ENCELADUS—SO HOT RIGHT NOW: ERUPTED VAPOR CONTRIBUTIONS TO OBSERVED THERMAL ANOMALIES AT THE SOUTH POLAR TERRAINS.

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Introduction: Enceladus, a putative Ocean World of Saturn, has an enigmatically warm and geologically active south pole [1]. The ongoing eruption within the South Polar Terrain (SPT) advects heat and mass from the subsurface to the space and surface environments, and comprises a major contributor to the mass and energy balance of the surface and ice shell.

Upwards of 200 kg/s of material delivery has been inferred from Cassini CIRS line-of-sight column densities and inferences of jet velocity [2], though significant uncertainties remain in estimates of these quantities. Further, while temperatures within close proximity to the active eruptions may near the melting temperature of water, the temperatures in the inter-vent regions (funiscular terrain) are elevated by upwards of 25 K above their expected values from solar radiation alone, as inferred by imagery and radiometery (e.g. [3]).

Motivated by this activity, numerous studies across the past decade have investigated the thermophysical processes driving change. Researchers heavily debate the ultimate source of the energy being dissipated as heat at the South Pole, with models incorporating mechanisms ranging from slip on the Tiger Stripe fractures to transport of the plume material (e.g. [4]). However, there remain fundamental inconsistencies that are difficult to resolve.

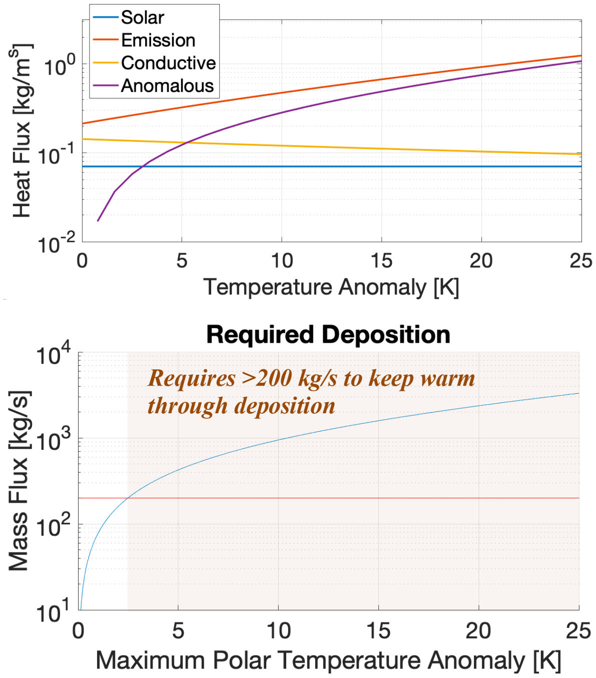


Figure 1: *Top: Heat fluxes considered in energy balance. Bottom: Required deposition of plume vapor to satisfy excess heat flux. The red line shows the canonical 200 kg/s total mass flux estimate.*

One of these inconsistencies is exists between the gravity-derived models of ice shell thickness and observations of SPT temperature. Inferences from Cassini gravity data for the ice and ocean thickness of Enceladus indicate an icy thickness at the south pole ranging from ~5 – 15 km [5]. However, the best-fit ice shells to the gravity data indicate that the SPT is actively hemorrhaging heat to space, with conductive losses in this region exceeding ~120 mW/m^2, where models of tidal dissipation estimate only ~65 mW/m^2 should be produced [5]. Passive rdaiative emission of heat due to the elevation of the south polar temperatures is elevated an additional order of magnitude above the expected production rates [3].

Enigmatically, Enceladus seems to be losing significantly more heat from its surface than is being transported \through conduction across the ice shell.

In this preliminary study, we bring together an energy and enthalpy balance framework to begin reconciling the SPT ice shell thickness, and surface temperature. Specifically, we investigate whether the apparent high temperatures at the SPT can be consistent with gravity-inferred thickness and conductive loss, we investigate the role of plume vapor deposition and particle accretion, and the importance of magmas, and consider the mass fluxes relevant to material transport.

Approach: We first construct a heat flux balance at the surface of the SPT (**Fig. 1**). We consider that $\dot{q}_{anom} = \dot{q}_{sol} + \dot{q}_{geo} - \dot{q}_{sublimated} - \dot{q}_{emit}$. Here, $\dot{q}_{anom}$ represents an unknown contribution to the heat flux balance, which may be a source or sink of heat or a process with heat capacitance (e.g. phase change). The largest contributors to the balance are $\dot{q}_{sol}$ and $\dot{q}_{emit}$, respectively the solar insolation corrected for latitude and obliquity, and the highly temperature-sensitive passive emission of radiant energy. The conductive heat flux, $\dot{q}_{geo}$, constitutes the heat leaving the surface from all subsurface sources, including tidal and radiogenic heating. At temperatures below ~150 K, the heat partitioned into the sublimation of surface ices, $\dot{q}_{sublimated}$, is generally negligible.

We model the full SPT, assuming that temperature anomalies are approximately cosine-distributed about colatitude over the pole, with a characteristic width of ~130 km (e.g. [3]). We adopt the approach Ojakangas and Stevenson [6] for latitude and obliquity dependent solar insolation. We estimate conductive heat flux using temperature-dependent properties, assuming pure, pore-free ice.

