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Long-term stability of Enceladus' ice shell

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Abstract

We present a new model of Enceladus' ice shell based on shape and gravity information and we investigate its long-term stability by computing the flow of ice induced by variations in hydrostatic pressure on the ice/water interface. We demonstrate that the ice shell is stable if the viscosity of ice at the melting temperature is equal to or higher than 3×10^{14} Pa s and the heat flux coming from the ocean varies by tens of mW/m^2 laterally.

1. Introduction

In the last few years, several models of Enceladus' internal structure based on the shape [1], gravity [2] and libration [3] data collected by Cassini have been presented [3-6]. All these models show that the thickness of the ice shell significantly varies, from probably less than 10 km in the south polar region to more than 30 km near the equator. This suggests that the base of the ice shell is subjected to large variations in hydrostatic pressure which induce flow in the ice shell tending to restore the hydrostatic equilibrium. For the shape of the bottom boundary of the ice shell to be stable in time, the flow in the ice shell must be counterbalanced by the phase change on the ice/water interface, i.e. the normal velocity of ice flow on the ice/water interface must be the same as the rate of melting/freezing [e.g. 7]:

$$\vec{n}\cdot\vec{v} = \frac{\vec{n}\cdot(\vec{q}_\mathrm{i}-\vec{q}_\mathrm{w})}{L\rho_\mathrm{i}}\ , \qquad (1)$$

where $\vec{n}$ is the normal vector to the boundary, $\vec{v}$ is the velocity of ice flow at the base of the shell, L is the latent heat, ρ_i is the density of ice, and $\vec{q}_\mathrm{i}$ and $\vec{q}_\mathrm{w}$ are the heat flux in the ice shell and in the ocean, respectively.

In this study, we derive a new model of Enceladus ice shell and we use it to determine the conditions under which the ice shell is stable on a geological time scale. This requires the computation of viscous flow in the ice shell with strongly irregular boundaries and large viscosity contrasts. Because of this complexity, the computation cannot be performed by a standard spectral code but requires the use of a finite element method which is able to capture the irregular shape of the ice shell.

2. Structural model of Enceladus

The model of the internal structure is based on the low-degree model of Enceladus' gravity [2], the measurement of physical libration [3] and the recent model of Enceladus' shape [8]. Assuming that the core is homogeneous and in hydrostatic equilibrium, we first develop a set of structural models that accurately reproduce the main characteristics of Enceladus' gravity field. In order to reduce this set to a single model, we impose the additional constraint that the topographic anomalies described by low-degree spherical harmonic coefficients are equally compensated. We find that the degree of compensation (ratio of the surface to the bottom topographic load) is 0.9–1, and we use this information to determine the shape of the ice/water interface for harmonic degrees that are not constrained by gravity data. Inclusion of density anomalies in the core that are compatible with the numerical simulations of hydrothermal circulation [9] results in an increase of the mean degree of compensation. For some simulations, the degree of compensation is found very close to 1 and the formal error of the solution is smaller than that corresponding to a homogeneous core. The derived model of the ice shell thickness (Fig. 1a) is similar in basic features to previous models [cf. 5, 6]. The ice shell thickness ranges from about 5 to 35 km and the best-fitting radius of the core is about 190 km.

3. Stability of the ice shell

Using the model shown in Fig. 1a, we compute the viscous flow in the ice shell generated by variations in pressure acting on the ice/water interface. The computation is performed using FEniCS software package (http://fenicsproject.org) for a temperature dependent viscosity corresponding to diffusion creep with a grain size of 1 mm. Substituting the flow velocity to Eq. (1)

and estimating $\vec{q}_\mathrm{i}$ from a conductive temperature profile, we determine the heat flux anomalies ($\vec{n} \cdot \vec{q}_\mathrm{w}$) on top of the ocean (Fig. 1b) that are required to maintain the ice shell thickness variations.

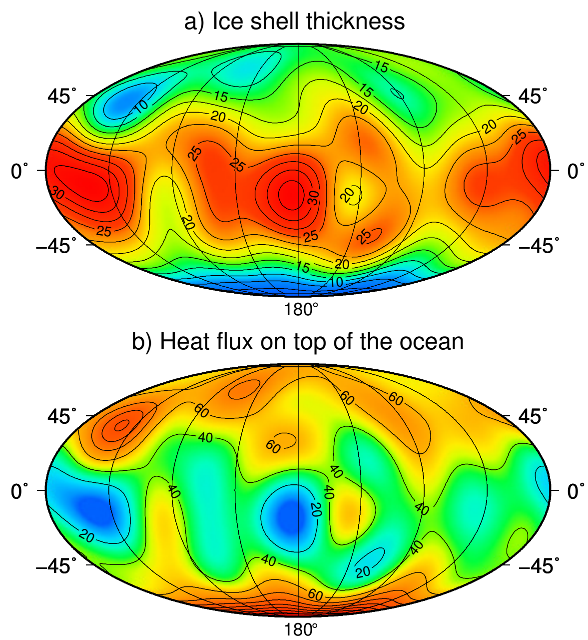

Figure 1: a) Thickness of Enceladus' ice shell in km. b) Normal component of the heat flux on top of the ocean in mW/m^2 computed from Eq. (1). Ice velocity $\vec{v}$ in Eq. (1) is evaluated for diffusion creep with a grain size of 1 mm, corresponding to viscosity of 3×10^{14} Pa s at the melting point.

The heat flux reaches the minimum near the equator where it decreases to zero. If viscosity at the ice/water interface was lower than 3×10^{14} Pa s, the heat flux on top of the ocean would be negative, leading to a contradiction with the assumption that the bottom boundary of the ice shell separates the solid and liquid phases. The pattern of the heat flux anti-correlates with the ice thickness and it is consistent with the numerical simulations of hydrothermal circulation in the core predicting sea floor spots of hot water outflow in the polar regions [9].

4. Conclusions

Our analysis of the gravity and topography data suggests that Enceladus' ice shell is close to equilibrium and the data are compatible with the model of hydrothermal activity in the core recently proposed by Choblet and co-workers [9]. The large variations in ice shell thickness predicted by previous studies and confirmed by our model are maintained by heat flux anomalies on top of the ocean which are of the order of tens of mW/m^2. A physically acceptable (non-negative) heat flux is obtained only if the viscosity of ice at the melting point is equal to or higher than 3×10^{14} Pa s. Our study provides a constraint on the thermal state of Enceladus' ocean that is needed for the ice shell to be stable. Strikingly large variations of the heat flux predicted by our model should be verified by future simulations of thermal convection in Enceladus' ocean.

Acknowledgements

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