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

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. Because a body as small as Enceladus would cool quickly, it is assumed that the observed thermal anomaly is an expression of ongoing internal heating due to tidal dissipation. However, the degree to which tidal heating can occur in a satellite is strongly dependent upon its viscosity structure, and its strength [2], characteristics which are poorly known for Enceladus.

We find that under any reasonable range of rheologic conditions it is not possible to generate significant tidal dissipation in the silicate core. A substantial amount of tidal heating may be produced in the ice shell if it is decoupled from the core by a subsurface ocean. However, we find that convective transport is sufficiently efficient, and core heat production sufficiently small, that a convecting ice shell on Enceladus is inconsistent with a liquid ocean in long-term thermal equilibrium.

The tidal deformation of a spherically symmetric, multi-layered body can be determined from its orbital and material properties [2,3]. The lateral dependence of the deformation is controlled by the tidal potential [4] and has a spherical harmonic degree (ℓ) 2 pattern.

We considered an Enceladus model with three primary layers, a silicate core, a water ocean, and an icy mantle. The silicate layer was fixed at 160 km radius. The water layers had a total thickness of 90 km, but the position of the ice-water interface was allowed to vary between models. Using a propagator matrix method similar to [3], we solved for the heating in the ice shell and silicate core. Fig. 1 shows the surface heat flux predicted by these tidal heating models as a function of ice viscosity and shell thickness. 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, and the total heat flux from the surface. These two competing effects result in a critical shell thickness, T_c at which the maximum heat flow occurs. T_c is viscosity-dependent but is less than 5 km for all the models considered here. The higher heating rates are consistent with the observed heat flux in the south polar region [1]. However, the length scales of surface features is inconsisitent 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, however, is very small for any reasonable core viscosity (Fig. 2). Even if we assume a high melt fraction (~ 0.3)in the core, near the critical melt fraction for disaggregation [5], and take the effective viscosity consistent with such a mixture ($\sim 10^{17}$ Pa s), assuming a Maxwellian behavior, we find that only about 10^{-11} W m^{-3} of heat can be disspiated in the core. This is about three orders of magnitude less than the expected radiogenic heating assuming a chondritic composition of the silicates. Radiogenic heating accounts for about 0.75 mW m^{-2} of heat flux at the

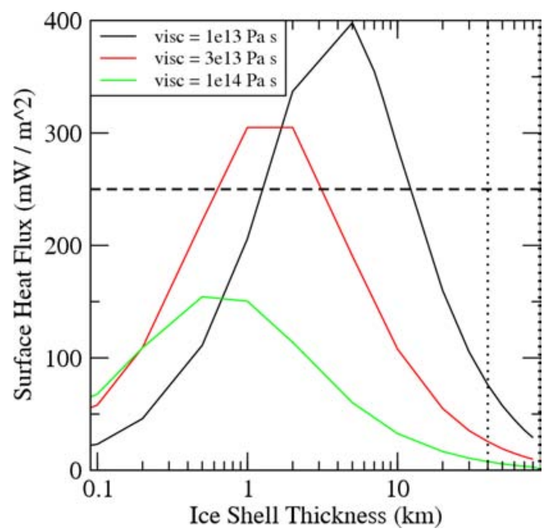

Figure 1: Surface heat flux on Enceladus predicted from tidal heating models for Enceladus. Dashed line shows the heat flux measured in the south polar region [1], dotted lines show the range of shell thicknesses considered for convection models. We assume a rigidity, μ of 4 GPa and constant viscosity within the ice layer.

surface. Io may have a viscosity around a few $\times 10^{15}$ Pa s [6], but even this value only raises the tidal heating to a few percent of chondritic. Although Io is tidally heated to a great degree, this is largely an effect of its size. Tidal heating is a strong function of radius, and Io's is ten times that of Enceladus' core. The core heat flux does not begin to get large until the viscosity drops to around 10^{13} Pa s, probably an unrealistic value.

We therefore assume that tidal heating is not significant in the core of Enceladus and that the heat flux out of the core is entirely due to radiogenic heating. The problem then becomes one of determining what ice shell thickness is consistent with this basal heat flow for a given ice shell viscosity structure.

We address this question by modeling convection in the ice shell. The ocean effectively decouples the ice layer from the silicate layer. We can therefore specify the temperature at the top and bottom boundaries. The bottom boundary is at the melting point of water, and the surface temperature is about 80 K, but varies with latitude [7].

