ENCELADUS' BRILLIANT SURFACE 2: RATIONALIZING CASSINI RADAR AND OPTICAL REMOTE SENSING.

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Introduction: The fresh, clean ice that dominates Enceladus surface makes it the most reflective surface of any Solar System body across a broad range of wavelengths, from visible to microwave. Fine-grained micron to 10s of micron particles resulting from plume or E-ring particle deposition dominate optical wavelengths, enabling enhanced geometric albedo due to coherent backscatter. However, high albedo at centimetric radar wavelengths suggests scattering from characteristic spatial scales of millimetric or greater. To date, no single model of surface material structure has been proposed that can explain all the observed phenomena. We propose that sintering of fine particles during past periods of low or zero cryovolcanic activity may create subsurface layers that enhance radar backscatter sufficiently to explain the observations. The thickness of the upper, unsintered layer is likely at least 1-2 cm, and probably well under a meter. More modeling and laboratory work is required to test the validity of our assertion that sintering during quiescent periods of plume activity is responsible for the enhanced radar backscatter.

Remote sensing constraints: Cassini carried a diverse suite of instruments which supplement terrestrial telescopic observations.

Visible imaging: Enceladus' visual geometric albedo is 1.38 [1]. A geometric albedo of >>1 means that, in addition to being remarkably bright, a target exhibits an considerable degree of retro-reflection. In Enceladus' case, this is best explained using a model that combines both moderate shadow-hiding and coherent backscattering components [2], the latter of which are common for surfaces that exhibit roughness at near-wavelength scales. Enceladus' nearest neighbours are nearly as bright (fig. 1), with geometric albedos following a trend best explained either as a function of E-ring density or distance from Enceladus; These factors are of course related, as the E-ring is supplied from Enceladus' plumes. Over a global scale, variations in color/scattering remain diffuse, rather than defined by geological units [3]. Like other icy worlds within the E-ring, Enceladus exhibits a leading-trailing dichotomy, albeit slight. This implies a direct control of scattering properties from plume and E-ring particle fallout, rather than something affected by surface age or maturity. Only on Dione and Rhea, where fallout rates are significantly lower, does surface age, specifically tectonized terrains, cause variations in brightness along boundaries.

IR spectroscopy: The VIMS instrument on Cassini enabled hyperspectral near IR imaging of Enceladus' surface at spatial resolution of up to few km/pixel, resulting in a clearer understanding of the composition of the surface. Brown et al. [4] analyzed the terrain of the south polar region in some detail based on the first three Enceladus flybys. The spectra are compositionally consistent with ground based observations, dominated by water ice, but with the additional detections of carbon dioxide and organic features. Grain sizes were estimated to be 50 to 100 µm globally, increasing to 100 to 300 µm near the tiger stripes. The degree of crystallinity of the ice was also shown to be greater in the region around the tiger stripes. Later analyses of additional VIMS spectra acquired as the mission progressed generally agree with Brown's initial findings. Smaller particles (~10-50 µm) are found away from the tiger stripes, while large particles (up to 200 µm) are concentrated in the tiger stripes [5]. This is consistent with ballistic deposition.

Cassini CIRS data analyzed by Howett et al. [6] show that the surface of Enceladus has an average thermal inertia of ~ 15 J m^{-2} K^{-1} $s^{-0.5}$. Such low values imply a highly porous material. The diurnal skin depth for the derived thermal properties is of 0.5 cm, consistent with a 1-2 cm cover of very loose materials.

Radar remote sensing: As discussed previously [7], Cassini RADAR observations at ~2.2-cm also show unusually bright surfaces in backscatter. This is inconsistent with a global layer of fine particles as discussed above, which would tend to absorb (loss tangents of 10^{-2} to 10^{-3} for snow reported by [8]) if sufficiently thick (at least centimeters thickness) and/or forward scatter if sufficiently smooth (at millimetric scales at beyond), and create relatively radar-dark surfaces. Three key observations may give hints as to the reason for the high backscatter: (1) Globally averaged backscatter from icy worlds in the Saturn system follows trends much like for optical albedo ([9]; fig. 1) implying a link to fine particle fallout; (2) Brightness varies discretely on Enceladus' surface, delimited by tectonically-resurfaced margins (as seen in E16 SAR imagery) rather than diffusively, suggesting that surface maturity/age plays a role; (3) The magnitude of the backscatter to radar is extreme, with units in the E16 SAR swath exhibiting σ_0 <= 3.9 (5.9 dB), where σ_0 is a single fixed polarization normalized radar cross section. Taken together, we infer that particle fallout is partly responsible, but that something else is going on causing enhanced backscatter.

