Sustained eruptions on Enceladus explained by turbulent dissipation in tiger stripes

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Spacecraft observations suggest that the plumes of Saturn’s moon Enceladus draw water from a subsurface ocean, but the sustainability of conduits linking ocean and surface is not understood. Observations show eruptions from “tiger stripe” fissures that are sustained (although tidally modulated) throughout each orbit, and since the 2005 discovery of the plumes. Peak plume flux lags peak tidal extension by ~1 rad, suggestive of resonance. Here, we show that a model of the tiger stripes as tidally flexed slots that puncture the ice shell can simultaneously explain the persistence of the eruptions through the tidal cycle, the phase lag, and the total power output of the tiger stripe terrain, while suggesting that eruptions are maintained over geological timescales. The delay associated with flushing and refilling of O(1)-m-wide slots with ocean water causes erupted flux to lag tidal forcing and helps to buttress slots against closure, while tidally pumped in-slot flow leads to heating and mechanical disruption that staves off slot freezout. Much narrower and much wider slots cannot be sustained. In the presence of long-lived slots, the 10^2-y average power output of the tiger stripes is buffered by a feedback between ice melt-back and subsidence to O(10^19) W, which is similar to observed power output, suggesting long-term stability. Turbulent dissipation makes testable predictions for the final flyby of Enceladus by Cassini. Our model shows how open connections to an ocean can be reconciled with, and sustain, long-lived eruptions. Turbulent dissipation in long-lived slots helps maintain the ocean against freezing, maintains access by future Enceladus missions to ocean materials, and is plausibly the major energy source for tiger stripe activity.

Enceladus’ tiger stripes have been erupting continuously since their discovery in 2005 (1–4). The eruptions have been sustained for much longer than that: Saturn’s E-ring, which requires year-on-year replenishment from Enceladus, has been stable since its discovery in 1966. Each of the four eruptive fissures is flanked by <1-km-wide belts of endogenic thermal emission (10^6 W/m for the ~500-km total tiger stripe length), a one-to-one correspondence indicating a long-lived internal source of water and energy (5). The tiger stripe region is tectonically resurfaced, suggesting an underlying mechanism accounting for both volcanism and resurfacing, as on Earth. Enceladus’ 30 ± 10-km-thick ice shell is probably underway by an ocean or sea of liquid water, and Enceladus’ plume samples a salty liquid water reservoir containing 40Ar, ammonia, nano-silica, and organics (6–9). A continuous connection between the ocean and the surface is the simplest explanation for these observations. However, the consequences of this connection for ice shell tectonics have been little explored. The water table within a conduit would be ~3.5 km below the surface (from isostasy), with liquid water below the water table, and rapidly ascending vapor plus entrained water droplets above. Condensation of this ascending vapor on the vertical walls of the tiger stripe fissures releases heat that is transported to the surface thermal-emission belts by conduction through the ice shell (Fig. 1) (1, 10–12). Because this vapor comes from the water table, there is strong evaporitic cooling of water < 100 m below the water table. Freezing at the water table could release latent heat but would clog the fissures with ice in <1 y. This energy deficit has driven consideration of shear heating, intermittent eruptions, thermal-convective exchange with the ocean, and heat engine hypotheses (5, 13, 14). It is easiest to explain the observations if the heat is made within the plumbing system.

The observed long-term steadiness of ice and gas output is modulated (for ice) by fivefold variability at the period P = 33 h of Enceladus’ eccentric orbit about Saturn (the diurnal tidal period). Peak eruptive output anomalously lags peak tidal extension (by 5.1 ± 0.8 h relative to a fiducial model of the tidal response), and fissure eruptions continue from all four tiger stripes at Enceladus’ periapse when all tidal crack models predict that eruptions should cease (1, 4, 11, 15). The sustainability of water eruptions on Enceladus affects the moon’s habitability (e.g., ref. 16), as well as astrobiology (follow-up missions to Enceladus could be stymied if the plumes shut down). Despite the importance of understanding the sustainability of the eruptions, basic questions remain open: How can eruptions continue throughout the tidal cycle? How can the liquid water conduits obtain the energy to stay open—as needed to sustain eruptions—despite evaporitic cooling and viscous ice inflow? Why is the total power of the system ~5 GW (not ~0.5 GW or ~50 GW)? Do tiger stripe mass and energy fluxes drive ice shell tectonics, or are the tiger stripes a passive tracer of tectonics?

