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Tidal dissipation in the ice-ocean system on Enceladus

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Abstract

We investigate how the interior structure and dissipation of tidal energy on Enceladus affect the lateral layering of its outer ice shell. Structural models are created that satisfy the satellite's mean density and polar moment-of-inertia factor as derived from Cassini gravity field data. We particularly consider variations in core density, ice shell thickness and ocean composition. A partly dehydrated core is found to be consistent with current ice shell thickness estimates and power output measurements for Enceladus.

1. Introduction

The Saturnian moon Enceladus is one of the most geologically active bodies in the solar system [1]. Ridged terrains dominated by intense tectonism are observed on both hemispheres while plume jets emanating from geological surface cracks are confined to the South Polar Terrain, thereby suggesting lateral heterogeneity of the satellite's internal structure [2]. The rotational state of Enceladus indicates that a global subsurface ocean mechanically decouples the outer ice shell from the satellite's deep interior [3]. While the latter is not directly accessible, thermodynamic modelling provides important insights and constraints on its composition and physical properties. This study aims at investigating the constraints imposed by the temperature distribution within the ice-ocean system on the rheological structure of the outer ice shell and its lateral variations, as well as on the density of the core.

2. Model

We subdivide Enceladus' interior into four chemically homogeneous layers and construct spherically symmetric structural models that are compliant with the satellite's mean density and polar moment-of-inertia factor derived from Cassini gravity field data [4]. The structural models consist of a core, a salty liquid water layer, a lower warm ductile ice layer and an upper cold brittle ice layer. The brittle-ductile boundary is related to a change in viscosity associated with a critical transition temperature. We first calculate the degree-2 body tide Love numbers for our structural models and obtain diurnal tidal stresses at the satellite's surface from combinations of those numbers [5]. We consider eccentricity tides and assume that the dissipation of tidal energy is restricted to the ductile sublayer of the outer ice shell. Since the total ice shell thickness is small compared to the satellite's mean radius (less than 10%), we apply a thin shell approximation to compute localized tide-induced dissipation and surface heat flow patterns [6].

3. Results and Discussion

The calculated interior structure model of Enceladus shown in Fig. 1 satisfies the mean density and moment-of-inertia factor. A model with a rocky core with radius of 152 km and an average density of 3000 kg m^{-3} satisfies observed total heat flux constraints. This core density suggests partial hydration of the core, which is consistent with the presence of substantial amounts of hydrogen in Enceladus' plumes as recently detected by the Cassini spacecraft [7]. The core is overlain by a substantial subsurface water ocean and a floating ice shell up to a few tens of kilometers thick. The change in viscosity at the brittle-ductile boundary reaches roughly 10^7 Pa s, and corresponds to a critical brittle-to-ductile transition temperature of about 84 K for a predominant ice creep mechanism involving grain boundary sliding [8]. The dissipation of tidal energy induced by eccentricity tides results in a polar surface heat flow roughly five times higher than the equatorial one. This may have an effect particularly on the polar surface temperature that is governed by the mean daily insolation. By computing radial temperature profiles, we emphasize that the temperature barely increases within the brittle ice layer in the absence of internal heating. On the other hand, large temperature increase takes place within the ductile ice layer in response to tidal energy dissipation.

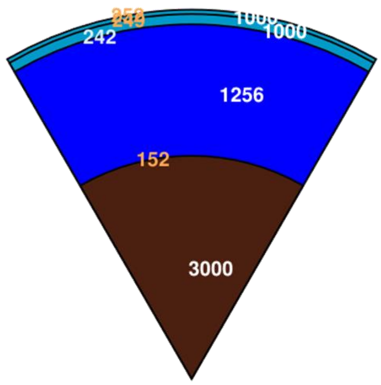

Figure 1: Interior structure model of Enceladus. Radial distance is given in units of kilometers; density is indicated in units of kg m^{-3} [8].

Fig. 2 presents the heterogeneous lateral temperature distribution at the brittle-ductile boundary. The highest temperatures are derived at the poles, while lowest values are calculated for sub-Saturnian longitudes, extending from the equator to mid-latitudes. This results in lateral depth variations of the brittle-ductile rheological boundary, which can be derived by extracting the critical brittle-to-ductile transition temperature from the computed three-dimensional temperature distribution.

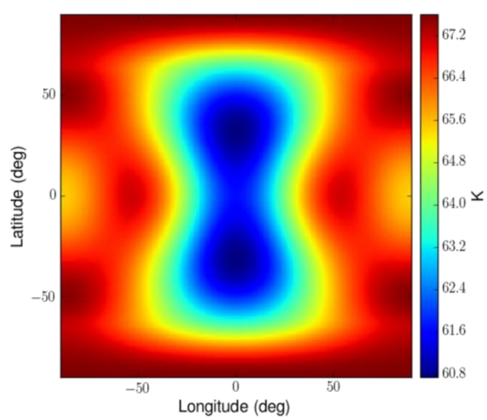

Figure 2: Heterogeneous temperature distribution at the brittle-ductile transition of the outer ice shell [8].

We show that the brittle layer becomes thicker at sub-Saturnian longitudes from the equator to mid-latitudes, and thinner towards the poles at all longitudes [8]. These results are consistent with the observed plume jets around the South Pole, since a thin brittle layer allows easy transport of material towards the surface. The global tidal dissipation that can be achieved within the ductile ice layer may even supersede the upper limit of the global output measurements [9]. Our structural model corresponding to a partly dehydrated core thus complies with current ice shell thickness estimations and tidal power output measurements.

4. Summary and Conclusions

Structural and tidal models of Enceladus are calculated. We propose a method to derive lateral variations of the rheological boundary between the brittle and ductile ice layers. This allows the construction of a consistent three-dimensional thermodynamic model of the ice-ocean system, accounting for the dissipation of tidal energy as induced by diurnal tides. The total ice shell thickness is found to decrease with higher core density in order to keep the ocean density within a realistic range for saltwater below 1250 kg m^{-3}. A partly hydrated core is compliant with current ice shell thickness estimates, dissipation of tidal energy, and hydrogen abundances in the plumes. A possible hydration of the core implies hydrothermal exchange processes between the latter and the ocean, which may result in density and composition variations of the salty water. This result is critical for the habitable potential of Enceladus.

References

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