Discussion: Microwave energy will tend to scatter preferentially from ice volumetrically, as the vacuum-ice interface only results in partial reflection of incoming energy. This means that any structural components responsible for high backscatter are likely to be in the subsurface, potentially at considerable depth (potentially thousands of wavelengths).

The only other known location in the solar system with comparable radar backscatters are in or near Xanadu on Titan [10], especially in sinuous channels on Titan [10] with $\sigma_0 \sim 3.2$ (5 dB). This is larger than easily explained by coherent backscatter effects, and is best explained by (near) spherical structures of corner reflectors (such as cubes), which seems reasonable for Titan's channels, as river/stream beds often include rubble or pebbles. On Enceladus, however, no plausible geological justification has been given for such structures, and indeed, given the rates of fine particle fallout (~1 um/yr), one might expect them to be buried over geological timescales.

In our previous work, we concluded that surface roughness was insufficient to produce the observed backscatter, and instead proposed that either organized or random subsurface structures at millimetric scales or greater might be sufficient to produce enhanced backscatter of the magnitudes observed [7].

One possible explanation is structural changes in fallout products resulting from sintering at cm-scale depth. Terrestrial research has shown that density is the dominant factor controlling the dielectric properties of dry snow (e.g. [11]), and thus sintering timescales can be used to constrain the time and spatial scales over which surface layering may develop at Enceladus. Following [12], we estimate sintering timescales of spherical ice grains in the near surface of Enceladus based on a mean surface temperature of 80 K and a grain size of 1 μm. We assume an aggregate density equal to the typical, random packing density of spheres (~64%). Significant sintering can occur over much shorter timescales (10000 years for ice, 100 years for salty ice), but densification effects would be negligible, and so it's unclear if there would be a difference in radar properties. An increase in 1-10% of the aggregate density is required to achieve a significant change in the dielectric properties of the ice, which we estimate occurs after 100 – 1000 Ma in pure water ice, and 10 – 100 Ma for ice containing 2.5% sodium chloride by mass. Compared with global resurfacing rates (~1 μm/yr), these timescales are long, but not ludicrous. Assuming a deposition rate of 1 μm/yr, fresh plume material would form a 10 cm layer over the surface after 0.1 Ma, effectively halting the densification in the subsurface. If activity ceases for these times periods, then sintering may well result in layering that would likely result in enhanced backscatter.

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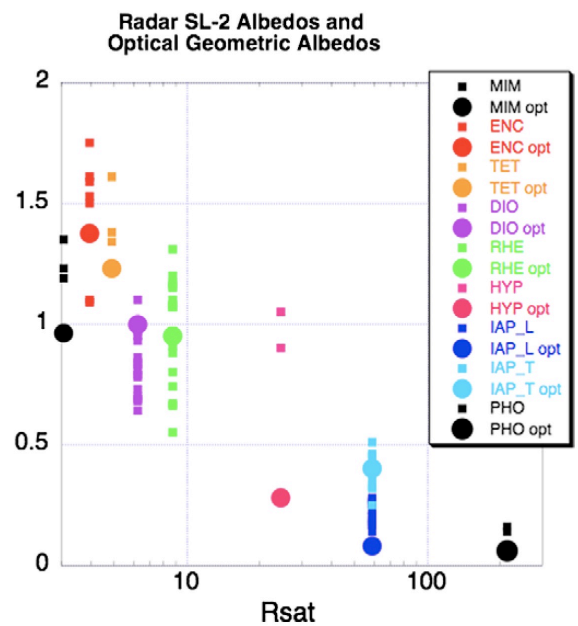

Figure 1: Cassini measurements of SL-2 (squares) and average optical geometric albedos (circles), plotted for satellites vs. distance from Saturn (Ostro *et al.*, 2010). SL-2 is radar equivalent to optical geometric albedo, and a summation of two orthogonal polarizations. Note that the radar SL-2 albedos reported here are a factor of 2 less than reality, due to a mistake in analysis (R. West, pers. comm.). Optical albedos for Mimas, Enceladus, Tethys, Dione, and Rhea are from Verbiscer *et al.* (2007). A trend in brightness for both optical and radar can be interpreted as relating either to E-ring density or to distance from Enceladus. Leading = L, trailing = T.