A DUST-DEVIL-LIKE VORTEX IN ENCELADUS' OCEAN: A MODEL FOR RAPID TRANSPORT OF HYDROTHERMAL PRODUCTS FROM OCEAN FLOOR TO ERUPTING ICE-SHELL FRACTURES

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Introduction. Kinematic analysis [1] and decomposition of tidal versus tectonic stress based on the timing of plume eruption rates [2] suggest that the parallel tiger-stripe fractures (TSFs) in the South Polar Terrain (SPT) of Enceladus have been accommodating left-slip bookshelf faulting. This mode of deformation requires the TSFs and SPT to be rotating *clockwise*. The rotating TSFs emit plumes containing sodium-salt-rich ice grains [3], nanometer-sized SiO_2 (silica) particles [4], a high abundance of hydrogen [5], and complex organic molecules [6]. The detected plume compositions imply that: (1) liquid water is in contact with the rocky core [3] where high-temperature (>50-90°C) hydrothermal alteration has occurred [4,7]; (2) the hydrothermal products have moved through the ocean column in less than a year [4]; (3) thermodynamic disequilibrium in the ocean favors methane production over CO_2 [5]; (4) the ocean may have been habitable [8].

Tidal heating is likely a primary mechanism contributing to the inferred hydrothermal activity, sending hydrothermal products to the erupting ice-shell fractures via a rising poloidal flow from the ocean floor [4,9]. Rotation of the satellite around Saturn may induce an excess fluid pressure; influence from the combined centrifugal and Coriolis forces could cause a counterclockwise toroidal flow in the liquid ocean. The combination of the thermally induced poloidal flow and the rotation-induced toroidal ocean flow potentially would favor a dust-devil-like vortex [10]. Here, we hypothesize that the vortex has caused entrainment and upward transport of the hydrothermal products from the oceanic floor to the TSFs and driven the *clockwise* rotation of the SPT (Fig. 1). Quasi-circular and concentric tectonized margins, similar to the SPT, also surround the Trailing Hemisphere Terrain and the Leading Hemisphere Terrain, suggesting analogous processes may have been at work when those regions formed [11]. Excess fluid pressure by Enceladus' rotation may also be perpetuating viscous heating inside the ocean and plume eruptions along the TSFs.

Burgers-Rott Vortex Model. A dust-devil-like vortex can be quantified with the Burgers-Rott model, which is an exact solution to the Navier-Stokes equation governing incompressible, viscous flow [12,13]. In cylindrical polar coordinates (Fig. 2):

$$u_r = -2ar \quad (1a)$$

$$u_\theta = \frac{\Gamma}{2\pi r}\left[1 - \exp\left(-\frac{ar^2}{2\upsilon}\right)\right] \quad (1b)$$

$$u_z = az \quad (1c)$$

Here, u_r,u_θ, and u_z are the radial, azimuthal, and axial velocity components of the vortex flow, a the stretching strain rate in the z direction, Γ the circulation related to vorticity (see below), and $\upsilon = \mu/\rho$ the kinematic viscosity with μ as viscosity and ρ as density of the vortex flow. The z-component vorticity is

$$\omega_z = \omega_0 \exp\left[-\left(\frac{r}{r_0}\right)^2\right] \quad (2)$$

where $\omega_0 = \frac{\Gamma a}{4\pi\upsilon}$ [14] is the angular vorticity at $r = 0$, and $r_0 = \sqrt{\frac{2\upsilon}{a}} = \sqrt{\frac{2\mu}{a\rho}}$ is the viscous radius at which the axial stretching is balanced by viscous dissipation [13]. Based on this insight, we assume $r_0 = R_{SPT}$, where R_{SPT} is the SPT tradius approximated as a flat plane (Fig. 1). This leads to

$$\mu = \frac{1}{2} a\rho {R_{SPT}}^2 \quad (3)$$

The shear stress associated with the toroidal flow is

$$\tau_{r\theta} = \frac{\mu\Gamma}{2\pi}\left\{\frac{a}{\upsilon}\exp\left(-\frac{r^2}{{r_0}^2}\right) + \frac{1}{r^2}\left(\exp\left(-\frac{2r^2}{{r_0}^2}\right) + 2\exp\left(-\frac{r^2}{{r_0}^2}\right) - 1\right)\right\} \quad (4)$$

