ON THE STABILITY OF AN OCEAN WITHIN ENCELADUS.

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Introduction: Enceladus is geologically active, with plumes of water vapor and dust erupting from its south polar terrain (SPT) [1,2]. The plumes are spatially associated with a region of anomalous heat flow, activity undoubtedly driven by the tidal flexing of Enceladus, which is in an eccentric orbit. Tidal strains of the magnitude possible in an ice shell that is decoupled from a rocky interior by an internal ocean are probably required to generate the quantity of tidal heat emanating from the south pole [3,4]. Recent work, however, suggests that Enceladus' ocean cannot be in thermodynamic steady state with a convective or conductive ice I shell [5]. Regardless of where Enceladus' tidal heating is concentrated, and regardless of whether its outer ice I shell convects, this recent work implies that Enceladus' ocean should freeze on a geologically rapid time scale, implying that activity on Enceladus can only be a transient phenomenon.

Here we show that the arguments in [5] strictly apply only to the case of pure water oceans. If salinity (or ammonia) is allowed for, the ocean may be slightly cooler and can be maintained essentially permanently by tidal heating in the ice above.

Internally or Basally Heated? We assume that Enceladus is fully differentiated into a rocky core and icy mantle or shell; a state consistent with vigorous heating of its interior either early in its history [6] or later by tides and/or long-lived radioisotopes [7,8]. We also assume that the ~80 mW m^{-2} heat flux in the SPT is due to tidal dissipation within the ice shell, by a combination of viscous dissipation in warm ice and frictional heating on lithospheric faults (i.e, core tidal heat can be neglected [5]). The ice shell is heated at its base by radiogenic heat from the core, $\rho_c R_c Q_r/3 \sim O(1)$ mW m^{-2}, where $\rho_c \approx 3450$ kg m^{-3} is a representative density for Enceladus' rocky+metal fraction, $R_c \approx 160$ km is an estimate of the radius of the core [7,8], and Q_r ~5 pW kg^{-1} is the present (ordinary) chondritic heating rate [9]. Because the basal heat flux from Enceladus' rocky core is much less than the surface heat flux, to first order Enceladus' ice shell can be treated as being heated purely from within.

Tidal Heating and Convective Transport: In the absence of poorly constrained tidal damage effects, the viscosity of ice in Enceladus' shell should be strongly temperature-dependent, leading to the formation of a thick "stagnant lid" of highly viscous, immobile ice at its surface that does not participate in convection. In a vigorously convecting, internally heated fluid with a strongly temperature-dependent, but Newtonian, viscosity, the dimensionless convective heat flux, Nu, is related to the logarithm of viscosity contrast from surface to interior, θ, and the dimensionless measure of convective vigor, Ra_i [10]:

$$Nu = 0.53\theta^{-4/3} Ra_i^{1/3} , \quad (1)$$

where $\theta = \ln(\Delta\eta) = Q^* \Delta T / R T_i^2$, and

$$Ra_i = \frac{\rho g \alpha \Delta T D^3}{\kappa \eta_i} \quad (2)$$

In these, T_i and η_i are the temperature and ice viscosity in the convecting interior, ρ is the ice density, g is gravity, ΔT is the temperature difference between the surface and the convecting interior, D is the ice shell thickness, κ is the thermal diffusivity, Q^* is the creep activation energy, and R is the gas constant. Because of the very low convective stresses expected, we adopt a Newtonian, volume diffusion rheology [7,11].

Equations (1) and (2) have been shown to apply to both basally heated and internally heated convection, as long as T_i (the maximum horizontally averaged internal temperature) is used as the reference temperature for the internally heated case [10]. In this case the heat flux at the surface depends directly only on T_i (through η_i); there is no explicit dependence on the basal temperature, T_b. The influence of the lower boundary layer is indirect, in that heat flow across the boundary layer, for finite $T_i - T_b$, must be accounted for in the overall convective flow.

We numerically illustrate this effect in Fig. 1. Parameters appropriate to Enceladus are used, but with some simplifications. A shell depth of 70 km is chosen for specificity and to match some calculations in [5]; tidal heating is mimicked by an appropriate level of uniform volumetric heating. The effects of shell curvature and temperature-dependent material parameters are ignored. The calculations shown are for $T_b = 273$ K and $\eta_b = 10^{13}$ Pa-s (T_i, calculated post-priori, is $\approx$270 K). Nu is calculated to be 4.2, giving a dimensional heat flow of ~35 mW m^{-2}. The basal heat flow is ~10 mW m^{-2}, but fluctuates as the convection is time-dependent. This value is significantly larger than core radiogenic heat release, so as in [5] cannot be in thermodynamic steady state — the ice shell must thicken. The ocean, however, must always be in chemical equi-

