Icarus 226 (2013) 898–904

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Impact of tidal heating on the onset of convection in Enceladus's ice shell

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ARTICLE INFO

Article history:
Received 12 February 2013
Revised 1 June 2013
Accepted 25 June 2013
Available online 18 July 2013

Keywords:
Enceladus
Ices
Tides, Solid body
Interiors
Thermal histories

ABSTRACT

By performing 3D simulations of thermal convection and tidal dissipation, we investigated the effect of tidal heating on the onset of convection in Enceladus's ice shell. We considered a composite non-Newtonian rheology including diffusion, grain-size-sensitive and dislocation creeps, and we defined an effective tidal viscosity reproducing the dissipation function as predicted by the Andrade rheology. For simulations with no or moderate tidal heating, the onset of convection requires ice grain sizes smaller than or equal to 0.5–0.6 mm. For simulations including significant tidal heating ($>10^{-6}$ W m^{-3}), the critical grain size for the onset of convection is shifted up to values of 1–1.5 mm. Whatever the width of the internal ocean, convection is initiated in the polar region due to enhanced tidal dissipation at high latitudes. For a given eccentricity value, the onset of convection depends on the ocean width, as tidal flexing and hence tidal heat production is controlled by the ocean width. For heating rates larger than 5–9 × 10^{-7} W m^{-3}, we systematically observe the occurrence of melting in our simulations, whatever the grain size and for both convecting and non-convecting cases. Grain sizes smaller than 1.5 mm, required to initiate convection, may be obtained either by the presence of a few percent of impurities limiting the grain growth by pinning effects or by the increase of stress and hence dynamic recrystallization associated with tidally-induced melting events.

1. Introduction

Observations of Enceladus by the Cassini spacecraft indicated that its south pole is very active, with jets of water vapor and ice emanating from warm tectonic ridges (Porco et al., 2006; Spencer et al., 2006, 2009). The heat power released from the south polar terrain was evaluated to be 15.8 ± 3.1 GW from the analysis of thermal emission spectra (Howett et al., 2011), which is much larger than what may be produced by decay of radioactive elements in the rocky core (Schubert et al., 2007). The abnormal endogenic power is most likely the consequence of strong tidal dissipation along the ridges and within the ice shell (Nimmo et al., 2007; Tobie et al., 2008). However, as tidal friction should result in a rapid damping of the orbital eccentricity, maintaining a highly dissipative state on geological timescales is challenging (Meyer and Wisdom, 2007; Zhang and Nimmo, 2009; Běhounková et al., 2012).

Convective processes in the ice shell are commonly advocated to induce the enhanced activity at the south pole (Nimmo and Pappalardo, 2006; Barr and McKinnon, 2007a; Mitri and Showman, 2008a,b; Roberts and Nimmo, 2008; Stegman et al., 2009; Běhounková et al., 2010; Han et al., 2012). The conditions under which convection may occur on Enceladus are, however, still puzzling. According to the estimation of Barr and McKinnon (2007a) based on scaling laws, convection may initiate in Enceladus's ice shell only for grain size smaller than 0.3 mm, which is very small compared the grain size observed on Earth in polar ice sheets for similar temperature and stress conditions (∼2–4 mm, Durand et al. (2006)).

Moreover, for the present-day value of eccentricity, the power generated by tidal friction in the ice shell is modeled to be much smaller than heat loss by thermal convection (Roberts and Nimmo, 2008; Běhounková et al., 2012), suggesting that Enceladus may have experienced a recent period of enhanced eccentricity and dissipation. Using 3D simulations of thermal convection and tidal dissipation, we showed in our previous study (Běhounková et al., 2012) that periods with enhanced eccentricity can lead to tidally-induced melting events in the ice shell, potentially resulting in enhanced surface activities. However, we showed that such enhanced activity periods associated with thermal convection and internal melting should be brief (∼1–10 Myr) followed by relatively long periods of inactivity (∼100 Myr) during which the cessation of thermal convection is likely.

In order to constrain the duration and periodicity of enhanced thermal activity, we need to better understand the conditions

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http://dx.doi.org/10.1016/j.icarus.2013.06.033

under which thermal convection may initiate. In particular, our goal is to understand how tidal heating, especially during periods of elevated eccentricity, may influence the onset of convection. To answer this question, we performed 3D simulations of thermal convection including a self-consistent computation of tidal dissipation using the code ANTIGONE previously described in Běhounková et al. (2010, 2012). To better simulate the mechanical properties of the ice shell, we considered a composite non-Newtonian rheology including three creep mechanisms following Durham et al. (2001) and Goldsby and Kohlstedt (2001), and we defined an effective tidal viscosity reproducing the dissipation function of the Andrade model (Castillo-Rogez et al., 2011). Section 2 provides a brief description of the numerical model and describes the new implementation in addition to Běhounková et al. (2012). The onset of convection in a heterogeneously heated shell is discussed in Section 3. In Section 4, we present the simulation results for the onset of convection in a tidally-heated shell and determine the critical grain size under which convection may occur in Enceladus's ice shell as a function of tidal heating. Finally, in Section 5, we briefly discuss the implications of our results for the evolution of Enceladus.

