Abstract #1

Modeling Solar-Wind Heavy-Ions' Potential Sputtering of Lunar KREEP Surface

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Recent laboratory data suggest that potential sputtering may be an important weathering mechanism that can affect the composition of both the lunar surface and its tenuous exosphere; its role and implications, however, remain unclear. Using a relatively simple kinetic model, we will demonstrate that solar-wind
heavy ions' induced sputtering of KREEP surfaces is critical in establishing the timescale of the overall solar-wind sputtering process of the lunar surface. We will also also show that potential sputtering leads to a more pronounced and significant differentiation between depleted and enriched surface elements. We briefly discuss the impacts of enhanced sputtering on the composition of the regolith and the exosphere, as well as of solar-wind sputtering as a source of hydrogen and water on the moon.

Modeling Solar-Wind Heavy-Ions' Potential Sputtering of Lunar KREEP Surface

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Outline

Interactions of Solar-Wind Ions with Lunar Surface Materials: Kinetic vs. Potential Sputtering

Sputtering in a Non-Equilibrium Model
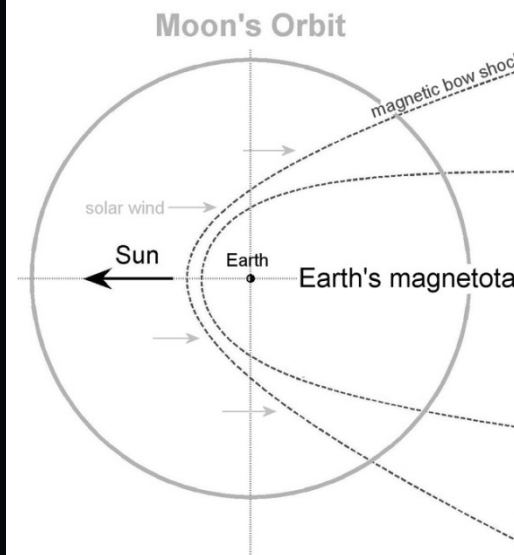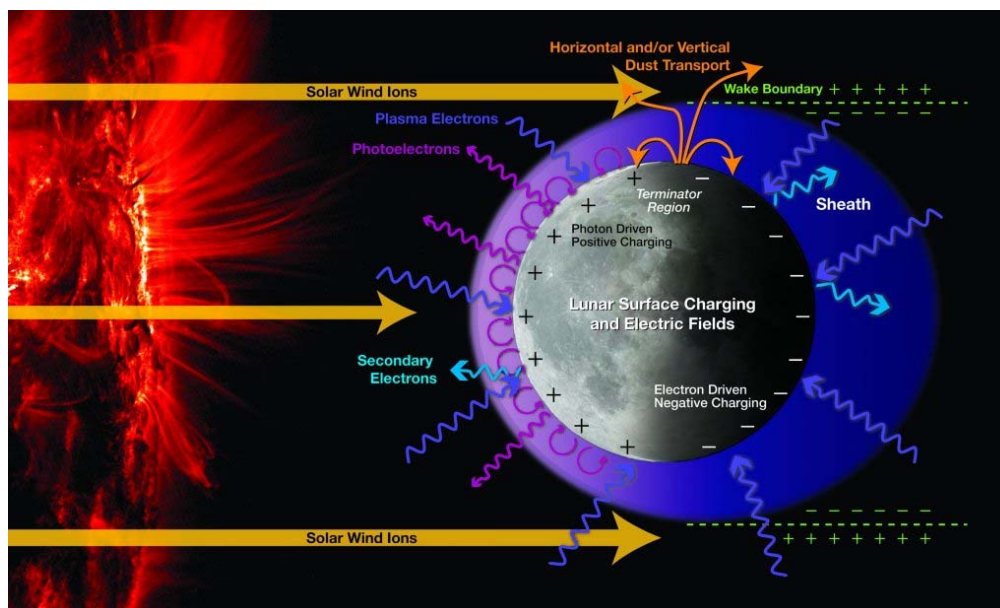
Implications of Enhanced Sputtering

Future Directions

Presentation is largely based on A.F. Barghouty et al., NIMB 269, 1310 (2011), and F.W. Meyer et al., NIMB 269, 1316 (2011).

Solar-wind heavy ions by number

SWHI	He	C	N	O	Ne	Mg	Si	S	Fe
Relative Abund.	7×10^{-2}	5×10^{-4}	5×10^{-5}	7×10^{-4}	6×10^{-5}	1×10^{-4}	1×10^{-4}	3×10^{-5}	8×10^{-5}
Charge State	2+	4+ – 6+	5+ – 7+	6+ – 8+	7+ – 9+	7+ – 10+	6+ – 12+	6+ – 11+	7+ – 14+

Interactions of the solar-wind ions with lunar regolith

►Protons and multiply charged ions striking amorphous surfaces at 1 keV/amu

►Surface atoms (in addition to ions, electrons, and photons) are ejected as the solar-wind ions get neutralized in the surface
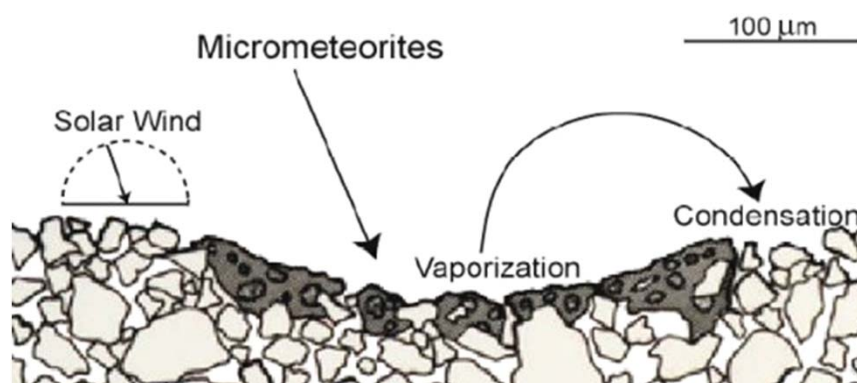
►The penetration depth is ~ 10s of nm, i.e., comparable to the thickness of the rim found on regolith soil grains
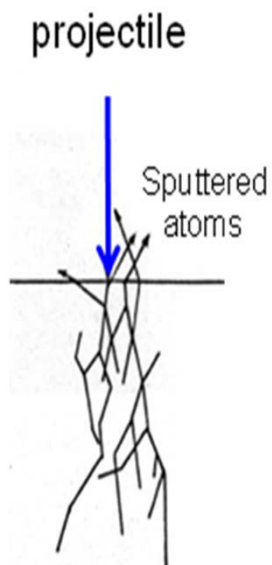
Kinetic Sputtering: Synopsis

projectile

Sputtered atoms
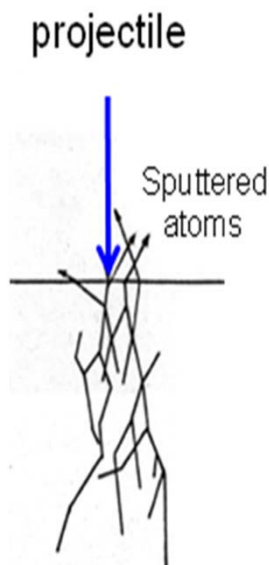
- **A collisional process initiated by an incoming energetic ion (projectile) by which an atom in the target surface can receive enough momentum or energy to escape the surface potential of the target material**

