HOW ROUGH IS THE SURFACE OF EUROPA AT LANDER SCALE?

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Introduction: The surface roughness of Europa on the meter scale is a vital parameter to understand if we wish to deliver a lander to this moon in the future. However, direct imaging of the surface is of too coarse a resolution to resolve features on this scale, and traditional photometric analyses of electromagnetic waves reflected or emitted from the surface have not sought to distinguish lander-scale surface roughness from finer and coarser scales. This is problematic, since degrading ice on Earth forced by solar radiation is known to develop significant surface roughness on 10^{-1} - 10^{1} m scales in the form of suncups, penitentes, and dirt cones. We aim to assess whether the icy surface of Europa might develop roughness on similar scales in the face of long timescale exposure to solar flux.

Key questions are: 1) Is meter scale surface roughness expected to develop on Europa? If so, is it likely to be spatially variable? Where will such roughness develop? 2) How fast will such features develop? Will they be outcompeted by other processes of surface modification? 3) What effect would development of surface roughness have on photometric properties of Europa, e.g., albedo, radiative flux, near-opposition phase function, etc.? i.e., can we detect this surface roughness remotely?

Ablation textures: On Earth, ablating snow develops meter scale surface roughness in the form of concave-up depressions of a variety of forms. Growth of all such features is linked to amplification of initial random depressions in the surface by lensing of scattered solar and radiant longwave radiations, but the final form of the surface roughness is controlled by a variety of factors. In clean snow, the dominant forms are known as suncups and penitentes; in dirty snow, dirt cones may develop.

Penitentes. Penitentes are tall (typically 1-5 m, though sub-meter scale structures are also known), sharp-edged blades and spikes of sculpted snow which point towards the elevation of the midday sun [e.g., 1]. They are almost entirely restricted to the tropics and subtropics, and form in cold, dry weather. Height:spacing ratios are typically ~1.5-2. Laboratory experiments [2] show penitentes form by sublimation, and that maintenance of strong thermal gradients between pit and tip is crucial. Small amounts of dirt on the surface do not inhibit formation.

Suncups and dirt cones. Suncups are bowl-shaped open depressions into a snow surface, normally wider than they are deep. They are quasi-periodic on 20-80 cm scales, and 2-50cm deep. They can form in both clean and dirty snow, with those in dirty snow forming by insulation of the local highs beneath the dirt (creating "dirt cones")[3].

The main distinction between the two types of ablation structure is in their aspect ratios; penitentes are deep, suncups are shallow. This demonstrates that in the formation of a penitente, ablation must occur more rapidly at the pit of the structure than it does on the sidewalls, with the opposite being true for suncups. For penitentes to form, the incoming solar flux must vary little in its angle of incidence, such that the incident light always strikes the walls of the blades at a high angle and the floors of the pits close to normal [4]. This maximizes the contrast in flux per unit area on the floor compared to the sidewalls, both in terms of direct and scattered radiation. Any process which acts to reduce the ablation (i.e., thermal) gradient between the walls and base of a growing depression will favor the growth of suncup-like forms over penitentes [5]. This accounts for the promotion of penitente growth by still air, and its suppression by wind, melting of the tips (heat advection), and high ratios of sensible to downwelling solar heat flux (i.e., warm, cloudy days).

Penitentes or suncups on Europa? The pressure at Europa's surface is far below the pressure of the triple point of water. This means that any ablation of the surface that occurs in contact with the atmosphere must be as sublimation; melt cannot be produced. The tenuousness of Europa's atmosphere means its heat capacity is essentially zero, and it makes almost no contribution to downwelling heat flux to the surface, i.e., the sensible heat flux is ~0. Europa's and Jupiter's low obliquities together lead to extremely limited variability in solar angle (<5°) for any given point on the surface; given the Europa's tidal locking and the stability of Jupiter's obliquity this is probably true across surface age (50 Ma) timescales. Together, these conditions will induce growth of penitentes if the surface sublimes. Mechanisms which could suppress growth by equalizing pit-to-tip thermal gradients are absent.

