

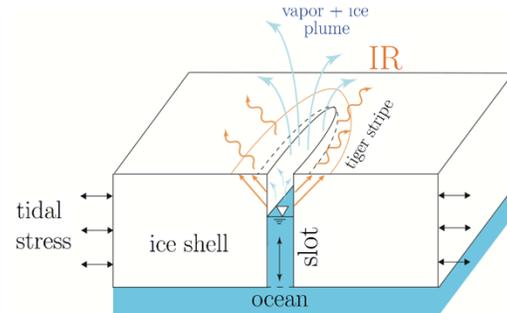
## SUSTAINED ERUPTIONS ON ENCELADUS EXPLAINED BY TURBULENT DISSIPATION IN TIGER STRIPES.

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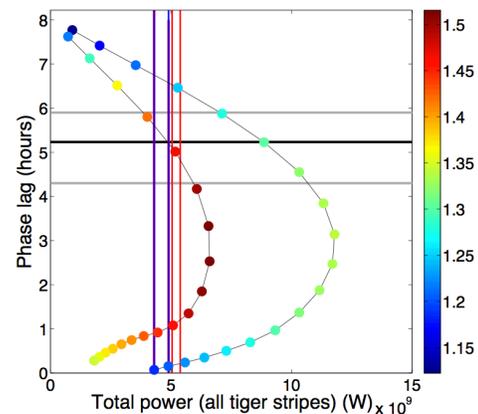
**Summary:** Enceladus geysers apparently draw water from a subsurface ocean, but the sustainability of conduits linking ocean and surface is not understood. “Tiger stripes” sourcing the geysers should be clamped shut by tidal stresses for much of the 1.3 day orbit, and liquid-water conduits should freeze over quickly, so eruptions should be intermittent. However, observations show sustained geysering, both throughout each orbit, and since 2005. A simple model of tiger stripes as tidally-flexed slots that puncture the ice shell can simultaneously explain: persistence of the eruptions through the tidal cycle; observed phase lag of eruptions relative to tidal stress; maintenance of fissure eruptions over geological timescales; and Enceladus’ power output. Delay associated with flushing and refilling of  $O(1)$  m-wide slots with ocean water generates a phase lag, while tidally pumped in-slot flow leads to heating and mechanical disruption that staves off slot freeze-out. Narrower and wider slots cannot be sustained. In the presence of long-lived slots, Myr-averaged power of Enceladus is buffered by a feedback between ice melt back and subsidence to  $\sim 5$  GW. This matches observed power, suggesting long-term stability.

**Background:** Each of Enceladus’ eruptive fissures is flanked by  $<1$  km-wide belts of endogenic thermal emission ( $10^4$  W/m for  $\sim 500$  km total fissure length) [1]. The tiger stripe region is tectonically resurfaced, suggesting an underlying mechanism accounting for both volcanism and resurfacing. Plume composition and gravity suggest that the geysers are sourced from a salty ocean [e.g. 2, 3]. A continuous connection between ocean and surface is a simple explanation for these observations, but leads to a severe energy-balance problem. The water table within a conduit would be  $\sim 3.5$  km below the surface (from isostasy), with liquid water below the water table, and vapor-plus-droplets above. Condensation of vapor on fissure walls releases heat that is transported to the surface thermal-emission belts by conduction (Fig. 1) [4-6]. Because this vapor comes from the water table there is strong evaporitic cooling of the water table. This cannot be re-supplied by thermal-convective exchange with the ocean unless fissures are unrealistically wide [7]. Freezing at the water table could release latent heat but would swiftly clog fissures with ice. This energy deficit has driven consideration of shear-heating, intermittent eruptions, and heat-engine hypotheses [e.g. 1,8]. It is easier to explain observations if the heat is made within the plumbing system. The observed long-term steadiness of ice and gas geysering is modulated (for ice) by fivefold tidal variability. Peak activity anomalously lags peak tidal extension (by  $5.1 \pm 0.8$  hours relative to a fiducial model of the tidal

response). Eruptions continue at Enceladus’ periapse, which is puzzling [e.g., 5-6]. Questions for any model include: How can eruptions continue throughout the tidal cycle? Why is the total power of the system 5 GW? How can conduits stay open despite evaporitic cooling?



