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Bimodal sputter depletion of adsorbates from granular, regolith-like targets: laboratory measurements and comparative simulations

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Regolith roughness is expected to modulate the sputter flux of surface atoms into the exospheres of airless bodies such as Mercury, and studies have shown that roughness from the nanometer scale upward promotes redeposition and diminishes total sputtering yields. Experiments involving irradiation of olivine, plagioclase, and single-element powders demonstrate yield reductions from 15% to 67% as compared to smooth targets, but the grain size dependence of this effect has not been adequately parameterized. Understanding this mechanism is therefore of critical importance for quantifying desorption and sputter ejection and for predicting the relative contributions of release processes from regolith surfaces.

We measured the sputter depletion of adsorbed Na from polished natural olivine and from synthetic granular forsterite targets with narrow grain size distributions from 45 μm up to 520 μm. Na vapor was deposited onto each target in an ultrahigh vacuum system and then irradiated at either 15° or 60° incidence (from global surface normal) to prescribed fluence steps using 4 keV He+ ions. All experimental steps were carried out at room temperature (~300 K). After each fluence step an X-ray photoelectron spectrum was acquired and used to quantify the remaining Na surface concentration. Depletion rates and cross sections were then extracted from the concentration vs. fluence data for each target.

For the polished targets, Na concentrations exhibited single-exponential decay with increasing fluence, and depletion at 60° incidence outpaced that at 15° due to increased energy deposition near the surface as expected from theory. Conversely, for all granular samples the Na concentrations exhibited at least double-exponential decay, suggesting a bimodal removal process, and depletion from the granular targets occurred more quickly at 15° than at °60, implying enhanced access to grain facets at near normal incidence. We propose that this reflects faster removal of Na that is directly exposed to the incident ion flux, convolved with slower removal of shadowed Na by reflected incident ions. We found that the shadowed sodium was sputtered away 10–100 times more slowly than the exposed Na, with a transition from single-exponential to double-exponential decay at some threshold between nanoscale roughness (polished targets) and microscale roughness (<45 um). These results may help to explain, for example, why current models underestimate the persistence of Na density enhancements in Mercury's dayside exosphere, as observed by the MESSENGER spacecraft's UltraViolet and Visible Spectrometer.

Additionally, we present a novel ray-tracing model that incorporates SDTrimSP simulated sputter distributions and high-resolution, triangulated surface reconstructions of the experimental sputter targets, obtained via digital optical microscopy. The model tracks the fluence of primary and reflected incident ions onto each facet of the triangulated surface, along with the transfer of adsorbate atoms from facet to facet and from each facet into space (i.e. loss). By tuning this model

to reproduce our laboratory observations, we investigate the redistribution of adsorbate atoms with increasing fluence and the associated surface shape parameters that modulate the transition from fast, single-exponential sputter depletion to slow, double-exponential sputter depletion.