The total pressure is the sum of the background pressure, p_0, and the pressure drop induced by the vortex flow, p_{vt} [13]. The background pressure splits into the static pressure p_s and the averaged excess pressure by Enceladus' rotation p_c. The three pressure terms are

$$p_s = \rho g(H + h - z) \quad (6a)$$

$$p_c = \frac{1}{2}\beta {\omega_E}^2 {R_E}^2 \rho \quad (6b)$$

$$p_{vt} = \frac{\rho(a^2r^2 + 4a^2z^2)}{2} + \frac{\rho\Gamma^2 a}{16\pi^2\upsilon}\int_x^\infty \left(\frac{1-\exp(-x)}{x}\right)^2 dx \quad (6c)$$

where $x = \frac{ar^2}{2\upsilon}$ and $0 \le \beta \le 1$ is a scaling factor measuring the fraction of the rotational kinetic energy that was converted to hydraulic head inside the liquid SPT ocean. In the above equations, $R_S \approx 2.4 \times 10^8$ m, $\omega_E \approx 5.3 \times 10^{-5}$ s^{-1}, $H \approx$ 60 to100 km [15], and $h \approx$ 10 km [16] are the orbital radius, orbital angular velocity, ocean thickness, and ice-shell thickness of Enceladus, respectively (Figs. 1 and 2). For simplicity, we do not distinguish between the density of water and ice as shown in equation (6a).

Results. Using average axial velocity $\bar{u}_z = aH$ from equation (1a), we define $\bar{T} = H/\bar{u}_z = 1/a$ as the characteristic transport time of the vortex flow from base to the top through its oceanic column. For $\bar{T}$ = 1 day to 1 year, the corresponding a = 1.2×10^{-5} s^{-1} to 3.2×10^{-8} s^{-1} and viscosity $\mu = 10^4$ Pa and 10^7 Pa s, respectively. The estimated viscosity is 7 to 10 orders of magnitude higher than that of liquid water [17], suggesting that the "ocean" could consist of a mixture of water and ice. Assuming that the SPT deformation was driven by the inferred vortex, the toroidal shear stress $\tau_{r\theta}(r = R_{SPT})$ would be on a similar order of magnitude to the ice-shell shear strength. Based on this assumption, we find that the pressure induced by the vortex at the basal rim of the SPT is $p_{Vt}(r = R_E, z = 0)$ = ~7 MPa, and the circulation $\Gamma \approx 1.7\ 10^9$ m^2 s^{-1} for $\tau_{r\theta}(r = r_0)$ = 1 MPa, $a = 10^{-8}$ s^{-1}, $\mu = 10^5$ Pa s, and $r_0 = 250$ km. The excess pressure induced by Enceladus' rotation at the base of the ice shell is limited by the ice-shell tensile strength, T_0, which requires $p_{c\_max} = T_0 + \rho g h$ and $\beta_{max} = \frac{2(T_0+\rho g h)}{\omega_E{}^2 R_E{}^2 \rho} \approx 2.6 \times 10^{-5}$ when $T_0 = 1$ MPa. This extremely low β value requires the kinetic energy of Enceladus' rotation to have mostly converted to heating through turbulence-induced viscous energy dissipation (i.e., the Kolmorogov process) [18], ice-shell deformation, and perpetual ejection of water-ice grains and heavy mineral particles to the space forming the E Ring. In this scenario, Enceladus may have been acting as a "washing machine", ejecting water particles through the TSF filter via the centrifugal force.