**Fig. 1.** Geysers (blue arrows) vary on tidal timescales due to flexing (dashed lines) of geyser source fissures by tidal stresses (horizontal arrows). Flexing also drives vertical flow (vertical black arrow) in slots beneath source fissures, generating heat. Heat maintains slots against freeze-out despite strong evaporitic cooling at the water table (downward-pointing triangle), which provides heat for warm surface material (orange arrows).



**Fig. 2.** Turbulent dissipation that matches the observed phase lag of Enceladus relative to a fiducial model of interior structure (gray lines bracket acceptable range) also matches observed Enceladus power (IR only - blue vertical lines; IR plus plumes - red lines). Thin black curves show calculated power for (left curve) four slots of length  $L=100$  km, and (right curve)  $L=93$  km outboard slots and  $L=151$  km inboard slots. Colored dots show fractional change in aperture. Aperture is sampled at 0.5 m width (uppermost dots) and then at 0.25 m intervals up to 5 m (lowermost dots). Best fit  $W_0$  are 1.25-2 m.

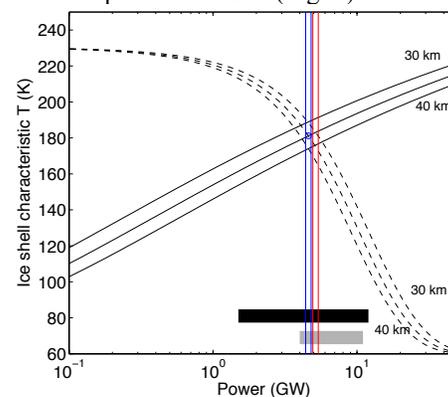
**Simple slot model:** Fissures are modeled as parallel rectangular slots (stress-free width  $W_0$ ), open to an ocean at the bottom (Fig. 1). Subject to sinusoidally time-varying

extensional slot-normal time-dependent stress of amplitude  $\sigma_n = (5 \pm 2) \times 10^4$  Pa modified by elastic interactions between slots, the water table initially falls, water is drawn into slots from the ocean (which is modeled as a constant-pressure bath), and slots widen. Wider slots allow stronger eruptions because flux of a supersonic choked flow increases with nozzle width [9]. Later in the tidal cycle, the water table rises, water is flushed from slots to the ocean, slots narrow, and eruptions diminish (but never cease).  $W_0 > 5$  m slots oscillate in phase with  $\sigma_n$ ,  $W_0 < 1$  m slots lag  $\sigma_n$  by  $\pi/2$  rad, and resonant slots ( $W_0 \sim 1$  m, tidal quality factor  $\sim 1$ ) lag  $\sigma_n$  by  $\sim 1$  radian. Net liquid flow feeding the eruptions is negligible compared to tidally-oscillating flow ( $\sim \pm 1$  m/s for  $W_0 \sim 1$  m).

Turbulent liquid water flow into and out of slots generates heat. Water temperature is homogenized by turbulent mixing. Aperture variations and vertical pumping help to disrupt ice forming at the water table. A long-lived slot must satisfy the heat demands of evaporitic cooling at the water table (about 1.2x the observed IR emission) plus re-melting of ice inflow driven by the pressure gradient between the ice and the water in the slot [10]. Turbulent dissipation can balance this demand for  $W_0 = 1-3$  m, corresponding to phase lags of 0.5-1 rad, as observed. Eruptions are then strongly tidally-variable but sustained over the tidal cycle.  $W_0 < 1$  m slots freeze shut, and  $W_0 > 5$  m slots would narrow. Near-surface apertures  $\sim 10$  m wide are suggested by modeling of high-temperature emission [11], consistent with near-surface vent flaring. Rectification by choke points [9], condensation on slot walls, and ballistic fall-back [3], could plausibly amplify the  $< 2$ -fold slot-width variations in our model to the 5-fold observed plume variations.

