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3 **EXTREME BLADED ROUGHNESS ON THE SURFACE OF EUROPA AT THE**  
4 **LANDER SCALE**

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## 27 **Extreme bladed roughness on the surface of Europa at the lander scale**

28 *Sublimation of massive ice deposits at equatorial latitudes, in the absence of any liquid melt, will*  
29 *form spiked and bladed textures, or roughness elements, eroded into the surface of the ice,*  
30 *known on Earth as penitentes. For this process to take place on a planet, the ice in question*  
31 *must be sufficiently volatile, and not subjected to other diffusive processes that erode the deposit*  
32 *faster than sublimation. We find H<sub>2</sub>O ice in the equatorial latitudes of Jupiter's satellite Europa*  
33 *should be eroded to form multi-meter scale bladed textures on time scales of the crater retention*  
34 *age of Europa's surface. This texture could pose an extreme hazard to a future lander on*  
35 *Europa.*

36

## 37 **The potential for sublimation-formed blades**

38 The Jovian moon of Europa hosts an interior ocean of liquid water<sup>1-3</sup>, and has been proposed as a  
39 target for future planetary missions due to the possible habitability of this ocean. Past studies of  
40 its icy shell have envisioned a surface that is smooth at the lander scale, dominated by diffusive  
41 impact processes such as impact gardening and sputtering by charged particles in Jupiter's  
42 magnetic field<sup>4-10</sup>. However, on Earth, icy surfaces ablated by solar radiation develop  
43 characteristic roughness patterns at the centimeter to multi-meter scale<sup>11-16</sup>. Here we show that  
44 under modern European conditions, sublimation processes driven by solar radiation flux are  
45 expected to dominate over diffusive processes in a band around the satellite's equator. As the  
46 surface at these latitudes degrades, it will develop an east-west aligned, spiked and bladed  
47 texture, or roughness, at the meter scale – known on Earth as penitentes. This interpretation can  
48 explain anomalous radar returns seen around Europa's equator<sup>4,5,17</sup>. Penitentes may well explain  
49 reduced thermal inertias and positive circular polarization ratios in reflected light from Europa's

50 equatorial region<sup>17,18</sup>. This formation mechanism is used to explain formation of bladed terrain  
51 on Pluto in methane ice<sup>19</sup>.

## 52 **Blade Formation**

53 Self-organized surface patterning is ubiquitous in terrestrial snow and ice during ablation by  
54 radiative heating, through both sublimation and melting. Europa's atmosphere is so tenuous  
55 ( $\sim 0.1 \mu\text{Pa}$ ,  $10^{12}$  times less than Earth's surface; 10-20 km particle mean free paths<sup>20</sup>) that its  
56 external heat budget is effectively radiative, and hence such textures might also be expected  
57 there on ablating surfaces, but solely due to sublimation. On Earth, growth of these patterns is  
58 linked to amplification of initial random depressions in the surface by lensing of scattered solar  
59 and thermal infrared radiation<sup>11,16,21</sup>.

60

61 On Earth, the dominant radiative structures that form in snow and ice under cold, dry conditions  
62 are called penitentes. These are tall, east-west aligned, sharp-edged blades and spikes of sculpted  
63 snow or ice which point towards the elevation of the midday sun<sup>12,22</sup> (Fig. 1). Typical heights are  
64 1-5 m. Formation of large and well-developed penitentes requires bright, sustained sunlight,  
65 cold, dry, still air<sup>11</sup>, and a melt-free environment<sup>12</sup>. Thus, they are almost entirely restricted to  
66 high-altitude tropics and subtropics<sup>14</sup>. Laboratory experiments<sup>22</sup> and numerical modeling<sup>16</sup>  
67 confirm that sublimation in the absence of melting is particularly essential for penitente  
68 formation<sup>11,12</sup>. Small amounts of dirt in the ice do not inhibit penitente formation if radiation can  
69 penetrate the ice, and the vapour can escape<sup>11,16,22</sup>.