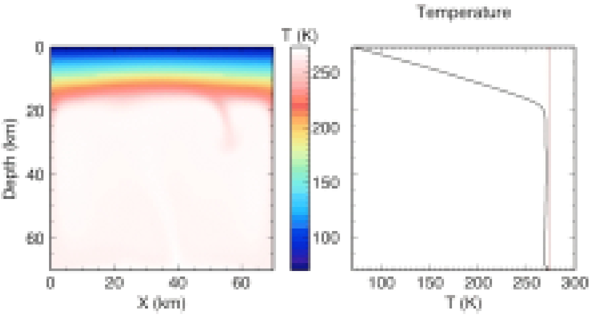

Fig. 1. (top) Convection in an internally (≈tidally) heated enceladan ice shell over a pure water ocean. Horizontally averaged $T(z)$ is show at right in black, with 273 K for reference in red. For a "salty" ocean with a lower basal melting temperature, however, the boundary layer carries less heat and can even disappear altogether (time averaged).

librium with the ice above as well. As it shrinks, concentrations of alkali halides, sulfates, and ammonia (if present [12]) should all increase, lowering the basal melting temperature. Despite incorrect assumptions in some earlier literature, this has *no effect* on the rheology of the pure ice shell above.

The scaling in Eq. (1) predicts, however, that if T_i were to drop to 260 K, then η_i should increase by a factor of e, and Nu decrease by ~25%. If T_b were also 260 K, then the temperature in the lower part of the convecting layer should be very close to T_b and the basal heat flow would be comparable to core radiogenic output. Steady state heat flows should be possible. An ocean on Enceladus need not be a geologically transient phenomenon.

Discussion: An ocean is in all likelihood necessary to provide the decoupling necessary to account for the plumes, heat flow, and tectonics of the SPT [e.g., 4,5]. Sufficiently warm ice in Enceladus' shell is necessary to provide adequate flexing and dissipation. The high thermal gradients implied, on the other hand, should freeze the ocean to its base in a geologically short interval, unless the tidal heating is sufficient to maintain it [5]. We have shown that, in principle, tidal heating in a warm ice shell overlying an impure, and thus somewhat cooler ocean, may be stable, but the impurity of the ocean, and lower basal melting temperature is key to our argument. Ammonia is not necessary; the temperature change required is consistent with the presence of simple salts in the ocean.

We have not shown that ocean cannot be a transient phenomenon. Indeed there is a discrepancy between the observed heat output today and what is possible on a long-term dynamical average [13]. Enceladus may respond, however, to tidal forcing in a non-steady or oscillatory fashion (a matter which needs detailed modeling specific to Enceladus); nor is the long-term average tidal Q for Saturn, upon which which the dynamical heat flow limit in [13] rests, necessarily the value at present (a similar argument for the Earth-Moon system is notoriously incorrect).

We have also not shown in detail that the magnitude of tidal heating in Enceladus' shell, which is rheology-dependent, is sufficient in the absence of basal heating to stabilize the ocean, but we suspect that this is the case, as the basal temperature, T_b, inserts an additional parameter into the problem.

Finally, we note that as vigorous as the convection is in Fig. 1, the heat flow still falls short of what is observed at the SPT by a factor of several, and we have already assumed a low viscosity of 10^{13} Pa-s at 273 K, which corresponds to a grain size of 0.1 mm, usually considered the lower limit of what is plausible in a natural system [e.g., 11]. To raise Nu in Eq. (1) by a factor of several requires raising Ra_i or lowering θ, or both. If we cannot raise Ra_i much more, then lowering θ is the only option, unless the majority of tidal dissipation takes place on faults [4]. A lower θ (or equivalently, $\Delta\eta$), would require a lithospheric weakening mechanism, and could move Enceladus (or at least the SPT) into the "sluggish lid" regime [see 14].

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References: [1] Spencer J.R. et al. (2006) *Science 311*, 1401–1405; [2] Porco C.C. et al. (2006) *Science 311*, 1393–1401; [3] Ross M. and Schubert G. (1989) *Icarus 78*, 90–101; [4] Nimmo F. et al. (2007) *Nature 447*, 289–291; [5] Roberts J. and Nimmo F. (2008) *Icarus*, in press; [6] Matson D.L. et al. (2007) *Icarus 187*, 569–573; [7] Barr A.C. and McKinnon W.B. (2007) *Geophys. Res. Lett. 34*, L09202; [8] Schubert G. et al. (2007) *Icarus 188*, 245–235; [9] Mueller S. and McKinnon W.B. (1988) *Icarus 76*, 437–464; [10] Solomatov V.S. and Moresi L.-N. (2000) *J. Geophys. Res. 105*, 21,795–21,818; [11] McKinnon W.B. (2006) *Icarus 183*, 435–450; [12] Mitri G. and Showman A.P. (2007) *Icarus*, in press. [13] Meyer J. and Wisdom J. (2007) *Icarus 188*, 535–539. [14] Barr A.C. and McKinnon W.B. (2007) this conf.