Breaking the symmetry and the ice shell of Enceladus. James H. Roberts[1], and Angela M. Stickle[1], [1]Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, James.Roberts@jhuapl.edu

Introduction: Enceladus is well known for jets of vapor and ice, which emanate from the four tiger stripes [1,2] in its south polar terrain (SPT). Salts observed in these plumes suggest their source is a subsurface ocean [3], which is thus in direct communication with the surface. A substantial thermal anomaly of ~10 GW is associated with the SPT [4] and strongly correlates with the location of the tiger stripes. Tides control these fractures and are the probable energy source for the thermal anomaly. However, tides alone are insufficient because the tidal potential is symmetric about the equator and no corresponding thermal anomaly or activity is observed in the north.

The presence of significant lateral variations in the mechanical properties of the ice shell could break this symmetry, and gravity measurements made by Cassini [5] suggest that the ice shell is thinner at the south pole. However, libration observations 6, require a global ocean rather than a regional sea [7], and lateral variations in ice shell thickness over a global ocean are difficult to sustain over long timescales [8].

A non-tidal, physical mechanism is therefore needed to break the tidal symmetry. Here we explore the possibility that a large impact into what is now the SPT could break not only the tidal symmetry, but the ice shell as well, penetrating into the ocean.

Models: Our standard model setup is for the vertical impact of a 15-km icy projectile into an ice shell over an ocean. We neglect the core, because the shock heating does not penetrate through the ocean for the impact considered here. Our standard impact velocity of 20 km/s was chosen such that our projectile would generate a final crater the approximate size (~150 km; [1]) of the SPT (although we note that the present-day topographic depression is not equivalent to the original crater). We use the CTH hydrocode [9] in 2D to simulate the impact process, and use the 5-phase ANEOS for ice [10] to compute the temperature change and melt production.

Results: Here, we consider a 20-km thick ice shell over an ocean [8,11]. In Fig. 1, we show the temperature and material profiles 19.5 s after the impact. The impact has melted a 40-km wide, quasi-spherical region in the ice shell, effectively making a hole right through it. The hole is initially filled with liquid that came from the ice shell and projectile, but much of this material will eventually be ejected to space.

The ocean will rebound [10,12] briefly forming a geyser (Fig. 2a) before settling to the level of neutral buoyancy. A liquid water ocean (even one containing significant contaminants) in direct contact with space

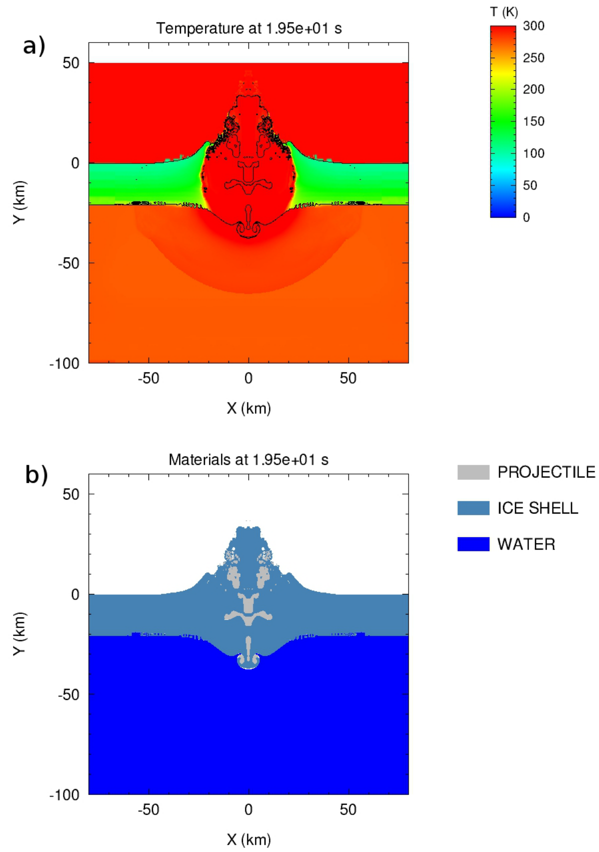

Figure 1: Temperature (a) and source material (b) in the ice shell and ocean of Enceladus 19.5 s after the vertical impact of a 15-km icy projectile into a 20-km thick ice shell at 20 km/s.

at < 80 K is unsustainable, and the surface will freeze at once (Fig. 2b). Assuming the impact is energetic enough to cause fracturing in the ice surrounding the hole (as in the example shown in Fig. 1), the sides of the hole may collapse, briefly breaking up the frozen surface. This material forms an assemblage of ice floes floating in the south polar sea, loosely held together by the thin re-frozen surface layer (Fig. 2c). Once the surface layer is no longer subject to external disturbances, freezing can proceed downward, thickening the ice shell over the hole (Fig. 2d).

