LONG-TERM STABILITY OF A SUBSURFACE OCEAN ON ENCELADUS. James H. Roberts, Francis Nimmo, *Department of Earth and Planetary Science, University of California at Santa Cruz, Santa Cruz CA 95064-1077, USA, (jhr@ucsc.edu).*

Introduction The discovery of the thermal anomaly in the south polar region of Enceladus [1], has launched a great deal of interest in potential activity in the ice shell. It is assumed that the observed thermal anomaly is an expression of ongoing internal heating due to tidal dissipation. Under reasonable rheologic conditions it is not possible to generate significant tidal dissipation in the silicate core. Substantial tidal heating may be produced in the ice shell if it is decoupled from the core by a subsurface ocean. Thus, such an ocean is believed to exist in order to explain the observed activity.

However, because the core heat production is so small, we find that convective and even conductive heat transport is sufficient to cool the interior, such that a liquid ocean cannot be in long-term thermal equilibrium.

Tidal Heating We computed the tidal heating in an Enceladus model with three primary layers, a silicate core of radius 160 km, and a water ocean and icy mantle with total thickness 90 km, and allowed the ice-water interface to vary between models. Using the general approach of [2], and a propagator matrix method similar to [3], we solved for the heating in a uniform viscosity (η) ice shell and silicate core [4]. A thinner shell is more easily deformable and has a greater tidal heating rate. However, a thin shell also has a smaller volume, limiting the total heat production within it. These two competing effects result in a critical shell thickness, d_c at which the maximum heat flow occurs. d_c is viscosity-dependent but is less than 5 km for all the models considered here. However, the length scales of surface features are inconsistent with a very thin ice shell, so the actual heating rate is unlikely to be near the maximum.

The tidal heating in the silicate core is very small for any reasonable core viscosity ($\eta \geq 10^{13}$ Pa s) , about three orders of magnitude less than the radiogenic heating assuming a chondritic core. We therefore assume that tidal heating is not significant in the core of Enceladus and that the heat flux out of the core, F_c is entirely due to radiogenic heating, resulting in F_c = 1.9 mW m^{-2}. For the ocean to be in thermal equilibrium, F_c must equal the heat flux across the base of the ice shell F_b (modified by an appropritate geometric factor). The problem then becomes one of determining what ice shell thickness, d, is consistent with this F_b for a given ice viscosity structure.

Convection We address this question by modeling convection in the ice shell. The bottom boundary is at the melting point of water, and the surface temperature is about 80 K, but varies with latitude [5]. We modeled the convection using the 2D-axisymmetric version of Citcom [6] modified to include the tidal heating from our earlier models. We assume a Newtonian temperature-dependent viscosity, with activation energy E_a = 60 kJ/mol [7]. The heating models assume that the material properties within a given layer are constant. We therefore modify the tidal heating at each point based on the local η, according to [5,8].

For the convection modeling, we only considered ice shells at least 40 km thick. Thinner ice shells are conductive. For each of the tidal heating models in this regime, we ran a corresponding convection model to statistical steady state and examined F_b. For a model to be in thermal equilibrium, F_b must match F_c. Fig. 1 shows F_b for each model. In virtually every case, the heat flux determined from the convection modeling is many times greater than that produced by a chondritic silicate core. Thus we conclude that a stable liquid ocean on Enceladus is inconsistent with a convecting ice shell. Only the low viscosity ($\eta = 10^{13}$ Pa s) series produces heat fluxes that intersect the chondritic core value (marked by the solid line). However, these cases are tidally heated to such an extent that convection cannot cool them, and the lower part of the ice shell melts. The ice shell thins and becomes conductive.

Our results suggest that no combination of η and d allows thermal equilibrium to be established for convective shell, subsurface ocean and chondritic core. In most cases, convection is able to remove the tidal heating as well as cooling the interior. This cooling would cause the ocean to freeze onto the base of the ice shell. Once the ocean freezes completely, the ice shell is no longer decoupled from the silicate core, and tidal heating is greatly reduced. Convection most likely ceases in this case.