- **Numerous encounters $\longrightarrow$ statistical description**

- **Theory is based on estimating the scattering cross section and the energy-loss rate (or stopping power), noting that**

  sputtering rate ⭐ *nuclear energy-loss rate*

- **Sputtering rate also depends on the assumed interaction potential as well as surface properties**
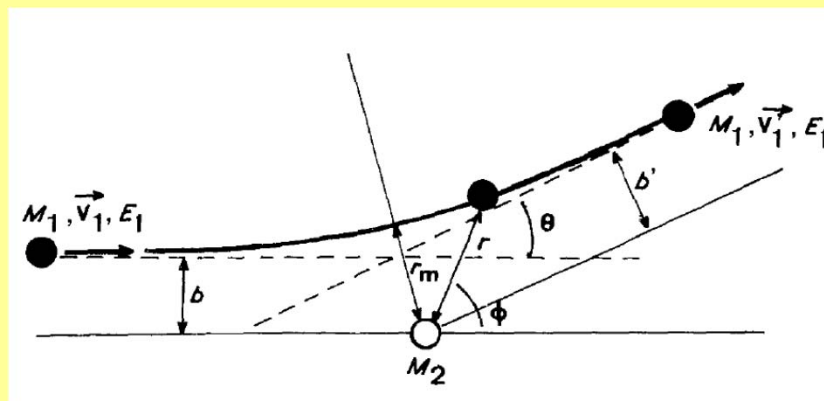
Kinetic Sputtering: Synopsis

- **Sigmund's expression for the sputtering rate:**

$$S = \frac{3}{4\pi^2} \frac{1}{C_0 U_s} \alpha_N (M_2/M_1) (\cos\theta)^{-5/3} \frac{1}{N} \frac{dE_1}{dx}\Big|_{nucl}$$

- **Two-body kinematics:**

projectile

Sputtered atoms

- **Two-body to kinetic-theory formulation**

- **Depth, angle, energy,…distributions**

Kinetic vs. Potential Sputtering

► Kinetic sputtering is the dominant sputtering mechanism for metals and semiconductors, where any induced electronic excitation can be rapidly accommodated

► Insulator surfaces have reduced electron mobility, hence fast electron removal from the target leads to structural modifications (defects) that cannot be restored

► This is enhanced for highly charged ions since they 'carry' a large amount of potential energy. This energy is dissipated rapidly through electron transfer and Auger de-excitation processes

► For many surfaces potential sputtering is significantly more effective in removing target material than kinetic sputtering

A^{q+} highly charged projectile

Sputtered particle

Neutral sputtered particle
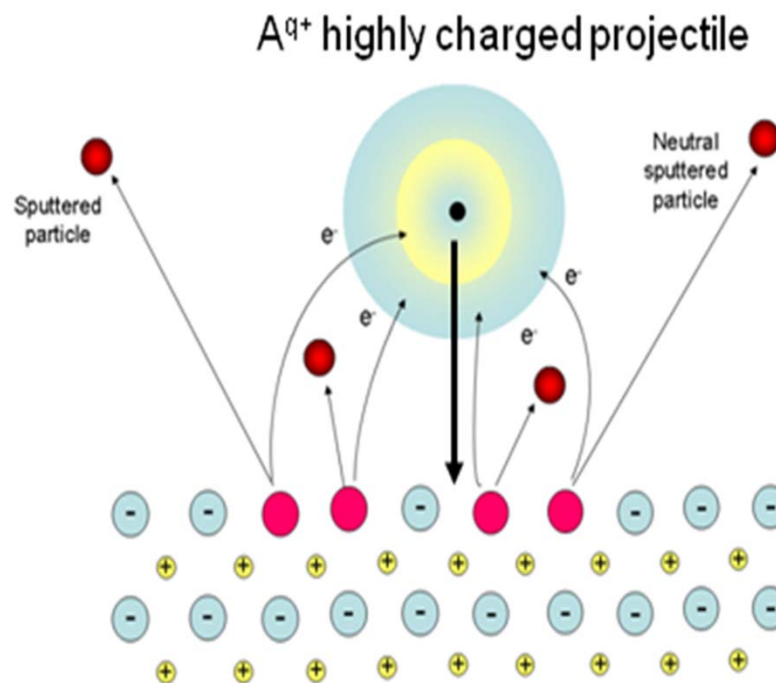
Is this relevant to solar-wind heavy-ions' interactions with the lunar surface?

Recent (few) references asking the same

Kracher et al. (2003): *suggested that potential sputtering might be an important space-weathering effect for asteroids' surfaces*

Shemansky (2003): *suggested that potential sputtering was an important, erosive mechanism affecting spacecraft structures*

Wurz et al. (2007): *suggested that potential sputtering might not be an important erosive factor affecting the lunar surface and the composition of its exosphere*

