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Sustainability of the melting in the silicate mantle of Europa

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Abstract

Thermal evolution and internal dynamics of Europa's silicate mantle represent necessary ingredients of global evolutionary models. The efficiency of the heat transfer in the deep interior and the resulting heat flux at the base of the ocean, directly influence the dynamics of both the oceans and the outer shells. Possible presence of volcanically-driven hydrothermal vents at the bottom of Europa's ocean, induced by a possible presence of the melt in the silicate mantle, have been hypothesized as crucial ingredients for habitability. We study the thermal evolution of the silicate mantle in Europa by means of numerical simulations. We address the conditions for the initiation and the possible sustainability of the presence of the melt in the silicate mantle of Europa.

1. Introduction

The thermal evolution of the deep interior is controlled by the efficiency of the heat transfer (presence of convection/melting) and by the available heat sources (radiogenic heating determined by the composition and tidal heating determined by the eccentricity and the viscosity of the mantle). Here, we investigate the thermal state of the silicate mantle of Europa and heat flux from the silicate mantle to water/ice shell. We focus on impact of the amount of radiogenic elements, viscosity at the melting temperature, the size of the core and the eccentricity.

2. Method

To reach our goals, we employ numerical tool Oedipus/Antigone [3, 1] – model of thermo-mechanical evolution of 3D planetary shells. The long-term evolution of the silicate mantle is governed by the mass, momentum, and energy conservation equations for a viscous material in the extended Boussinesq approximation. The model includes the volumetric (radiogenic and tidal) heating, partial melting with instantaneous melt extraction and parameterized evolution of the iron core. The temperature-dependent viscosity is taken into account:

$$\eta = \eta_{\mathrm{melt}} \exp\left(\frac{E^*}{RT_{\mathrm{sol}}}\left(\frac{T_{\mathrm{sol}}}{T} - 1\right)\right), \qquad (1)$$

where η_{melt} is viscosity at the solidus temperature, E^* is the activation energy, e.g. [6], T is the temperature and T_{sol} is the depth-dependent solidus temperature [5].

The radiogenic heating follows decay law, e.g. [4]. The tidal deformation, resulting in the tidal dissipation, is determined by solving the mass and momentum conservation equations for an Andrade-like constitutive law with temperature dependent parameters. Tidal heating is re-computed as a function of time as the temperature structure of the mantle evolves [1, 2].

3. Results

In our preliminary study, we focus on the influence of the viscosity at the melting point η_{melt} and the value of the eccentricity e. Our simulations start shortly after the moon's formation and differentiation where the temperature reaches the melting temperature except for the uppermost layer. After the initial stage of the evolution, the onset of convection occurs. Shortly after the onset (see example in Figure 1, first row), we observe the melting and positive temperature anomalies in the polar regions where the tidal dissipation is the largest. During the convective stage of the evolution, both the temperature and the tidal heating decrease rapidly and the melting is mainly observed beneath the stagnant lid (Figure 1, second row).

For all models, the radiogenic heating decays from 1800GW at the beginning (0Gy) to the present-day value ($\sim$ 200GW at 4.5Gy). Evolution of the tidal heating and the melting rate is shown in Figure 2. The tidal dissipation is significantly lower than the radiogenic heating shortly after the formation (Figure 2). Nevertheless, the two energy sources can be comparable at the present day for some models. For mod-

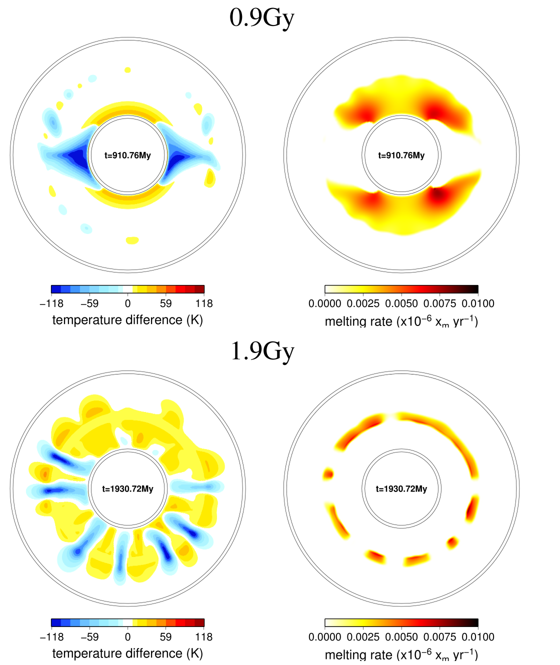

Figure 1: Snaphots of temperature lateral variations and melting rate in Europa's silicate mantle, model with the present-day eccentricity $e = e_0$ and $\eta_{\rm melt} = 10^{19}$Pas.

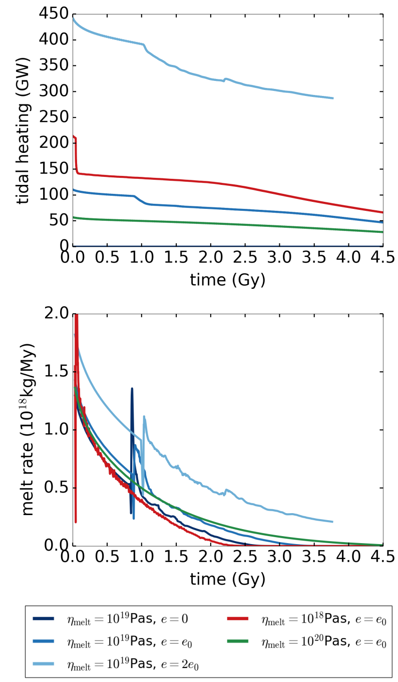

Figure 2: Evolution of tidal heating (top) and melting rate (bottom).

els with the viscosity $\eta_{\rm melt} = 10^{19}$Pas (Figure 2, blue line), the presence of the melt can be prolongated by ~ 0.5Gy if the tidal dissipation for the current value of the eccentricity e_0 is included and the melting can be sustained for 3Gy. If the eccentricity was twofold larger in the history, the melting can persist until the present day. For lower viscosity $\eta_{\rm melt} = 10^{18}$Pas (Figure 2, red line), the tidal dissipation is larger due to lower viscosity but the heat transfer is more efficient. The increased tidal dissipation does not compensate the increased heat lost and we predict that the melting can be sustained for 2Gy. For higher viscosity ($\eta_{\rm melt} = 10^{20}$Pas, Figure 2, green line), the onset of convection does not occur within the 4.5Gy and even though the tidal dissipation is rather small, observed until the present day.

4. Summary and Conclusions

Our preliminary results suggest that the melting can be sustained at least for 3Gy by the radiogenic and tidal dissipation for viscosity at the melting point is 10^{19}Pas and the present-day value of the eccentricity. The melting can persist up to the present day for higher viscosity and/or higher eccentricity in the past.

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