ENCELADUS' BRILLIANT SURFACE: CASSINI RADAR OBSERVATIONS & INTERPRETATION.

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Introduction: Previous workers [1,2,3,4] have reported unusually high microwave albedos (full disc radar backscatter) of icy satellite surfaces, particularly at shorter (<13 cm) wavelengths, with the dominant interpretation being that coherent scattering is necessary to explain the brightness. The most brilliant (in terms of absolute radar backscatter) of all of the icy satellites is Enceladus, with close neighbour Tethys only slightly less so.

On November 6th, 2011, Cassini RADAR had its first and probably only opportunity for a dedicated SAR pass of an icy satellite: The Enceladus E16 flyby. The results include a high-resolution (up to 50 m) SAR swath of southern latitudes down to ~66º S (Fig. 1, top). Additionally, more coarse resolution imaging (>~1 km) was achieved using the Hi-SAR technique [5], allowing much of the surface to be resolved.

The results confirm the unusually brilliant surface, revealing even brighter-than-anticipated surfaces near the South Pole. Previously, we proposed [6] that some sort of organised coherent structure at scales comparable to the Cassini RADAR wavelength (2.17 cm) were responsible, in a manner akin to that found for radar-bright regions in the Greenland ice-sheet on Earth [7], and for dry river-beds on Titan [8]; A familiar equivalent optical phenomenon would be as observed in cat's eyes or reflective road paint. However, a geological explanation for the proposed structures proved elusive.

Recent, more detailed modeling analysis [9] suggests that this may not in fact be necessary, however. Preliminary 2-D radar backscatter modeling suggests that a subsurface 'porous' medium, modeled as triangular voids within a pure ice medium, may produce similarly brilliant surfaces. This is made possible by the very low-loss characteristics of water ice at the cold temperatures of Enceladus' surface, which means that structure at scales comparable to the observation wavelength, in the near-surface, is highly visible to Cassini RADAR. This might be considered akin to fine structure in ice cubes at optical wavelengths, or even snow. Such a phenomenon is unlikely to occur in terrestrial ice at cm-scales, as ice remains sufficiently ductile at terrestrial surface temperatures that such voids and structure would diminish over time.

This modeling alone does not explain the many characteristics of Enceladus' surface as observed by RADAR, but it does now provide a framework as a basis for making interpretations.

RADAR Observations: Previously [6], we described clearly delimited spatial domains bounded by major tectonic faults (Fig. 1, bottom), parts of the network of sulci associated with the active tiger stripes, characterised by surface textures and backscatter properties. One such domain (labeled B1a) exhibits a mean backscatter as great as ~6 dB, far in excess of any other icy satellite or terrestrial surfaces. The lack of craters and close association with the active tiger stripes, as well as interpreted stratigraphic relations to adjacent terrain (we interpret R1 and R2 to be younger than B1), suggests that this radar-bright area is particularly geologically young, despite not being currently observed as active. An adjacent domain (R1), also tectonised, is one of the darkest on Enceladus (~1 dB).

Distant observations [2,3] reveal that Enceladus backscatters brilliantly and emits little across the entire surface, even when the south polar region is only a minor constituent. In HiSAR data, there is clear contrast between units observed by SAR, but no significant contrast between cratered and un-cratered tectonised terrain in mid-to-low latitudes. Hence, even the older, cratered terrain is unusually radar-bright. Furthermore, there are possible indications that the surfaces are largely isotropic, i.e., they have only a weak dependence on incidence and azimuth angles.

Processes: The lack of backscatter contrast between cratered and tectonised terrain at low-to-mid latitudes means that we require a process that operates on a global scale in order to explain Enceladus' remarkable radar-brightness.

Tectonism: Despite crisp margins between domains near Enceladus' South Pole, we can find no reason for tectonic processes to be the cause for the absolute brightness across all of Enceladus. Tectonics may play a role in causing the cm-scale structure, but the presence of bright, cratered terrain rules out a process that seems to be fundamentally regional. Furthermore, the adjacency of both the brightest and one of the darkest mapped surfaces (B1a and R1), both of which are predominantly tectonic, suggests that tectonised and uncratered terrains are not uniquely radar-bright. However, it may be that particularly pristine surfaces do exhibit different backscatter properties.

Cryovolcanic lithics: In high resolution "skeet-shoot" ISS images, we see surfaces covered with decametre-scale boulders. These are too coarse to be primary cryovolcanic products, the size distribution of which is in the sub-micron to sub-millimetre range.

