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## Where should amorphous water ice be observed on Ganymede?

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The surface of Ganymede is dominated by crystalline water ice, but amorphous water ice has been observed at the poles of both hemispheres [1]. Recent hyperspectral data from the James Webb Space Telescope have confirmed the presence of amorphous water ice in the north polar region of the leading hemisphere [2]. Because Ganymede is embedded in the Jovian magnetosphere, its surface is continuously irradiated by charged particles (ions and electrons), which induces radiolysis, chemistry, sputtering of surface molecules, and likely amorphization of water ice [3,4]. However, the irradiation flux is not uniform across Ganymede's surface due to its own magnetic field [5], and the equatorial region is partially shielded from ion and electron irradiation. This fact, along with higher temperatures at lower latitudes that efficiently promotes recrystallization, may explain that the presence of amorphous water ice is restricted to the polar regions.

Here, we question the presence of amorphous water ice in the north polar region using a numerical approach. The ion and electron fluxes impinging on the polar and equatorial regions are taken from a number of previous publications [6,7]. We first estimate the erosion rate of water ice at the surface for different case models using sputtering yields of H<sub>2</sub>O and O<sub>2</sub> [8,9,10]. The nuclear and electronic doses deposited in the subsurface with depth were calculated using the stopping powers generated by the SRIM software (<http://www.srim.org/>) [11]. The contribution of bremsstrahlung emission from decelerating electrons was not included in this calculation. The erosion rate mitigates the actual doses accumulated in the surface, and our numerical code included a moving surface front.

Our calculations show that water ice erosion is dominated by O and S ions, and the contribution of electrons is 3 orders of magnitude smaller. Although sputtering is more efficient at high temperatures [12], we found that the polar regions are more eroded due to a higher ion flux. The doses accumulated in the surface reach a steady state within  $\sim 100000$  years and are in the range of 100-1000 eV/atom. These values are underestimates, corresponding to a maximum erosion rate where no sputtered water molecules sink back to the surface. The fraction of crystalline water ice transformed into amorphous water ice was estimated using the kinetics reported in [13]. Since amorphous water ice crystallization competes with radiolytic amorphization, we also considered this process and used the kinetic parametric equation of [14]. Finally, our calculations show that amorphous water ice is essentially formed in the polar regions, where temperatures are  $< 100$  K, to a depth of  $\sim 600$   $\mu\text{m}$ . This result is consistent with the detection of amorphous water ice at the north

pole of Ganymede by the JWST telescope, but not with the lack of detection at the south pole. Our analysis of experimental data in the literature shows that the kinetics of water ice amorphization is not well constrained in the temperature range 90-120 K for low energy projectiles. This issue is being addressed through irradiation experiments. Ongoing simulations also include more realistic erosion rates.

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