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. 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.

Background: Each of Enceladus' eruptive fissures is flanked by <1 km-wide belts of endogenic thermal emission (10^4 W/m for ~500 km total fissure length). 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. 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 ~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). Because this vapor comes from the water table there is strong evaporitic cooling of the water table. This cannot be resupplied by thermal-convective exchange with the ocean unless fissures are unrealistically wide. 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. 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. Surprisingly, eruptions continue at Enceladus' periapse.

Simple slot model: Fissures are modeled as slots open to an ocean at the bottom. Subject to tidal stress, 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. 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>5 m slots oscillate in phase with σ_n, W<1 m slots lag σ_n by $\pi/2$ rad, and resonant slots ($W \sim 1$ m, tidal quality factor ~ 1) lag σ_n by ~ 1 radian. Net liquid flow feeding the eruptions is negligible compared to tidally-oscillating flow. 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 plus re-melting of ice inflow driven by the pressure gradient between the ice and the water in the slot. Turbulent dissipation can balance this demand for W=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 <1 m slots freeze shut, and W>5 m slots would narrow. Near-surface apertures ~10 m wide are suggested by modeling of high-temperature emission, consistent with near-surface vent flaring. Rectification by choke points, condensation on slot walls, and ballistic fall-back, could plausibly amplify the <2-fold slot-width variations in our model to the 5-fold observed plume variations. In summary, turbulent dissipation of tidal flows could plausibly explain the inter-annual-to-decadal sustainability of liquid-water-containing tiger stripes. At the conference, we will describe how a coupling between long-lived slots and the ice shell drives a 10^6 yr geologic cycle that buffers Enceladus' power to 5 GW.

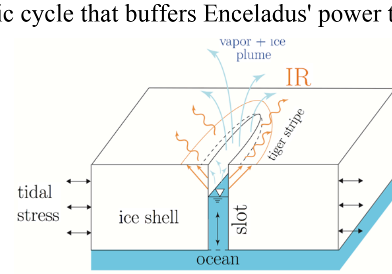

Fig. 1. Geysers vary on tidal timescales due to flexing of geyser source fissures by tidal stresses. Flexing also drives vertical flow in slots beneath source fissures, generating heat. Heat maintains slots against freeze-out despite strong evaporitic cooling at the water table, which provides heat for warm surface material.

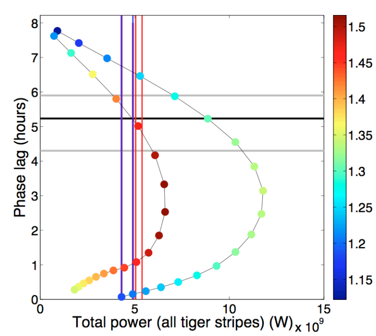

Fig. 2. Turbulent dissipation that matches the observed phase lag of Enceladus relative to a fiducial model of interior structure (gray lines bracket acceptable range) also matches observed Enceladus power (vertical lines). Thin black curves show power for two plausible slot geometries. Colored dots show fractional change in aperture. Aperture is sampled at 0.25 m intervals up to 5 m (lowermost dots). Best fit W are 1.25-2 m.