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Dissipation of tidal energy and Love numbers on Enceladus

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1 Introduction

The Cassini mission to the Saturnian system has revealed that the tiny moon, Enceladus is one of the most geologically active bodies in the solar system though its radius is less than 250 km [1]. The satellite's mean density of 1600 kg m^{-3} suggests that its interior is composed of silicate rock and ice in nearly equal amounts by mass [1].

Whereas its northern hemisphere appears geologically dormant, large-scale tectonic features ("tiger stripes") in the south pole region together with gas- and dust-venting plumes connected to the thermal anomalies suggest that Enceladus has been undergone intense cryovolcanic resurfacing that is still ongoing.

Estimates of the intrinsic heat flow range between 5.8 [2] and even 15.8 GW [3] in the southern hemisphere, thereby exceeding heat production due to long-lived radiogenic isotopes in the silicate component by up to 50 times. Therefore, the existence of a liquid reservoir at depth has been invoked to explain the extremely large and heterogeneous heatflow by dissipation of tidal energy [4, 5].

In this work, by using free oscillation theory, we calculated energy dissipation in Enceladus by considering the several inner structure models and rheologies. We also estimated Love and Shida numbers with and without the liquid layer, which is effective way to consider the heat mechanism and design future missions.

2 Interior structure

Cassini observation of Enceladus' shape implies that Enceladus is undifferentiated if hydrostatic equilibrium is assumed [1]. However, the relatively high silicate content of Enceladus implies that the satellite's interior once was hot enough to fully separate rock and ice constituents. This large mean density implies that Enceladus is differentiated. Schubert *et al.* consider two layered model composed of silicate core and icy mantle and estimate the moment of inertia factor (MoI) could be 0.31 [6]. In the case of differentiated model, hydrostatic equilibrium is not consistent with observed shape [6]. Therefore, the interior of Enceladus may be either (1) partly or weakly differentiated and hydrostatic of (2) fully differentiated with non-hydrostatic constituents to the satellite's gravity field.

3 Tidal dissipation

Tidal potential Φ generated by Saturn can be represented as

$$\Phi = R^2\omega^2 e\Big[-\frac{3}{2}P_2^0(\cos\theta)\cos\omega t + \frac{1}{4}P_2^2(\cos\theta) \times [3\cos\omega t\cos 2\phi + 4\sin\omega t\sin 2\phi]\Big] \quad (1)$$

where R, ω and e are radius of the satellite, orbital frequency and eccentricity [7]. θ and ϕ are colatitude and longitude. In free oscillation theory about spherically symmetric body, internal stress and displacement are given by so-called y-method. The equation of motion is degenerated into six sets of ordinary differential equation (2).

$$\frac{dy_i(r,\omega)}{dr} = \sum_{j=1}^{6} A_{ij}y_j(r,\omega) \quad (2)$$

where r is radial distance from the center. A_{ij} is the component of 6×6 matrix whose representation is by Alterman *et al.* [8] and Takeuchi and Saito [9]. We calculate stress and strain tensor (σ_{ij} and ϵ_{ij}) by using equation (1), (2) and correspondence relation between stress and strain. Then we calculated tidal dissipation rate per volume averaged over one cycle using dissipation equation [10] as follows:

$$h_t = \frac{\omega}{2}[\mathrm{Im}(\tilde{\sigma_{ij}})\mathrm{Re}(\tilde{\epsilon_{ij}}) - \mathrm{Re}(\tilde{\sigma_{ij}})\mathrm{Im}(\tilde{\epsilon_{ij}})] \quad (3)$$

tilde represents the Fourier transformed stress and strain tensor. The local heating rate depends on the radial distance, latitude and longitude of Enceladus.

4 Love and Shida number

Tidal Love and Shida numbers are important dimensionless parameters, which describe the tidally-induced distortion of planetary bodies in terms of radial displacement (h_2), tangential displacement (l_2) and potential variation (k_2). In addition to that the difference of these numbers with and without liquid layer is a key factor to detect the existence of water layer for the future mission. Love and Shida numbers of degree 2 (h_2, l_2 and k_2) can be represented as follows:

$$\begin{cases} h_2(\omega) = y_1(R,\omega)g \\ l_2(\omega) = y_3(R,\omega)g \\ k_2(\omega) = y_5(R,\omega) - 1 \end{cases} \tag{4}$$

where g is the gravitational acceleration at the surface of Enceladus [11]. We apply the theory of free oscillation to calculate Love and Shida numbers for Enceladus. Furthermore, we investigate the likely range of interior structure models consistent with the satellite's size and average density and assess maximum possible tidal dissipation rates and related thermal states. We particularly consider relevant ranges of rheology parameter, like viscous and tidally-effective rigidities of the ice and rock components, short- and long-lived radiogenics, and orbit parameters.

5 Summary

Ice rheology of Maxwell type is universally assumed in the previous works. Here we considered several types of rheology to compare the efficiency of heating. To understand the mechanism that drives such an intense activity including the linkage between interior and surface and the connection to Enceladus' thermal-orbital evolution is still a challenge. It involves investigations of Enceladus' interior structure, surface geology, composition and texture, in-situ measurements of plume composition and dynamics, and characterization of the satellite's orbital and rotational state. In the present study, we investigate dissipation scenarios for Enceladus assuming various interior structure models and rheological laws.

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