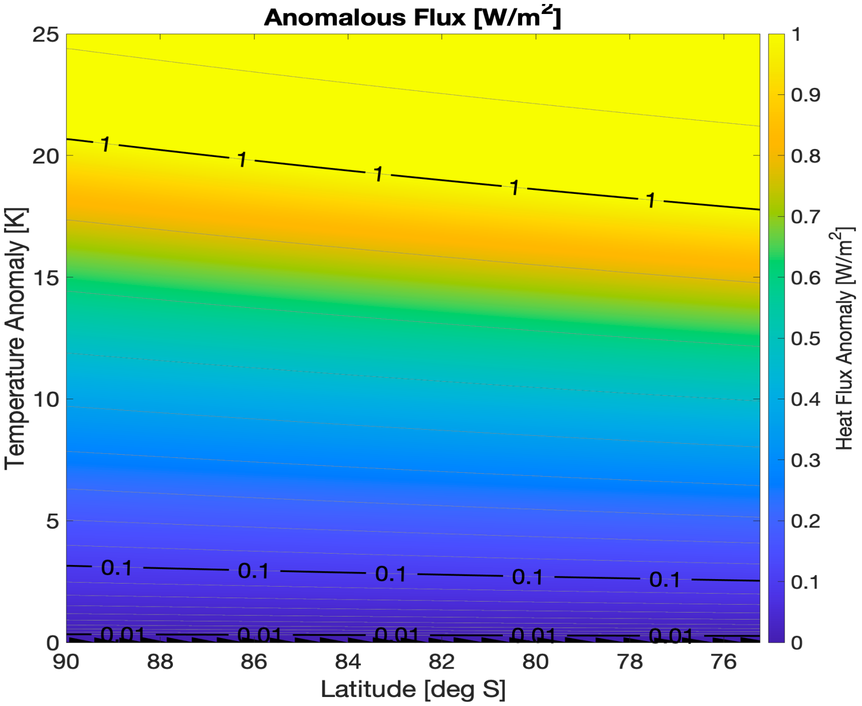
First Thoughts on Plume Heating: As others have reported previously, we find that over the range of temperature anomalies reported, a significant residual heat flux of ~300 – 3,000 mW/m^2 is required to satisfy the energy balance (**Fig. 2**). However, a paucity of options to explain the imbalance in surface heating remain, given empirical constraints from gravity on the ice shell thickness [5]. Any mechanism that would deposit heat within the ice shell to then flow outward towards the surface, such as tidal heating, radiogenic heating, the lateral transfer of heat from flow beneath the tiger stripes, vapor and/or liquid intruded into the shallow subsurface, etc. would result in the rapid thinning of the ice shell to reach conductive equilibrium (e.g. [7]). For the thermal anomalies observed, thicknesses of ~0.5 – 3.5 km would be required, inconsistent with gravity inferences of the icy thickness.

We therefore investigate whether the surface may be warmed by processes that bypass conductive transfer through the icy shell to bring heat to the surface by vapor advection [8]. In this scenario, the steady-state conductive ice shell temperature is not significantly elevated at depth, but instead a warm veneer at the surface is maintained by the deposition of erupted ice grains that are warm, and vapor carrying latent heat in its phase stored during sublimation and vaporization at depth.

By balancing the heat flux required to maintain observed thermal anomalies with the deposition of the latent heat of sublimation of the gas, we find that the canonical plume gas flux upper estimate of 200 kg/s would only maintain a temperature anomaly of 2.5 K through deposition (**Fig. 1**).

Warm grains, even at their melting temperature, have a specific thermal enthalpy that is the product of their specific heat capacity and temperature. At melting, this is at most ~500 kJ/kg of additional thermal energy, though would unlikely contribute to the overall thermal balance given the high radiative emission of ice grains suspended in the plume (e.g. [7]). Gaseous water depositing on the surface (desublimating) carries the most heat energy, given that the latent heat of sublimation, ~2.8 MJ/kg, is equal to that of fusion and vaporization, plus the energy required to transverse the melting to vaporization temperatures.

Figure 2: *Anomalous heat flux required to support a thermal anomaly at polar latitudes.*



To explain the upper-estimates of inter-fracture temperatures within the SPT requires a plume flux of 1000 – 3000 kg/s, exceeding literature estimates by approximately one order of magnitude (**Fig. 1**). This value does however agree with early predictions of Nimmo et al. [8] for a potential sublimation origin of the plumes via diurnal shear heating on strike-slip fractures.

While thermal anomalies inferred from CIRS and passive radar cannot be explained through deposition, a more reasonable plume vapor flux of >350kg/s can wholly explain the discrepancy in SPT heat flux estimated from inference of the global ice shell thickness structure with that estimated for tidal dissipation, in this initial case [5].

References: [1] J. R. Spencer *et al.*, 2006, *Science*, doi: 10.1126/science.1121661. [2] C. J. Hansen *et al.*, *GRL*, doi: 10.1029/2011GL047415. [3] C. Howett, F. Nimmo, and J. Spencer, 2022, *EPSC*, #2022-219. [4] P. M. Schenk, *et al.*, 2018, University of Arizona Press. [5] D. J. Hemingway and T. Mittal, *Icarus*, doi: 10.1016/j.icarus.2019.03.011. [6] G. W. Ojakangas and D. J. Stevenson, *Icarus*, doi: 10.1016/0019-1035(89)90052-3. [7] A. P. Ingersol, A. A. Pankine, 2010, *Icarus*, doi:10.1016/j.icarus.2009.09.015. [8] F. Nimmo et al., 2008, doi: 10.1038/nature05783.