Potential Sputtering: New Data

Using lunar regolith simulants, Meyer et al. have found that:
(1) Compared to the proton-induced O yield, O production by incident same-velocity Ar^+ is increased by a factor of ~80, and an additional factor of two for incident Ar^{9+} .
(2) No significant fluence dependences in O production were observed up to the maximum fluences investigated (10^{15}–10^{16}/cm^2).
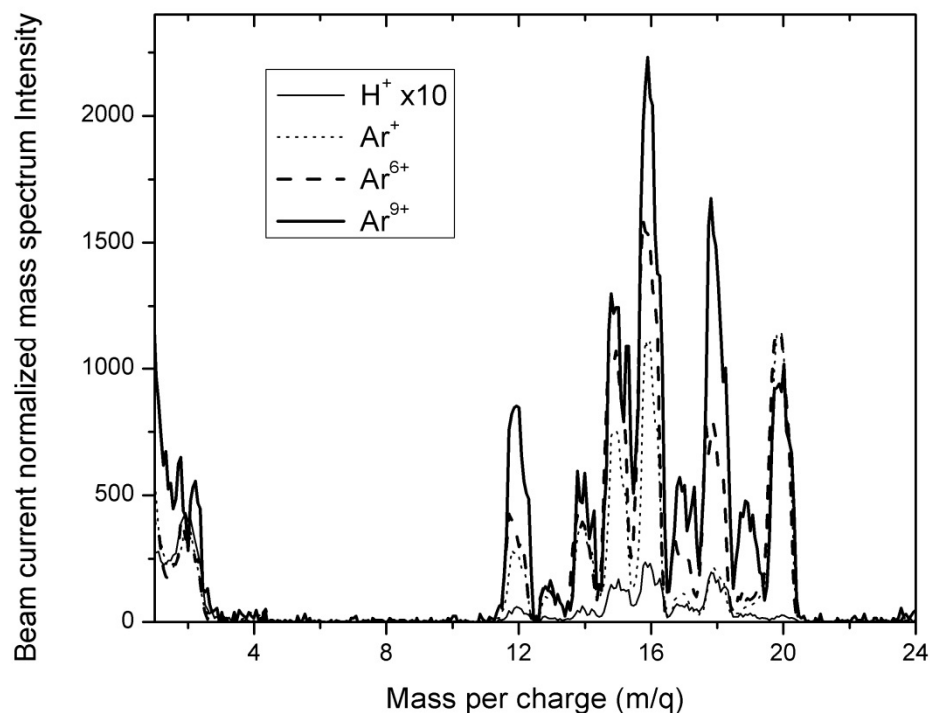
Mass distribution of sputtered species and beam species reemission in the range 2 – 24 amu, normalized to the respective beam particle currents for protons, Ar^+, Ar^{6+}, and Ar^{9+} incident on room temperature lunar regolith simulant at 375 eV/amu. The mass-20 peaks are due to the incident Ar beams, and their similar peak heights support the beam current normalization used.

[From Meyer et al. (2011).]

Potential Sputtering: Charge dependence

Proton yield from potential sputtering has been shown to depend very sensitively on the charge of the impacting ion:
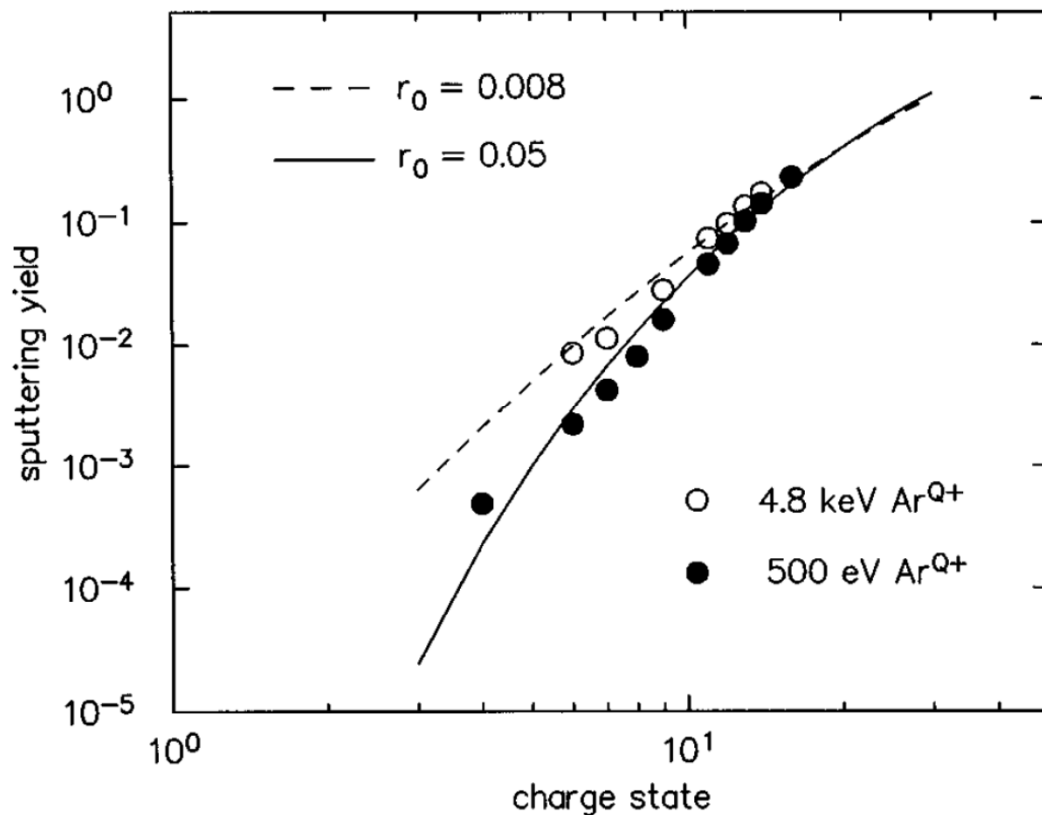
[From Burgdorfer and Yamazaki (1996).]
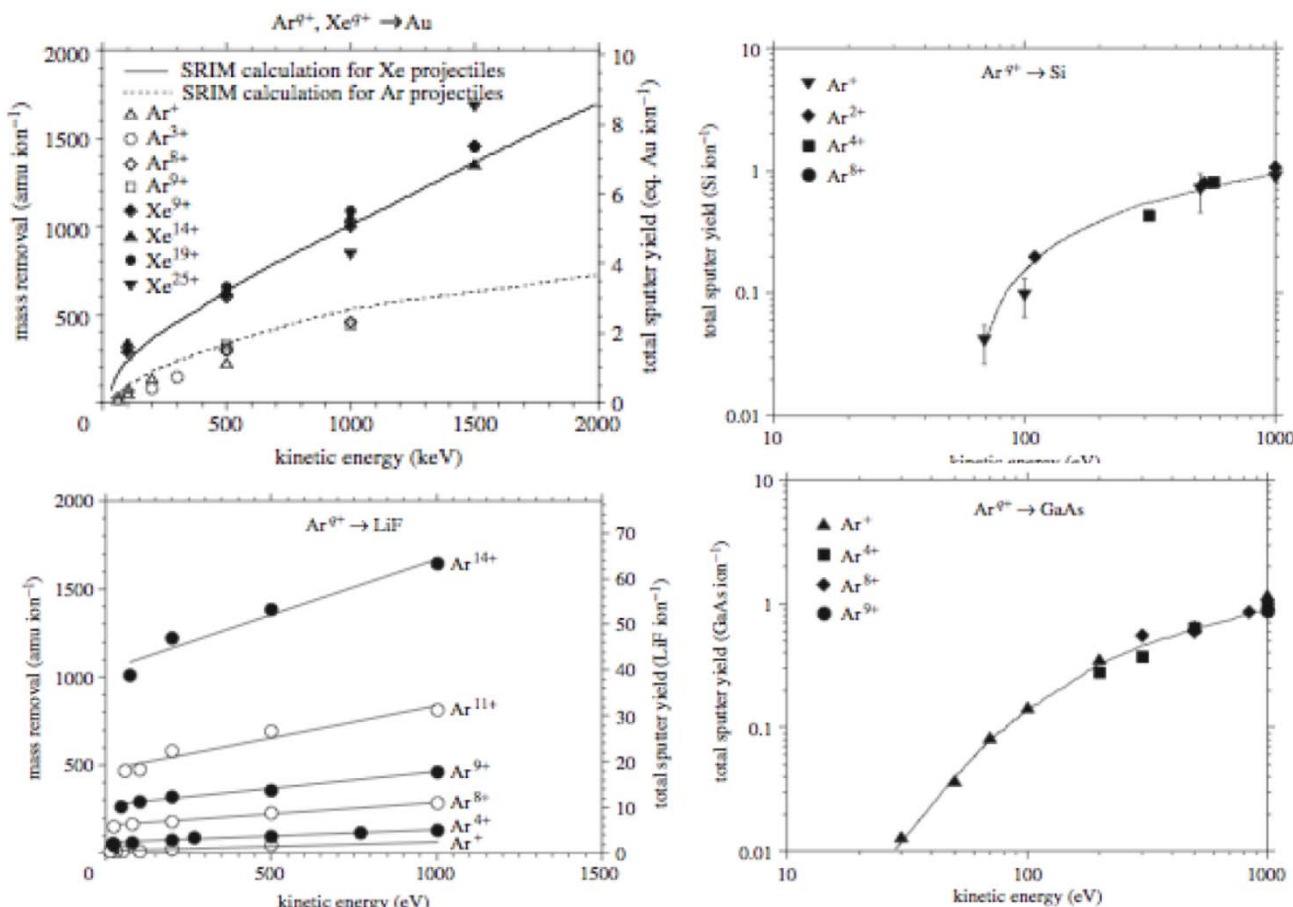
Potential Sputtering: Dose dependence