2. Model and rheological description

In order to describe the onset of convection in a body undergoing strong tidal friction, we use a numerical tool described in Běhounková et al. (2010, 2012). This tool solves simultaneously the long-term viscous flow and the short-term viscoelastic response to a tidal forcing in a 3D spherical shell. Both processes are coupled via the viscosity field. For the viscous flow, the equations describing the mass, momentum and energy conservations are solved using the finite volume method ŒDIPUS (Choblet, 2005; Choblet et al., 2007). In the case of the viscoelastic response, the deformations (mass and momentum conservations) are solved in the time domain (Tobie et al., 2008). Owing to the different time scales of both processes, tidal deformation has no mechanical effect on convective motions, and therefore only the dissipative part is included as a heterogeneous source of volumetric heating in the energy equation for thermal convection.

2.1. Parameters and numerical procedure

In the present study, we concentrate on the onset of convection in a tidally-heated ice layer for different grain size values. As previously demonstrated in Běhounková et al. (2012), the amplitude and distribution of tidal dissipation are determined by the orbital eccentricity and the width of the internal water reservoir at the boundary between the ice layer and the rocky core. Following Běhounková et al. (2012), the presence of a deep water reservoir of finite lateral extent is included via the boundary conditions at the base of the ice layer. At the water/ice interface, a constant temperature corresponding to the melting point of pure water (273 K) is prescribed and a free-slip/force equilibrium mechanical condition is used. Outside the water region, a constant heat flux, q_b, and a no-slip mechanical condition are prescribed (see Běhounková et al., 2012 for more details). For simplicity, the deep water reservoir is assumed to be axisymmetric and centered at the south pole. Reservoir widths varying between 120° and 360° are considered. For reservoir widths smaller than 120°, no significant enhancement of tidal dissipation at the south pole is obtained (Tobie et al., 2008; Běhounková et al., 2012), and as we are mainly interested in the effect of large tidal heating on the onset of convection, configurations with a small liquid reservoir are not considered here.

Simulations are performed for fixed eccentricity values, varying between zero and five times the current value ($e_0 = 0.0045$). Simulations with no eccentricity/tidal heating are used as a reference to better highlight the influence of tidal dissipation. As illustrated in Běhounková et al. (2012), during periods of reduced dissipation, the orbital eccentricity may rapidly grow due to tidal dissipation in Saturn. Following the model of Meyer and Wisdom (2007), eccentricity values up to $5 \times e_0$ can be reached within few Myr for Saturn's quality factor, $Q_S = 1800$, and for a weakly dissipative interior of Enceladus (<1 GW). Although the orbital eccentricity is expected to vary on timescales of Myr, the value remains fixed in our simulation to better understand the role of enhanced tidal heating. Consistent time evolution of the orbital eccentricity will be considered in the future.

Our model includes a simple description of melting where any melt produced within the convective ice shell (once the temperature reaches the melting point) is instantaneously extracted downward to the underlying water reservoir. This simplification assumes that the melt extraction timescale is shorter than the convection timescale and that no residual melt remains in the ice matrix. Recent results of Kalousová et al. (2013) based on two-phase flow modeling of water–ice mixture show that water produced in tidally heated hot plumes is transported downwards very efficiently in the form of porosity waves, and that the melt fraction remains always below 1%. Although these results were obtained for Europa, they remain valid in Enceladus' conditions. Here, as no melt is considered in the matrix, no melt effect on the ice viscosity and density are included. The role of interstitial melt is further discussed in Section 5.

The physical parameters used are listed in Table 1. The initial conditions correspond to the conductive solution for the given width of the ocean, and they are initially perturbed with a maximum perturbation corresponding to 1% of the global temperature contrast. The discrete grid mesh is 6×64^3 for the computation of thermal convection. For the computation of the viscoelastic response, the same radial resolution (i.e. 64 layers) is used, and a spectral decomposition up to degree 80 in lateral directions is considered. For numerical reasons, a maximum viscosity contrast of 10^8 is considered within the computational domain in the case of thermal convection. When the computed viscosity exceeds $10^8 \times \eta_b$ (viscosity at the bottom of the ice shell), the viscosity is set to this cut-off value. The tidal deformation is recomputed every

Table 1
List of physical parameters used in this study.

Thermal conductivity[a]	k	2.3	$\mathrm{W\,m^{-1}\,K^{-1}}$
Thermal expansivity[a]	α	1.6×10^{-4}	$\mathrm{K^{-1}}$
Heat capacity[a]	c_p	2100	$\mathrm{J\,kg^{-1}\,K^{-1}}$
Thermal diffusivity[a]	κ	1.19×10^{-6}	$\mathrm{m^2\,s^{-1}}$
Latent heat[a]	L	333	$\mathrm{kJ\,kg^{-1}}$
Water ice density[a]	ρ_0	920	$\mathrm{kg\,m^{-3}}$
Water density	ρ_w	1000	$\mathrm{kg\,m^{-3}}$
Silicate core density	ρ_c	3000	$\mathrm{kg\,m^{-3}}$
Reference gravity acceleration	g_0	0.113	$\mathrm{m\,s^{-2}}$
Outer radius of the ice shell	r_t	252.3	km
Inner radius of the ice shell	r_b	169.5	km
Heat flux on bottom boundary	q_b	0.8471	$\mathrm{mW\,m^{-2}}$
Chondritic heating		5×10^{-12}	$\mathrm{W\,kg^{-1}}$
Empirical parameter for Andrade model[b]	α_A	0.33	
Empirical parameter for Andrade model[b]	ζ	1	
Current eccentricity	e_0	0.0045	
Orbital period	T_O	1.37	day
Spin period	T_R	1.37	day
Ocean width	Δ	120,180,360	deg
Temperature contrast	ΔT	200	K
Temperature at the surface	T_S	73	K

[a] Physical parameters estimated at melting temperature from Hobbs (1974).
[b] From Castillo-Rogez et al. (2011).