THERMAL CONVECTION IN THE ICE-I SHELLS OF TITAN AND ENCELADUS. G. Mitri[1] and A. P. Showman[2], [1] Jet Propulsion Laboratory, California Institute of Technology (Giuseppe.Mitri@jpl.nasa.gov), [2] Department of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona.

Introduction: Cassini-Huygens observations have shown that Titan and Enceladus are geologically active icy satellites [1,2,3]. Titan should be partially differentiated into a rocky interior and an outer water layer [e.g., 4,5]. Accretion and differentiation probably caused widespread melting (at least in the outer layers), which would release ammonia and other trapped volatiles into the liquid layer [6,7].

Enceladus exhibits a complex tectonic history, with both extensional and compressional geologic features and a variety of surface ages that suggest a multi-billion-year tectonic history [8,9]. Enceladus appears to be hydrostatically relaxed and could be a differentiated body [10,11], although debate exists [e.g., 2]. The Cassini Ion and Neutral Mass Spectrometer (INMS) did not detect ammonia in the plume and obtained an upper limit ammonia abundance of 0.5% [12]. However, the plume reservoir may reside relatively close to the surface, and the ammonia abundance in the deep interior could well be greater.

At the critical Rayleigh number Ra_{cr}, convection jumps into a finite-amplitude state for a fluid with strongly temperature-dependent viscosity [13,14]. In our previous work [13], we have shown that for the ice shell of Europa, the conductive-convective transition produces radial expansion of a cooling ice shell. The rapidity of these switches implies that the stress build up, hence extensive fractures, could occur.

We explore the hypothesis for Titan and Enceladus that in the presence of an internal ocean, a conductive-convective transition of the ice-I shell can produce geological activity. To reach this objective, we perform numerical simulations of thermal convection with ConMan code for the ice-I shells, with Newtonian rheology and temperature-dependent viscosity. We assume that each satellite is differentiated into an outer ice/water layer overlying a silicate core. We further assume that each body contains an internal liquid-water ocean. This assumption is reasonably plausible for Titan [4,5], but less certain for Enceladus.

Results and Discussion: The results of our numerical simulations show that thermal convection in stagnant lid regime can occur in the ice-I shells of Titan and Enceladus under a range of conditions. Because of Rayleigh number Ra dependence on δ^3/η_b where δ is the thickness of the ice shell and η_b is the viscosity at the base of the ice shell, and because the ammonia in the liquid layer strongly depresses the melting temperature of the ice, Ra equals its critical value ($\sim 3 \cdot 10^6$) at two critical thicknesses: for a relatively thin ice shell ($\delta_{cr,I}$) with a warm, low-viscosity base (Onset I) and for a thick ice shell ($\delta_{cr,II}$) with a cold, high-viscosity base (Onset II). Figs. 1 and 2 summarize the results of our numerical simulations on the thermal state of the ice-I shells on Titan and Enceladus, respectively. The models in Figs. 1 and 2 assumes a reference viscosity $\eta_0 = 10^{13}$ Pa s at 273 K. The basal temperature of the ice shell equals the subsurface ocean temperature (left vertical axes). The right vertical axes give the basal viscosity of the ice shell. The solid lines show the heat flux (tidal and radiogenic) from the interior of the satellite in 10^{-3} W m^{-2}. We plot in dashed-dotted lines the critical Rayleigh number: the heat flux is transported by thermal conduction in the overhanging part of the plot (grey area) and by thermal convection in the underlying (white area). The dotted lines show the Rayleigh number $Ra_{tr} = 1 \cdot 10^8$ corresponding to a transition in the convective regime; see [13,14] for discussion.