Potential-sputtering yield from some surfaces has also been shown to depend on dose:

[From Hayderer et al. (2001).]
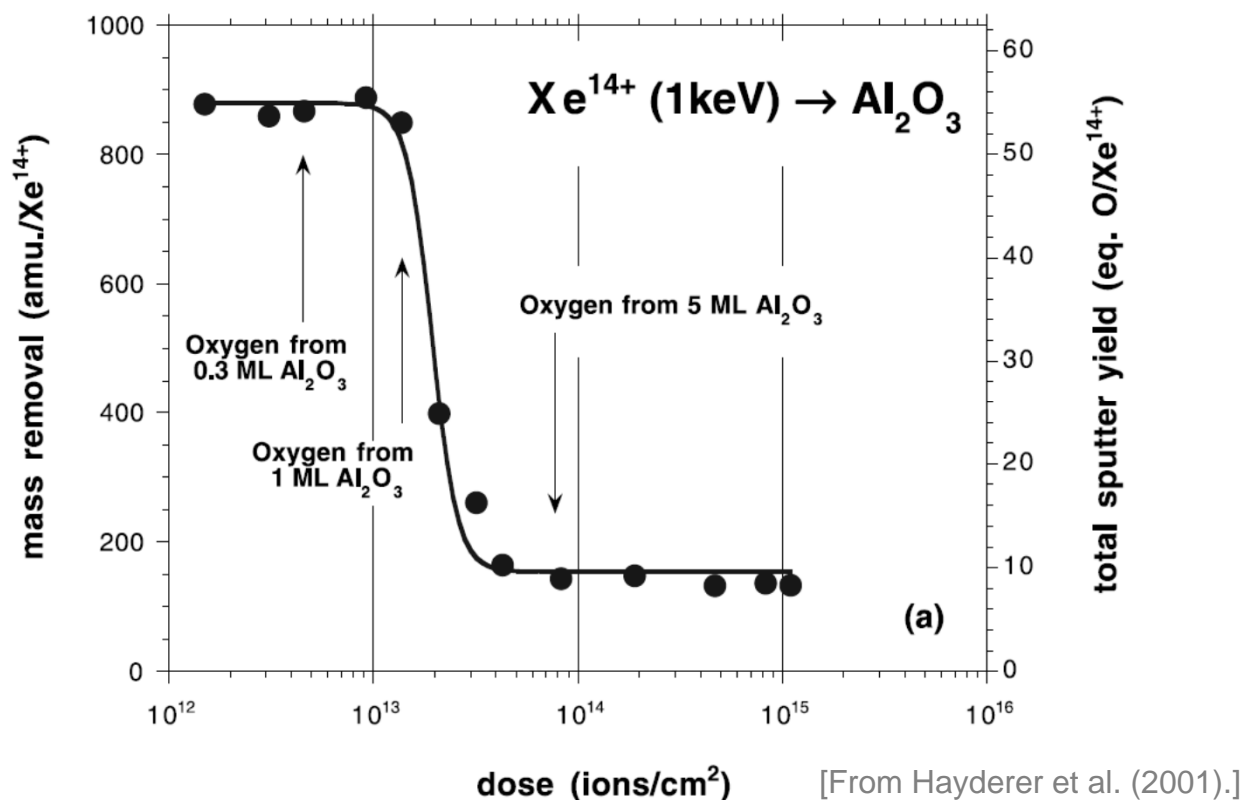
This effect was not seen in the recent ORNL data!

Potential Sputtering: Surface dependence

Potential-sputtering yield is seen to vary with the conductivity of the impacted surface:

[From Aumayr and Winter (2004).]

