Snow spikes (penitentes) in the Dry Andes, but not on Europa: A defense of Lliboutry's classic paper

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Abstract

There is a concern that in the low latitudes of Jupiter's moon Europa, the ice surface has developed meter-scale bladed roughness, which would pose a hazard to a lander. That concern was inspired by the presence of such structures ("penitents") on Earth's subtropical mountains, but their formation requires melting along with sublimation, which cannot occur on Europa. The troughs deepen rapidly by melting while the peaks remain dry and cold by sublimation, losing little mass, because of the 8.5-fold difference in latent heats of sublimation versus melting. Penitents cause a reduction of albedo by ˜30% by trapping sunlight. The high albedo of Europa (˜0.7 at visible wavelengths) therefore also argues against the existence of extreme surface roughness.

Don’t give up on the Europa lander

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Abstract.

There is a concern that in the low latitudes of Jupiter's moon Europa, the ice surface has developed meter-scale bladed roughness, which would pose a hazard to a lander. That concern was inspired by the presence of such structures ("penitents") on Earth's subtropical mountains, but their formation requires melting along with sublimation, which cannot occur on Europa. The troughs deepen rapidly by melting while the peaks remain dry and cold by sublimation, losing little mass, because of the 8.5-fold difference in latent heats of sublimation versus melting.

Penitents cause a reduction of albedo by ~30% by trapping sunlight. The high albedo of Europa (~0.7 at visible wavelengths) therefore also argues against the existence of extreme surface roughness.

1. Formation of penitents on Earth

On Earth, penitents (or “penitentes” in Spanish) reach their greatest heights of several meters in a restricted altitude range on high subtropical mountains; they have been most intensively studied in the Andes of Chile and Argentina. Penitents are exotic and beautiful (Figure 1), but they can cause difficulty, for example slowing the progress of mountaineers climbing Aconcagua. And Wentworth (1940) complained that snow spikes on Mauna Kea (Hawaii) made tobogganing impossible. Now Hobley et al. (2018) have identified perhaps a more severe hazard for the Europa lander, which I will critique.

Most of the tall penitents formed in the Andes (Figure 1) consist of old snow, but they can also form in glacier ice. The explanation for their formation was given by Lliboutry (1954a) in his classic paper “The origin of penitents”, augmented by his second paper (Lliboutry 1954b) and his book (Lliboutry 1964). Penitents are the result of a selection process, in which surfaces facing the Sun absorb more radiation and ablate more quickly, so the surviving surfaces are nearly-vertical wedges oriented east-west, parallel to the solar beam. To remain parallel to the solar beam during the midday hours of maximum irradiance, the wedges are tilted toward the north in the Southern Hemisphere, at approximately the noontime solar zenith angle, which varies seasonally. They were given the name “penitentes” because a field of these inclined spikes had the appearance of white-robed monks on a religious pilgrimage. Their mechanism of formation was concisely stated in Lliboutry’s abstract: “The sublimation of the snow or ice allows the crests to maintain their temperature below 0°C, while in the spaces or passages between the penitents, where radiation is concentrated and removal of water vapour not so easy, melting takes place.”

Lliboutry identified three zones of altitude in the Andes above Santiago, Chile:

(a) In the lowest zone, below 4000 m, the snow surface developed the familiar scalloped surface called “suncups”, “ablation hollows”, or “honeycombed snow”, seen in summer on mountain glaciers and snow-fields worldwide. Suncups are melting at all parts of the surface (both hollows and ridges), but some topography does develop from initial small irregularities, by two mechanisms: (1) Different orientations of surfaces relative to the Sun are illuminated differently; also the hollow is illuminated not only directly but additionally by radiation reflected from the neighboring walls. (2) Evaporation of meltwater occurs more readily at the ridges, which are exposed to wind and can therefore dispose of much of their absorbed solar energy without further melting, in contrast to the hollows where the air is more stagnant and therefore more humid.

(b) In the highest zone, above 5200 m, the snow was colder than 0°C everywhere, so melting could not occur; the dry snow surface remained nearly flat.

(c) The intermediate zone, 4000-5200 m, where penitents developed, was characterized by sublimation at the peaks and melting in the troughs. In the troughs the air became stagnant and humid, so that sublimation was impossible, so the snow heated up to the melting point and consumed the absorbed solar energy by melting. Penitents are spikier than suncups because on penitents there is no melting at the peaks. In this intermediate zone the snow is nearly flat in winter because only sublimation can occur then; the penitents begin to develop in late spring when the weather is warm enough that melting can begin in the troughs.