Rates and locations of sublimation: Following [6], we can use existing estimates of Europan surface temperatures [e.g., 7,8] to model the rates of surface sublimation, and hence understand the likely size and spacing of developing penitentes and whether they would be outcompeted by other surface modification processes. Total sublimation is a very sensitive function of the peak temperature attained by a given point on the surface (Table 1; Fig. 1). Using likely surface densities (~53% [9]) and integrating through time, Figure 1 corresponds to an equatorial bulk ablation rate of ~4x10^{-2} m/Ma (see also Table 1). Beyond ~20 °N, ~25 °S, lower surface temperatures ≤126 K mean <<1 m of total ablation is expected across 50 Ma, the approximate average age of the Europan surface [8,10,11].

TABLE 1. Sublimation by peak temperature

Peak temperature (K)	Sublimation rate (m/Ma)	Total sublimation in 50 Ma (m)
132	1.1E-01	5.66
130	5.4E-02	2.72
128	2.6E-02	1.28
126	1.2E-02	0.59
124	5.3E-03	0.26
122	2.3E-03	0.12
120	9.8E-04	0.05
118	4.0E-04	0.02
116	1.6E-04	0.01
114	6.3E-05	0.00

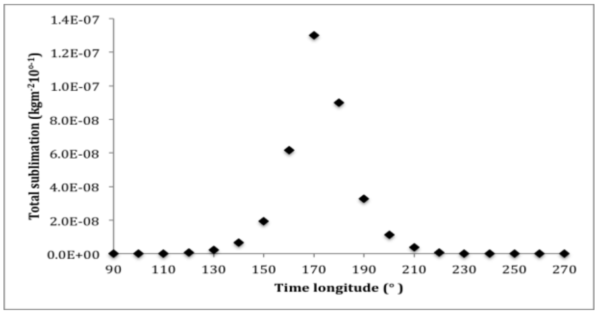

Figure 1. *Variation of sublimation rate with time longitude, for mean temperatures ±15 °N/S. The vast majority of sublimation occurs within a few 10s of degrees of solar noon.*

Europa's surface is also subject to ongoing disruption by both sputtering erosion and bolide impact cratering. The most recent estimates of rates suggest sputtering occurs at ~2x10^{-2} m/Ma [10,12], probably outcompeting modern impact gardening [8]. Peak surface temperatures >126 K are necessary to allow surface sublimation to proceed faster than sputtering erosion, and hence growth of penitentes is probably restricted to ±15-20 degrees of latitude from the equator. Within this band, penitente height and spacing are likely 10^{-1} - 10^{1} m (Table 1); depth and spacing grow linearly with surface age. True polar wander [13] could reduce size, but also translate penitentes away from the equator.

Remote sensing of surface roughness: Existing studies of Europan heat flux, radar reflectivity and optical photometry model surface roughness as essentially random [e.g., 14], and have not sought to understand the role of penitente-like ordered and anisotropic roughness elements. Equatorial bands of penitentes could strongly influence interpretation of the strong Europan opposition effect (brightness surges at ~0 phase angle [e.g. 15]). It should also be considered as a cause for the "pacman" type thermal radiation patterns seen in the Europan thermal IR returns [8], and potentially more widely in the outer planet moons. The repeated reflections between blades involved in development of penitentes could easily alter the effective IR albedo of the surface during transient heating and cooling[5]. Our inference of equatorial penitentes appears in conflict with previous estimates of surface roughness angle (10-22 ° [9,16]), but this may be resolved by explicit consideration of the roughness scales at which existing estimates are defined, and by known imperfections in photometric estimates for high albedo surfaces like Europa. The key remotely detectable property of our hypothesized surface roughness distribution is its east-west anisotropy. We suggest the crucial and thus far unexploited test for penitentes on icy satellites will be in east-west polarization of photometric and radar returns when the viewing spacecraft has a nontrivial sub-spacecraft latitude.

Conclusions: The ±15-20° latitude band on typical 50 Ma-age Europan crust is likely to develop east-west penitente blades, with depths 10^{-1}-10^{1} m and spacing roughly half this. This would be extremely problematic for a putative future lander. Outside this band, surface texture is likely to be much smoother at this scale, due to dominance of diffusive sputtering erosion. Depositional processes, thick dust accumulation, or true polar wander could all play a role in modifying this roughness magnitude and distribution, but are all underconstrained for Europa. The key test for the penitente hypothesis would be whether equatorial photometric or radar measurements have a substantial east-west polarization, which may vary with sub spacecraft latitude.

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