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Non-steady state tidal heating of Enceladus

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ABSTRACT

Enceladus is one of the most geologically active bodies in the Solar System. The satellite's diverse surface suggests that Enceladus was subject to past episodic heating. It is largely probable that the activity of Enceladus is not in a steady state. In order to analyze the non-steady state heating, thermal and orbital coupled calculation is needed because they affect each other. We perform the coupled calculation assuming conductive ice layer and low melting temperature. Although the heating state of Enceladus strongly depends on the rheological parameters used, episodic heating is induced if the Q-value of Saturn is less than 23,000 and Enceladus' core radius is less than 161 km. The duration of one episodic heating cycle is around one hundred million years. The cyclic change in ice thickness is consistent with the origin of a partial ocean which is suggested by plume emissions and diverse surface states of Enceladus. Although the obtained tidal heating rate is smaller than the observed heat flux of a few giga watt, other heating mechanisms involving e.g., liquid water and/or specific chemical reactions may be initiated by the formation of a partial or global subsurface ocean.

1. Introduction

Enceladus is one of the most interesting and enigmatic satellites in our Solar System. Despite its small radius of around 250 km, at least 4.2 GW of heat is radiated and water plumes are emanated from the south polar terrain (Porco et al., 2006; Spencer et al., 2006, 2013; Howett et al., 2011). Although the origin of the large heat flux and plume emissions is not known, many studies indicate that liquid water in Enceladus plays an important role (e.g., Postberg et al., 2009). Liquid water as a subsurface ocean is considered to exist in some icy satellites such as Europa (e.g., Kivelson et al., 2000). Thus it may be conceivable that Enceladus also has a subsurface ocean. In order to maintain the subsurface ocean, heat sources are required. For icy satellites, radiogenic and tidal dissipation are the most effective heat sources. However, in case of Enceladus, the current magnitude of radiogenic heat is around 0.3 GW (Roberts and Nimmo, 2008), which is not sufficient to maintain a subsurface ocean. Thus tidal heating is important to analyze with respect to Enceladus' activity.

Roberts and Nimmo (2008) estimate whether a global ocean can be maintained by tidal heating. Their calculation reveals that tidal heating is insufficient to maintain a global subsurface ocean at the current eccentricity. Even though a global ocean is impossible, Enceladus may have a regionally confined ocean. Enceladus shows diverse surface features (Spencer et al., 2009). Around the south polar terrain, the surface is relatively smooth and young, whereas many craters are observed around the north polar region (Porco et al., 2006). Plume emissions are concentrated at the south polar terrain. Because of this heterogeneous surface state, it has been suggested that the subsurface ocean in Enceladus may be localized (Collins and Goodman, 2007). Běhounková et al. (2012) conducted detailed calculations of tidal heating assuming that a melting zone exists only at the southern hemisphere. By their calculation, a partial ocean is easier to freeze compared to a global ocean at the current eccentricity since heat production decreases faster than the cooling rate when the ocean is localized. However, if the eccentricity was larger in the past, they conclude that a partial ocean could have been maintained.

In a previous paper, we calculated tidal heating rates of Enceladus focusing on ice rheology (Shoji et al., 2013). In the case of Burgers rheology and assuming a conductive ice model, the generated heat is greater than the cooling rate. Thus an ocean can be maintained. However, there is an important constraint on the generated heat by tides. Meyer and Wisdom (2007) calculated the magnitude of tidal heat assuming a steady state. Currently Enceladus is locked in resonance with Dione. This resonance forces Enceladus' eccentricity. On the other hand, by dissipation of energy, tidal heating has the effect to reduce its eccentricity. Thus a steady state in which the eccentricity does not change could exist. By their

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calculation, around 1.1 GW of tidal heat is generated in the steady state. An important aspect of this model is that the heating rate is independent from the interior structure of Enceladus. Thus, Enceladus can generate only 1.1 GW of tidal heat in the steady state, which is smaller than the cooling rate of the ice shell (Shoji et al., 2013).

If current Enceladus is in steady state, it is difficult to maintain a subsurface ocean. One hypothesis to explain Enceladus' current state is that heating is not steady state implying that the eccentricity and heat production rate are changing. As Běhounková et al. (2012) suggest, larger heat could be generated if the eccentricity was greater in the past. The presence of a localized ocean may be a remnant of the large heating rate in the past. Non-steady state heating is consistent with the surface state of Enceladus. As mentioned above, the surface state is diverse and the currently active area is concentrated around the south polar terrain. However, around the equatorial and northern regions, there are topographic depressions which may imply large heating in the past (Bland et al., 2007; Giese et al., 2008, 2010). Crater relaxations on Enceladus also imply large heating in the past (Bland et al., 2012).

In order to analyze non-steady state heating, thermal–orbital coupling is needed because the thermal and orbital states affect each other. The tidal heating rate strongly depends on eccentricity, temperature and ice thickness, and the latter are affected in turn by the heating rates. Dissipation causes the temperature in the ice to increase, which results in even further heat production. Thus, temperature and tidal heating rate can be in a state of positive feedback. However, dissipation of tidal energy also causes the eccentricity to decrease, reducing the heating rate. Moreover, the ice thickness changes with the temperature gradient of the ice, and the heat production is also affected by the ice layer thickness. If the ice layer is relatively thin, the magnitude of deformation becomes large. However, the volume of the ice in which heat is generated decreases. Because of these complex mechanisms, we have to calculate the heating rate by coupling the thermal and orbital states of Enceladus.