Quoting Lliboutry: “[We] have alternately troughs where the snow melts and penitents where it sublimes. In both cases the speed of the process depends on the thermal balance, so that melting goes further than sublimation. . . . Although sublimation is indispensible for penitent formation, in a field of penitents most of the ablation proceeds from melting” (Lliboutry, 1954a).

The mechanism identified by Lliboutry has been confirmed in subsequent studies, by Untersteiner (1957) in the Pakistani Karakoram at 36°N, by Kotlyakov & Lebedeva (1974) in the East Pamirs of Tajikistan at 38°N, and by Naruse & Leiva (1997) in the Argentinian Andes at 32°S. Quoting Untersteiner, "Evaporation/sublimation plays a definite role in the *energy budget* [of penitents] . . . but a significant contribution to *ablation* is ruled out. . . . Growth of penitents by sublimation-ablation appears not to be possible, . . . so it must come about by means of melting." Quoting Kotlyakov and Lebedeva, "The facets were dry, but in the hollows the firn was soft and humid. . . . The melting on the surface perpendicular to midday solar rays can reach 20-30 mm/day in water equivalent. . . . The surface was smooth on the upper part of the glacier." Quoting Naruse and Leiva, "All the field data . . . support Lliboutry's hypothesis . . . enhanced melting at the bottoms due to absorbed shortwave radiation and ceased melting at the top due to cooling by sublimation . . . ."

Hobley et al. (2018), in proposing the existence of penitents on Europa, cited Lliboutry's classic paper (as their Reference 12) to claim that "On Earth, . . . [f]ormation of large and well-developed penitentes requires . . . a melt-free environment. . . . [S]ublimation in the absence of melting is particularly essential for penitente formation." Hobley et al. have thus attributed to Lliboutry a statement which is the exact opposite of what he wrote.

2. Are penitents possible on Europa?

With a maximum daytime surface temperature of 134K on the equator of Europa, melting cannot occur, thus ruling out the terrestrial mechanism for formation of penitents on that planetary body. But we must still consider the possibility of a different mechanism on Europa using sublimation only, because of the long time available. Penitents on Earth have only about 4 months to grow before they melt away in late summer. But Hobley et al. estimated that the time available for penitent formation on Europa would be eight orders of magnitude longer, because the average age of the Europan ice surface before resurfacing is ~50 million years.

Lliboutry observed “micropenitents” with heights of a few centimeters, in the spring before melting began, resulting from trapping of incident sunlight in incipient troughs. And in a laboratory experiment with vertical illumination of a snow block, Bergeron et al. (2006) were able to create conical micropenitents to heights of a few centimeters by sublimation alone.

Inspired by the laboratory experiments, Hobley et al. estimated the height that penitents could attain on Europa. They did not model the evolution of surface roughness. Instead they assumed an aspect ratio (height-to-spacing ratio) of 2, and equated the energy of sublimation to the radiation energy budget, concluding that, at the equator, 15 m of ice could sublimate in 50 million years. If most of this sublimation occurred from troughs (and if erosion of the spikes by sputtering and impact-gardening were slow), the penitents could be 15 m high. But modeling by Hand et al. (2020) has found that penitents cannot grow on Europa, because of the absence of an atmosphere to limit the diffusion of water vapor.

As evidence for their hypothesis, Hobley et al. cited radar measurements of Europa at wavelength λ=12.6 cm, in particular the latitudinal variation of reflectivity and an anomalous polarization ratio, which might be explained by penitents, or alternatively by subsurface irregularities (Ostro et al., 1992). But we can also use shorter wavelengths to evaluate their hypothesis, by considering how penitents would alter the reflection of sunlight. Penitents trap solar radiation, resulting in reduced albedo of a field of penitents relative to a flat surface. The triangular-shaped penitents of Glaciar Tapado in Chile, with heights 2 m and spacing 1.4 m, caused a reduction of broadband albedo from its flat-surface value of 0.64, down to 0.32, as estimated by Lhermitte et al. (2014, Figure 2D and Table 4D). A similar albedo-reduction, from 0.60 to 0.33, was obtained for idealized penitents in a radiative transfer model by Cathles et al. (2014). If the flat-surface albedo of Europan ice at a particular wavelength is ~0.7, for example, penitents would thus be expected to reduce the area-averaged albedo to ~0.4. But the area-averaged albedo of the leading hemisphere of Europa is quite high, averaging 0.72 at mid-visible wavelengths 550-750 nm (Figure 13c of Carlson et al., 2009), suggesting that penitents, if present, are not prominent.

In conclusion, the low latitudes of Europa are likely to have smooth surfaces, suitable for a lander. We eagerly await high-resolution images from the Clipper flybys.

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Figure 1. A field of snow-penitents in the Elqui Valley above La Serena, Chile, 21 December 2007.