We have found that a simple model of the fissures as open conduits can simultaneously explain both the maintenance of Enceladus’ eruptions throughout the tidal cycle and the sustainability of eruptions on 10^2-y to 10^3-y timescales, while predicting that eruptions are sustained over 10^3-y timescales. Fissures are modeled as parallel rectangular slots with length L ≈ 130 km,
Fig. 1. The erupted flux from Enceladus (blue arrows) varies on diurnal timescales, which we attribute to daily flexing (dashed lines) of the source fissures by Saturn tidal stresses (horizontal arrows). Such flexing would also drive vertical flow in slots under the source fissures (vertical black arrows), which through viscous dissipation generates heat. This heat helps to maintain the slots against freezing despite strong tidal forcing by vapor escaping from the water table (downward-pointing triangle). The vapor ultimately provides heat (via condensation) for the envelope of warm surface material bracketing the tiger stripes (orange arrows; "IR" corresponds to infrared cooling from this warm material).

depth $Z = 35$ km, stress-free half-width $W_0$, and spacing $S = 35$ km. Slopes are connected to vacuum at the top, and open to an ocean at the bottom (Fig. 1 and SI Appendix). Subject to extensional slot-normal tidal stress $\sigma_n = (5 \pm 2) \times 10^4 \sin(2\omega t/p)$ Pa modified by elastic interactions between slots, the water table initially falls, water is drawn into the slots from the ocean (which is modeled as a constant-pressure bath), and the slots widen (Fig. 2). Wider slots allow stronger eruptions because the flow is supersonic and choked (17). Later in the tidal cycle, the water table rises, water is flushed from the slots to the ocean, the slots narrow, and eruptions diminish (but never cease) (Fig. 2). Solving the coupled equations for elastic deformation of the icy shell with turbulent flow of water within the tiger stripes allow us to compute $W(t)$ (SI Appendix). $W_0 > 2.5$ m slots oscillate in phase with $\sigma_n$, $W_0 < 0.5$ m slots lag $\sigma_n$ by $\sim \pi/2$ rad, and resonant slots ($W_0 \sim 1$ m, tidal quality factor $\sim 1$) lag $\sigma_n$ by $\sim 1$ rad (SI Appendix, Fig. S4). The net liquid flow feeding the eruptions (< 10 mm/s) is much smaller than the peak tidally pumped vertical flow (approximately $\pm 1$ m/s for $W_0 \sim 1$ m, $Re > 10^5$). Although the amplitude of the cycle in water table height is reduced when the slot is hydrologically connected to the ocean relative to a hypothetical situation where the slot is isolated from the ocean, the flow velocity, driven by the deviation of the water table from its equilibrium elevation, is very much larger than in the hydrologically isolated case.

Turbulent liquid water flow into and out of the slots generates heat. Water temperature is homogenized by turbulent mixing, allowing turbulent dissipation to balance water table losses and prevent icing over. Ice forming at the water table is disrupted by aperture variations and vertical pumping; water cooled by evaporation, if sufficiently saline, will sink and be replaced by warmer water from below. A long-lived slot must satisfy the heat demands of evaporitic cooling at the water table (about 1 kx the observed IR emission; SI Appendix) plus heating and melt-back of ice driven into the slot (18) by the pressure gradient between the ice and the water in the slot (19) (SI Appendix). Turbulent dissipation can balance this demand for $W_0 = (1 \pm 0.5)$ m, corresponding to phase lags of 0.5–1 rad, consistent with observations. Eruptions are then strongly tidally variable but sustained over the tidal cycle, also matching observations. $W_0 < 0.5$ m slots freeze shut, and $W_0 > 2.5$ m slots would narrow. Power output is sensitive to the amplitude $k$ of conduit roughness, which is poorly constrained for within-ice conduits. For the calculations in this paper, we use $k = 0.01$ m; for discussion, see SI Appendix. Near-surface apertures $\sim 10$ m wide are suggested by modeling of high-temperature emission (19), consistent with near-surface vent flaring (20). Rectification by choke points (18) which are required to explain the absence of sodium in the gas phase (21), together with condensation on slot walls, and ballistic fallback (6) could plausibly amplify the less than twofold slot-width variations in our model to the fivefold variations in the flux of ice escaping Enceladus. Water’s low viscosity slows the feedback that causes the fissure-to-tine transition for silicate eruptions on Earth (22, 23), which is suppressed for Enceladus by along-slot mixing (SI Appendix).