Conduction We have also investigated the possiblity that an ocean may exist beneath a conductive ice shell. To determine d that is consistent with the previously established low value for F_c, we make an initial guess as to the thickness and viscosity structure of the ice shell, and find the tidal heating using the same procedure as before. We then compute the

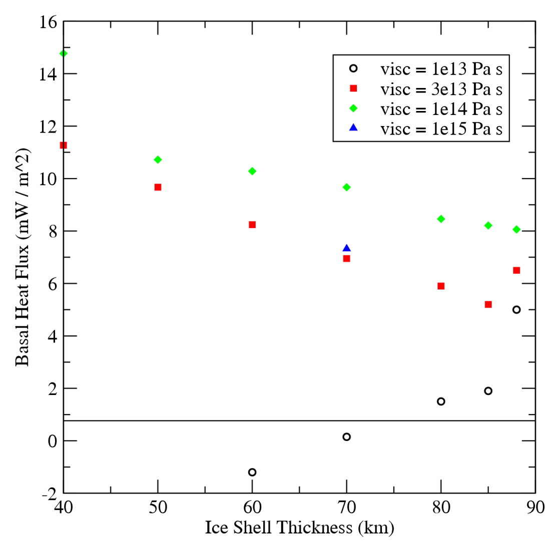

Figure 1: F_b as a function of d from convection models. Blue line denotes that expected from a chondritic core. Values have been normalized to the surface area of the planet. "visc" refers to the viscosity at the base of the ice shell.

conductive temperature, and resulting $\eta(T)$ consistent with this heating, subject to the same temperature boundary conditions used in the convective model, adjusting d as needed in order to match F_b (the computed heat flux at the base of the ice shell) to F_c. We iterate between the heating and temperature models until we have a self-consistent solution.

We find however, that there is no possible d that results in a sufficiently low F_b to match F_c. The heat flux generally scales with the inverse of d. However, even a 90 km (the maximum possible thickness) ice shell (assuming a η_0 = 3×10^{13} Pa s), has $F_b \sim 8$ mW m^{-2}, or about 4 times F_c. Fig. 2 shows the dependence of the F_b on η_0.

The physical explanation for this is as follows. Although the conductive heat flux is less than the convective heat flux, the reduction in the case of Enceladus is not that great. Heat flux tends to scale with the thickness of the stagnant lid. For the convection models in this study, the stagnant lid is nearly half of d. Thus, the conductive heat flux is only a factor of ~2 lower than the convective flux. A strongly heated ice shell may result in a low temperature difference across the bottom boundary, and thus a low heat flux (e.g. Fig. 1, circles). However, the larger viscosity variations in the conductive cases result in stiffer outer layers. This restricts the deformation of the warmer, lower layers, and reduces the tidal heating everywhere. Although tidal dissipation deep in the ice shell is still the dominant heating mechanism in a conductive ice shell, it is insufficient to reduce F_b to match F_c. This will result in the freezing of any subsurface ocean, and the reduction of the interior temperature. A 40 km thick ocean will freeze in ~30 Ma, a similar timescale to that of the orbital evolution.

Discussion In order to maintain a steady-state subsurface ocean on Enceladus, at least one of the following conditions must be met:

1. The silicate core is more strongly heated, raising F_c and relaxing the severe restriction on F_b. The radiogenic heating is unlikely to deviate significantly from chondritic value assumed here. Under no plausible Maxwellian rheology can the core experience siginificant tidal dissipation. Thus, in order for this condition to be satisfied, the core must behave in some non-Maxwellian manner that is more dissipative.

