LIMITS ON HEAT TRANSPORT AND RESURFACING RATES DUE TO MOBILE LID CONVECTION BENEATH ENCELADUS' SOUTH POLAR TERRAIN. Amy C. Barr, Department of Space Studies, Southwest Research Institute, Boulder CO 80302 (amy@boulder.swri.edu).

Background & Motivation: *Cassini* CIRS data indicate that Enceladus' south polar terrain (SPT) has a large endogenic power output $P_{CIRS} \geq 5.8 \pm 1.9$ GW [1]. Spread over the ~70,000 km^2 region of the SPT, P_{CIRS} corresponds to a heat flux, F_{CIRS}~ 55 mW/m^2 to 110 mW/m^2. The terrain is dominated by extensional tectonics with a component of right-lateral shear and is bounded by cycloidal arcs with wedge-shaped regions of intense folding at their cusps [2]. The SPT has few craters, and none larger than 1 km, suggesting a < 0.5 Myr surface age [3].

In Barr (2008) [4], I hypothesized that the high heat flux and intense surface deformation indicate that the SPT is a location on Enceladus where the near-surface ice had become rheologically and mechanically weakened. This would permit convective plumes to reach close to Enceladus' surface and for the surface ice to be "dragged" along by the underlying convective flow. Simulations of convection using the simplest possible representation of an ice shell with a weak upper surface were used to show that so-called "mobile-lid" convection could transport a heat flux comparable to F_{CIRS}. The same rheological parameters for which the convective heat flux, F_{conv}, was comparable to F_{CIRS}, predicted near-surface spreading velocities ~ tens mm/yr and an implied surface age for the SPT of ~ 0.1 to 1 Myr, comparable to the estimated age, 0.5 Myr [3].

In the last year, analyses of new CIRS data [5,6] suggest that P_{CIRS} may be larger than originally estimated. Forthcoming crater counts on the SPT will also provide tighter constraints on the age of the terrain than the original analysis. Here, I summarize the results of Barr (2008) and show that mobile lid convection can transport a heat flux $F_{conv} \geq F_{CIRS}$. An upper limit on the convective heat flux for mobile lid convection is derived. Scalings between ice shell properties and velocities in the near-surface ice are used to constrain the upper limit on the SPT age consistent with this style of convection. Finally, I discuss the requirements on ice physical properties for this style of convection to occur and suggest laboratory experiments that could help bridge the gap between theory and data.

Convective Heat Flux: *Rayleigh Number-Nusselt Number Relationship.* To constrain the relationship between convective heat flux and rheological and physical properties of an ice shell with a weak surface, Barr (2008) performed numerical simulations of convection in a simple 2-dimensional, 1x1 Cartesian geometry using CITCOM [7]. The ice shell is heated solely from beneath and has thickness D and an effective surface Rayleigh number,

$$Ra_0 = \frac{\rho g \alpha \Delta T D^3}{\kappa \eta_0}, \quad (1)$$

with ice density ρ=920 kg/m^3, surface gravity g=0.13 m/s^2, coefficient of thermal expansion $\alpha=1.7\times10^{-4}$ K^{-1}, $\Delta T=(T_b-T_s)$=(273 K–80 K)=193 K is the difference between the surface and basal ice shell temperature, thermal diffusivity $\kappa=1.23\times10^{-6}$ m^2/s [4,8].

The viscosity is solely temperature-dependent, appropriate for Newtonian volume diffusion [9], expected to accommodate convective flow in Enceladus' ice shell [8]. The variation in viscosity as a function of temperature is described by $\eta=\eta_0\exp(-\gamma T')$, where $T'=(T-T_s)/(\Delta T)$ is nondimensional temperature. Constant-temperature boundary conditions hold the upper surface of the ice shell at T'=0 and T'=1 at its base. The parameter $\gamma=\theta/\Delta T$, and $\theta=\ln(\Delta\eta)$. With this simplified rheology, $\Delta\eta < \exp(8)$ for mobile lid convection [10]. The effective viscosity of the surface ice, η_0, is related to the melting-point viscosity appropriate for T_b, η_1, as $\eta_0=\eta_1/\Delta\eta$, where $\Delta\eta$ is the viscosity contrast across the ice shell. Accordingly, Ra_0 is related to the commonly used basal Rayleigh number, $Ra_1=Ra_0\Delta\eta$.

The value of F_{conv} is related to properties of the ice shell as $F_{conv}=(k\Delta T/D)\,Nu$, with ice thermal conductivity k=3.3 W/m/K and Nusselt number, Nu. The Nusselt number is a function of Ra_0 and $\Delta\eta$ and expresses the relative efficiency of convective over conductive heat transport. Analysis of Nu values obtained in the simulations shows that $Nu \sim 0.32 Ra_o^{1/3}\Delta\eta^{1/19}$ [4,11]. Note that similar to the Ra-Nu relationship for stagnant lid convection, $Nu \sim Ra^{1/3}$, implying that the convective heat flux is independent of the thickness of the ice shell.

Comparison to CIRS Data. Combining the expressions for F_{conv} and Nu, and using values of thermal and physical parameters appropriate for Enceladus' ice shell,

$$\begin{aligned} F_{conv} &= 0.32\left(\frac{\rho g \alpha \Delta T^4 k^3}{\kappa \eta_0}\right)^{1/3} (\Delta\eta)^{1/19} \\ &= 70\ \mathrm{mW/m^2}\left(\frac{10^{17}\ \mathrm{Pa\ s}}{\eta_0}\right)^{1/3}\left(\frac{\Delta\eta}{10^3}\right)^{1/19}. \end{aligned} \quad (2)$$

Assuming plausible basal ice viscosities of 10^{13} to 10^{15} [12], and a range of $\Delta\eta=10^2$ to $10^{3.25}$ appropriate for mobile lid convection gives $F_{conv} \sim F_{CIRS}$ [4].