Soil Texture: A complex dynamic of lunar soil and micro-meteorite flux
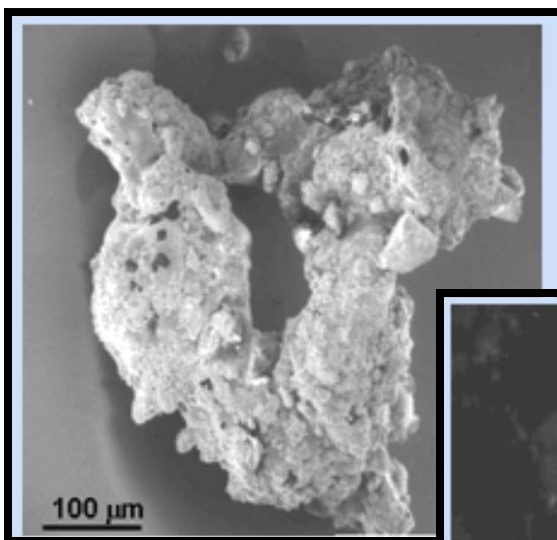
Agglutination: aggregation of soil particles by impact-produced glass **vs.**
Comminution: crushing and fracturing resulting from these impacts

Vaporized material is injected into the soil to form a layer or **rim**
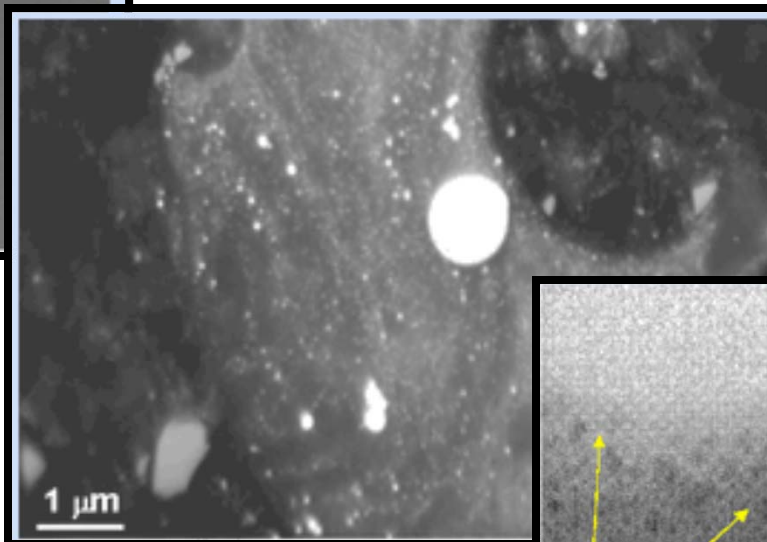
Rim with nano-phase iron
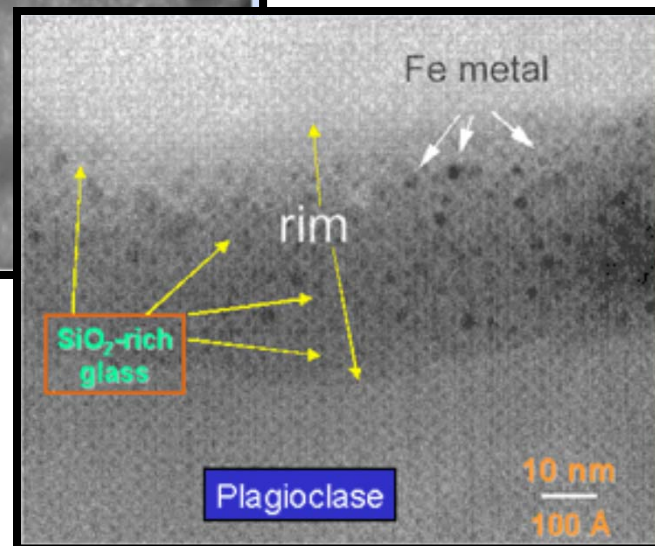
[From Keller et al. (1999).]

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Lunar samples and lunar simulants

Different simulants were designed to mimic different properties - depending on what is being studied. For example, JSC 1A *for geochem. and* JSC-2+MLS *for radiation protection.* Real samples are are very limited.

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Materials: Kinetic vs. Potential Sputtering

Sputtering in a Non-Equilibrium Model

Implications of Enhanced Sputtering

Future Directions

Sputtering in a non-equilibrium model

Model the solar-wind sputtering induced changes in the elemental abundances of a KREEP soil exposed to solar wind ions (p thru Fe) as a function of time [cf. Starukhina (2003)]:

$$\frac{dC_i}{dt} = \tau^{-1}\left(-C_i\sum_j y_{ij}f_j + C_i^b\sum_{k,j} C_k y_{kj}f_j\right)$$

C_i : abundance of element i in KREEP surface

C_i^b : abundance of element i in KREEP bulk

y_{ij} : yield of element i by solar-wind ion j

f_j : fraction of solar-wind ion j in solar-wind flux

$\tau = h\rho/J \sim 10^9$ s; for:
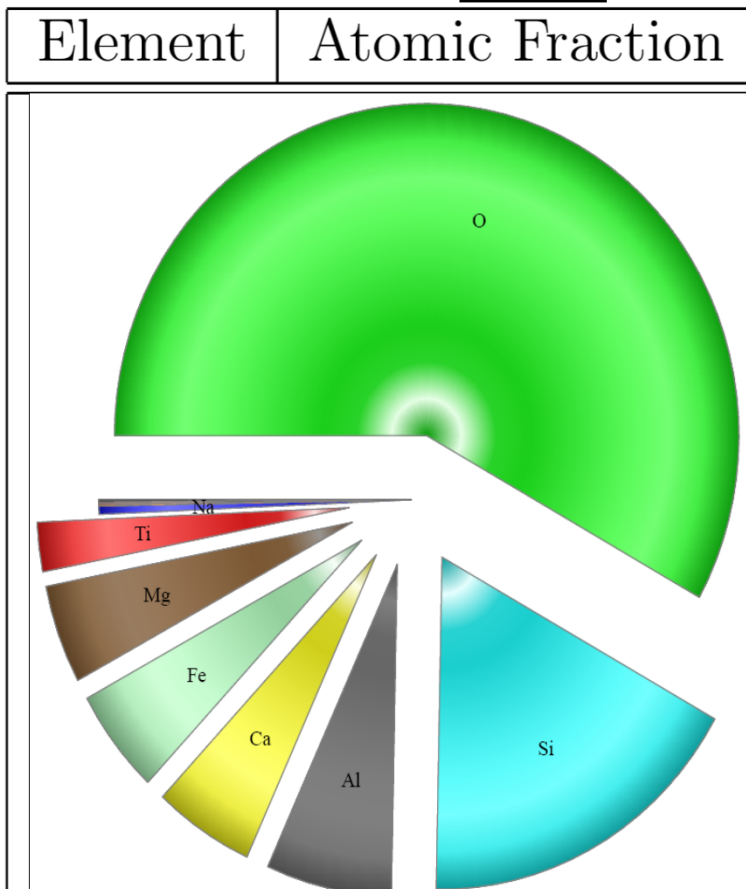
h penetration depth in KREEP $\sim 100\mathring{A}$

