Contributions of solar-wind induced potential sputtering to the lunar surface erosion rate and it's exosphere

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ABSTRACT

Sputtering of lunar regolith by solar-wind protons and heavy ions with kinetic energies of about 1 keV/amu is an important erosive process that affects the lunar surface and exosphere. It plays an important role in changing the chemical composition and thickness of the surface layer, and in introducing material into the exosphere. Kinetic sputtering is well modeled and understood, but understanding of mechanisms of potential sputtering has lagged behind. In this study we differentiate the contributions of potential sputtering from the standard (kinetic) sputtering in changing the chemical composition and erosion rate of the lunar surface. Also we study the contribution of potential sputtering in developing the lunar exosphere. Our results show that potential sputtering enhances the total characteristic sputtering erosion rate by about 44%, and reduces sputtering time scales by the same amount. Potential sputtering also introduces more material into the lunar exosphere.

1. Introduction

Space weathering is a term used to describe the interaction of the surface material, also known as regolith with space energetic particles and radiation. Surfaces of celestial bodies that lack atmospheres and global magnetic fields, like our Moon, are exposed to many space weathering factors. Examples include (1) micrometeorite bombardment, which results in melting and vaporizing of the regolith [1], (2) Galactic Cosmic rays (GCRs), which result in chemical changes in the regolith through nuclear reactions [2], and (3) Solar-Wind Particles (protons and heavy ions), which results in particles ejection [1]. With varied energy ranges and penetration depths, GCRs and solar-wind particles interact with the lunar regolith through many processes. The most important process is the atomic sputtering by solar-wind, which takes place at the top layers of the regolith and can change the chemical composition (stoichiometry), roughness, and thickness of the surface as well as yield material for the lunar atmosphere.

Sputtering is the removal of near-surface species (atoms, ions, or molecules) from a target by the impact of high energy particles (atoms or ions). When an energetic particle imparts a target atom energy greater than the target's surface binding energy, the atom is likely to be sputtered. The sputtering efficiency of a surface is characterized by the "sputtering yield", which is defined as the mean number of the sputtered target atoms per incident ion.

Ions that are singly charged and have kinetic energies in the keV range (like solar-wind protons) will mainly interact with the target atoms via binary collisions [3]. The kinetic energy and momentum of an incident particle is transferred to a target atom, causing radiation damage and ejection of atoms and/or ions from the target; this is known as "kinetic sputtering" (knock-on sputtering). The situation is completely different for multi-charged ions (like the solar-wind heavy ions), which are characterized by their high charge state and potential energy. While interacting with the surface, the multi-charged ions liberate and deposit this potential energy within a very small area ($1 \, nm^2$) in a very short time (100 fs) [4]. This liberation and deposition always leads to nonlinear excitation processes, such as hollow atom formation or removal [5]. Ejection of target atoms by slow multi-charged ions impact is called potential sputtering. Multi-charged ion induced processes take place more effectively in insulators, because of the reduced electron mobility and fast electron removal from the target [6].

[7] studied the elemental changes of the lunar regolith due to kinetic and potential sputtering by solar-wind protons and heavy ions. In their work they used KREEP simulant to model the lunar regolith, which is a material composed of potassium, (K), rare Earth elements, (REE), and phosphorus, (P). They reported that potential sputtering has a significant effect on changing the chemical composition of the

regolith. To support their finding, we used in this study the JSC-1A AGGL simulant for lunar regolith and estimated the elemental changes of the regolith elements due to kinetic and potential sputtering. We have extended their study by estimating the surface erosion rate, characteristic time scale, and the density of elements provided by sputtering into the lunar exosphere.

In the following section we discuss solar-wind constituents and flux, and composition of the JSC-1A AGGL simulant. In Section 3 we use a non-equilibrium model for sputtering to calculate elemental changes in a target due to incident particles, and study the effect of kinetic and potential sputtering. The effects of geometrical and gravitational factors in the sputtering process are discussed in Section 4. In Section 5 we calculate the erosion rate and the characteristic sputtering time scale of the lunar surface. Finally in Section 6 we calculate the density of the sputtered atoms that will contribute in developing the lunar exosphere.

