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Heterogeneous effects of non-uniform tidal heating: Implications for Io's asthenosphere

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Abstract

The non-uniform distribution of tidal dissipation within Io's mantle and asthenosphere could cause regional variations of the temperature-dependent rheology of Io's interior. Since the dissipation itself depends on the rheological structure, a feedback between Io's heterogeneous tidal heating pattern and its tidally induced heterogeneous rheological structure emerges. We explore under which conditions tidal heating causes regional variations of Io's melt fraction and viscosity, and study to which extent these variations can in turn affect the tidal dissipation pattern. To relate the dissipated heat to the viscosity and melt fraction, we use steady-state scaling laws for mantle convection and a simple melt migration model. The resulting thermal long-wavelength heterogeneities (5 K-190 K) strongly depend on the thickness of the convective layer, the viscosity of the asthenosphere, and the ratio between magmatic and convective heat transport. To investigate the effect of these induced heterogeneities on Io's dissipation we employ a finite element model that can to handle the heterogeneous viscosity structure. The comparison between the resulting dissipation patterns and the initial dissipation patterns resulting from spherical symmetric visco-elastic structures reveals that the boundary-focused dissipation in the asthenosphere is strongly affected by inhomogeneities.

1. Introduction

Undergoing extreme tidal dissipation, Io serves as an archetype of strongly tidally heated rocky exoplanets and exomoons. Therefore, understanding dissipation processes in Io's interior as well as their interactions with Io's interior could provide insight into the evolution of these tidally heated bodies. Io's tidal dissipation pattern depends on the tidal potential caused by Jupiter and on Io's unknown rheological structure. Simultaneously, the dissipated heat influences Io's rheological structure. Specifically, the heterogeneous nature of the tidal heating pattern can also influence Io's melt fraction and viscosity laterally. So far, studies computing Io's tidal dissipation pattern did not incorporate any tidally induced three-dimensional distribution of interior properties. As a first step to investigate the described feedback we focus on Io's upper mantle, i.e. the asthenosphere, as this layer is thought to significantly contribute to Io's total dissipated heat. We explore under which conditions lateral heterogeneities due to heterogeneous heating occur for a purely asthenosphere-heated model and quantify the effect of the lateral differences of the viscosity distribution on the resulting dissipation pattern.

2. Method

To investigate the spatial effect of the heterogeneous heat production on Io's interior viscosity distribution we develop a model that couples Io's non-uniform heating pattern and Io's main heat transport mechanisms [1], i.e. convection and melt advection. We assume that Io is in thermal equilibrium. The lateral and radial heat flow due to convection is modelled using steady-state scaling laws [2] [3]. The heat transported by melt is a function of the temperature and pressure below the stagnant lid. Since the fraction $\overline{f}_{cc}$ between heat transport by convection and total heat transport is unknown, we test a wide range of parameter values. From the resulting temperature and melt distribution we derive a lateral varying lid thickness and viscosity distribution. In a second step, we re-calculate the tidal dissipation using an updated version of the rheological structure. For that we use a three-dimensional finite-element model [1], which can deal with a heterogeneous viscosity distribution. Finally, we compare the resulting heating patterns with the initial heating patterns that originate from radial symmetric rheological structures.

3. Results

Our results reveal that depending on the dominant heat transport mechanism, peak-to-peak variations in the global temperature field (Figure 1) of up to 190 K arise. However, for models with a convection-dominating heat transport (high $\overline{f}_{cc}$) and low reference viscosities of the convective layer, these variations are significantly damped. We find that inhomogeneities in the low-viscosity layer, such as lateral variations in the layer thickness or the lateral viscosity distribution, reduce the boundary-focused heating scheme in Io's asthenosphere, even if their average values were kept constant.

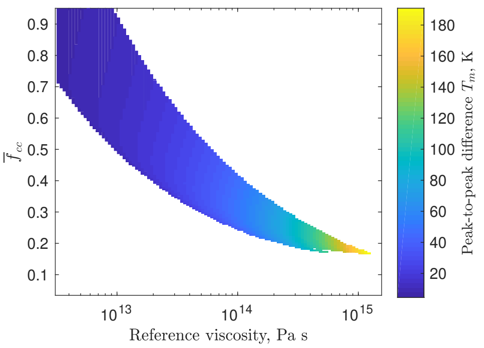

Figure 1: Temperature difference (T_m) below the stagnant lid for a purely asthenosphere-heated interior model with an asthenosphere thickness of 200 km. Peak-to-peak values are given as a function of the reference viscosity of the convective layer and the global heat flux fraction $\overline{f}_{cc}$. The latter quantifies the dominant heat transport mechanism: Small values represent models with a magma-dominating heat transport and values close to unity represent models with a convection-dominating heat transport.

4. Conclusions

Tidal heating has a quantifiable effect on Io's lateral long-wavelength viscosity structure and thickness of the melt containing layer. The strength of these variations depends on the initial heating pattern, the heat transport mechanism, and the thickness and viscosity of the upper convective layer. We re-assess the effect of these tidally induced heterogeneities on the tidal dissipation pattern. First results with a three dimensional visco-elastic finite element model show that Io's asthenosphere boundary-focussed heating is substantially reduced even by small lateral variations of the viscosity.

References

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