Upper Limit on Heat Flux in the Mobile Lid Regime. Evaluating equation (2) using lower limits for $\Delta\eta$ and η_1 of $\Delta\eta=10^2$ and $\eta_1=10^{13}$ Pa s (which in turn implies $\eta_0=10^{15}$ Pa s), gives an upper limit of F_{conv}~290 mW/m^2. This corresponds to a total endogenic power output from the south polar region of ~20 GW. If power estimates from new CIRS observations show that P_{CIRS}>20 GW, this would indicate that mobile lid convection is not the sole agent of heat transport in the region.

Geological Consequences: In mobile lid convection, the near-surface ice is "dragged" along with the convective flow. Characteristic velocities in the upper boundary layer are related to Ra_o and $\Delta\eta$ as $v_{sf} \propto Ra_o^{2/3}$ (κ/D) [10]. The maximum horizontal velocity of the surface material obtained in the simulations, max(v_{sf}), scales as max(v_{sf})=0.08 $\text{Ra}_o^{0.8}$ (κ/D).

Comparison with Estimated SPT Ages. Evaluating the expression for max(v_{sf}) using parameters appropriate for Enceladus' ice shell gives

$$\max(v_{sf}) = 25 \text{ mm/yr} \left(\frac{10^{17} \text{ Pa s}}{\eta_o}\right)^{0.8} \left(\frac{D}{30 \text{ km}}\right)^{1.4}. \quad (3)$$

For a circular SPT with an area 70,000 km^2, the equivalent radius of the region is ~150 km. If mobile lid convection is the driving force for resurfacing, the age of the surface is related to the shell thickness and viscosity as,

$$\tau_{SPT} \sim \frac{150 \text{ km}}{\max(v_{sf})} \sim 6 \text{ Myr} \left(\frac{\eta_0}{10^{17} \text{ Pa s}}\right)^{0.8} \left(\frac{30 \text{ km}}{\text{D}}\right)^{1.4}. \quad (4)$$

The same nominal rheological parameters giving F_{conv}=F_{CIRS} also predict a young surface in the SPT comparable to that observed, ~0.5 Myr [3].

Upper Limit on SPT Age Consistent with Mobile Lid Convection. Evaluating max(v_{sf}) at the upper limit of $\Delta\eta=10^4$ appropriate for mobile lid convection and a plausible upper limit on $\eta_1=10^{15}$ Pa s gives a lower limit on v_{sf} consistent with mobile lid convection, v_{sf} ~ 0.6 mm/yr. Accordingly, if the SPT is shown to be older than τ_{SPT} = (150 km/0.6 mm/yr) ~ 250 Myr, the effective surface viscosity of the ice shell will be too high to permit mobile lid convection, and the mobile lid hypothesis could be ruled out.

Requirements for Mobile lid Convection: The most straightforward method of lowering the effective viscosity of the surface ice is to suppose that the viscosity of the cold near-surface ice is limited by the finite yield strength of ice, so that $\eta_0 \sim \sigma_Y / \dot{\varepsilon}$ [11, 13, 14, 15], where $\dot{\varepsilon}$ is the convective strain rate. The critical yield strength (σ_Y) for lid mobilization [16],

$$\sigma_Y \le 13 \frac{\alpha \rho g}{\Delta T} \left(\frac{R T_i^2}{Q_v^*}\right)^2 l_{hor}, \quad (5)$$

where T_i~T_b=273 K is the characteristic temperature beneath the upper thermal boundary layer, Q^*_v=59.4 kJ/mol is the activation energy for diffusion creep in ice [9], R=8.314 J/mol-K is the gas constant, and l_{hor}~D is the horizontal length scale over which stress accumulates in the lid, comparable to the ice shell thickness.

For parameters appropriate to convection in a 30 km-thick ice shell on Enceladus, σ_Y<1 to 10 kPa for this style of convection to occur. This is lower than estimates of σ_Y for terrestrial ice sheets, but is comparable to the diurnal tidal stresses on Enceladus assuming a global ocean. If the tiger stripes open and close in response to diurnal tidal stresses [17,18], and if the tiger stripes represent locations of cracking to warm, ductile ice, this low value of σ_Y may be plausible.

Summary: Simulations of mobile lid convection in Enceladus' ice shell show that F_{conv} and v_{sf} are consistent with *Cassini* observations. If future *Cassini* data shows that P_{CIRS}>20 GW, mobile lid convection is not the sole agent of heat transport in the ice shell. If the surface age of the SPT is shown to be > 250 Myr, near-surface ice viscosities are too high to permit this style of convection. Laboratory and field measurements of cyclically deformed polycrystalline ice at low temperatures appropriate for Enceladus' surface are needed to evaluate whether the low value of σ_Y required for this style of convection is realistic. Because F_{CIRS} is much larger than the radiogenic or modeled tidal dissipation heat fluxes [4, 17, 19], future laboratory work characterizing the methods of energy dissipation in polycrystalline ice are needed to match theory to observation. Simulations of convection including passive and/or actively heated tiger stripes can shed light on the spatial distribution of the thermal emission.

Acknowledgements: This work is supported by NASA *Cassini* Data Analysis grant NNX07AE80G.

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