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Ice rheology and tidal heating of Enceladus

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ABSTRACT

For the saturnian satellite Enceladus, the possible existence of a global ocean is a major issue. For the stability of an internal ocean, tidal heating is suggested as an effective heat source. However, assuming Maxwell rheology ice, it has been shown that a global scale ocean on Enceladus cannot be maintained (Roberts, J.F., Nimmo, F. [2008]. Icarus 194, 675–689). Here, we analyze tidal heating and the stability of a global ocean from the aspect of anelastic behavior. The Maxwell model is the most typical and widely used viscoelastic model. However, in the tidal frequency domain, energy is also dissipated by the anelastic response involving time-dependent or transient creep mechanisms, which is different from the viscoelastic response caused by steady-state creep. The Maxwell model cannot adequately address anelasticity, which has a large effect in the high viscosity range. Burgers and Andrade models are suggested as suitable models for the creep behavior of ice in the frequency domain. We calculate tidal heating in the ice layer and compare it with the radiated heat assuming both convection and conduction of the ice layer. Though anelastic behavior increases the heating rate, it is insufficient to maintain a global subsurface ocean if the ice layer is convecting, even though a wide parameter range is taken into account. One possibility to maintain a global ocean is that Enceladus' ice shell is conductive and its tidal response is similar to that of the Burgers body with comparatively small transient shear modulus and viscosity. If the surface ice with large viscosity is dissipative by anelastic response, the heat produced in the ice layer would supersede the cooling rate and a subsurface ocean could be maintained without freezing.

1. Introduction

The observation of plumes from the small saturnian satellite Enceladus indicates that it is volcanically active (Porco et al., 2006; Spencer et al., 2006). In addition to plume emission, the Cassini probe observed that 6–16 GW of heat is radiated from the surface of Enceladus (Spencer et al., 2006; Howett et al., 2011). Although it is not well understood how plume emissions and such a large amount of heat are generated, various models are suggesting an internal ocean (e.g., Waite et al., 2009; Matson et al., 2012). Thus the possible existence of a subsurface ocean is an important issue for Enceladus. In order to prevent the internal ocean from freezing, Enceladus needs heat sources other than radiogenic heating in the satellite's rock core. The magnitude of heat from radio active decay is around 0.3 GW (Roberts and Nimmo, 2008), which is insufficient to contribute to the activity of Enceladus. One of the most effective heat sources is tidal heating, which is caused by the dissipation of tidal energy transferred from Saturn.

The magnitude of tidal dissipation is usually calculated by using a viscoelastic body such as a Maxwell body. Maxwell bodies are widely used in Earth science because their material response is expressed by solely two parameters: the elastic shear modulus and the long-term or steady-state viscosity. Maxwell bodies have also been applied as rheological models for icy satellites in general (e.g., Tobie et al., 2005) and Enceladus in particular (Roberts and Nimmo, 2008). Tidal heating is an effective heating mechanism for the Galilean satellites because they have relatively large radii and orbits close to Jupiter. However, considering reasonable structural models of Enceladus and assuming the Maxwell rheology, the heating rate caused by tidal dissipation is much smaller than the heat loss by convection and by conduction of the ice layer (Roberts and Nimmo, 2008). This result implies that Enceladus may not have a global ocean at present. Instead of a global ocean, Běhounková et al. (2012) consider partial melting in the ice layer, which is consistent with the concentration of plume emissions and large heat flux around the south polar terrain. However, partial melt is easier to freeze compared with a global scale ocean. One hypothesis for the current large heat flux and plume emissions is that Enceladus had a large eccentricity, which would enhance tidal heating (Běhounková et al., 2012). It is not clear, however, whether this is consistent with the satellite's orbital evolution.

In addition to the structure of the ocean and the orbital eccentricity, there is another problem regarding the rheology of ice. As

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mentioned above, Maxwell bodies are widely used for calculating tidal heating. They are suitable for estimating the viscoelastic behavior of ice. However, materials exhibit anelastic behavior as well as viscoelastic responses. While the viscoelastic response is caused by elastic and plastic responses of materials and induces steady-state creep, the anelastic response is caused by time-dependent or transient creep. Detailed mechanisms of the anelastic response are discussed by McCarthy and Castillo-Rogez (2013). Karato and Spetzler (1990) give a detailed analysis of the creep behavior of minerals. They state that anelasticity dominates when the temperature and the stress are low and the forcing frequency is high. This is because viscoelastic behavior caused by dislocations is limited by impurities or jogs, which is known as pinning. A Maxwell body cannot adequately describe this anelastic response of materials. Efroimsky (2012) states that a Maxwell body becomes inadequate when the forcing period is much smaller than the Maxwell time, i.e. the ratio between steady-state viscosity and shear modulus, because the elastic response of the Maxwell body predominates. The Maxwell time increases with increasing viscosity. Thus, a Maxwell body becomes ineffective at high viscosities. Ice also exhibits anelastic behavior (Castillo-Rogez et al., 2011).

Sotin et al. (2009) showed that a Maxwell body is less dissipative than ice at high viscosities (low temperatures). For a Maxwell body, the elastic response dominates at high viscosities and less heat is generated. However, as mentioned above, the actual material response includes anelastic behavior, which reduces the effect of the elastic response so that energy is dissipated. Consequently, a Maxwell body becomes less dissipative at high viscosities. Enceladus has an orbital period of 1.37 days ($\sim 1.2 \times 10^5$ s), which corresponds to a Maxwell time of $\sim 10^5$ s for a shear modulus of a few gigapascals and a viscosity of 10^{15} Pa s. Thus, a Maxwell body cannot give an accurate dissipation rate when the ice viscosity significantly exceeds 10^{15} Pa s. Rambaux et al. (2010) found that Enceladus' tidal response is dominated by anelastic response for viscosities of more than 4×10^{14} Pa s. Although the viscosity of Enceladus' outer ice shell is unknown, it is plausible that it exceeds 10^{14} Pa s. Especially, when Enceladus' ice is not convective but conductive, the viscosity of surface ice can be large because of low temperatures.

