Introduction: In 2005 data returned by the Cassini’s Composite Infrared Spectrometer (CIRS) revealed anomalously warm region surrounding “tiger stripes” (TS) fractures at the southern polar region (SPR) of Enceladus. Subsequently data from Cassini revealed the TS fractures as the source of the Enceladus' plumes of water vapor and ice particles. Several theories were put forward to explain the origin of the plumes and high thermal emission in the SPR. The emerging view is that water from the global sub-ice ocean partially fills ice fractures at the SPR and the plumes are formed by evaporation from the ocean water exposed to near-vacuum inside fractures. Results of numerical modeling [1, 2] suggest that latent heat of the vapor condensing on ice fractures’ walls and conducted to the surface is the main source of the heat observed by the CIRS in the SPR.

Estimates of the endogenic heat emitted from the SPR of Enceladus range from ~4.2 GW [3] to ~15.8 GW [4]. These estimates rely on observations with different sensors on CIRS and cover different spatial and spectral regions: the lower one is from high spatial resolution observations by CIRS FP3 and FP1 detectors observing the vicinity of TSs [3], while the higher one is from low spatial resolution observations by CIRS FP1 detector observing large fraction of the SPR south of the latitudes 60°–70°S including TSs [4]. The FP3 detector is sensitive to thermal emission from surfaces with temperatures ~100 K and higher, while FP1 detector is sensitive to lower temperatures. The large difference in the estimates of the emitted endogenic heat is puzzling. Numerical modeling of the heat exchange in the fractures and accounting for the heat conducted from the sub-ice ocean allows reconciling these estimates. Vapor condensing in ice fractures produces ~2.7 GW, heat conducted from the water-filled portion of the fractures produces another ~1.5 GW of power, and the heat conducted from the sub-ice ocean results in another ~11.6 GW for the entire SPR. The relatively large power conducted from the ocean corresponds to the relatively thin (~2–4 km) ice shell over the SPR, consistent with the recent estimates of ice thickness based on topography and gravity data [5]. The existing endogenic heat estimates [3,4] are thus interpreted as FP3 detection of ~2.7 GW heat flux from vapor condensing in the fractures and FP1 detection of ~1.5 GW heat flux conducted from water-filled portion of the fracture, for a total of ~4.2 GW [3]. The low-resolution FP1 observations also register heat flux from these sources (~4.2 GW) and the broader distributed heat flux conducted from the sub-ice ocean (~11.6 GW), for a total of ~15.8 GW. The details of the analysis are presented below.

Vapor flow and heat exchange in fractures: To estimate power generated by various processes within ice fractures at Enceladus’ SPR the updated numerical model [1, 2] was used. Straight ice fractures penetrate through the ice shell and connect to the sub-ice ocean. Water fills ~92% of the fracture’s height due to isostasy. Water-filled portion of the fracture is cooled by conduction through ice (next section). Cooled water inside fracture sinks down and is replaced by upwelling warmer water from the ocean, preventing freezing and closing of the fractures. At the water surface within fracture evaporation and controlled boiling [2] create a vapor plume that accelerates upward towards the surface. The vapor plume ascending through fracture partially condenses on fracture walls, transferring latent heat to ice. This heat is conducted to the surface and is emitted to space.

Numerical model describing vapor flow and heat exchange in the vapor-filled portion of the fracture [1, 2] was updated to include sublimation of ice near the fracture outlet at the surface, effects of snow layer on the surface, higher spatial resolution near surface where most of the vapor condensation takes place and temperature dependent ice thermal conductivity. Accounting for surface ice sublimation limits maximum surface temperatures to ~216 K, consistent with observations [6]. A surface snow layer ~2 m thick reduces surface temperatures near fractures’ outlets by ~20–50 K. The model was applied to ice shells with thicknesses 2–12 km in accordance with the recent estimates of ice thickness at the SPR [5]. The resultant estimated heat output per fracture (without snow on the surface) is ~1.8–2.4 GW (assuming 500 km for total length of TSs) depending on fracture width (0.05–0.1 m) and depth to water table. A surface snow layer ~2–10 m thick reduces heat output by a factor 2–3.