We modeled the convection using the 2D-axisymmetric version of Citcom [8] modified to include the tidal heating from our earlier models. Because the ice shell on Enceladus is likely to be in the diffusion creep regime [9], we assume a Newtonian temperature-dependent viscosity. The heating models assume that the material properties within a given layer are constant. In a convective system, however, lateral variations in viscosity may be considerable. We therefore modify the tidal heating at each point based on the local viscosity according to [7,10].

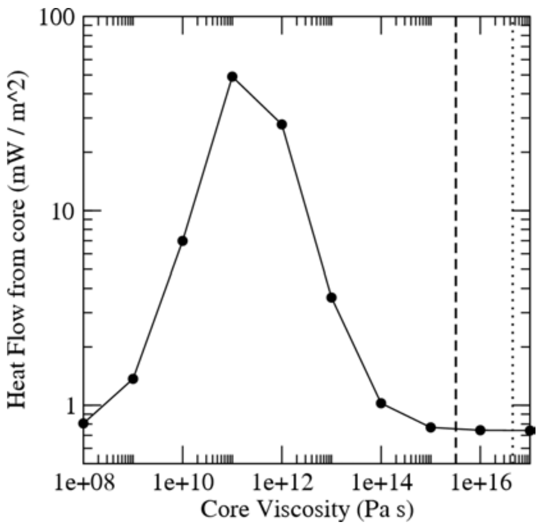

Figure 2: Surface heat flux due to heating in the core as a function of the core viscosity. Dashed line denotes Io's estimated viscosity, dotted line marks viscosity at critical melt fraction for disaggregation (see text). μ = 70 GPa.

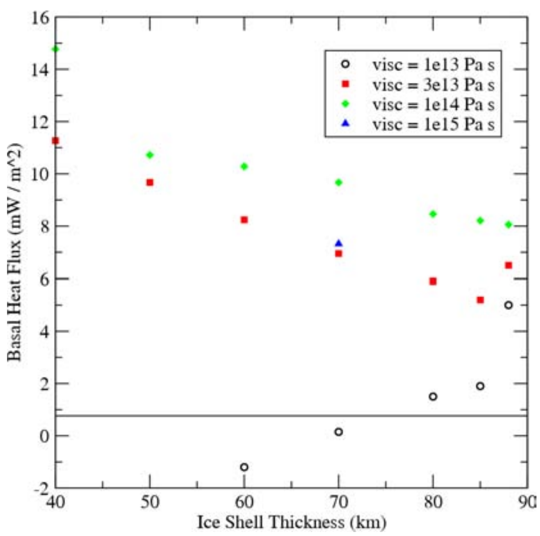

Figure 3: Bottom heat flux as a function of ice shell thickness from convection models. Blue line denotes that expected from a chondritic core. Values have been normalized to the surface area of the planet. "visc" refers to the viscosity at the base of the ice shell.

For the convection modeling, we only considered ice shells at least 40 km thick (Fig. 1). 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 the heat flux across the lower boundary layer. For a model to be in thermal equilibrium, the bottom heat flux should match that produced by a radiogenically heated core. Fig. 3 shows the bottom heat flux 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 (10^{13} Pa s) viscosity 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 becomes much thinner than in the model, and the heat flux changes accordingly and is no longer consistent with the chondritic core heat flux.

Our results suggest that no combination of ice viscosity and convective shell thickness allows thermal equilibrium to be established for a subsurface ocean and chondritic silicate 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. Convection is likely to cease, and tidal heating to be greatly reduced.

Our results also have implications for the south polar thermal anomaly. None of the convection models produce the heat flux of 250 mW m^{-2} observed by [1], suggesting that global tidal dissipation cannot produce all the heat, and that some regional process dominates in the Tiger Stripe region. The existence of exactly one thermal anomaly is also puzzling. Tidal heating occurs in an $\ell = 2$ pattern, and convection models tend to produce two plumes, one at each pole. Some regional enhancement at the south pole is required to reconcile this. It has been suggested that activity in the silicate core may form an $\ell = 1$ pattern in the core which provides localized heating of the base of the ice shell, transmitting this convective pattern [11]. However, our results suggest that the core is inactive and unlikely to help.

Thus far, we have assumed that Enceladus behaves as a Maxwellian body, and that the ice shell is convecting. We have not yet investigated the possibility of an ocean beneath a conductive ice shell. Subject to these caveats, our results suggest that it is not possible to have a stable ocean on Enceladus, under the range of viscosities one would expect to find, although a transient ocean might be possible. We further conclude that the south polar thermal anomaly is likely a result of a regional and possibly transient effect rather than global convection.

References

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