EVOLUTION OF THE ICE SHELL ON ENCELADUS. J. H. Roberts[1], [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD 20723 (James.Roberts@jhuapl.edu)

Introduction: The plumes [1] and heat flux [2] emitted by the south polar region of Enceladus strongly suggest the presence of a subsurface ocean beneath the ice shell. The long-wavelength gravity [3] field suggests at least a regional sea at the south pole. A regional sea is easier to maintain over geologic time than a global ocean [6,7], but may not be compatible with the present-day libration amplitude [4], which requires a full decoupling of the ice shell and the silicate core.

Maintenance of a global ocean is difficult from a thermal standpoint; in general heat is removed from the interior faster than it can be produced by radioactive decay in the silicate layer and tidal dissipation in the ice shell, and the ocean tends to freeze [5]. Fluid tidal dissipation in the ocean layer itself is potential heat source at tidal resonances that could halt complete freezing [8,9] but may not be substantial in Enceladus unless the ocean is quite thin [10].

A further complication is that the observed heat flux [2] exceeds the long-term sustainable level [11] unless Saturn is significantly more dissipative than generally assumed [12], suggesting that the interior of Enceladus is not in steady state. Consequently, freezing and melting occur, and the ice shell thickness is not constant. Past modeling efforts often address this by treating shell thickness as a free parameter and examining instantaneous snapshots of the thermal structure. Here I describe a self-consistent method to compute the thermal evolution and tidal dissipation in the ice shell of Enceladus, including freezing of the ocean and melting of the ice shell.

Thermal Evolution and Tidal Dissipation: I model thermal evolution in the ice shell using the finite-element code Citcom in 2D-axisymmetric geometry [13]. The viscosity is temperature-dependent [14]. A constant temperature is prescribed at the surface and at the base of the ice shell, as consistent with a phase boundary. It is not possible to also impose a heat flux boundary condition, and in general the heat flux across the bottom boundary F_b will not be consistent to the heat produced in the core H_c. If the heat loss exceeds production (e.g. [5]), the top of the ocean freezes and the ice shell thickens. The mass m added to the ice shell over a time δt is determined by:

$$4\pi r_b^2 F_b - \tfrac{4}{3}\pi r_c^3 H_c = m L \delta t$$

where r_b and r_c are the radii of the base of the ice shell and the silicate core respectively, and L is the latent heat of fusion. A negative value for m implies melting and thinning of the ice shell. If the thickening (or thinning) is spherically symmetric, a change in shell thickness δh can be computed:

$$\delta h = \frac{\left(F_b - \tfrac{1}{3} H_c r_c^3 / r_b^2\right)}{\rho L} \delta t$$

where ρ is the ice density.

Preliminary Results: I consider an example case initial ice shell thickness of 46 km. Using 252 km for the radius of Enceladus and 183 km for a core radius (corresponding to a fully consolidated core of CM chondrite composition [15]), this model has a 23 km thick ocean initially. The core is heated by radioactivity consistent with the composition. The ice shell is heated by tidal dissipation computed using the propagator-matrix code TiRADE [5,16] for a spherically symmetric body with an arbitrary number of viscoelastic layers [17], using the horizontally-averaged viscosity structure obtained from the thermal model. Figure 1 shows the growth of the ice shell thickness over time. I find that the entire ocean freezes out in less than 15 My, a timescale consistent with previous estimates [5].

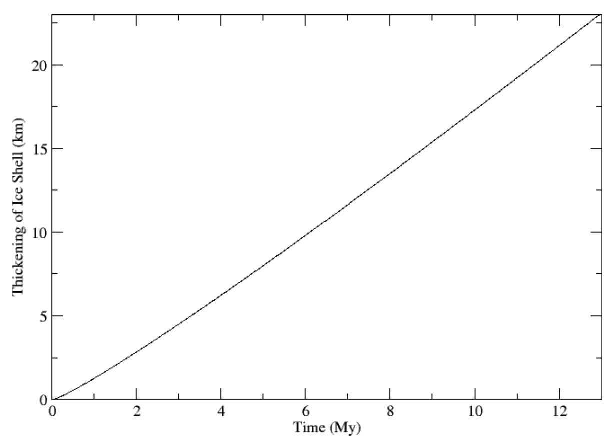

Figure 1: Growth in thickness of the ice shell of Enceladus

The rapid growth rate of the ice shell means that the model domain changes substantially over time as well. In the case shown in Figure 1, it has grown by 50% over only 1000 timesteps. Thus it is necessary to implement a radially adjustable bottom boundary to account for this. I periodically define a new grid spanning the new shell thickness. A schematic demonstration of how this regridding is done is shown in Figure