2. Solar-wind flux, the JSC-1A AGGL simulant, and the lunar exosphere

Typical solar-wind fluxes are of the order 10^8 ion/cm^{2}s, with energies in the range 350–1200 eV/amu. About 93% of the flux is protons, and the other 7% are light and heavy ions (He, O, C, Ne, N, Si, Mg, S, Fe, and Ar) (see Table 1), which are characterized by charge state and potential energy [8,9]. Actual lunar regolith material is composed of oxides in the form of soil grains surrounded by amorphous melt layers, called rims [10]. Kinetic and potential sputtering by solar-wind protons and heavy ions take place effectively in the lunar regolith material. The impact on lunar regolith by singly charged ions (e.g., protons) will result in kinetic sputtering, while the multi-charged ions (e.g., solar-wind light and heavy ions) will result in both kinetic and potential sputtering. The JSC-1A AGGL is a lunar regolith simulant developed by the company Orbitec.[1] This simulant is composed mostly of oxides of the elements given in Table 2. [11] studied the JSC-1A AGGL elemental chemical composition experimentally using X-ray photoelectron spectroscopy (XPS). The elemental composition of JSC-1A AGGL is an averaged between cores and rims elements.

The lunar exosphere composition has been studied and identified by different instruments [12–20]. The sources of elements in the lunar exosphere are mainly atomic sputtering by solar-winds, vaporization by micrometeorites impact and photon stimulated desorption [21,22]. In this work we focus on the sputtering process, and we estimate the contribution of potential sputtering as an additional source.

3. Modeling of the regolith elemental changes

The two erosive processes, solar-wind induced sputtering and micro-meteoritic impacts, can be coupled through an important characteristic property; the time scale. The erosion process time scale due to micro-meteoritic impacts is believed to be on the order of thousands of years [23,24], while for the solar-wind it is expected to be shorter [23,7]. [23] proposed a non-equilibrium model to study elemental changes in a target, which is the same model used by [7] to study the elemental changes in the lunar regolith KREEP. The elemental change of element i in a multi-element target is given by,

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

where C_i is the abundance of element i in the target, C_i^b is the fractional abundance of element i in the target 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, and τ is a constant that has the dimension of time defined as:

[1] www.orbitec.com.

Table 1
Charge state[a], and fraction[b] in the solar-wind flux.

Ion	Charge State	Fraction
H	1$^+$	0.93
He	2$^+$	0.04
O	6$^+$–8$^+$	7×10^{-4}
C	4$^+$–6$^+$	3×10^{-4}
Ne	7$^+$–9$^+$	3×10^{-4}
N	5$^+$–7$^+$	1×10^{-4}
Si	6$^+$–12$^+$	3×10^{-5}
Mg	7$^+$–10$^+$	3×10^{-5}
S	6$^+$–11$^+$	1.6×10^{-5}
Fe	7$^+$–14$^+$	8×10^{-6}
Ar	7$^+$–10$^+$	4×10^{-6}

[a] From [8]
[b] From [9]

Table 2
XPS analysis of JCS-1A AGGL sample surface composition.[c]

Element	% Atomic fraction
C[d]	2.3
O	55.6
Si	19.5
Al	8.4
Fe	1.4
Ca	4.3
Mg	3.9
Ti	0.4
Na	3.3
P	0.3
K	0.3
Cr	0.1
F	0.1

[c] From [11]
[d] The source of carbon in the JSC sample is a carbon tape used in the experiment [11].

$$\tau = \frac{h}{j \langle Y \rangle a^3} \tag{2}$$

where $j = 10^8$ cm^{-2} s^{-1} is the solar-wind flux, $\langle Y \rangle$ is the total sputtering yield (see Section 4), $a = 2.23 \times 10^{-8}$ cm is the average enter-atomic spacing, and $h = 300$ Å is the ion penetration depth.

To study the effect of potential sputtering, we begin by calculating the changes in the elemental abundance for JSC-1A AGGL. We assume that the dynamics of the sputtering process is only due to kinetic sputtering and ignore the effect of the potential sputtering. Applying Eq. (1) on JSC-1A AGGL elements, given in Table 1, we obtain a set of 13 coupled differential equations, with the initial condition $C_i(0) = C_i^b$. The equations are solved using the numerical method of lines [25]. The kinetic sputtering yields Y_{ij} are calculated using the simulation package SRIM (The Stopping and Range of Ions in Matter) [26], where the default values for the density, lattice, displacement, and surface binding energies of the target are used in the simulation. The energy of the solar-wind ions is set to 1 keV/amu at normal incident.

Fig. 1 shows the calculated changes in the elemental abundance of JSC-1A AGGL due to the solar-wind protons. These changes approach a steady state for times after 300 τ. Fig. 2 shows the calculated changes in the elemental abundance of JSC-1A AGGL due to the solar-wind protons and heavy ions. These changes approach a steady state for times after 200 τ. Steady-state compositional changes are summarized in Table 3, where the sign $+$ ($-$) means enhancement (reduction).

The expected compositional changes, shortened time scale, and overall enhancement in the sputtering yield (due to inclusion of heavy ions) are all consistent with the KREEP results of [7].

In light of the experimental data of [11,7] have shown that