70

71 Radiative modeling confirms that penitentes form by scattering and lensing of light on and into  
72 snow and ice<sup>11,16</sup>. A key factor controlling penitente formation is that the pit of the structure must  
73 ablate faster than the sidewalls; if the sidewalls ablate faster, an alternate bowl-like stable form  
74 known as a suncup may develop<sup>13,15,16</sup>. Penitente growth requires a daily low solar incidence  
75 angle, such that light strikes the walls of the blades at a high angle, and illuminates the floors of  
76 the pits.<sup>13,14</sup> This maximizes the contrast in flux per unit area on the floor compared to the  
77 sidewalls, both in terms of direct and scattered radiation<sup>14</sup>, and explains why terrestrial examples  
78 are usually found near the equator, or also on steep equatorward-facing slopes at higher  
79 latitudes<sup>23</sup>. Physical analysis indicates that the scale and stability of penitentes are critically  
80 controlled by the thermal absorption of solar radiation into the ice and by the ability of the  
81 system to sustain gradients in the vapour pressure of the atmosphere that is in contact with the  
82 ice.<sup>16</sup> Theory suggests that the minimum size of penitentes may be governed by any of the  
83 following physical parameters: light extinction depth<sup>11,22</sup>, atmospheric vapor diffusion<sup>16</sup>, or heat  
84 conduction<sup>16</sup>. Their growth is most rapid for penitentes of sizes close to this minimum scale.  
85 This implies that ice grain size, porosity, roughness and impurity concentrations affect penitente  
86 size. Experiments, however, suggest that penitente size increases with depth of incision, and that  
87 a characteristic depth-to-width (aspect) ratio of about 2 is obtained, similar to 1.5-1.7 in  
88 terrestrial penitente fields<sup>13</sup>. The focusing of radiation in shallow hollows means that they will  
89 deepen, but shadowing and multiple reflections limit the depth of penitentes<sup>23,24</sup>, implying an  
90 optimum aspect ratio. Whether penitentes grow in size without limit during continued  
91 sublimation is uncertain, but eventually the mechanical strength of H<sub>2</sub>O ice will limit the size.

92

93 These observations suggest that sublimation on Europa could create penitente-like textures on its  
94 surface. Europa is tidally locked to Jupiter, with an inclination to Jupiter's equator of  $0.47^\circ$ .  
95 Jupiter's obliquity is only  $3.13^\circ$ , and thus for any given point on Europa's surface, the solar  
96 zenith angle never varies by  $>4^\circ$ . This orbital configuration has likely been stable over the  
97 lifetime of the surface<sup>25</sup>. Based on Galileo Photopolarimeter-Radiometer (PPR) data, surface  
98 brightness temperatures have been calculated to vary between  $\sim 70$  K and  $132$  K<sup>4,5</sup>. Its  
99 photometric properties, in particular its albedo, show that the surface of Europa is fairly pure  
100 water ice, with a minor component of silicate materials and salts<sup>2,5,7</sup>. Thus, the surface fulfills  
101 three essential requirements for penitente growth - it is dominantly exposed ice; it would sublime  
102 without melting; and there is very little variation in solar incidence angle.

103

104 Furthermore, for penitentes to develop, they must grow faster than any other geomorphic process  
105 can modify the surface. Europa is subjected to bombardment both by conventional impactors  
106 (meteoroids, comets) and by ions accelerated by Jupiter's magnetic field<sup>5,26,27</sup>. Both of these  
107 processes will act diffusively to smooth out local topographic highs. The most recent  
108 estimates<sup>5,8,9</sup> suggest that ion sputtering is probably dominant over impact gardening on Europa  
109 today, with rates of  $\sim 2 \times 10^{-2}$  m/Ma. At first order, for penitentes to develop, the sublimation rate  
110 must minimally exceed these diffusive processes. We assess sublimation rates using global maps  
111 of peak brightness temperatures coupled to profiles of temperature variation throughout the  
112 day<sup>4,5</sup> to input into temperature-dependent equations of state (see Methods). This allows us to  
113 predict the approximate rates of uniform sublimation at varying European latitudes (Fig. 2). Bulk  
114 surface sublimation rates exceed likely sputtering erosion rates equatorwards of latitudes  $24^\circ$ N/S

115 ( $\pm 6^\circ$ ), dependent on the modeling assumptions. We hypothesize that penitentes can grow, and  
116 indeed have grown, in this region.

