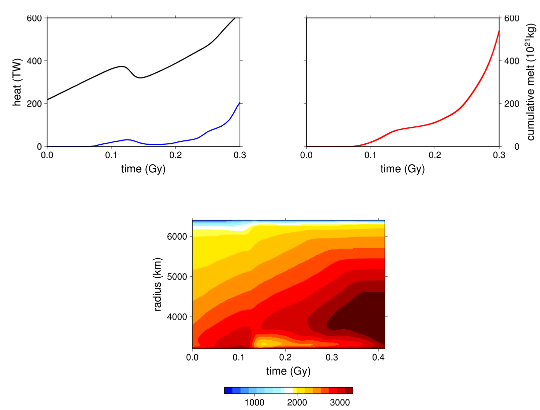

Figure 1: Example of the coupled tidal-thermal evolution of close-in Earth-like exoplanet; top left: evolution of tidal dissipation (black) and heat loss due to melting extraction (blue); top right: melt production; bottom: evolution of the average temperature; $Ra_{\mathrm{bot}} = 10^8$, $\Delta\eta = 150$, $h_{\mathrm{rad}} = 20\,\mathrm{TW}$, $Di = 0.5$, $\Delta T = 3000\,\mathrm{K}$, $T_{\mathrm{S}} = 300\,\mathrm{K}$, 1:1 spin-orbit resonance, $e = 0.005$, $P_{\mathrm{orb}} = 2\,\mathrm{days}$.

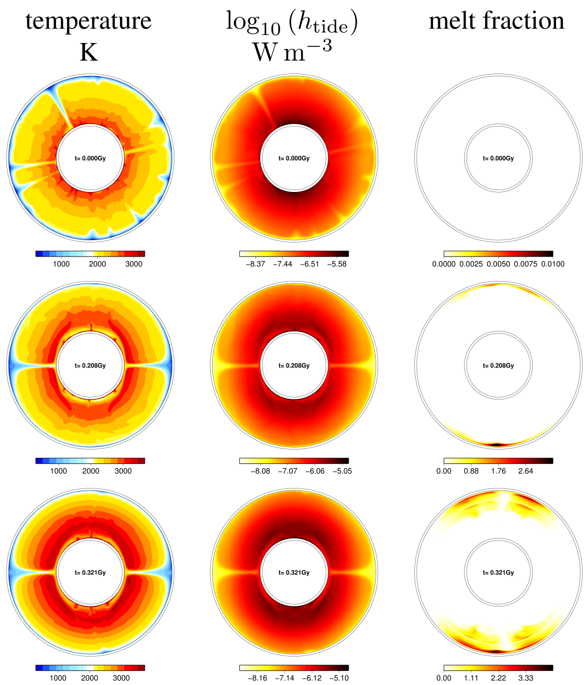

Figure 2: Snapshot of temperature field, tidal heating and fraction of melt, polar cross-section going through sub-stellar and anti-stellar points; model described in Figure 1.

The initial conditions for the simulation correspond to a statistical steady state of the system without any tidal heating. Once tidal heating is switched on ($t = 0\,\mathrm{Gy}$), a positive feedback between the temperature and the tidal heating is observed (see Figure 1). The dependence is not, however, monotonous as a mantle overturn occurs due to the low viscosity contrast and the increase of tidal heating with depth (Figure 2), leading to the formation of a low temperature zone above the core mantle boundary. Small scale upwellings are observed in this zone. Tidally induced melting first occurs at shallow depth in the polar regions ($t = 0.208\,\mathrm{Gyr}$, Figure 2). Then, the melt zone propagates downward and extend to lower latitudes ($t = 0.321\,\mathrm{Gyr}$). Interestingly, the warming and melting of the polar regions is accompanied by a migration of downwellings to the equator, as already observed in our previous study [2]. For this simulation with very strong tidal heating, even if melt extraction increase the surface heat flux (see Figure 1) and somehow limit the temperature increase in the polar region, no thermal equilibrium is reached at the end of simulation. The increase of global heating and average temperature even accelerate after $t = 0.25\,\mathrm{Gyr}$ (Figure 1).

Simulations with different initial states and orbital configurations will be presented during the conference, and the implications for the thermal evolution of close-in Earth-like planets will be discussed.

Acknowledgements

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