For the Galilean satellites and Titan, coupled calculations have been conducted (Ojakangas and Stevenson, 1986; Hussmann and Spohn, 2004; Tobie et al., 2005a; Bland et al., 2009). For Enceladus, Meyer and Wisdom (2008) estimated the heating state based on a homogeneous model proposed by Ojakangas and Stevenson (1986). This simple model cannot induce episodic heating and Enceladus rapidly evolves into steady state. Zhang and Nimmo (2009) performed a detailed analysis imposing constraints on the orbit and interior structure of Enceladus locked in resonance with Dione. However, they assume that the magnitude of dissipation (k_2/Q) is constant.

In this paper, we perform coupled calculations among ice thickness, temperature, tidal heating and eccentricity using a layered structure. Enceladus is likely to be differentiated into a rocky core and an icy mantle (Schubert et al., 2007). Thus, coupled calculation with a layered structure can provide more accurate heating states of Enceladus. Based on the orbital model by Ojakangas and Stevenson (1986), we combine tidal dissipation and eccentricity of Enceladus at each time step. In this coupled calculation, we assume a Burgers rheology. The Burgers model can represent anelastic behavior by using two material parameters (transient shear modulus and viscosity). Since these parameters are less well constrained, we perform the calculations varying the parameter range analogous to Iapetus (Robuchon et al., 2010).

In Section 2, we outline the theory and describe the model for our calculation. Results are given in Section 3. In Section 4, we discuss the relationship between our calculation results and observed Enceladus' properties. Finally, conclusions are presented in Section 5.

2. Model and theory

2.1. Transfer and generation of heat

The thermal state in an ice layer is affected by its heat balance. In this work, we consider a thermally conductive ice layer. It is also possible that convection occurs in the ice shell if it is thick enough. Coupled calculation by a convective model has been performed (Shoji et al., 2012), in which a convective layer with homogeneous temperature and stagnant lid layer are assumed based on the model by Hussmann and Spohn (2004). For the scaling law between Nusselt number Nu and Rayleigh number Ra, we used the estimation by Reese et al. (1999), which is given by

$$Nu = 2.51\theta^{-1.2}Ra^{0.2} \quad (1)$$

where θ is the Frank-Kamenetskii parameter. The heating rate by tides is calculated by the method by Roberts and Nimmo (2008). In the case of a convective ice shell, the heat loss is large compared to a conductive ice shell. If the dissipation factor (Q-value) of Saturn is on the order of a few thousand, episodic large heating might be induced although additional conditions such as slush ice with low viscosity is needed. Saturn's Q-value is not known and estimates range from a few thousand (Lainey et al., 2012) to a few tens of thousand (Meyer and Wisdom, 2007). Because a small Q-value is controversial, we consider the conventional range of Q-values in this paper, which is more than 18,000 (Meyer and Wisdom, 2007). For this range, the generated heat is much smaller than the convective heat loss, the ocean freezes rapidly, and remelting of the ice does not occur.

As a next step we analyze conductive ice shells. In addition to the conductive ice shell, we assume low melting temperatures of the ice by impurities such as ammonia. If the base of the ice layer contains ammonia, the melting temperature of the ice decreases to 176 K (Durham et al., 1993). Observations of the water plume strongly suggest the existence of ammonia in Enceladus (Waite et al., 2009).

We divide the ice mantle into 50 thin spherical shells of equal thickness. The changing rate of the ice temperature T in each shell is given by the thermal transfer equation as follows

$$\rho_i c_p \frac{\partial T(r,t)}{\partial t} = \frac{d}{dr}\left(k\frac{dT}{dr}\right) + \frac{2k}{r}\frac{dT}{dr} + \psi(r,t), \quad (2)$$

where r is the radial distance from the center of Enceladus. ρ_i is the density of the ice. Although heat is transferred laterally as well, we consider only the radial heat transfer for simplicity. k is the thermal conductivity. For pure ice, the thermal conductivity depends on the ice temperature, and thus it changes with radius. In this work, we consider the ammonia content of the ice. Lorenz and Shandera (2001) observed that the thermal conductivity of water–ammonia ice is lower than that of pure ice and only slightly dependent on temperature. Thus, we use a constant value of $k = 2.0\ \mathrm{W\ m^{-1}\ K^{-1}}$. This value is consistent with the results by Lorenz and Shandera (2001). c_p is the specific heat of ice, which is given as (Hillier and Squyres, 1991)

$$c_p = 7.037T + 185\ \mathrm{J\ kg^{-1}K^{-1}}. \quad (3)$$

ψ is the tidal heating rate per unit volume in each shell. Tobie et al. (2005b) derive an equation about the volumetric tidal heating rate $h(r,\theta,\phi)$, which depends on the radial distance r, colatitude θ and longitude ϕ. We calculate ψ as averaged volumetric tidal heat in each ice shell as

$$\psi(r,t) = \frac{1}{V}\int h(r,\theta,\phi)\,dV, \quad (4)$$

where V is the volume of each thin ice shell. The volumetric tidal heating rate $h(r,\theta,\phi)$ is determined by stress and strain at each