Can Re-Distribution of Material by Sputtering Explain the Hemispheric Dichotomy of Europa?

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Abstract: Sputtering and re-deposition make up a significant geologic process on Europa, and may contribute to the color differences between the leading and trailing hemispheres. Our model traces the trajectories of sputtered molecules to derive the patterns of re-deposition. Net deposition (which occurs when re-deposition is higher than sputtering) can occur locally in some cases. In one such case, our results show a correspondence between the region of net deposition and the bright, yellowish region seen in Voyager and Galileo images.

Sputtering/Re-Deposition as a Geologic Process

Spectroscopic differences between the leading and trailing hemispheres of Europa have been observed at near infrared, visible, and ultraviolet wavelengths. Although such a distribution is highly likely to be linked to the bombardment of Europa's surface by ions caught up in Jupiter's magnetic field (which preferentially strike the trailing hemisphere), the spectral signature of non-ice material is also clearly associated with surface geologic activity, and therefore cannot be simply due to ion implantation. The full explanation of the hemispheric dichotomy remains a subject of debate.

Sputtering and re-deposition make up a significant geologic process on Europa, and may contribute to the color differences between the leading and trailing hemispheres. The high rate of ion bombardment from the Io Plasma Torus, together with Europa's easily sputtered icy surface, combine to make sputtering particularly efficient there as an erosive process. The global sputtering erosion rate on Europa is estimated at 15 to 16 mm Myr^{-1}. However, a significant fraction of sputtered water molecules survive to re-deposit onto the surface again. On Europa, 56% of sputtered water molecules have enough kinetic energy to reach the Hill radius, and more are ionized in flight by electron impact and carried away by Jupiter's magnetosphere. These processes hinder re-deposition from overcoming erosion, and thus the global average result of sputtering is net erosion (8.6 mm Myr^{-1}). However, neither sputtering nor re-deposition is globally uniform, and differences in the global distributions of the two processes can result locally in net deposition.

We propose that the observed hemispheric color dichotomy might be explained by the process of sputtering and re-deposition, which maintains a cleaner surface on the trailing hemisphere by scouring away any weathered crust, and, if net deposition occurs, may obscure the non-ice signature on the leading hemisphere by covering it with a thin water frost. To test this hypothesis, we have created a simulated model of the sputtering erosion/re-deposition process on Europa. Our objectives are to determine the conditions under which net deposition occurs on the leading hemisphere, and to evaluate the effects on this process of Jupiter's gravity, of Europa's rotation, and of the loss of water molecules to the jovian magnetosphere.

Description of Model

After estimating the location and velocity distributions of sputtered molecules, we carried out a Monte Carlo simulation integrating the trajectories of hundreds of thousands of molecules under the restricted 3-body problem, including the gravitational effects of both Jupiter and Europa. Trajectories are followed for each molecule until it either re-impacts Europa's surface, or is ionized by electron impact.

Our most poorly-constrained input parameter is the global distribution of the ions bombarding Europa's surface, which controls the global distribution of sputtering. To characterize this, we ran our model twice, using the two end-member profiles (see Figure 2) derived by Pospieszalska and Johnson (1989). Low-energy ions (Case A) have a highly heterogeneous global distribution; they are greater in number but less efficient in sputtering, all in contrast to relatively higher-energy ions (Case B).

Conclusions

Our results show that net deposition, leading to burial of material under a water ice frost, can occur on Europa's leading hemisphere under certain circumstances. The global net erosion map for Case A (assuming sputtering concentrated on the trailing hemisphere), seen in Figure 1c, shows net deposition of up to 3 mm Myr^{-1} over most of the leading hemisphere. The rate of net deposition is seen to be highly sensitive to initial conditions, especially the global distribution of ion bombardment. Given the uncertainty in this parameter, it is difficult to rule out net deposition, which thus remains a viable explanation for the global color dichotomy. The patterns of net deposition obtained from our model for Case A match with the brighter, yellow-hued region in Voyager and Galileo mosaics, even better than does the distribution of implantation or radiolysis. Neither sputtering redistribution nor radiolysis are viable explanations for the hemispheric color asymmetry in the more spatially homogeneous case of impact by higher-energy ions (Case B). Further experiments using these techniques can explore the effects of other global distributions of ion bombardment (and, thus, of sputtering). The effects of Europa's rotation and Jupiter's gravity on the overall outcome are discernible but not large. In conclusion, depending on the actual ion impactor distribution, burial of non-ice materials on the leading hemisphere remains a plausible explanation for Europa's color dichotomy.

Figure 2. Two scenarios for the global distribution of sputtering, from Pospieszalska and Johnson (1989): Case A (solid), with a high concentration of sputtering on the trailing hemisphere; and Case B (dashed), with a less heterogeneous distribution.

Figure 1. Four maps are shown in an equal-area cylindrical projection centered on the anti-Jupiter point. The right-hand half is the orbital leading hemisphere; the left-hand half is the trailing hemi-sphere. (a) Mosaic of Voyager 1 Narrow Angle Camera false-color images of Europa. (b) Mosaic of Galileo false-color images of Europa. (c) Net erosion rates derived from the numerical model in Case A. (d) Net erosion rates derived from the numerical model in Case B. Note that the bright, yellowish region in the spacecraft images corresponds with the region of net deposition (green) in the model results for Case A.