117

118 Studies of terrestrial development of penitentes provide support for order-of-magnitude estimates  
119 of the dimensions of these structures, at least with respect to their aspect ratios. On Earth, the  
120 rate of growth as well as the characteristic separation scale of the ice blades is modeled to be set  
121 by the balance between heat conductivity in the ice, mass diffusion, and bolometric albedo<sup>16</sup>. On  
122 Earth the mass diffusion term is, in turn, set by an atmospheric boundary layer thickness. This  
123 does not apply to Europa, however, due to its insignificant atmosphere ( $\sim 10^{-8}$  Pa). For Europa,  
124 we first estimate the rate of ice sublimation at the equator, finding approximately 0.3 m/Ma (see  
125 Methods). Based on this analysis we infer that sublimation outpaces sputtering and impact  
126 gardening by an order of magnitude.

127 Based upon our analysis, up to 15 meters of sublimation has occurred over 50 Ma, which is the  
128 average surface age of Europa<sup>5,8</sup>. We next assume that penitentes grow with constant aspect  
129 ratio, which we assume to be  $\sim 2:1$ . Thus we conclude that maximum penitente depth could  
130 reach  $\sim 15$  meters with spacing of  $\sim 7.5$  meters near the equator (Fig. 2). We infer that the  
131 penitentes will become shallower, less well developed and increasingly asymmetric (and thus  
132 mechanically unstable) with distance from the equator<sup>23</sup> (see Methods).

133 Our sublimation calculations are zonally averaged, and do not account for a number of local or  
134 poorly constrained effects. For example, fissured, ridged, and chaotic textures seen at  $>0.1$  km  
135 scales indicate that resurfacing occurs in different places at different times.<sup>1,26</sup> Young areas will  
136 clearly lack major penitentes, and older areas should have better developed structures. Local

137 surface inclination will also alter growth rates and stability. We have not accounted for spatial  
138 variation in sputtering rates, particularly with respect to their leading-trailing hemispheric  
139 asymmetry<sup>27,28</sup>. We also cannot quantify the role of particulate impurity within and on the ice,  
140 and so this is not treated here<sup>6,7</sup>. Magnitudes of local relief and surface non-volatile  
141 contamination at Europa are badly constrained, especially at the key meter scales, but are likely  
142 variable and might be locally substantial<sup>29</sup>. Contamination can produce both positive and  
143 negative feedbacks<sup>11,22</sup>, and locally suppress penitente growth entirely if a substantial non-  
144 volatile surface lag has formed<sup>11,15</sup>. Re-deposition of sublimated ice will occur at high latitudes,  
145 polar-facing slopes, and local cold-traps<sup>5,6</sup>.

146

### 147 **Supporting Observations**

148 Given our estimates of penitente spacing ( $\leq 7.5$  meters), available imaging from the Galileo  
149 orbiter's camera is too coarse to permit detection. Current roughness estimates are either at  
150 scales too coarse ( $>10^1$  m, from imaging<sup>30</sup>) or too fine ( $<10^{-2}$  m, from optical photometry<sup>10</sup>). Two  
151 independent and largely unexplained sets of ground-based radar and *Galileo* orbiter thermal  
152 observations reveal, however, that the surface properties of Europa equatorwards of  $\sim\pm 25^\circ$  are  
153 systematically different to those polewards of those latitudes:

- 154 1. Instantaneous disk resolved radar returns from Europa reveal a striking equatorial minimum in  
155 the total power returned at 13 cm wavelengths<sup>17</sup> (Fig. 3a).
- 156 2. Maps of Europa's nighttime brightness temperatures from Galileo's PPR instrument reveal a  
157 very similar equatorial minimum<sup>4,5</sup> (Fig. 3b). Previous authors have interpreted such

158 brightness temperatures as indicating a relative minimum in surface thermal inertia at the  
159 equator<sup>4,31</sup>.

