The Effect of Libration Heating on the Thermal State of Enceladus's Ice Shell. Wencheng D. Shao[1] and Francis Nimmo[1], [1]University of California Santa Cruz, 1156 High St., Santa Cruz, CA 95064, the United States. Corresponding to wshao7@ucsc.edu.

Introduction: Cassini observed that Enceladus is losing heat at a high rate [e.g., 1]. Cassini's observations also indicate the presence of a global subsurface ocean inside Enceladus [e.g., 2]. These two observations require Enceladus to possess high endogenic heat to keep in thermal balance.

Tidal dissipation is a good candidate for the heat requirement. The shell tidal dissipation has been studied and seems insufficient to match the observed high heat flow [e.g., 3]. The ice shell experiences forced librations. These forced librations can enhance the shell tidal dissipation. Previous studies did not address the question how libration heating affects the thermal state of Enceladus. Luan and Goldreich [4] proposed a thermal runaway scenario for Enceladus's ice shell. Then the question emerges whether libration heating can lead to such a scenario. In this study, we will shed light on these questions.

Method: We use the elastic libration model established by Van Hoolst et al. [5] to calculate the forced librations. This model can examine the forced librations of a tidally locked satellite with three homogeneous layers: an ice shell, a subsurface ocean and a rocky core. This model considers the finite elasticity of the shell in the calculations.

We construct 41 interior models with shell thickness varying from 5-50 km. The core size is assumed as 190 km [6]. Densities of ice and water are fixed as 900 and 1000 kg/m^3 and the ice shell viscosity is depth-dependent. Required tidal displacements are calculated via the model of Roberts and Nimmo [7]. Orbital variation data are from JPL/Horizon. We estimate ice-shell libration heating by the formula in Wisdom [8]. The conductive heat loss rate is estimated through a formula in Hemingway et al. [6].

Libration Heating: Libration heating (Fig. 1) is greatly dependent on the shell thickness. The libration heating reduces from 10 GW to less than 1 GW as the shell gets thicker from 5 to 50 km. However, this shell libration heating is less than the observed high heat flow on Enceladus. This suggests that additional heat sources in the ocean or in the silicate core are taking place if Enceladus is in equilibrium.
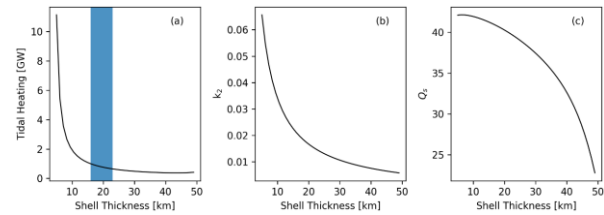

Fig. 1 (a) Shell's tidal dissipation rate (including the effect of the diurnal forced libration), (b) Love number k2 and (c) dissipation factor Qs for different interior models. The blue region is the shell thickness range inferred from the libration data [9].
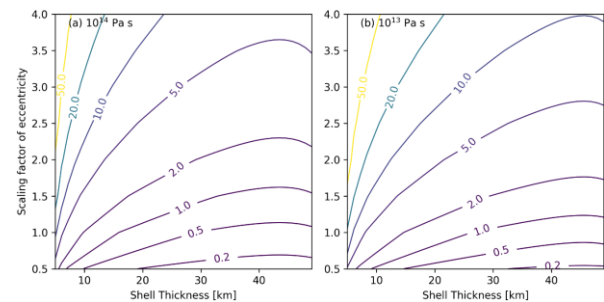

Fig. 2 Dependence of total shell heating rate (in GW) on shell thickness and eccentricity. Value of y axis is the scaling factor with respect to the current eccentricity of Enceladus (0.0047). Bottom viscosity of the ice shell is 10^{14} Pa s for (a) and 10^{13} Pa s for (b).

To consider Enceladus's possible thermal states in its past, we calculate the shell's total tidal dissipation with different eccentricities (Fig. 2). Different shell basal viscosities are also considered. Basically, larger eccentricity and lower viscosity produce more heat in the ice shell.

Ice Shell's Thermal State: We add a constant heat source to study the thermal equilibrium of Enceladus. Comparing the total tidal heat to the conductive loss of Enceladus (Fig. 3), we find a stable equilibrium state for Enceladus, which resists small perturbations to the shell thickness and does not favor the occurrence of a runaway melting on Enceladus.

We also find that only under some extreme situations (high eccentricity and thin shell), Enceladus's thermal equilibrium could be unstable and vulnerable to small perturbations to the shell thickness. Our results indicate that episodic heating or runaway melting (if it occurred) is unlikely to originate from the librations of Enceladus's ice shell.
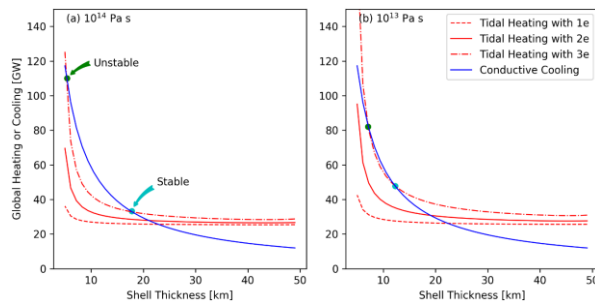
Fig. 3 Total global heating rate (red) versus conductive cooling rate (blue) for interior models with the shell basal viscosity of (a) 10^{14} Pa s and (b) 10^{13} Pa s. The heating consists of dissipation in the ice shell and a heat source of 25 GW below the shell. Different line styles indicate different orbital eccentricities. Enceladus's surface temperature is taken as 75 K. Stable and unstable equilibrium points are marked out.

References: [1] J. R. Spencer *et al.*, *Science*, vol. 311, no. 5766, pp. 1401–1405, Mar. 2006. [2] L. Iess *et al.*, *Science*, vol. 344, no. 6179, pp. 78–80, Apr. 2014. [3] M. Běhounková, O. Souček, J. Hron, and O. Čadek, *Astrobiology*, vol. 17, no. 9, pp. 941–954, Aug. 2017. [4] J. Luan and P. Goldreich, *AGU Fall Meet. Abstr.*, vol. 51, Dec. 2017. [5] T. Van Hoolst, R.-M. Baland, and A. Trinh, *Icarus*, vol. 226, no. 1, pp. 299–315, Sep. 2013. [6] D. Hemingway, L. Iess, R. Tajeddine, and G. Tobie, *Enceladus and the Icy Moons of Saturn*, pp. 57–77, 2018. [7] J. H. Roberts and F. Nimmo, *Icarus*, vol. 194, no. 2, pp. 675–689, Apr. 2008. [8] J. Wisdom, *Astron. J.*, vol. 128, no. 1, p. 484, Jul. 2004. [9] T. Van Hoolst, R.-M. Baland, and A. Trinh, *Icarus*, vol. 277, pp. 311–318, Oct. 2016.