Discussion: To first order, the propagation of the solidification front is an example of the Stefan problem. In Fig. 3, we show the thickness of the solidifying ice over the melt hole as a function of time. A hole through a 20-km thick ice shell would be expected to re-freeze completely after about 8 Myr. Gravity and libration data suggest that the present-day ice thickness may be < 5 km at the south pole [11]; this would occur in less than 0.5 Myr.

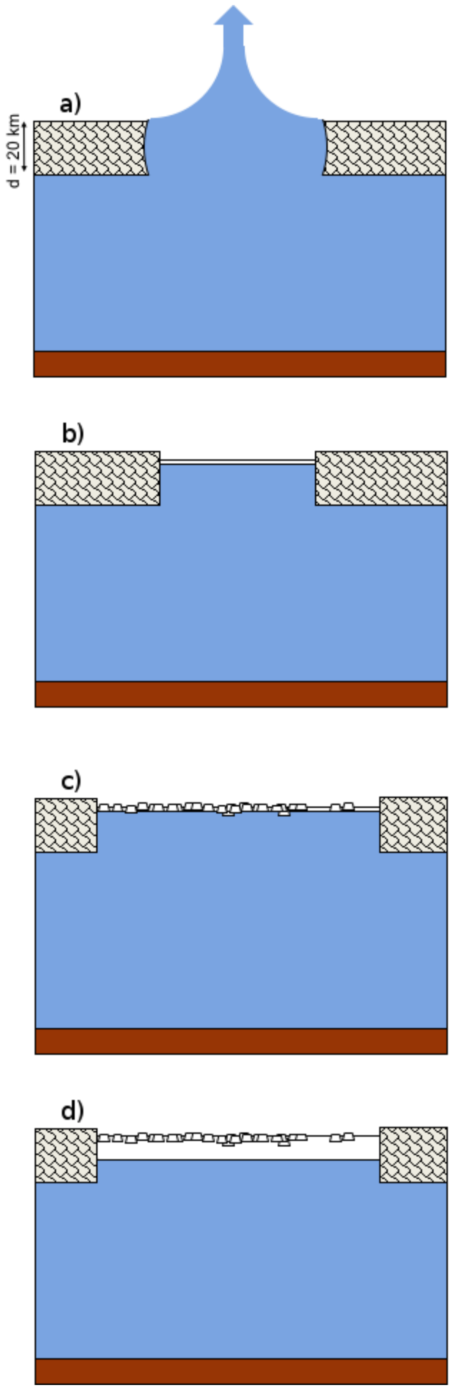

Figure 2: Sketch of the fractured ice shell (cross-hatched gray) and ocean (blue) of Enceladus at the impact site after complete penetration of the ice shell by an impactor. Panels show excavation and geyser (a, t ~10 min.); return of ocean to neutral buoyancy and freezing of surface layer (b, t ~1 hr.); collapse of side walls (c, t ~few hr.); freezing of ocean and thickening of ice in the hole (d, ~My).

The ice shell is probably too thin to support convection, which would hasten cooling. Thus, the time-scales described above are minimum estimates, as the generation of tidal heating will slow down the freezing rate [13]. The tidal heat must also be conducted away from the ice-water interface in addition to the latent heat of fusion, although even the highest expected levels of tidal heat (~10^{-6} W m^{-3}) only prolongs the growth of the ice shell back to the original level by ~10%. The tidal heating primarily serves to inhibit growth beyond its pre-impact thickness.

Here we have illustrated a mechanism for breaking the tidal symmetry about the equator, and to enable communication between the ocean and the surface. Ongoing finite element analysis [15] explores the initiation of fracture development, propagation, and iteraction as the ice shell cools in the presence of tidal stresses, from a floating raft of ice blocks to only four huge fractures.

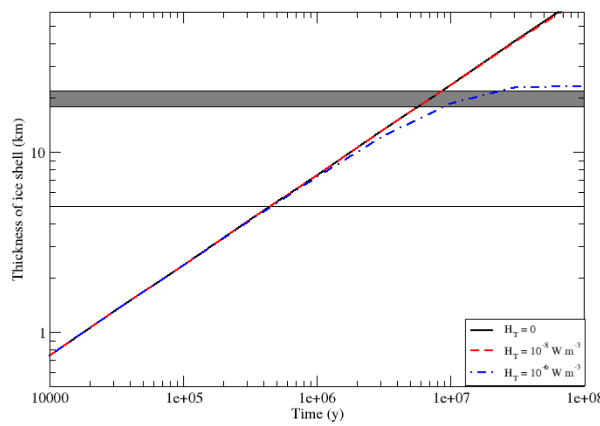

Figure 3: Thickness of the ice shell above the melt hole as a function of time. The solid horizontal lines mark the range of average ice shell thicknesses and the dashed line marks the thickness of the ice above the south pole from gravity and libration data [11].

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