160 The known geology and visible surface patterning of Europa do not systematically change at the  
161 equator<sup>4,5</sup>, and this has made the above observations enigmatic. However, a penitente-like,  
162 ordered surface roughness, or texture, provides a possible solution. Because light entering a  
163 penitente hollow will, on average, interact more than once with the walls before emerging, the  
164 development of ice blades in these latitudes would increase the flat-surface-equivalent absorption  
165 coefficient, even with no change to fine scale material properties. In other words, the form of  
166 such a surface makes it an effective absorber for wavelengths shorter than the scale of the  
167 structure. By Kirchhoff's law, this also means that such a surface will be a more effective  
168 emitter, compared to an equivalent flat surface.

169 Further support comes from the leading/trailing hemispheric asymmetry in radar albedo of the  
170 equatorial regions. The trailing hemisphere (270°W) is much more heavily contaminated with  
171 particulates transported there by the magnetosphere. The trailing hemisphere, however, has a  
172 higher equatorial radar albedo than the leading hemisphere (Fig. 3a). This is counterintuitive if  
173 the contaminants aid absorption of radar in the subsurface, but fits if high particulate  
174 concentrations partially suppress penitente formation.

175 Europa radar observations reveal atypical circular polarization ratios. This atypical pattern may  
176 also result from the presence of penitente fields. Earth-based whole-disc radar observations at  
177 wavelengths  $\lambda = 12.6$  cm reveal that unlike all known rocky bodies, the ratio of same-sense to  
178 opposite-sense circularly polarized radar,  $\mu_c$ , exceeds 1.0 for Europa, i.e., the typical ray strikes  
179 an even number of surfaces before being detected<sup>17,18</sup>. Traditional explanations for this

180 “startling”<sup>18</sup> effect have relied on arbitrary, complex subsurface geometries – either randomly  
181 orientated ice dykes and fractures<sup>32</sup>, or buried, ideally-shaped impact craters<sup>33</sup>. However, a  
182 bladed surface texture at the surface could easily fulfill such a role, with the steeply inclined,  
183 opposing walls of the blades replacing the fractures or buried crater walls<sup>34</sup>. In incident radar at  
184 decimeter scales, the equator appears to be an anomalously effective absorber, hence the low  
185 radar albedo.

186 The apparent depression of the instantaneous nighttime brightness temperatures (Fig. 3b) derived  
187 from the *Galileo* Orbiter’s Photopolarimeter-Radiometer (PPR) data observed in the equatorial  
188 band is harder to explain than the radar analysis. Published models of increased surface  
189 roughness struggle to reproduce this effect<sup>4</sup>. However, we speculate that the reported reduction  
190 in instantaneous nighttime brightness temperatures may be a consequence of viewing angle  
191 effects. Because of the radiative scattering occurring within the penitentes, the tips of their blades  
192 cool significantly faster than the pits between them; oblique viewing angles will obstruct views  
193 of the pit interiors and so proportionately cooler temperatures would be presented to the  
194 observer.

195 Moreover, if anomalous circular polarization ratios on Europa observed in radar data are driven  
196 primarily by ordered surface roughness, similar polarization ratios on other icy moons of  
197 Jupiter<sup>18</sup> may indicate surfaces likewise roughened by penitente growth. We note that the Jovian  
198 system may occupy a restricted “sweet spot” in the solar system for the development of such  
199 features formed in H<sub>2</sub>O ice. Penitente formation is used to explain the extremely large ridges in  
200 the bladed terrain of Pluto, which are carved in massive deposits of methane ice<sup>19</sup>.

201

## 202 **Conclusions**

203 In summary, we have performed an approximate calculation of sublimation rates on Europa,  
204 indicating that fields of penitentes may grow up to 15 m high in 50 Ma near the equator. We  
205 suggest that in equatorial regions sublimation erosion likely dominates over other erosional  
206 processes. Puzzling properties of the radar and thermal observations of Europa's equatorial belt  
207 can be explained by the presence of penitente fields in this region. The implications of penitente  
208 fields at potential landing sites should motivate further detailed quantitative analysis.

209 Observations made by the upcoming *Europa Clipper* mission high-resolution imaging system  
210 and ground-penetrating radar of these regions can directly test our conclusions.

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301 revision of the manuscript. A.D.H. was involved in the study, design, interpretation, and  
302 revision. Both J.M.M. and A.D.H. performed preliminary analyses. O.M.U. significantly revised  
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304 commented on the manuscript.