ρ number density of KREEP $\sim 10^{24}$ cm^{-3}

J solar-wind flux $\sim 10^8$ cm^{-2}

Sputtering in a non-equilibrium model

KREEP Surface: C_i^b

y_{ij}

Element	Atomic Fraction

$$y_{ij}^{total} = y_{ij}^{kinetic} + y_{ij}^{potential}$$

$$y_{ij}^{potential} = \alpha_i \left(\mathcal{E}_j\right)^{\beta_i} ;$$
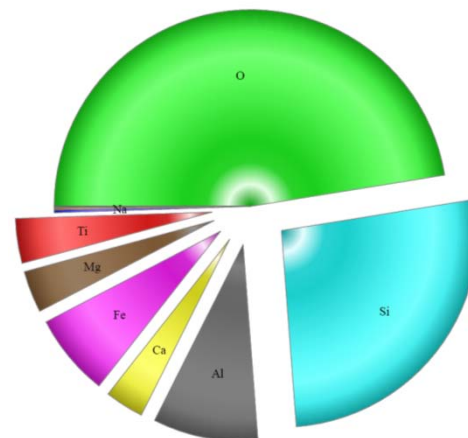
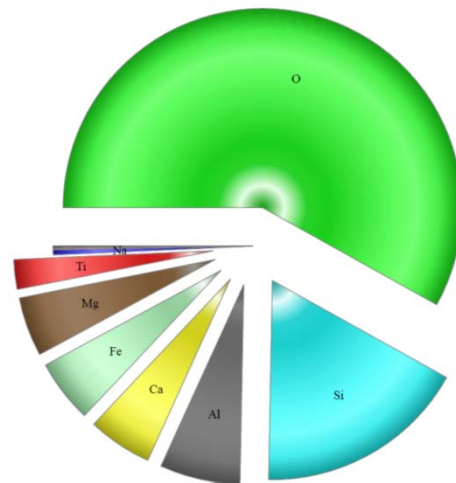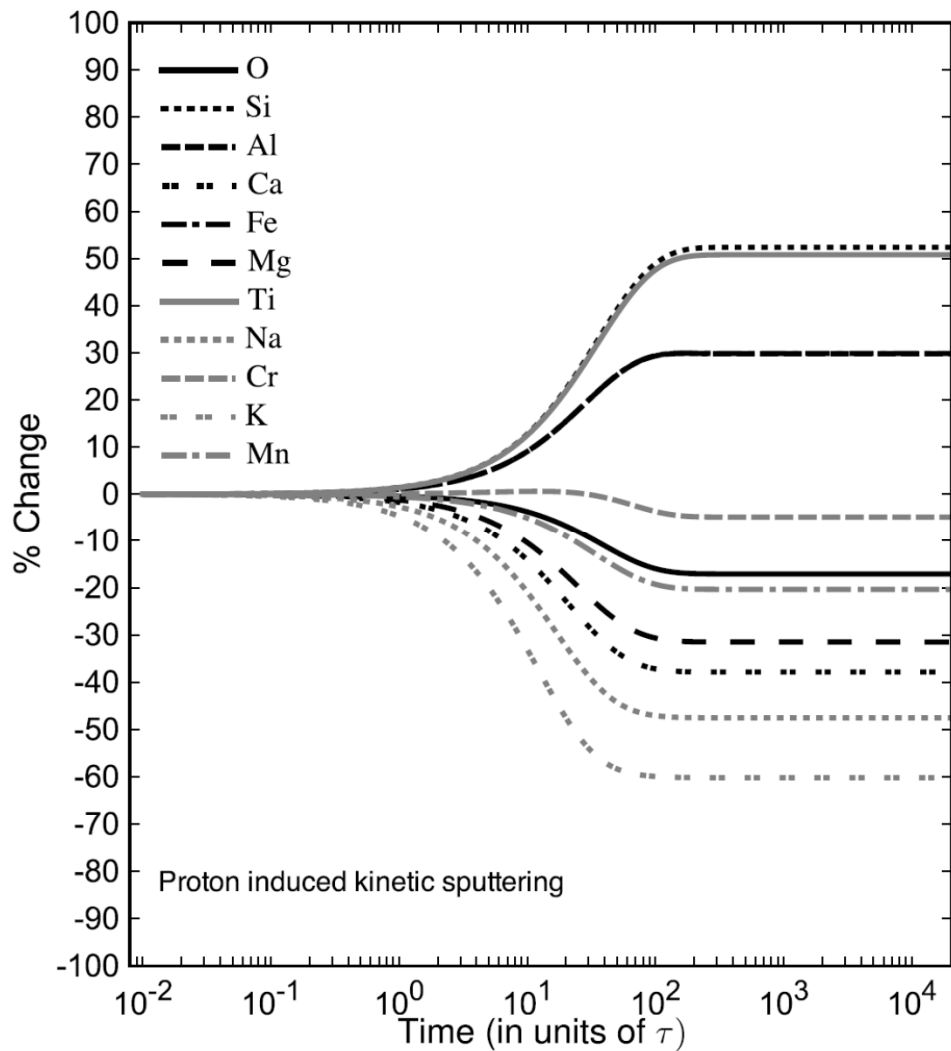$$\alpha_i \text{ and } \beta_i \quad \{\text{from ORNL data}\}$$

$$\mathcal{E}_j = \sum_{n>1} E_n$$

First ionization potential is subtracted so that singly-charged ions and protons have no potential-sputtering contribution