The mass and heat fluxes associated with long-lived slots (24) would drive regional tectonics (SI Appendix). Slow inflow of ice into the slot (25) occurs predominantly near the base of the shell, where ice is warm and soft. Inflowing ice causes necking of the slot, which locally intensifies dissipation until inflow is balanced by melt-back. Melt-back losses near the base of the shell cause colder ice from higher in the ice shell to subside. Because subsidence is fast relative to conductive warming timescales, subsidence of cold more-viscous ice is a negative feedback on the inflow rate. This negative feedback adjusts the flux of ice consumed by melt-back near the base of the shell to balance the flux of subsiding ice (SI Appendix, Fig. S6), which in turn is equal to the mass added by condensation of ice from the vapor phase above the water table (SI Appendix, Fig. S6). The steady-state flux of ice removed from the upper ice shell via subsidence and remelting at depth depends on $Z$, $S$, moon gravity, and the material properties of ice. Using an approximate model of ice shell thermal structure, this steady-state flux is approximately proportional to $Z$ in the range $20 < Z < 60$ km (SI Appendix, Fig. S6) and is $\sim 3$ ton/s (7 mm/s subsidence, $Pe \approx 6$) for $Z = 35$ km. This long-term value for ice removal is comparable to the inferred post-2005 rate of ice addition to the upper ice shell, 2 ton/s (assuming the observed 4.4 m/s 0.5 m/s cooling of the surface is balanced by recrystallization of water vapor on the walls of the tiger stripes above the water table (5, 11, 23, 26)). If near-surface condensates are distributed evenly across the surface of the tiger

![Fig. 2. Tidal flexing cycle for interacting slots assuming two inboard (ib) and two outboard (ob) slots, $k = 6$ GPa, and $l = 100$ km. Slot half-width $W_0 = 1$ m, wall roughness $k = 0.01$ m. $\Delta W_{ob}$ is maximum width change, $\Delta V/V$ is fractional change in slot water volume, and $\sigma_n$ is extensional stress to 90% of its own peak amplitude.](image)
wide thermal emission that is expected if the phase lag is caused not by water flow in slots, but instead by a $a \sim 1$ ice shell (11, 28, 29). In our view, the tiger stripes are the loci of sustained emission because other fractures are too short ($L < 100$ km) for sustained flow. Because sloping homogenizes water temperatures along stripe strike ($SI$ Appendix), the magnitude of emission should be relatively insensitive to local tiger stripe orientation, a prediction that distinguishes the slot model from all crack models. Variations in thermal emission on 10-km length scales have been reported (e.g., ref. 1) and might allow this prediction to be tested. The slot model predicts a smooth distribution of thermal emission at the greater-than-kilometer scale. Our model is more easily reconciled with curtain eruptions (4) than jet eruptions (1), and it can provide a physical underpinning for curtain eruptions. Localized emission might still occur, for example near Y junctions. The pattern of spatial variability in orbit-averaged activity should be steady, in contrast to bursty hypotheses, and vapor flux should covary with ice-grain flux. Spatially resolved variability with orbital phase (1, 4) should correspond to the effects of water transfer along-slot, elastic interactions between slots and along slot walls, and possible along-slot width variations. Our basic model might be used as a starting point for more sophisticated models of Enceladus coupling fluid and gas dynamics (26), as well as the tectonic evolution and initiation of the tiger stripe terrain (e.g., ref. 29). Such coupling may be necessary to understand the initiation of ocean-to-surface conduits on ice moons including Enceladus and Europa, which remains hard to explain (30, 31). Initiation may be related to ice shell disruption during a past epoch of high orbital eccentricity: such disruption could have created partially water-filled conduits with a wide variety of apertures, and evaporative losses caused by tiger stripe activity would ensure that only the most dissipative conduits (those with $W_0 = 1 \pm 0.5$ m; Fig. 2) endure to the present day. Eccentricity variations on $>10^3$-yr timescales may also be required if the ocean is to be sustained for the $>10^8$-yr timescales that are key to ocean habitability (32-34). Ocean longevity could be affected by heat exchange with self-sustained slots in the ice shell. Testing habitability on Enceladus (or Europa) ultimately requires access to ocean materials, and this is easier if (as our model predicts) turbulent dissipation keeps the tiger stripes open for >>Ky.

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