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317 **Figure Captions**

318 **Figure 1 | Terrestrial penitentes from the southern end of the Chajnantor plain, Chile.** The  
319 view is broadly northwards; blades can be seen perpendicular to the viewing direction. The  
320 extreme relief of the structures is typical. The depressions between these examples have ablated  
321 down to the underlying rock surface. Credit: ESO,  
322 [https://www.eso.org/public/images/img\\_1824/](https://www.eso.org/public/images/img_1824/).

323

324 **Figure 2. | Modeled variation in rates of surface sublimation, and equivalent total depth of**  
325 **ice removal, with European latitude.** Latitudinally dependent sublimation rates (top axis) and  
326 corresponding total sublimated ice over a 50 Ma timescale (bottom axis) are derived from  
327 distinct brightness temperature data sets from two Galileo orbits, G7 (blue circles, solid line) and  
328 I25 (green crosses, dotted line), each of which are centered on opposite hemispheres. Due to  
329 truncated observations, both maxima and minima are shown for orbit I25. Temperatures are  
330 estimated based on an emissivity value of 0.90 (see Methods). Green and blue shaded regions  
331 indicate conservative rate estimates for the two data sets. Red dashes show average rates of  
332 surface overturn by sputtering. Red arrows indicate the latitudinal range in which predicted  
333 sublimation rates, based on G7 and I25 orbit observations, equal the overturn rate driven by  
334 sputtering. In both hemispheres, sublimation outcompetes sputtering erosion in a broad  
335 equatorial band equatorwards of  $\sim\pm 24^\circ$  latitude, and it is this surface that could develop  
336 penitentes.

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338

339 **Figure 3 | Remote sensing evidence consistent with an equatorial band of penitentes on**  
340 **Europa. a.** Instantaneous total power radar albedo,  $M$ , returned from 12.6 cm radar sounding of  
341 Europa using the Arecibo telescope, redrafted from reduced data presented in Ostro et al.<sup>17</sup> **b.**  
342 Instantaneous nighttime brightness temperatures from the E17 orbital pass of Europa as inferred  
343 from *Galileo* PPR data (wavelength range 0.35~100  $\mu\text{m}$ ), after Spencer et al.<sup>4</sup> Local time (top  
344 axis) is presented in Europa equivalent hours of the day. The instantaneous acquisition of the  
345 PPR data used here causes much of the surface viewed by that instrument to be seen at an  
346 oblique angle. Base map, from *Galileo* and *Voyager* images, is in a cylindrical projection and  
347 gridded at 30° of latitude and longitude (courtesy Paul Schenk). This figure was drafted using  
348 reduced data originally presented in Rathbun et al. (2010)<sup>31</sup>.

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## 359 **Methods**

360 We estimate a daily averaged amount of sublimated H<sub>2</sub>O ice from Europa based on following the  
 361 methodology of Lebofsky<sup>35</sup>. We identify  $\rho_s q^{avg}$  to be the daily averaged mass loss rate of H<sub>2</sub>O  
 362 ice (kg m<sup>-2</sup>s<sup>-1</sup>). The formula expressing this sublimation rate is given by

$$363 \quad \rho_s q^{avg} \approx \frac{\delta(T_{s0}) \cdot P_{vap}(T_{s0})}{4\pi v_a(T_{s0})} = \frac{P_{vap}(T_{s0})}{2\pi\sqrt{L}}; \quad v_a \equiv \sqrt{\frac{kT_{s0}}{2\pi m_{H_2O}}}, \quad \delta(T_{s0}) \equiv \sqrt{\frac{2kT_{s0}}{\pi L m_{H_2O}}},$$

364 [1]