**Consequences:** Do geysers drive ice shell tectonics, or are geysers a passive tracer of tectonics? Inflow of ice into the slot occurs predominantly near the base of the shell. Inflowing ice causes necking of the slot, which locally intensifies dissipation until inflow is balanced by melt-back. Melt-back losses draw down cold ice from higher in the ice shell. At steady state this requires horizontal shortening in the region of slot freeze-on, consistent with compressional folds observed between tiger stripes [12]. Because subsidence is too rapid for conductive warming of subsiding ice, subsidence of cold viscous ice is a negative feedback on the inflow rate. In equilibrium, ice consumed by melt-back near the base of the shell is balanced by subsiding ice, which in turn is equal to the mass added by condensation of ice from vapor above the water table. The steady-state flux of ice removed from the upper ice shell via subsidence and remelting at depth theoretically depends only on ice shell dimensions, gravity, and the material properties of ice. Preliminary calculations of this value, which is insensitive to reasonable variations in ice shell thickness and ice viscosity (Fig. 3), match the *observed* rate of ice addition to the upper ice

shell,  $(4.6 \pm 0.2)$  GW =  $(1.6 \pm 0.1)$  ton/s (assuming observed IR flux is balanced by re-condensation of water vapor on the walls of the tiger stripes above the water table [1,6,13]). The balance is self-regulating because increased (decreased) tiger stripe activity will reduce (increase) the rate at which accommodation space for condensates is made available via subsidence in the near surface. This is consistent with sustained geysering on Enceladus at the Cassini-era level over  $> 10^6$  yr. Under these conditions the ice shell is cold and nondissipative. In summary, turbulent dissipation of diurnal tidal flows (Fig. 1) could plausibly explain the interannual-to-decadal sustainability of liquid-water-containing tiger stripes (Fig. 2), and coupling between long-lived slots and the ice shell drives a  $10^6$  yr geologic cycle that buffers Enceladus' power to 5 GW (Fig. 3).



**Fig. 3.** (Preliminary:) Power output/mass flux of Enceladus, linking  $10^{-2}$  yr through  $10^6$  yr timescales. Solid black lines show power corresponding to vaporization of ice flowing from the ice shell into slots for ice shell thicknesses of (from top) 30, 35, & 40 km. Dashed lines show the cooling of ice shell corresponding to subsidence of cold ice at that mass flux; where the dashed lines intersect the solid lines, shell equilibrium is possible on Myr timescales. Gray bar shows power for turbulent dissipation models that match observed phase lag of Enceladus' eruptions to within  $1\sigma$ . Black bar shows range of turbulent dissipation model runs where slot aperture varies by  $> 1.3$ , consistent with observations of large-amplitude volcanic plume amplitude diurnal variations. The preliminary results show that Myr- and day-average powers implied by long-lived slots independently match observed Enceladus power (blue and red vertical lines).

**References:** [1] Nimmo & Spencer (2013) *AREPS* [2] Iess et al. (2014) *Science* [3] Postberg et al. (2011) *Nature* [4] Abramov & Spencer (2009) *Icarus* [5] Porco et al. (2014) *AJ* [6] Nimmo et al. (2014) *AJ* [7] Postberg et al. (2009) *Nature* [8] Matson et al. (2012) *Icarus* [9] Schmidt et al. (2008) *Nature*. [10] Cuffey & Patterson (2010) *The physics of glaciers*, C.U.P. [11] Goguen et al. (2013), *Nature* [12] Barr & Pruess (2010), *Icarus*. [13] Ingersoll & Pankine (2010), *Icarus*.