STABILITY OF A SUBSURFACE OCEAN ON ENCELADUS.

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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 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.

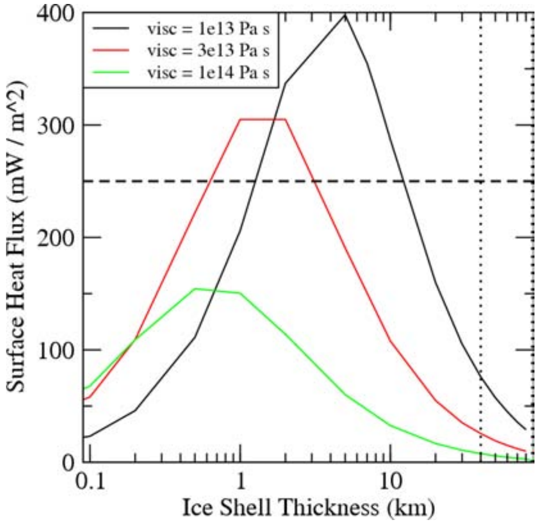

Figure 1: Surface heat flux on Enceladus predicted from tidal heating models for Enceladus. Dashed line shows the heat flux measured in the south polar region [1], dotted lines show the range of shell thicknesses considered for convection models. We assume a rigidity, μ of 4 GPa and constant viscosity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

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