365 The derivation of the above expression for  $\rho_s q^{avg}$  (see details below) takes into account the fact  
 366 that most sublimation occurs in the few hours straddling high noon. The density of water ice is  
 367  $\rho_s = 920 \text{ kg m}^{-3}$ .  $P_{vap}$  is the temperature dependent vapor pressure of H<sub>2</sub>O.  $T_{s0}$  is the noon time  
 368 temperature on Europa at a given latitude  $\lambda$ .  $\delta$  is a factor that is much less than one and  
 369 accounts for the fact that most sublimation occurs around high noon. The characteristic velocity  
 370 of particles in a Maxwell-Boltzmann gas is  $v_a$ . The Boltzmann constant is  $k$  and  $m_{H_2O}$  is the mass  
 371 of a H<sub>2</sub>O molecule.  $L = 3 \times 10^6 \text{ J kg}^{-1}$  is the heat of sublimation for H<sub>2</sub>O. The noon time  
 372 temperature at a given latitude  $\lambda$  is estimated from the relationship

$$373 \quad T_{s0} = \left[ \frac{(1-\omega)}{\sigma\epsilon} F_{inc} \right]^{1/4}; \quad F_{inc} = F_{eur} \cos \lambda, \quad F_{eur} \approx 50 \text{ W m}^{-2},$$

374 [2]

375 in which  $F_{inc}$  is the incident solar irradiance at latitude  $\lambda$ ,  $F_{eur}$  is the solar irradiance at Jupiter,  
 376  $\omega \sim 0.67$  is the surface albedo of Europa's ice and  $\epsilon \approx 0.9$  is its emissivity<sup>4,5,36</sup>. The Stefan-

377 Boltzmann constant is  $\sigma$ . An analytic form for H<sub>2</sub>O's vapor pressure, which accounts for new  
 378 experimental findings<sup>37</sup>, is discussed in detail below. Adopting an equatorial noon value of  $T_{s0} =$   
 379 134 K, we find that equation [1] predicts a sublimation lowering rate of about 0.3 m/Ma, which  
 380 amounts to 15 m of ice sublimated in 50 Ma which is the given average age of Europa's surface.  
 381 The remaining Methods section provides a detailed description of how we estimate the amount  
 382 of ice sublimated away from Europa's surface. To lowest order we follow the methodology of  
 383 Lebofsky<sup>35</sup> supplemented by the work of Claudin et al.<sup>16</sup> We define  $q$  to be the sublimation rate  
 384 of surface ice ( $\text{kg m}^{-2} \text{s}^{-1}$ ) divided by the surface ice density ( $\text{kg m}^{-3}$ ). Therefore  $q$  has units of  
 385 m/s and we write  $\partial_t h = q$ , where  $h$  is the level height of the ice. Three equations govern the  
 386 evolution of  $h$  and the vapor content in Europa's ballistic atmosphere. The first of these  
 387 represents the rate of change of  $h$  as driven by the balance of energy gained and lost,

$$388 \quad \rho_s L \partial_t h = (1 - \omega) F_{inc} - \epsilon \sigma T_s^4, \quad F_{inc} = F_{jup} \cos \lambda,$$

389 [3]

390 where  $L = 3 \times 10^6 \text{ J kg}^{-1}$  is the heat of sublimation for H<sub>2</sub>O,  $F_{inc}$  is the incoming solar radiation at  
 391 a given latitude on Europa's at noon where  $F_{jup} \sim 50 \text{ W m}^{-2}$  is the solar irradiance at Jupiter and  
 392  $\lambda$  is latitude.  $\omega \sim 0.67$  is the measured ice albedo for Europa's surface.  $\epsilon$  is the emissivity of  
 393 Europa's surface ice. The surface ice density is  $\rho_s \sim 920 \text{ kg m}^{-3}$ . Finally,  $\sigma$  and  $T_s$  are respectively  
 394 the Stefan-Boltzmann constant and the ice surface temperature. Note that  $T_s$  varies over the  
 395 course of the day as the sun crosses the sky. The first expression on the right hand side of eq. [3]  
 396 represents the gain of solar irradiance while the second represents radiative losses to space. Note  
 397 that for Europa, eq. [3] is in very nearly steady state which means that to lowest order the

398 expression is satisfied when  $(1 - \omega)F_{inc} = \epsilon\sigma T_s^4$ . Based on analysis of brightness temperature  
 399 data acquired by Galileo<sup>4,5</sup> as well as Voyager thermal emission spectra<sup>4,36</sup>, we adopt an  
 400 emissivity  $\epsilon = 0.90$ . With peak brightness temperatures at equatorial noon to be about  $T_b \sim 131$   
 401 K<sup>9</sup>, the above albedo and emissivity estimates yield a surface ice temperature at equatorial noon  
 402 of  $T_s(t = \text{noon}) \equiv T_{s0} = T_b / \epsilon^{1/4} \approx 134.5\text{K}$ . We shall use assume this value to be typical of the  
 403 equator at noon throughout.