2. I define new shape functions for the new grid and interpolate the pressure, temperature, velocity, and viscosity fields from the old grid onto the new one. The bottom temperature and stress boundary conditions are applied at the new bottom boundary. This regridding and interpolation need not be done at every timestep, but must be done frequently enough that the bottom boundary has moved by significantly less than the thickness of one model element. Benchmark tests to determine the necessary frequency of regridding are currently in progress.

Pressure and Stress: As the ice shell thickens (or thins), the volume change associated with the phase transition will change the pressure in the ocean, and induce radial and tangential stresses in the ice shell [18]. The volume change also drives an increase (or decrease) in the outer radius of Enceladus, requiring that the outer boundary of the model domain be adjusted as well. Because many geodynamic quantities are nondimensionalized by the radius, these parameters are also rescaled during the regridding.

Past studies on the pressurization of subsurface oceans due to freezing [18] show that the tangential stresses may overcome the tensile strength of the ice shell of Enceladus after as little as a few hundreds of m of freezing, and could lead to substantial eruption of oceanic material. The results shown in Figure 1 suggest that this requires only around 100 ky, and that eruptions could continue for several My after that. This latter timescale is consistent with that estimated for the duration of episodic overturn events [19].

Compositional Effects: The preliminary analysis assumes a pure water ice shell over a water ocean. The actual composition is likely to be significantly more complicated. Ammonia, hydrocarbons, and salts have been detected in the south polar plumes [20,21], and are expected to be found in some concentration in the ocean itself. All of these serve to depress the freezing point of the ocean, which could inhibit the rate of freezing, but probably cannot prevent it [16]. More significantly, the different crystallization temperatures of the various chemical components would result in a weak partial melt or "slush" layer at the base of the ice shell. The rheology of such a slush is not well known, but may substantially affect the tidal heating in this layer. This effect is under investigation.

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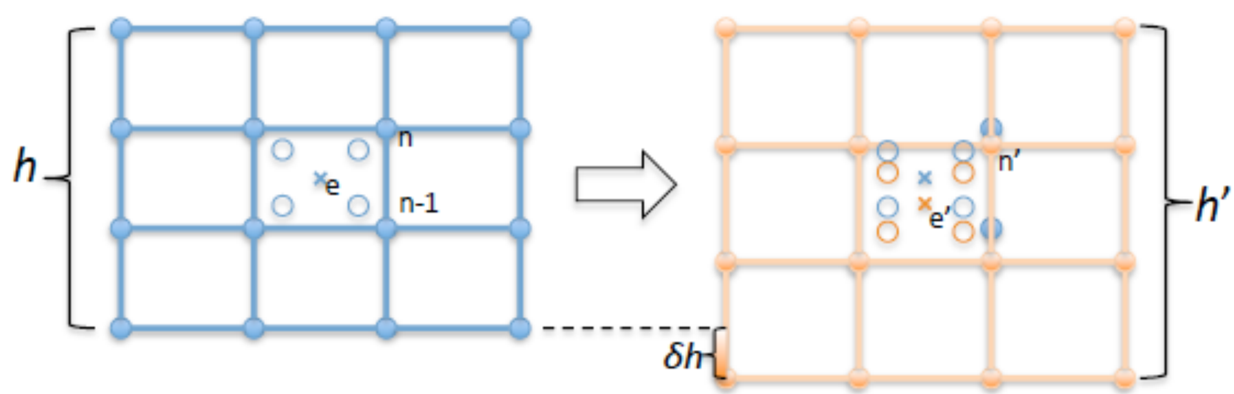

Figure 2: Example of regridding and interpolation after thickening of an ice shell. Grids are shown for thickness *h* (left) and final thickness *h′* (right). Nodes are shown by filled circles. An example node *n* is indicated on the left and the corresponding node *n′* on the right. Temperature, velocity, and other information are interpolated from nodes *n* and *n*-1 onto *n′*. Elements *e* and *e′* are also shown with centers marked by crosses and Gaussian quadrature points by open circles. The locations of some initial nodal and element points are shown on the final grid to emphasize the radial shift. The grid does not evolve horizontally.