Sputtering of Lunar Regolith by Solar Wind Protons and Heavy Ions

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Outline

• Motivation
• Background
• Sputtering Mechanism
• Theory
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• Conclusion
Motivation

• All previous simulations considered the kinetic sputtering and ignored the potential sputtering.
• Our motivation is include the potential sputtering in the simulation of lunar regolith by solar-wind protons and heavy ions.
• Our results showed that the potential sputtering has significant effects in:
  1. Changing the surface chemical composition
  2. Surface erosion rate
  3. Sputtering process timescale.
Background

- Lunar surface material is accessible to the space weathering factors
- Solar wind protons and heavy ions with kinetic energies of about 1 keV/amu interact with the regolith
Sputtering Mechanism

When a target atom gains energy greater than the surface binding energy, then the atom may be sputtered.

\[ Y = \frac{\text{Number of sputtered atoms}}{\text{Number of incident ions}} \]
Sputtering

Kinetic Sputtering
(Singly charged ions)

Potential Sputtering
(Multi-charged ions)

Binary collisions

Radiation damage
and/or atom ejection

nonlinear electronic
excitation processes

Atom-hole formation
and atoms ejection

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Lunar Regolith Simulant JSC-1A AGGL

XPS: Surface of the simulant consists mostly of oxides

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>O</th>
<th>Si</th>
<th>Al</th>
<th>Fe</th>
<th>Ca</th>
<th>Mg</th>
<th>Ti</th>
<th>Na</th>
<th>P</th>
<th>K</th>
<th>Cr</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic %</td>
<td>2.3</td>
<td>55.6</td>
<td>19.5</td>
<td>8.4</td>
<td>1.4</td>
<td>4.3</td>
<td>3.9</td>
<td>0.4</td>
<td>3.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Experimental contamination
Mass distribution of sputtered species
Non-Equilibrium Model

\[ \frac{dC_i}{dt} = \frac{1}{\tau} \left[ -C_i \sum_j Y_{ij}F_j + C^b_i \sum_k C_k Y_{kj}F_j \right] \]

- $C_i$ is the abundant of element $i$ in JSC
- $C^b_i$ is the fractional abundant of element $i$ in the JSC bulk
- $Y_{ij}$ is the yield of element $i$ by solar wind ion $j$,
- $F_j$ is the fraction of solar wind $j$ in the solar wind flux
- $\tau$ is a constant has dimension of time.
- $A$ is the inter-atomic distance
- $h$ is the penetration depth
- $Y$ is the sputtering coefficient

\[ \tau = \frac{h}{A^3 jY} \]
Calculated changes in the elemental composition of a JSC-1A AGGL surface as a function of time due to the kinetic sputtering of the solar-wind protons and heavy ions.
Potential Sputtering

\[ Y_{ij}^{\text{potential}} = \alpha_i \left( \sum E_n - E_1 \right)^{\beta_i} \]

\[ \alpha_o = 3.12 \]
\[ \beta_o = 0.57 \]
% changes in the elemental composition of a JSC-1A AGGL surface

![Bar chart showing percentage changes in elemental composition](chart.png)

- **O**: (Kinetic) -40, (Kinetic + Potential) 0
- **Si**: (Kinetic) 40, (Kinetic + Potential) 60
- **Al**: (Kinetic) 20, (Kinetic + Potential) 30
- **Fe**: (Kinetic) 10, (Kinetic + Potential) 20
- **Ca**: (Kinetic) -20, (Kinetic + Potential) -10
- **Mg**: (Kinetic) -10, (Kinetic + Potential) -5

The chart illustrates the percentage changes in elemental composition for a JSC-1A AGGL surface, comparing kinetic and kinetic + potential effects.
Erosion Rate and Sputtering Time Scale:

- The erosion rate is given by:
  \[ V_s = jY S_l \omega \]

- Sputtering process timescale

<table>
<thead>
<tr>
<th>Y</th>
<th>Time scale (Years)</th>
<th>Erosion rate (A⁺/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12</td>
<td>724</td>
<td>0.224</td>
</tr>
<tr>
<td>0.14</td>
<td>621</td>
<td>0.261</td>
</tr>
<tr>
<td>0.15</td>
<td>543</td>
<td>0.298</td>
</tr>
<tr>
<td>0.18</td>
<td>434</td>
<td>0.335</td>
</tr>
<tr>
<td>0.20</td>
<td>395</td>
<td>0.373</td>
</tr>
<tr>
<td>0.23</td>
<td>362</td>
<td>0.447</td>
</tr>
<tr>
<td>0.28</td>
<td>310</td>
<td>0.522</td>
</tr>
<tr>
<td>0.31</td>
<td>271</td>
<td>0.597</td>
</tr>
<tr>
<td>0.35</td>
<td>241</td>
<td>0.671</td>
</tr>
<tr>
<td>0.40</td>
<td>214</td>
<td>0.746</td>
</tr>
</tbody>
</table>

Starukhina

Our results (Kinetic)

Our results (Kinetic and potential)
Conclusions

• Potential sputtering is effective process in regolith-like materials (insulators).
• Solar wind heavy ions contribute about 52% of the proton yield.
• Potential sputtering decreases the sputtering time scale and increases the erosion rate by (33%).
Thanks!
Questions?
Energy distribution of sputtered atoms 1:

- Energy distributions of sputtered particles from several targets bombarded with 900 eV $\text{Ar}^+$ ions

![Graph showing energy distribution of sputtered particles from different targets.](image)
Energy distribution of sputtered atoms 2:

- Energy distribution of sputtered lunar regolith atoms due to kinetic sputtering by solar-wind protons (Starukhina 2003)
Energy distribution of sputtered atoms 3:

- For multi-charged ions ($\text{Ar}^{7+}$ and of $\text{Ar}^{9+}$) and graphite target, experimental results show broad energy distribution.
Energy distribution of sputtered atoms 4:

- Based on the previous observations and models and including potential sputtering we can suggest the following energy distribution: