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Localized tidal heating in icy shells of variable thickness

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Abstract

Several icy bodies are suspected to harbour an ocean beneath their surface icy shell. Candidates include Europa, Ganymede, Callisto, Titan, Enceladus, Triton and Pluto. Though the mean shell thickness is the quantity of primary interest, determining thickness variations is also useful to predict tectonics [1], long-wavelength topography [2, 3] or the rotational state of the body [4]. Variations in shell thickness are due to nonuniform solar insolation and internal heating. In particular, diurnal tides periodically deform the icy shell causing friction that heats the shell from within. Dissipation is much higher at the poles than at the equator and generates shell thickness variations if tides are large enough. This could be the case for Europa, Enceladus and Titan. In turn, tidal stresses and strains are modified by shell thickness variations so that there is a feedback loop between tidal dissipation and shell thickness. Using the 2D formalism of thin spherical shells, I investigate the interaction between shell thickness and tidal heating, which results in enhanced localized heating and stresses.

Method

In thin shell theory, stresses can be expressed as second-order derivatives of a scalar stress function. The stress function F, the radial displacement w and the transverse load q satisfy two linear differential equations of the fourth order which also depend on the thickness and viscoelastic properties of the shell. These equations take a simple form in the membrane approximation valid for long wavelength deformations [5]. The dependence on depth of the rheology can be taken into account as explained in [6]. Besides, the load q is related to the displacement w and the geoid w_G by

$$q = \rho g (w - w_G) \, ,$$

where ρ is the ocean density and g is the surface gravity. Finally, the geoid w_G can be expressed in terms of the radial displacement and the tidal potential. Given the shell thickness and local viscoelastic properties, there are now three equations for the three unknowns F, w and q.

The dissipated power per unit volume is proportional to the square of the Fourier-transformed strains (see Figure 1 for the case of constant thickness). Alternatively, it can be expressed directly in terms of the stress function F. This source of heat is then included in the 1D conduction equation (or in a parameterized convective model) which can be solved for the shell thickness. The two sets of equations (deformation and thermal) are iteratively solved in order to reach a self-consistent solution for shell thickness and tidal heating.

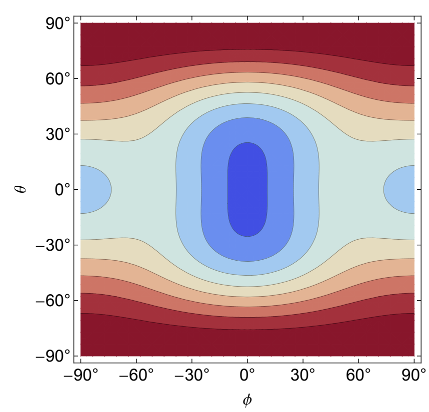

Figure 1: Nonuniform tidal heating due to eccentricity tides in a thin shell of constant thickness above an ocean [6]. Longitude and latitude are denoted ϕ and θ with zero longitude at the sub-primary point. Blue is cold, red is hot.

Acknowledgements

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References

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