Observations and experiments indicate that the Burgers and Andrade models are more suitable rheological models than the Maxwell model. Because these two rheological models contain a unit that models time-dependent anelastic behavior, they can be used to describe the tidal response of Enceladus. Burgers and Andrade bodies have been proposed as suitable rheological models for Europa and Iapetus (Castillo and Johnson, 2010; Robuchon et al., 2010; Castillo-Rogez et al., 2011).

In this study, we use Burgers and Andrade bodies to calculate the tidal heating rate and we estimate the effect of anelasticity on the tidal heating of Enceladus and on the stability of a global subsurface ocean. For simplicity, we employ a spherical shell model in which physical properties such as viscosity of the ice do not depend on latitude and longitude, and calculate the heating rates with different ice viscosities. Whether convection occurs in Enceladus' ice shell is not known. Thus we assume both convective and conductive ice layers.

In Section 2, we describe in detail the three rheological models (Maxwell, Burgers and Andrade models) applied to Enceladus' outer ice shell. The calculation procedure for the tidal heating rate is provided in Section 3 together with the construction of the underlying structural models of Enceladus' interior. In Section 4, the resultant tidal heating rates are compared and the effect of anelasticity is discussed. In Section 5, we compare the tidal and radiated heat to each other. Conditions to maintain the global ocean are discussed from the aspect of ice rheology. Finally, conclusions from the present study are drawn in Section 6.

2. Ice rheology

A spring–dashpot viscoelastic model is widely used to calculate the tidal heating rate. The spring and the dashpot exhibit elastic and plastic responses, respectively. In the frequency domain, the stress $\tilde{\sigma}_{ij}$ and the strain $\tilde{\epsilon}_{ij}$ are related by

$$\tilde{\sigma}_{ij} = 2\tilde{\mu}\tilde{\epsilon}_{ij} + \left[K - \frac{2}{3}\tilde{\mu}\right]\tilde{\epsilon}_{kk}\delta_{ij} \tag{1}$$

where K is the bulk modulus and δ_{ij} is the Kronecker delta (Roberts and Nimmo, 2008). $\tilde{\mu}$ is the complex shear modulus, which strongly depends on the rheology.

A Maxwell body consists of one spring and one dashpot serially connected (Fig. 1). The complex shear modulus of a Maxwell body $\tilde{\mu}_M(\omega)$ is given by

$$\tilde{\mu}_M(\omega) = \frac{\mu\omega^2\eta^2}{\mu^2 + \omega^2\eta^2} + i\frac{\mu^2\omega\eta}{\mu^2 + \omega^2\eta^2} \tag{2}$$

where μ and η are shear modulus and viscosity (e.g., Tobie et al., 2005). i represents $\sqrt{-1}$. ω is the angular velocity of the forcing cycle, which corresponds to the mean motion of Enceladus. One deficiency of the Maxwell body is that it overestimates the elastic response of materials with high viscosity. Laboratory experiments indicate anelastic material behavior of high-viscosity materials owing to time-dependent transient creep phenomena; a Maxwell body cannot model this anelastic effect (Efroimsky, 2012).

A Burgers body consists of a serial connection between a Maxwell body and a spring and a dashpot connected in parallel (the Kelvin–Voigt unit) (Fig. 1). The complex shear modulus $\tilde{\mu}_B(\omega)$ is then given by (Henning et al., 2009)

$$\tilde{\mu}_B(\omega) = \frac{\omega^2(C_1 - \eta_1 C_2/\mu_1)}{C_2^2 + \omega^2 C_1^2} + i\frac{\omega(C_2 + \eta_1\omega^2 C_1/\mu_1)}{C_2^2 + \omega^2 C_1^2} \tag{3}$$

where C_1 and C_2 can be written as

$$\begin{aligned} C_1 &= \frac{1}{\mu_1} + \frac{\eta_1}{\mu_1\eta_2} + \frac{1}{\mu_2} \\ C_2 &= \frac{1}{\eta_2} - \frac{\eta_1}{\mu_1\mu_2}\omega^2. \end{aligned} \tag{4}$$

The Kelvin–Voigt unit can model anelastic responses. Although the Burgers body is less frequently used, it fits the response of terrestrial glaciers to tidal forces more accurately than a Maxwell body (Reeh et al., 2003). In icy satellite research, the Burgers body has been applied to calculate the despinning of Iapetus (Robuchon et al., 2010). However, the Burgers body has four parameters,

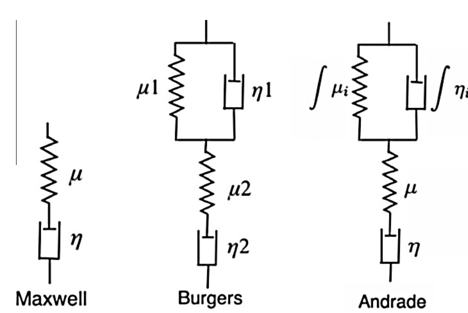

Fig. 1. Schematic view of three rheological bodies with spring and dashpot. The Maxwell body can be represented by only one spring and one dashpot in a linear arrangement. The Burgers body contains four elements (including the Maxwell unit). η_1 and μ_1 represent the transient viscosity and shear modulus, respectively. η_2 and μ_2 are respectively the steady-state viscosity and shear modulus, which respectively correspond to the viscosity and shear modulus of the Maxwell body. The Andrade model is represented by infinite springs and dashpots connected in parallel and a Maxwell unit (Castillo-Rogez et al., 2011).