Evolution of the ice shell of Enceladus including expansion due to freezing. J. D. Krier[1] and J. H. Roberts[2], [1]University of Utah, 201 Presidents' Cir, Salt Lake City, UT 84112, Krier.jd@gmail.com [2]Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, James.Roberts@jhuapl.edu

Introduction: The south polar terrain (SPT) of Saturn's moon Enceladus is known for being more geologically active than the crater-filled northern hemisphere [1]. The SPT exhibits an array of four "tiger stripes"; long, linear troughs from which jets of vapor and ice escape. With a current heat flux at the SPT of 20 mW/m^2 and this is believed to be similar or lower to global heat fluxes of the past [2]. Here, we look at changes in tidal heating rates over time and the effect this has on ice shell evolution and the building of pressure within the moon as the shell thickens.

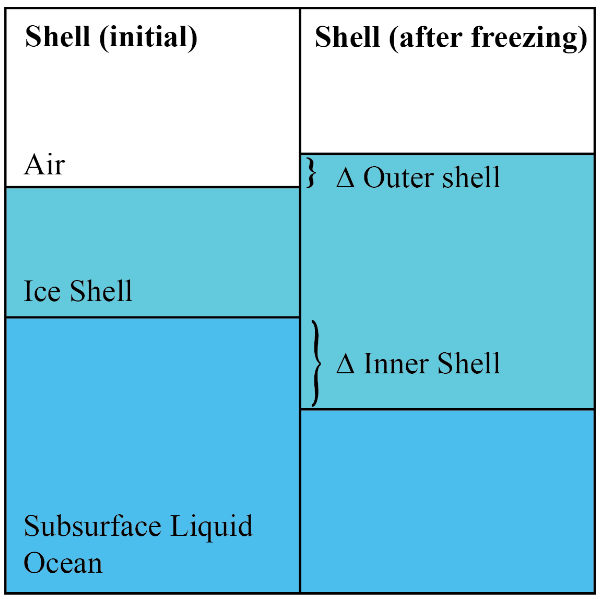

Figure 1: When ice forms at the ice-ocean boundary the ice takes up more space due to density differences. This density difference creates pressure within the boundary. To relieve this stress either water must be removed to create space for the ice, the ice must move physically outward from the water, or a combination of the two.

The jets in the SPT have been hypothesized to be a product of geyser activity [3], suggesting that there is an accumulation of pressure below the ice shell. A mechanism for pressurizing the ocean may arise from the freezing water at the water-ice boundary as the ice shell thickens. As water freezes, the density contrast between ice and water causes the total volume of the combined liquid and ice layers to increase as illustrated in (Figure 1). Here, we investigate this volume change from ice shell evolution would be significant enough to be the root cause of the breaks in the ice shell and geyser activity. We model heat transfer within the ice shell, which self-consistently adjusts to reflect the evolution of the ice shell thickness due to freezing of the ocean.

Model: We investigated the phase transition between the ocean and ice shell by simulating the thermal evolution of Enceladus using the finite-element convection code Citcom [4] in 2D axisymmetric geometry to model the thermal evolution in a spherical shell. We updated the Citcom software to account for changing the thickness of the ice shell along with adjusting the inner and outer radii of ice shell. We simulated changes in the temperature profile and thickness of the ice shell over a period of ~60–100 Myr. Ranges of internal (i.e., tidal) heating rates ranging from $2.7\text{x}10^{-6}$ to $1.7\text{x}10^{-7}$ W/m^2 and the initial ice shell thickness ranging between 20 and 40 km.

Results: We found that growth in the ice shell and overall satellite radius is limited by the total water available and the presence of a rocky core. With this lower boundary at 190 km radius [5], and the surface initially at 252 km, the outer shell radius can increase by up to 5 km and accommodate a total ice shell thickness of 66 km if the ocean freezes completely. By changing the parameters of the initial shell thickness and tidal heating we find a limited range of tidal heating rates (6.6×10^{-7} – 1.3×10^{-6} W m^{-3}; Figure 3, Top) ranges in which convection (Figure 2) can take place.

The models presented here all started with the same initial radius, but different shell thicknesses. Because liquid water is denser than ice, the total mass of water plus ice varies slightly. Because a largest mass of water available occurs when the ice shell is initially thinnest, this case has the largest final ice shell once the satellite froze through (Figure 3, Bottom). We also found a narrow range of tidal heating (9.06×10^{-7} – 1.01×10^{-6} W m^{-2}) and Rayleigh number of 3.34×10^{8} at which convection is not sustained. Outside of this "dead zone," convection takes place.

Discussion: Freezing at Enceladus' ice-ocean boundary will increase the shell thickness. As the shell thickens, pressure builds within the moon due to the volume expansion associated with the phase change. This pressurization could lead to fracturing of the ice shell, and the formation of the jets that is seen on Enceladus [1]. In this scenario, fracturing would occur at weakest (or thinnest) parts of the ice shell. On Enceladus, this is observed at the SPT in and may explain formation of the tiger stripes that are found in this region [1].