404  
 405 The next equation follows the detailed change of the surface as a result of direct exchange  
 406 between the atmosphere and vapor pressure driven sublimation,

$$407 \quad \rho_s q = \rho_s \partial_t h = v_a (\rho_a - \rho_{vap}(T_s)); \quad v_a \equiv \left( \frac{kT_s}{2\pi m_{H_2O}} \right)^{1/2}.$$

408 [4]

409 The quantity  $v_a$  is the typical value of the velocity in a Maxwell-Boltzmann distribution at  
 410 temperature  $T_s$  and  $\rho_{vap}(T_s)$  is the saturation vapor density at  $T_s$ .  $m_{H_2O}$  is the mass of the  
 411 hydrogen molecule.  $\rho_a$  is the surface mass density of water vapor. The equation represents the  
 412 rate at which H<sub>2</sub>O molecules get absorbed by the surface (assuming 100% sticking probability)  
 413 minus the rate the solid ice ablates due to its ice vapor pressure. Observations of Europa's noon  
 414 time surface temperature<sup>4,5,9</sup> indicates a partial vapor pressure of H<sub>2</sub>O near its surface to be about  
 415 a several  $10^{-8}$  Pa (see further below). With the relationship between vapor pressure and density  
 416 given by  $\rho_{vap} = P_{vap}/c_s^2$ , where  $c_s \equiv \sqrt{kT/m_{H_2O}}$  is the isothermal sound speed, we find that the  
 417 corresponding value for  $\rho_{vap}$  is approximately  $9.85 \times 10^{-13} \text{ kg/m}^3$ .

418 To illustrate the potential for penitente formation, we assume that all emitted water vapor is  
 419 effectively lost which means setting  $\rho_a$  to zero, because Europa's atmosphere can be  
 420 approximated as a vacuum. Thus, an upper bound estimate to the amount of surface H<sub>2</sub>O lost is  
 421 given by

$$\rho_s \partial_t h = -v_a \rho_{vap}(T_s) = -P_{vap}(T_s) v_a / c_s^2, \quad [5]$$

424 Our task is to estimate a daily averaged value for  $v_a \rho_{vap}$ , which we hereafter refer to as  $\rho_s q^{avg}$ ,  
 425 and then extrapolate from this daily average to 50 Ma.

426 Because  $T_s$  varies over the course of the day and since  $P_{vap}$  has an Arrhenius form, calculating a  
 427 daily average for the total number of H<sub>2</sub>O molecules emitted requires some finesse. However, an  
 428 analytical form is possible. We designate  $t_{day}$  to be the length of one European day. We define  
 429 the daily averaged vapor pressure to be

$$P_{vap}^{avg} \equiv \frac{1}{t_{day}} \int_{t_{day}} P_{vap}(T_s) dt, \quad [6]$$

432 For the vapor pressure of H<sub>2</sub>O, we fit a curve based on the data points acquired for water's phase  
 433 diagram as summarized in Fray and Schmitt (2009)<sup>37</sup>. We note that the theoretical extrapolation  
 434 of Feistel et al (2007)<sup>38</sup> significantly underestimates H<sub>2</sub>O's vapor pressure compared to  
 435 experimental findings for temperatures below T=140K<sup>39,40</sup>, see also Figure 3 of Fray and  
 436 Schmitt (2009)<sup>37</sup>. We adopt the following fitted form to be a more accurate representation of  
 437 H<sub>2</sub>O's behavior for the temperature range below 140 K:

438 
$$P_{\text{vap}}(T) \approx P_0 \exp \left[ \frac{Lm_{\text{H}_2\text{O}}}{k} \left( \frac{1}{T_{130}} - \frac{1}{T} \right) \right]; \quad P_0 = 2.30 \times 10^{-8} \text{ Pa}, \quad T_{130} \equiv 130 \text{ K.}$$

439 [7]

440  $P_0$  is the measured value of  $\text{H}_2\text{O}$ 's vapor pressure at  $T=130\text{K}$  based on a fit to the aforementioned  
 441 experimental measurements<sup>39,40</sup>. We note that the previously estimated  $\text{H}_2\text{O}$  sublimation rates  
 442 on Europa<sup>9</sup>, which are based on Feistel et al.'s theoretical extrapolation, are underestimated by a  
 443 factor of six or more.