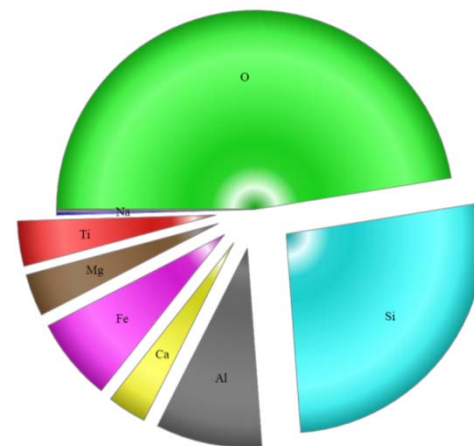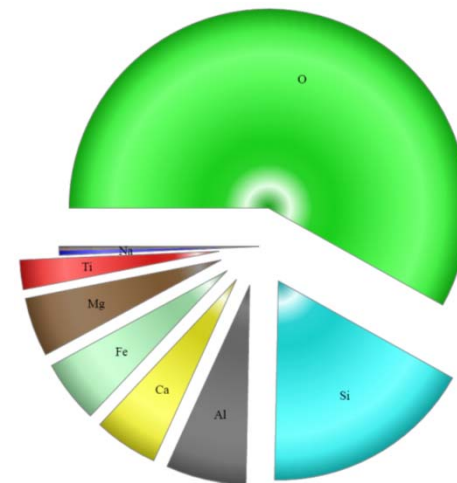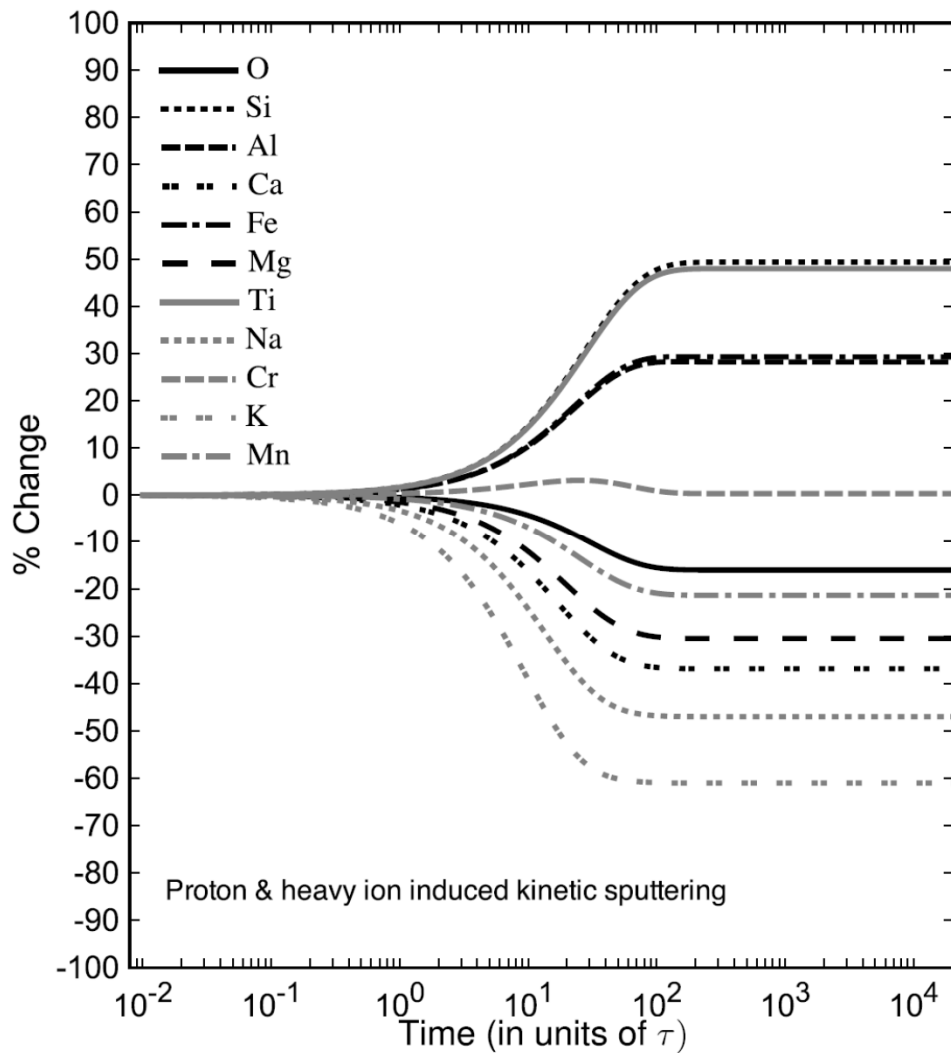*All kinetic-sputtering contributions are calculated using SRIM/TRIM*

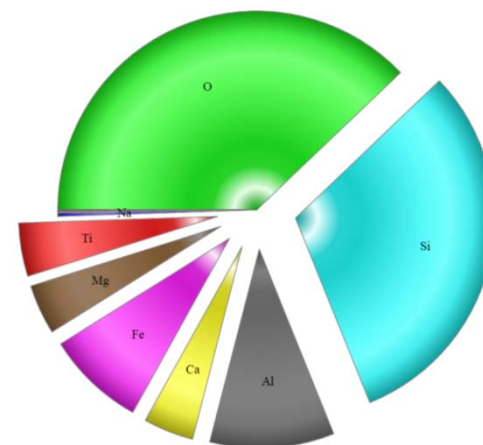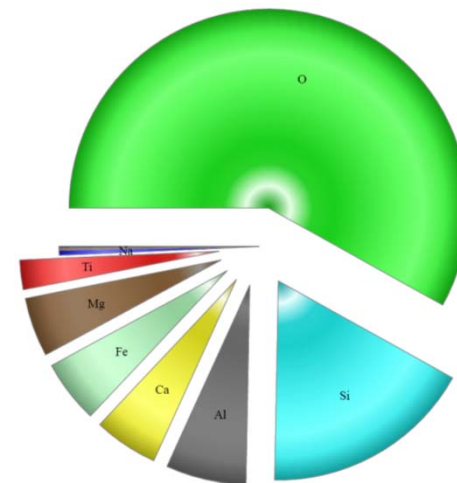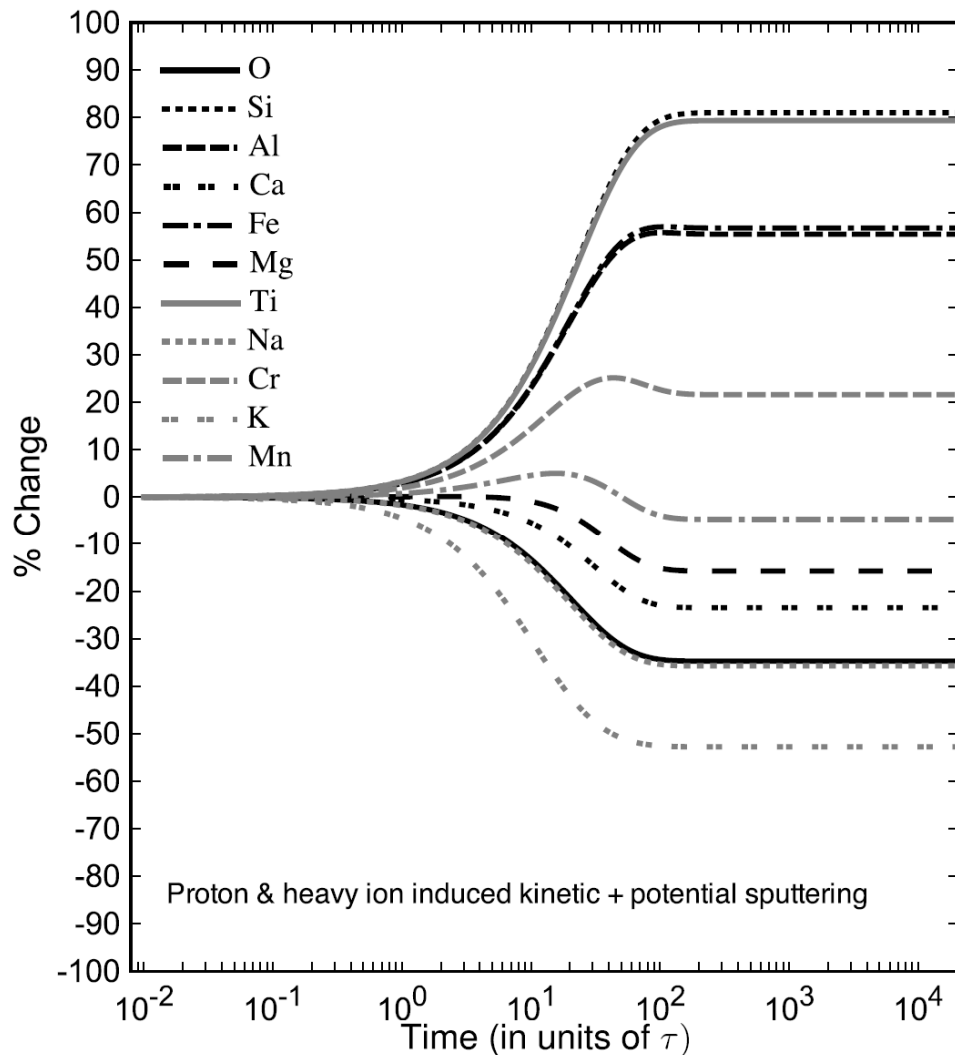# KREEP composition as a function of time: Proton-induced sputtering only