Discussion and Conclusions. The Burgers-Rott vortex model does not consider the spherical geometry of Enceladus (Fig. 1) nor the mechanical and thermal couplings between the vortex and the upper and lower bounding interfaces with the ocean floor and ice shell. These simplifications could obscure essential physics such as the relationship between the axial stretching strain rate and the thermal regime of the core-ocean interface. Despite these shortcomings, our vortex hypothesis implies (1) Enceladus' ocean could consist of an ice-water mixture, (2) the vortex flow could provided a mass-transport link between the ocean floor and ice shell, and (3) rotation-generated kinetic energy in the viscous ocean may have caused sustained heating of the satellite through viscous dissipation and driven the ejection of water ice and heavy mineral grains in the erupting plumes. A key feature of our model is that the ocean below the SPT is in a turbulent state, which exerts a lifting force of heavy minerals and places them in contact with the ice shell. The proposed vortex structure may be thought of as a funnel-like chimney through which warm water moves, both upwards and in a circle. Warm ocean water rising through a vortex structure in Enceladus' ocean would displace colder water, causing it to descend outside the core of the vortex. Such a structure may facilitate the circulation of necessary life chemistry within the ocean, such as biogenic elements [5,8] and hydrothermal products [4,20]. Ultimately, further understanding the conditions of Enceladus' ocean environment could impose boundary conditions on the possible origin, evolution and persistence of life [21].

References: [1] Yin and Pappalardo (2015), *Icarus*, 266, 205-216, [2] Schoenfeld and Yin (2019), AGU Fall Meeting Abstract. [3] Postberg et al. (2009), *Nature*, 459 (7250), 1098-1101. [4] Hsu et al. (2015), *Nature*, 519 (7542), 207-210. [5] Waite et al. (2017), *Science*, 356 (6334), 155-159. [6] Postberg et al. (2018). [7] Sekine et al. (2015), *Nature Communications*, 6, 8604. [8] Kahana et al. (2019), *Astrobiology*, 19 (10), 1263-1278. [9] Choblet et al. (2017), *Nature Astronomy*, 1 (12), 841-847. [10] Sinclair (1973), *Journal of Atmospheric Sciences*, 30 (8), 1559-1619. [11] Crow-Willard et al. (2015), *JGR Planets*, 120, 928-950. [12] Burgers (1948), *Advances in Applied Mathematics*, 1, 171-199. [13] Rott (1958), *Zeitschrift für angewandte Mathematik und Physik ZAMP*, 9 (5-6), 543-553. [14] Moffatt (2011), *Environmental Hazards*, 1-27. [15] Schubert et al. (2007), *Icarus*, 188 (2), 345-355. [16] Spencer et al. (2018), *University of Arizona Press, 163-174*. [17] Abramson (2007), *Physical Review*, 76 (5), 051203. [18] Jimenez et al. (1993), *J. Fluid Mech*. 255, 65. [20] McKay et al. (2018), *University of Arizona Press*, 437-449. [21] McKay et al. (2008), *Astrobiology*, 8 (5), 909-919.

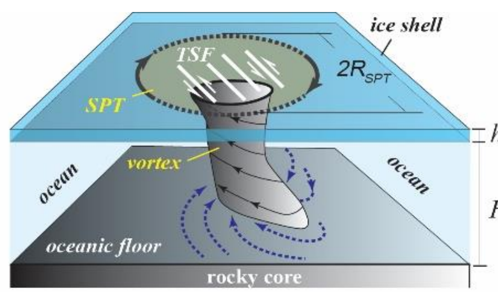

Figure 2. Conceptual diagram of the inferred vortex below the South Polar Terrain.

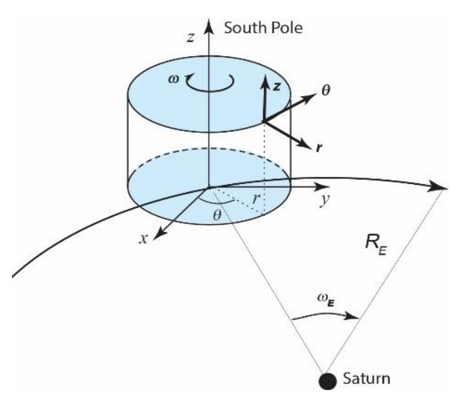

Figure 1. Model geometry and parameters.