One possibility is that they are lithics: solid material torn away from the walls of cryovolcanic conduits, carried upwards in the jet and then thrown ballistically to the surface. We have made no attempt yet to survey the distribution of these boulders or to determine both their ballistic range and how likely they would be to survive impact relatively intact, and so at this stage such a mechanism is considered highly speculative. If proven viable, however, then it seems reasonable to speculate that a broad distribution of lithic material might be scattered over the entire surface, contributing to the radar signal. One potential issue with this is that we would expect to see some evidence of radial variations in particle size distribution, and at this stage – admittedly one at which the near-global HiSAR data is poorly calibrated – we see no such signs.

Cryovolcanic "snow": What appears to make Enceladus special relative to other icy satellites is the prevalence of cryovolcanic activity. However, using cryovolcanism as an explanation for radar brightness is problematic, as the type of activity we see at Enceladus is that the expected volcanic products are extremely fine in scale, possibly dominated by micro- and certainly sub-millimetre, particles [10,11]. This is the result of extreme expansion of volatiles during eruption into the near-vacuum of Enceladus' ambient environment causing massive adiabatic cooling, disruption and fragmentation of erupting materials. Such snow-like deposits are unlikely to be radar-dark compared with ice with centimetre-scale structure, due to a lack of scattering surfaces, and so their net effect is more likely to darken the surface. Different levels of deposition on surfaces with different ages may explain variations in brightness although it is not a compelling explanation on its own for global brightening.

Space Weathering: If lithics are not responsible, however, then we are left with one further possibility, that sintering of fine particles (particularly the "snow") by space weather can result in larger particles. For this to work, the accumulation rate of snow would have to be comparable with or less than the rate at which the snow were sintered to the centimetre scale, and so it is possible that there might be areas on Enceladus, potentially close to the tiger stripes, that are darker, due to un-sintered snow accumulation. This idea has the additional advantage of potentially explaining why Enceladus' closest neighbours, chiefly Tethys, are also bright, as plume ejecta is likely to mantle their surfaces to some extent too. In fact, space weathering has already been proposed to be important in affecting thermal inertia on Tethys and Mimas [12,13].

Conclusions: These lines of evidence make for an interesting if confusing picture. Given the lack of simple causal relations consistent with observations, we conclude that multiple processes control Enceladus' brightness, in a complex manner. Unraveling their relative importance will be the subject of future work, and involve data from multiple instruments.

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Acknowledgement: This research was carried out at the California Institute of Technology Jet Propulsion Laboratory under a contract from NASA. It was supported by the Cassini project, and a JPL R&TD Innovative Spontaneous Concept grant. We thank Ralph Lorenz, Mike Janssen, Richard West, John Spencer, Paul Helfenstein, Bob Pappalardo and Geoff Collins for fruitful discussions.

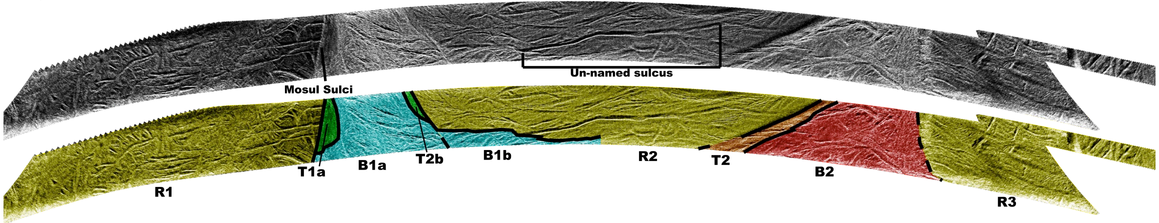

Figure 1: (top) Cassini RADAR E16 SAR swath. Azimuthal (along-track) resolution is ~200 m, and range (across-track) resolution is ~50 m. The unusual aspect ratio is due to the high speed (~7.4 km/s) fly-by at ~500 km closest approach. As a result, features aligned along the direction of motion are better resolved than those across. Image swath width at center is ~24 km. (bottom) Map of the observed area, with domins defined by differences in both RADAR backscatter and tectonic expression. Dashed lines represent greater uncertainty in the unit contact. Difficulty in distinguishing among B1a, B1b, R2 and T2 along the southern edge may be due to problems with the predicted ephemerides, so those contacts should not be considered final. Mean radar backscatters for mapped areas are as follows: R1 = 1.2 dB; T1a = 0.5 dB; B1a = 5.9 dB; T1b = 3.2 dB; B1b = 5.2 dB; R2 = 2.4 dB; T2 = 5.8 dB; B2 = 4.6 dB.