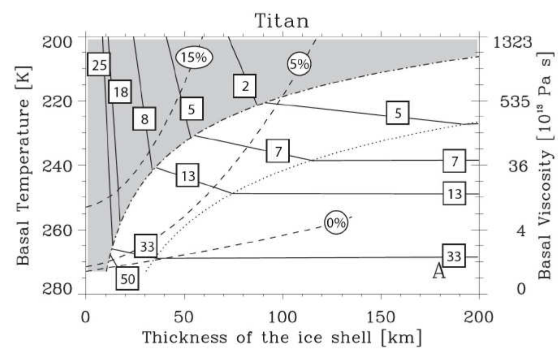

Figure 1. *Thermal state of the Titan ice-I shell. See the text.*

The dashed curves in Figs. 1-2 show the locus of basal temperatures/viscosities, heat fluxes, and ice-shell thicknesses for a specified initial ammonia-water concentration (0%, 5% and 15% for Titan in Fig. 1 and 0%, 1%, 2%, 3%, 4% and 5% for Enceladus in Fig. 2). Therefore, each point along a dashed line represents a possible state of the ice shell for that initial ammonia-water concentration. For a given mass of total ammonia, the system must remain along the relevant dashed curve as the heat flux changes. The dashed curves therefore correspond to evolutionary trajectories. There are several key points. First, small variations of ammonia concentration change drastically the thermal state of the ice shell. Second, the Onset-I transition implies that two solutions exist for a range of heat fluxes. As described in [13], this can induce large and rapid changes in the ice-shell thickness, with consequences for surface tectonics. Third, because the addition of ammonia causes a decrease in Rayleigh number at large thicknesses, a qualitatively new convective-conductive transition occurs. This transition therefore differs qualitatively from Onset I because, at Onset II, *no steady-state solutions exist* for a range of fluxes (e.g. 0.0025 - 0.005 W m^{-2} for Titan with 5% initial ammonia concentration and $\eta_0 = 10^{13}$ Pa s). At heat fluxes within this range, the system would be forced to episodically oscillate between convective and conductive regimes on either side of Onset II over a timescale comparable to the thermal diffusion time, which is ~300 Myr for a 100-km-thick ice shell. During the oscillations, the ice-I shell would change in thickness. The oscillations between conduction and convection at Onset II could therefore have implications for surface tectonics.

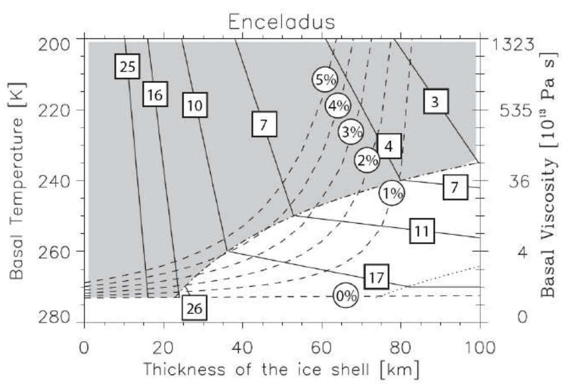

Figure 2. *Thermal state of the Enceladus ice shell. See text.*

For Enceladus, at Onset II, these arguments imply modest satellite expansion as the system oscillates from convective to conductive and satellite contraction as the system returns from conductive to convective. (The situation is more complex at Titan, because modest ice-I shell thickness changes caused by Onset-II oscillations may induce modest oscillations in the thickness of high-pressure ice phases, which cause a volume change counteracting that of thickness changes in the ice-I shell.) These effects would lead to surface strains, perhaps reaching ~10^{-3}, with associated elastic stresses of ~100 bars (which would alternate in sign from one part of the oscillation to another). Repeated oscillations around Onset II could therefore generate surface fractures and deformation, which could be either extensional or compressional depending on whether they formed during the conductive-to-convective or convective-to-conductive phase of the oscillation.

We emphasize that, for plausible ammonia abundances, the range of heat fluxes necessary for the system to encounter Onset I and/or Onset II are within the plausible range of heat fluxes that could have occurred on Titan and Enceladus. For Titan, the expected radiogenic heating (assuming chondritic radionuclide abundances in the rocky portion) ranged from ~0.04 W m^{-2} early in solar system history to ~0.003 W m^{-2} today; tidal heating could have increased these fluxes by a modest amount. For Enceladus, the radiogenic heating flux is over an order of magnitude lower than on Titan, but tidal heating probably makes up the difference, at least episodically [15]. The episodic nature of the resurfacing on Enceladus [8] suggests that Enceladus' heat flux may have varied in time, perhaps by a large factor. Thus, given the probable variation of heat flux over time on Titan and Enceladus, it is quite plausible that these satellites encountered Onset I and/or Onset II during their histories.

High-pressure ice polymorphs (with a mean density of ~1300 kg m^{-3}) could exist on Titan between the ocean and the rocky interior. During the cooling of the planet, the radial expansion of the ice-I layer is, in general, counterbalanced by the radial contraction of the ice high pressure layer. Therefore, a global contraction of Titan could occur during its cooling. The radial contraction of Titan could build compressive surface structures. Enceladus lacks a high-pressure ice polymorph layer. We computed the stress during the radial expansion due to the Onset I as function of the ice shell temperature using the flow law of a Maxwellian viscoelastic body. The Onset I of Enceladus ice shell floating on an ocean produces tectonic stress of ~500 bars and fractures of few tens of km depth. The expected increase in surface area is $2 \cdot 10^4$ km^2; extensional fractures, graben formation, and perhaps necking instabilities could occur, helping to explain Enceladus' rifted terrain [8].

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