444 Given  $P_{\text{vap}}$ 's strong exponential dependence on  $1/T$ , over the course of one day the majority of  
 445 surface sublimated  $\text{H}_2\text{O}$  is emitted within a few hours around noon. Combining eq. [3] with  
 446 Europa's surface brightness temperature analysis<sup>4</sup>, the latter of which shows that Europa's  
 447 surface temperature does not fall much below 74 K after the Sun sets, we adopt the following  
 448 expression for Europa's surface temperature over the course of one European day:

449 
$$T_s = \max \left[ T_{s0} \left( \cos \frac{2\pi t}{t_{\text{day}}} \right)^{1/4}, T_{\text{min}} \right]; \quad T_{s0} \equiv \left[ \frac{(1-\omega)F_{\text{inc}}}{\sigma\epsilon} \right]^{1/4},$$

450 [8]

451 where we have introduced  $T_{s0}$  to be the latitudinal dependent local noontime surface temperature.  
 452 Because our concern is mostly centered on the few hours around noon, the surface temperature  
 453 expression in equation [8] may be Taylor expanded as

454 
$$T_s \approx T_{s0} \left[ 1 - \frac{1}{8} \left( \frac{2\pi t}{t_{\text{day}}} \right)^2 \right].$$

455 [9]

456 Inserting equation [9] into the daily averaged integral expression eq. [6] via eq. [7], and making  
 457 use of well-known techniques in the asymptotic evaluation of integrals<sup>41</sup> we arrive at

$$458 \quad P_{vap}^{avg} = \delta(T_{s0}) \cdot P_{vap}(T_{s0}); \quad \delta(T_{s0}) \equiv \sqrt{\frac{2kT_{s0}}{\pi L m_{H_2O}}} = \frac{2v_a}{\sqrt{L}}.$$

459 [10]

460 and the corresponding daily averaged flux of sublimated gas is given by the expression

$$461 \quad \rho_s q^{avg} \approx \frac{P_{vap}^{avg}(T_{s0})}{4\pi v_a(T_{s0})} = \frac{\delta(T_{s0}) \cdot P_{vap}(T_{s0})}{4\pi v_a(T_{s0})} = \frac{P_{vap}(T_{s0})}{2\pi\sqrt{L}}.$$

462 [11]

463 Equation [10] says that the daily averaged vapor pressure is equal to the vapor pressure at noon  
 464 diminished by the multiplicative factor  $\delta$ , while equation [11] gives the corresponding daily  
 465 averaged sublimated mass-flux of H<sub>2</sub>O from the surface.

466 For example, for a surface temperature at the equator in which  $T_{s0} = 134\text{K}$ , we find that

467  $v_a \approx 98.5 \text{ m s}^{-1}$  and that  $\delta = 0.114$ . Based on equation [7],  $P_{vap}(T_{s0}) \approx 1.02 \times 10^{-7} \text{ Pa}$ . Thus, the

468 daily averaged mass flux of H<sub>2</sub>O at the equator is approximately

469  $\rho_s q^{avg} = 9.37 \times 10^{-12} \text{ kg m}^{-2}\text{s}^{-1}$ , which is equivalent to  $3.13 \times 10^{10} \text{ H}_2\text{O molecules cm}^{-2}\text{s}^{-1}$  – a

470 figure that is 6-9 times larger than previous estimates<sup>42,43</sup>. This loss rate translates to

471 approximately  $2.98 \times 10^3 \text{ kg m}^{-2}\text{Ma}^{-1}$ , which is equivalent to about 15 meters of ice over 50 Ma.

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474 **Data Availability:** The data that support the findings of this study are available on the NASA  
475 Planetary Data System (PDS) (<https://pds.nasa.gov/>).

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