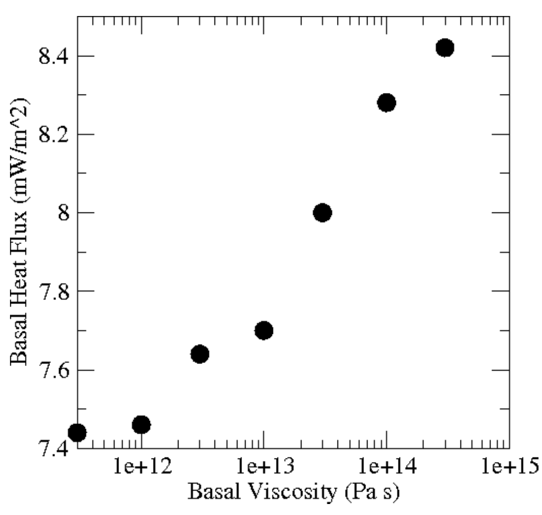

Figure 2: Minimum F_b for a 90 km conductive ice shell

2. The ice shell is more strongly heated, reducing ΔT across the base, and likewise F_b. One way is to reduce the overall viscosity in the ice shell. However, no value of η_0 reduces F_b by enough in the conductive case. A convective shell with $\eta_0 \leq 10^{13}$ Pa s, may have sufficiently low F_b (Fig. 1), but will melt and evolve to a conductive state in which the heating is reduced. Dissipation in the ice shell may also be increased if the orbital eccentricity, e was higher in the past [9]. Increasing e by a factor of 3 from the present-day value is sufficient to sustain an ocean.

3. The ocean may not be pure water. If the ocean contains substantial amounts of other volatiles (e.g. ammonia), the melting point may be severely depressed. However, even at the H_2O - NH_3 peritectic temperature of 175 K [10], $F_b \sim 4$ mW m^{-2}. Furthermore, there is no observational evidence for so vast an amount of NH_3.

We do not find any of these alternatives particularly attractive. An increased e in the past is plausible [9], but implies an ocean would be transient. We also point out that our models fail to reproduce the observed surface heat flux (F_s) of 100 mW m^{-2} in the south polar region [1], a result also found by [10]. F_s for the convection models was ≤ 35 W m^{-2} for all cases.

We suggest therefore that the south polar thermal anomaly may be the result of a regional and possibly transient effect rather than global convection and heating. Shear heating resulting from slip along the "tiger stripes" [11] may produce sufficient heating in the near surface to explain the observation and may also affect the interior dynamics [12]. The regional shear heating can explain the existence of exactly one thermal anomaly, despite the tendency of the degree 2 tidal heating to produce two plumes, one at each pole.

Our results suggest that a subsurface ocean on Enceladus cannot exist in the steady-state. Independent dynamical arguments [9] suggest that the observed heat anomaly [1] cannot be sustained given Enceladus' current orbit. This does not preclude a transient or periodic ocean. A low-viscosity convecting shell may undergo melting and thinning until it becomes conductive. The heating in the conductive shell would drop and the shell may thicken until convection set in again. Alternately, periodic eccentricity variations may cause an ocean to grow and shrink on that timescale, provided it never freezes completely. These remain intriguing problems for future study.

References [1] Spencer et al. (2006) *Science* 311, 1401. [2] Tobie et al. (2005) *Icarus* 177, 534. [3] Sabadini and Vermeerson (2004) *Global Dynamics of the Earth.* [4] Roberts and Nimmo (2007), LPSC XXXVIII, 1429. [5] Ojakangas and Stevenson (1989) *Icarus* 81, 220. [6] Roberts and Zhong (2004) *JGR* 109, E03009. [7] Goldsby and Kohlstedt (2001) *JGR* 106, 11,017. [8] Sotin et al. (2002), *GRL* 29, 1233. [9] Meyer and Wisdom (2007) *Icarus*, in press. [10] Barr and McKinnon (2007), *GRL* 34, L09202. [11] Nimmo et al. (2007), *Nature* 447, 289. [12] Nimmo et al. (2007), this volume.