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Heat generation and transport on Enceladus

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1. Introduction

Observations by Cassini have revealed that Enceladus' south pole is highly active, with jets of icy particles and water vapour emanating from narrow tectonic ridges, called the tiger stripes [1]. This jet activity is associated to a very high thermal emission mainly focused along the tectonic ridges [2]. Heat power required to sustain such an activity is probably related to the dissipation of mechanical energy due to tidal forces exerted by Saturn. However, the dissipation process and its relation to the tectonic features are not clearly established. Both shear heating along the tectonic ridges and viscous dissipation in the convective part of the ice shell should contribute to the energy budget [3,4]. However, the exact contribution of each of these dissipation mechanismes as well as the heat transport processes remains unclear.

2 Heat generation by tidal friction on Enceladus

Enceladus, like most of the other icy moons, is subjected to a periodic variation of gravitational forces owing to its eccentric orbit around Saturn. Depending on its viscoelastic properties, each internal layer deforms differently to this periodic forcing. On Enceladus, the presence of a decoupling liquid layer between the ice shell and the rocky core would strongly increase the surface deformation [3,4]. The existence of faults in the brittle part of the ice shell [3] as well as a low viscosity material at depth [4] can also significantly increase the tidal motions. If the conversion of mechanical energy into heat by viscous friction is efficient enough, volumetric heating rates of the order of 10^{-6} W.m^{-3} can be locally generated.

On microscopic scales, the viscous mechanisms are mainly related to the motions of defects and their interaction with the crystal lattice, resulting in friction. The efficiency of such dissipative processes depends on the population of existing defects (or dislocations). From a macroscopic point of view, the anelastic behavior of a material sample results in a time delay of the material response relative to the tidal forcing, in a smaller effective shear modulus and in the production of heat. As the mobility of crystal defects is strongly temperature dependent, the amount of the dissipated energy at a given frequency strongly varies within an active ice layer, which may be characterized by strong lateral and radial temperature contrast.

If the temperature of ice exceeds 220-240 K, viscous friction in the convective part of the ice shell as well as along active faults is expected to significantly contribute to the internal energy budget of Enceladus [3,4]. Models predict that large tidal dissipation in the south polar region occurs only if a decoupling liquid layer exists between the ice shell and the rocky core [4]. From a coupled 3D model of thermal convection and tidal dissipation, Behounkova et al. [5] have recently demonstrated that convective instabilities in Enceladus's south polar terrains lead to a further increase of tidal strain rate in the warmest regions, resulting in an enhanced tidal energy in hot rising plumes (Fig. 1). Moreover, these calculations show that the energy production is mainly localized at the base of the ice shell layer, where warm convective instabilities initiate.

By contrast, tidal energy associated to fault motions is mainly localized at the top of the convective layer, at the ductile/brittle transition [3]. By applying a shear deformation model initially developed for Earth applications, Nimmo et al. [3] showed that large tidal heating can be generated at the base of the faults if they are subjected to large shear displacements (of the order of $0.1 - 0.5$ m per day). Such large shear velocities can occur only if the lithosphere is subjected to very large tidal deformations, implying the existence of a decoupling liquid layer a few tens of kilometers below the surface. In their model, Nimmo et al. [3] prescribed the displacement rate, independently of the amount of work that might be needed to create the shear motions. Smith-Konter and Pappalardo [6] later showed that the tidal displacements along the

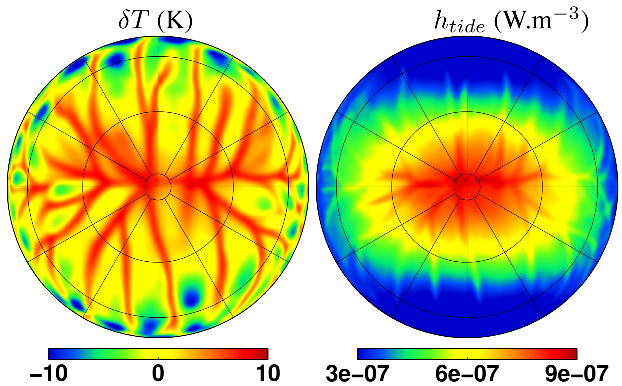

Figure 1: *Modeled temperature variations and corresponding tidal heating at the base of the ice shell, centered at the South Pole, for a long-term viscosity of 10^{14} Pa.s and an effective tidal viscosity of 10^{13} Pa.s (Behounkova et al. 2010).*

tectonic faults are smaller than initially anticipated by Nimmo et al. [3]. This mainly follows from the fact that the shear velocity rates prescribed by Nimmo et al. [3] are valid for two sliding rigid blocks above a totally fluid layer. In reality, the viscosity of the underlying ice shell should limit the motions along faults and in return the existence of faults should affect the tidal deformation of the convective sublayer. Further modelling efforts are required to assess the feedback effects between convective instabilities and faulting.

3 Heat transfer to the surface

Convective instabilities and faulting are also likely to play a key role in the heat transport mechanism. From 3D modelling of thermal convection with temperature-dependent viscosity, we estimate that 2 to 8 GW may be transported by thermal convection from deeper levels to the surface in the southern hemisphere [7,5]. However, in this conductive lid regime, the lateral variations of heat flux at the surface are quite small and do not reflect the strong lateral heterogeneities suggested by the thermal emission data [2]. These data strongly indicate the existence of a transfer mechanism that focalizes heat in narrow areas along the faults. Nimmo et al. [3] proposed vapour production induced by tidally-driven shear heating and subsequent escape as plumes through cracks being the main heat transport process. Although vapour production and transport can be considered as a major factor in advection of heat in the first hundred meters below the surface, it cannot efficiently extract heat from deeper levels as vapor saturation pressure is rapidly reached with increasing depth.

Below the porous and fractured outer layer, other transport mechanism must be considered. Thermal conductivity of water ice or other icy material candidates is too low to efficiently remove heat toward the surface. Heat is more likely advected through thermal convective instabilities. However, as explained above, stagnant lid convection appears to be unable to reproduce the lateral variations of the observed infrared flux. Such convection regimes do not take into account the mobility of the overlying lithosphere, which may participate in the convective cycle. Lithosphere rupture due to stress accumulation near the surface may result in episodic active spreading [4], possibly associated to catastrophic lithosphere overturning [7,8], resulting in enhanced heat transfer associated to short-lived surface heat pulse. In this context, the surface emission would not be in equilibrium with the heat production, and enhanced surface emissions would occur during only brief periods of time during Enceladus' evolution. Such episodic events may repeat only if the ice shell remains dissipative, thus suggesting that the liquid water layer, required to induce strong dissipation, should remain stable during most of Enceladus' evolution. Future models will need to address how these episodic surface activities affect the evolution of a subsurface liquid reservoir.

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