These model estimates of the heat flux correspond to the observed ‘high temperature’ component (surface temperatures ~120–165 K) of the emission from the SPR registered by the CIRS FP3 detector near TSs [3], but they are lower than the observed flux of ~2.7 GW, especially if a snow layer is present on the surface. Modeling and observations can be reconciled if multiple closely-spaced fractures exist within TSs. Indeed, some high-resolution CIRS observations hint
at two fractures separated by ~100 m distances within a TS (e.g. Plate 9(c) in [7]). Doubling the number of fractures does not increase the heat output by a factor of 2. For fractures separated by distances ~100 m heat conduction is affected by the presence of a fracture nearby and the resultant heat output increase is less than 100% per added identical fracture. Therefore, groups of 2 or 3 fractures per TS are responsible for generating the ~2.7 GW emission from the ‘high temperature’ component observed by FP3 [3].

**Heat conduction from water-filled fracture:** To calculate the heat conducted from the water-filled portion of the fracture, an analytical solution for heat flux from a thin vertical plate at constant temperature buried in a semi-infinite media was used [1,2]. The total flux is the sum of fluxes into the ice walls from the base of the ice shell up to the water table level. After integration the resultant expression for total conducted heat flux \( F_{c,\text{total}} \) is:

\[
F_{c,\text{total}} = \frac{4k(T_0 - T_i)}{\pi} \ln\left(\frac{d_2}{d_1}\right) \times L
\]

where \( T_i=273 \) K is temperature inside water-filled fracture, \( T_0=53 \) K is surface temperature in equilibrium with annual insolation at SPR, \( k=4.5 \) W/m/K is effective thermal conductivity of ice, \( d_2 \) is depth to the ocean, \( d_1 \) is depth to the water table inside fracture, \( L \) is total horizontal length of fractures (~500 km). \( d_2/d_1=1/0.08=12.5 \) (from isostasy) and \( F_{c,\text{total}} \) estimate is independent of the fracture depth \( d_2 \). Substituting the above values into the expression for total flux, \( F_{c,\text{total}} \approx 1.5 \) GW. Close-spaced groupings of fractures produce the same output, because temperature inside water-filled portion of the fracture cannot be higher than 273 K. Heat conducted from the water-filled portion of the fracture increases surface temperatures on both sides of the fracture over distances comparable to fracture depth (~1–10 km). Because the flux is spread out over larger area, the surface temperature increase is relatively small. This emission corresponds to the ‘low temperature’ ~1.5 GW component of the heat flux observed by high spatial resolution CIRS FP1 observations near TSs [3]. The presence of a snow layer on the surface does not significantly affect this estimate.

**Heat conduction from the ocean under SPR:** Heat conducted from the ocean underneath the SPR was calculated by solving the non-linear equation balancing radiative heat loss from the surface with conduction through ice:

\[
\sigma(T_s^4 - T_0^4) = k(T_s - T_0)/h
\]

where \( \sigma \) is Stefan-Boltzmann constant, \( T_s \) is surface temperature, \( T_0=273 \) K is the temperature at the base of the ice shell, \( h \) is the thickness of the ice shell. Two sets of calculations were carried out for a range of ice shell thicknesses, one without snow on the surface, and the other with a 10-m layer of snow. Total heat flux calculated for areas of two CIRS FP1 observations analyzed in [4] (revolution (rev) 61 (26619 km²) and rev 91 (47199 km²)) are shown Figure 1.

![Figure 1. Heat flux from the subsurface ocean for SPR areas observed on FP1 rev_61 (dashed) and rev_91 (solid) as a function of ice shell depth without (lines) and with snow on the surface (lines with symbols).](Image)

The endogenic SPR heat flux measured by the CIRS FP1 detector on rev 61 (12.9 – 15.5 GW) and rev 91 (15.0 – 17.2 GW) includes emission from all sources. Subtracting 4.2 GW that are due to condensing vapor and conduction from water-filled fracture from these estimates leaves 8.7 – 11.3 GW (rev 61) and 10.8 – 13.0 GW (rev 91) for heat conducted from ocean. From Figure 1 these ranges are consistent with the heat conducted from the sub-ice ocean through ~2–4 km ice shell in SPR, consistent with ice thickness estimates in [5]. The difference in rev 61 and rev 91 flux estimates is mostly due to difference in surface area of SPR within FP1 field-of-view. The average FP1 estimate of ~15.8 GW endogenic heat corresponds to ~11.6 GW conducted from the ocean.

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**References:**