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Modification of the lunar surface composition by micro-meteorite impact vaporization and sputtering

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Abstract

Over the past 4.5 billion years the Moon has been under constant bombardment by solar wind particles and micro-meteorites. These impactors liberate surface material into space, and, over time, result in a modification of the surface composition due to the species' different loss rates. Here we model the loss of the 7 major lunar surface elements over the past 4.5 billion years and show how the lunar surface composition changed over time.

1. Introduction

The prevailing Moon formation theory today is the giant impact event. In this hypothesis an impact of a Mars-sized body (named Theia) with the proto-Earth liberated material into Earth's orbit. This liberated material accreted more material over time and formed the Moon. In this scenario, the Moon's initial composition would have been equal to the composition of the bulk silicate Earth (BSE).

We track the evolution of the lunar regolith composition based on the relative species enrichment or depletion over time starting with the BSE composition.

2. Monte-Carlo Model

The Monte-Carlo code used herein was originally developed for studying Mercury's exosphere [1] and has since been upgraded to include many different planetary objects (planets, moons, comets, exoplanets, etc.). In the study presented herein, surface atoms are either sputtered from the lunar surface by solar wind ions or are released through micro-meteorite impact vaporization. For the solar wind particle flux and solar wind UV flux we implement three different conditions: (i) a slowly rotating Sun, (ii) medium rotation speed Sun, and (iii) a fast rotating Sun [2]. For the micro-meteorite flux we scale today's measured micro-meteorite flux with the relative impact rate of a Late Heavy Bombardment model with a half-life time of 100 Myr. Time steps vary between 25 Myr (at the beginning) and 560 Myr (today).

The only required inputs for this study are the original surface composition, the solar wind particle flux, the solar UV flux, and the micro-meteorite impact rate. For the surface composition we implement at t=0 (at the beginning) the BSE composition according to [3]. We run the simulations for O, Mg, Si, Fe, Al, Ca, and K, which together make up more than 99% of today's lunar soil [4]. After each time step we compute for each species the fraction lost from the lunar regolith, and update the current surface composition accordingly before simulating the next time step.

Table 1: Bulk silicate Earth (BSE) and lunar regolith compositions according to [3] and [4].

	O	Mg	Si	Fe	Al	Ca	K
BSE	0.583	0.184	0.154	0.041	0.019	0.019	2.7e-4
Moon	0.605	0.055	0.172	0.059	0.056	0.044	6.0e-4

3. Results

Figures 1 and 2 show that micro-meteorite impact vaporization is much more efficient than sputtering in stripping off lunar surface material in the early Solar System. In addition, whereas sputtering only affects the topmost 2-3 mono-layers on the surface, micro-meteorite impact vaporization affects the top few meters of regolith. Out of these two processes, micro-meteorite impact vaporization is thus the more important process when considering global regolith modification.

Depending on a species' mass and ionization efficiency, different species escape the Moon's gratvitational attraction (esc) and ionize (ion) to a different degree. Figures 3 and 4 show the fates of two quite different species in that respect: Fe has quite a high mass but low ionization efficiency, wheras Al has a much smaller mass but a much higher ionization efficiency.

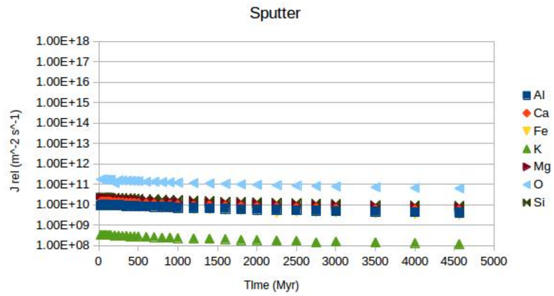

Figure 1: Flux of atoms released through sputtering.

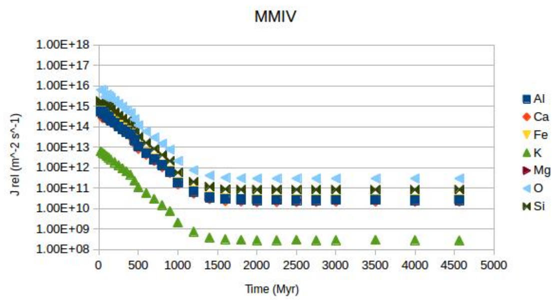

Figure 2: Flux of atoms released through micro-meteorite impact vaporization.

Accordingly, the return (ret) flux of Fe to the surface is much higher than the return flux of Al. Accordingly, the Fe / Al ratio increases steadily over time.

In addition, a clear correlation between the decrease in UV flux and in number of atoms being ionized is evident in both Figures. Finally, due to their smaller mass, the amount of Al atoms escaping would be expected to be higher than the amount of escaping Fe atoms, but with ionization being so efficient in the case of Al this trend cannot be observed.

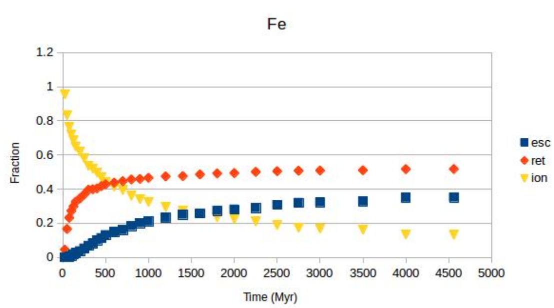

Figure 3: Fate of the released Fe atoms.

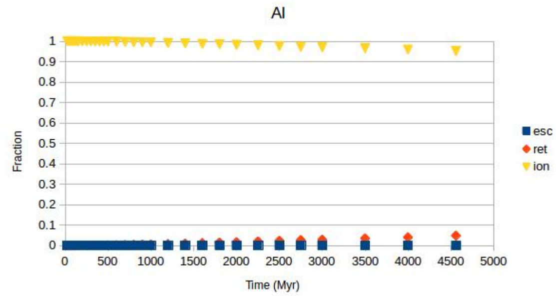

Figure 4: Fate of the released Al atoms.

4. Summary and Conclusions

Our studies showed that sputtering is not only less efficient than micro-meteorite impact vaporization in fractioning the lunar surface during early Solar System times, it is also only effective on the top 1–3 monolayers. Micro-meteorite impact vaporization, on the other hand, is not only efficient enough to produce a visible fractionation over time, but is also effective on a larger scale (a few meters). When modelling lunar surface composition modification over the past 4.5 Gyrs, one thus has to include micro-meteorite impact vaporization in the model.

References

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