Revisiting Ion-Induced Electronic Sputtering of Na at the Moon and Mercury

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Abstract

- Solar Wind ions sputter regolith atoms by depositing kinetic energy directly by momentum transfer and indirectly by exciting electrons leaving neighboring atoms in repulsive states (Johnson, 1990).

- The ion-induced electronic excitations leave atoms with repulsive energy that decays through momentum transfer and can eject atoms from the surface, a process referred to as electronic sputtering (ES) (Johnson 1990, chapter 3 p. 112; Madey et al., 1998).

- We calculated ES yields of Na using linear cascade theory (Sigmund, 1981, chapter 2; Johnson, 1990; McGrath et al., 1986) and modeled the contribution of Na atoms to the near surface exospheric densities of the Moon and Mercury.

Methods

- The expression of the ES yield \( Y \) (ejected atoms/ion) has been previously obtained from solutions of Boltzmann’s transport equation for atoms in an ES cascade energized by an incident ion (Johnson, 1990, equation 3.10a & chapter 3 appendix B).

- The yield is equivalent to a ratio of sputter depth and distance between energizing events for low density cascades (Johnson, 1990), see below.

Electronic Sputter (ES) Yield

\[
Y = \frac{\Delta Z_{e}}{l_{i}}
\]

(\( \Delta Z_{e} \)) is the solar zenith (Moon). \( \Delta Z_{e} \) is the electron energy loss depth in the surface. \( l_{i} \) is the mean free path of the incident ion.

- The ES yield is the product of the yield, Na surface fraction and solar wind flux, where \( Z \) is the solar zenith.

ES Flux: \( \psi = Y \cdot f_{Na} \cdot \psi_{SW}(Z) \)

- The sputter flux was used in an exosphere model (Tucker et al., 2019) to track the quasi-steady state diurnal near surface exospheric densities produced by ES.

Results: Electronic Sputter (ES) Yield

| Table 1 | ES Na \( Y^*f_{Na} \) (H\(^+\), He\(^+\)) | \( n \) cm\(^{-2} \) | \( f_{Na} \) | SW Flux cm\(^{-2} \) s\(^{-1} \)
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<tbody>
<tr>
<td>Moon</td>
<td>( 9 \times 10^{-4}, 0.006 )</td>
<td>7.4 x 10(^{14} )</td>
<td>( ^{0.08} )</td>
<td>2 x 10(^{8} )</td>
</tr>
<tr>
<td>Mercury</td>
<td>( 9 \times 10^{-4}, 0.006 )</td>
<td>7.4 x 10(^{14} )</td>
<td>0.08</td>
<td>( *6.7 \times 10^{8} )</td>
</tr>
</tbody>
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\*McGrath et al., 1986

\*Max FIPS measurements, *Previous Mercury Estimate, *Albite Na fraction used as an upper limit, global values are likely lower by more than a factor of \( ^{2} \).

Near surface sodium densities from electronic sputtering

Figure 1: Mercury day-night exosphere densities

The Mercury model used a North/South cusps source with no surface sticking and full thermal accommodation for Na atoms that impact the surface.

Figure 2: Moon day-night exosphere densities

The Moon model used a subsolar source with no surface sticking and full thermal accommodation for Na atoms that impact the surface.

Sputter depth, \( T \) is not well characterized.

ES Flux was used in an exosphere model to better constrain sputtering form planetary surfaces.

Final Notes

- Electronic sputtering (ES) yields of Na for the Moon and Mercury are given in Table 1, and the resulting exospheric densities are shown Figure 1 (Mercury) and Figure 2 (Moon).

- The ES source fluxes (Table 2) are balanced by losses to photoionization (1.72 x 10\(^{-8} \) s\(^{-1} \) s\(^{-1} \) scaled by the distance from the Sun). Most ES atoms obtained speeds below the escape speed (Figure 3). New simulations should examine surface sticking.

- As expected, for full thermal accommodation the near surface exospheric densities peak on the night side and the poles limited by the source location, loss rate and migration. For example, the peak source rate for Mercury occurs at the high latitude cusps.

- Dynamical simulations with variable sources can predict if conditions exists for electronic sputtering to produce an observable signature on the Moon or Mercury.

- New laboratory (e.g., Wiens et al., 1997) and numerical sputtering experiments (e.g., Morrissey et al., 2022; Killen et al., 2022) of Na atoms ejected from silicate minerals are needed to better constrain sputtering form planetary surfaces.

Table 2

<table>
<thead>
<tr>
<th>Na Sputter Flux cm(^{-2} ) s(^{-1} )</th>
<th>Moon</th>
<th>Mercury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic sputtering</td>
<td>( *5.7 \times 10^{4} )</td>
<td>( *7.6 \times 10^{5} )</td>
</tr>
</tbody>
</table>

\*sputter from cusps (1-2x10\(^{22} \) m\(^{-2} \)) and max FIPS flux, *Flux calculated using global surface area \( f_{Na} = 0.08 \) and \( n = 7.4e14 \) m\(^{-2} \).

Figure 3: Speed Distribution used for ES

\( V_{esc} \) is the velocity distribution of electronic sputtered Na atoms from silicates is not well characterized. Madey et al., (1998) note the ejection of Na via electronic sputtering is comparable to electron stimulated desorption (ESD). Therefore, we ejected Na atoms using the ESD spectra measured from Na atoms desorbed from S1O2 in Yakshinskiy and Madey, (1999).