KREEP composition as a function of time:
Proton & heavy-ion kinetic sputtering

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KREEP composition as a function of time:
Proton & heavy-ion kinetic+potential sputtering

# KREEP composition as a function of time: Effects of combined sputtering

From the behavior of the total sputter yield as a function of time,

$$\sum_{k,j} C_k y_{kj} f_j$$

we can infer:
- Heavy ions contribute about 26% of the proton-induced effect without potential sputtering, but 52% when included
- Timescale of the overall sputtering process is largely set by the heavy-ion component of the solar wind
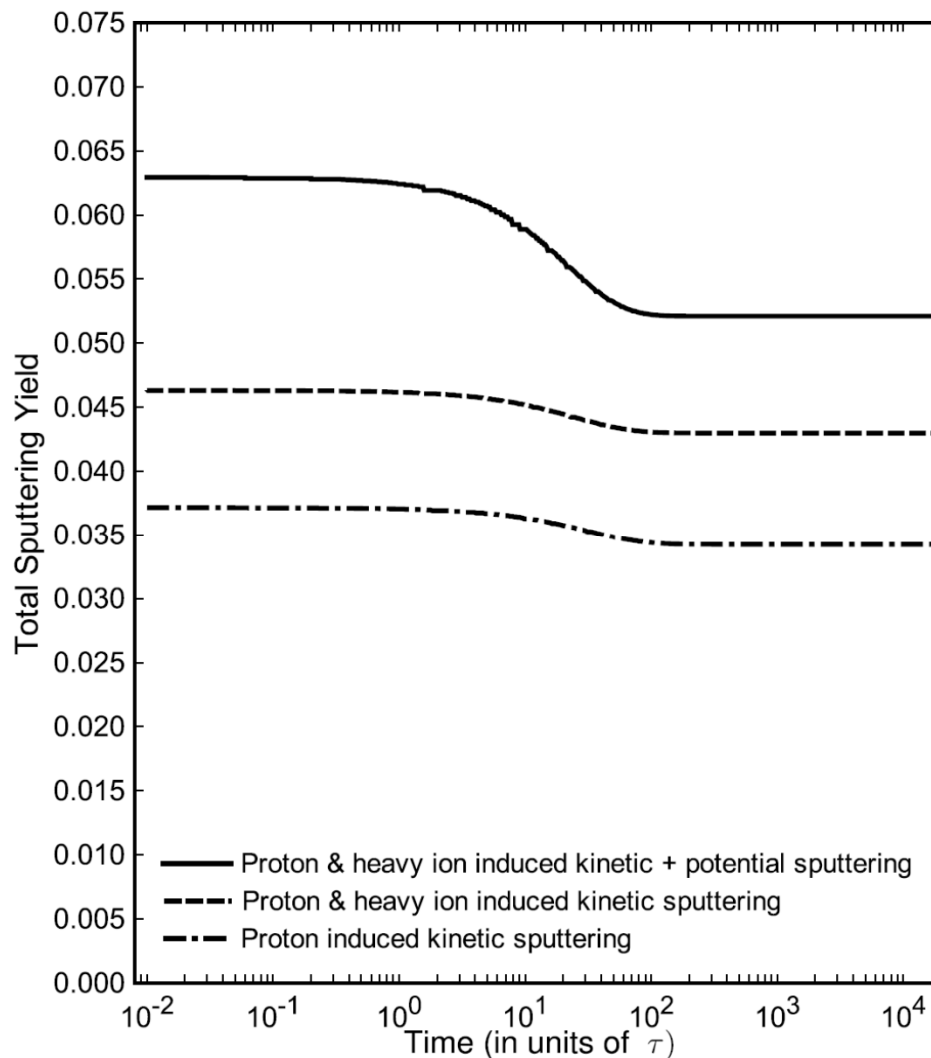
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Some possible implications of enhanced sputtering

To the composition of the lunar regolith:
Enhanced yield leads to efficient mixing. This can effect estimates of some interesting elements!

To the composition of the lunar exosphere:
Solar wind is not seen as a major contributor here. Enhanced sputtering is not likely to change this.

To estimates of hydrogen and water deposits on the moon:
Uncertainty in the solar-wind role? Earth's magneto-tail?

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Future Directions

Measurement of relevant yields at ONRL's MIRF
Simulants vs. actual samples

Theoretical estimates of unmeasured yields
Difficult from first principles; but will be needed

Theoretical modeling based on new yields
Role of the solar-wind, temporal scale of process

Without a theory the facts are silent.   *-A.J. Hayek*