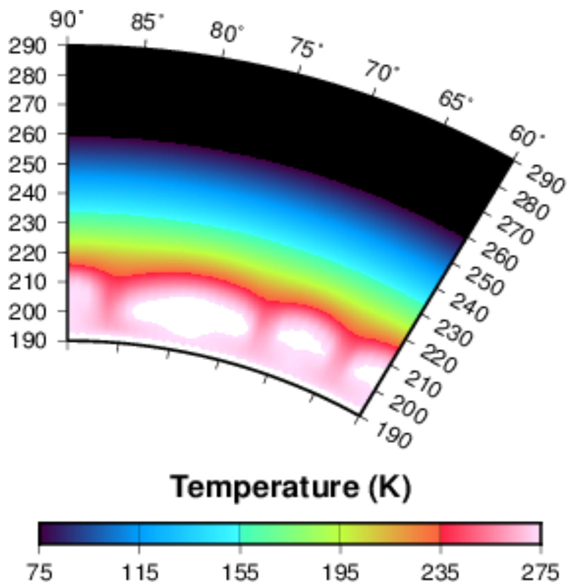

Figure 2: Model of Enceladus' ice shell evolution after 47 Myr based on parameters from Iess *et al.* (2014) in which convection is occurring. At this point the outer shell radius gas increased by 3.65 km and is an overall thickness of 65.75 m. Initial ice shell thickness of 30 km and internal heating of 6.66×10^{-7} W/m^3.

We would also like to note the range of tidal heating rates in which the ice shell is stable to convection. Within this range, an equilibrium takes place in which the ice layer stays in conduction rather than switching over to convection to maintain heat distribution. In these cases, Enceladus is still freezing through but conduction is efficient enough of a heat loss mechanism that convection never initiates. This result merits further exploration to identify if the phenomenon at different levels convective vigor to quantify the trend under a greater range of parameter space.

Ice shell thickening and planetary expansion of Enceladus has been hypothesized [3], and we followed up on this idea with 2D modeling. Here, we have explored the effects of ice shell thickening on increasing internal pressure. Using model results of the ice shell evolution, we can gain a better understanding of processes seen on the moon's surface. In conjunction with observations, modeling could describe the mechanisms that result in the SPT's tiger stripes and jets found in this region. Future work includes extending the current results with a self-consistent model of tidal heating to more accurately capture the spatial variation of heating rates, and to include and fracture mechanics models to better understand effects of ice shell thickness on fracture formation and pressure relief.

Although the work presented here is particular to the case of Enceladus, many other icy bodies in the outer solar system are known or suspected to have a subsurface ocean, such as Titan, Europa, and Ganymede. The methodology discussed here may be broadly applicable to other bodies in which the ice shell thickness may not be constant with time.

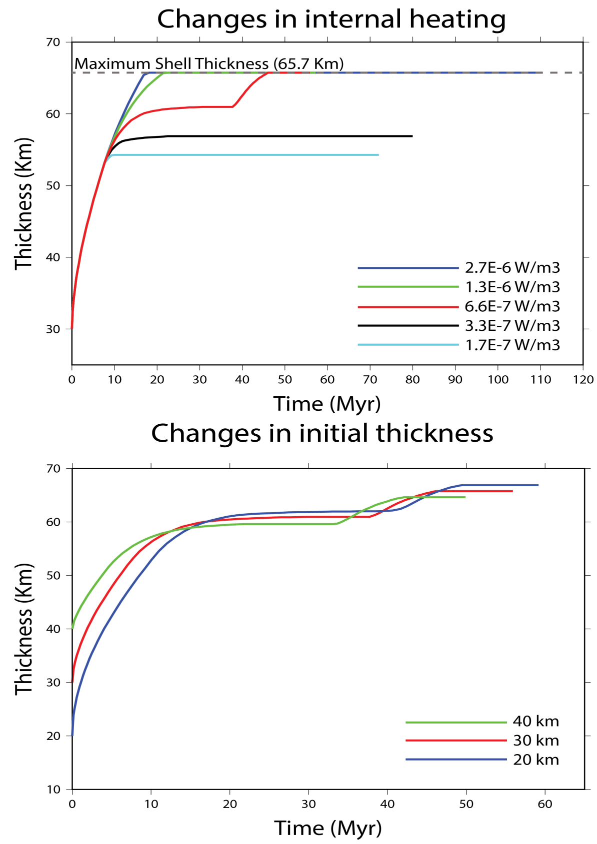

Figure 3: (Top) Comparison of internal heating ranging from 1.7×10^{-7} W/m^3 to 2.7×10^{-6} W/m^3 all of which had an initial ice shell thickness of 30 km. Convection only took place at 6.6×10^{-7} W/m^3 and 1.3×10^{-6} W/m^3. (Bottom) Comparison in initial ice thickness from 20 km to 40 km and an internal heating of 6.6×10^{-7} all show changes to a final ice shell thickness reaching a maximum around 60 km.

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References: [1] Porco C.C. et al. (2006) Science, 311, 1393-1401. [2] Spencer J.R. et al. (2013) DPS 45, 403.03. [3] Manga M. and Wang C.-Y. (2007) Geophysical Research Letters, 34, L07202. [4] Roberts J.H. and Zhong S. (2004) JGR 109, 10.1029/2003JE002226. [5] Iess L. et al. (2014) Science, 344, 78-80.