THE IMPORTANCE OF SOLAR WIND IN THE PRODUCTION OF "SPACE WEATHERING" FEATURES ON THE MOON AND ON ASTEROIDS.

M. S. Kareev[1], D. W. G. Sears[1], P. H. Benoit[1], B. G. Atabaev[2], [1]Center for Space and Planetary Sciences and Chemistry and Biochemistry Department, University of Arkansas, AR 72701, USA. mkareev@uark.edu , [2]Arifov Institute of Electronics, Academy of Sciences of Uzbekistan, Tashkent 700143, Uzbekistan.

Introduction: "Space weathering" has been invoked to explain apparent mismatch between spectra of meteorites and asteroids. Space weathering is the alteration of the surface of small bodies with time, and it results in changes of the depth of absorption bands in the optical spectra. This process potentially masks the composition of the asteroid that can be determined by reflectance spectroscopy [1]. Various mechanisms have been suggested for space weathering, that appears as the reddening and darkening of the spectra, the most popular involving the formation of iron nanoparticles ($npFe^0$) by the evaporation of minerals during micrometeorite impact and condensation of iron. Here, we discuss the role of radiation, especially the solar wind, on this proposed space weathering process.

In the case of lunar regolith samples, mineral grains are observed with rims enriched in $npFe^0$. These inclusion-rich rims show either a random distribution of iron nanoparticles throughout the thickness of the rim or they show a distinct layering of iron nanoparticles [2]. One of the intriguing results of previous work was the identification of multiple rims on the soil grains consisting of discrete layers that are microstructurally and chemically distinct from one another. This is probably the best evidence that several processes are involved in rim formation. The presence of $npFe^0$ in the rims of host soil grains that are Fe-free plagioclase demonstrates that $npFe^0$ has been added to the surface either by condensation of impact-generated vapors or by the deposition of atoms sputtered from nearby grains [3-7]. In an effort to reproduce $npFe^0$, their sizes, shapes and layered structures, we have used conventional thin-film vapor-deposition techniques to produce condensates and afterwards exposing the samples to radiation.

Experimental: A thick (~100nm) amorphous SiO_x film was used as substrate. Gold films were deposited on the substrate at ultrahigh vacuum conditions, using a calibrated evaporator. The effective thickness of vapor-deposited Au thin film was approximately 4 nm. After deposition, the Au/SiO_x films were irradiated with argon ions (E=1keV, current density $j=10^{-6} A\times cm^{-2}$, exposure time t=1800s) and with electrons (E=1keV, t=900s). After irradiation, the samples were covered by an ultra thin SiO_x protective layer, exfoliated, and imaged using a transmission electron microscope (TEM) JEOL JEM-100C.

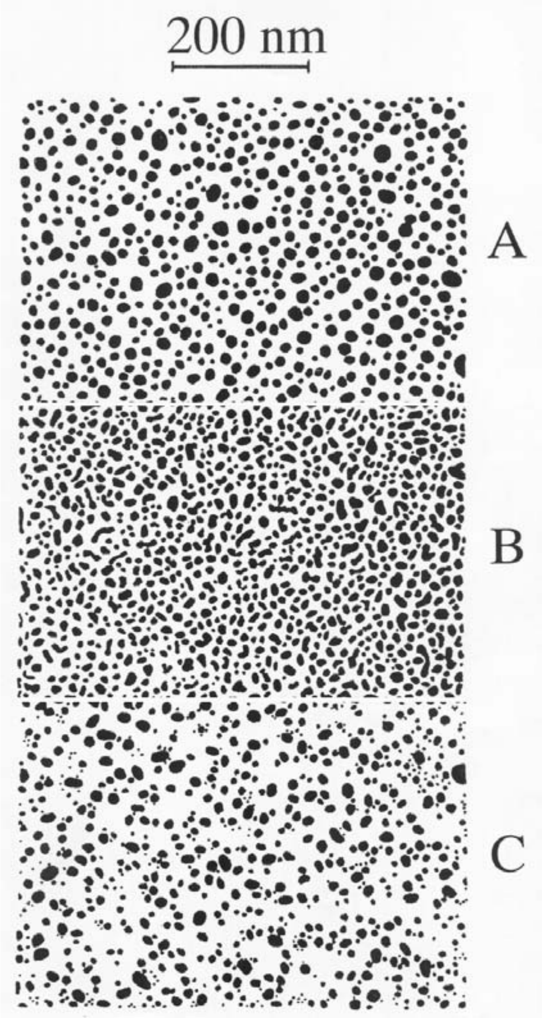

Fig.1. TEM views of gold Au island film deposited onto SiO_x. (A) - corresponds to electron exposure; (B) - initial (unexposed) film; (C) - shows the effect of ion irradiation.

Three TEM views of gold islands deposited onto SiO_x are presented on Fig.1 in which the denser Au appears dark. An unexposed, initial thin film sample is shown in the middle image (B), whereas the upper (A) and lower (C) images are of films exposed to electrons and ions, respectively. From the comparison of all three images it is clearly seen that coalescence occurs during irradiation, with decreasing island density and the increasing size of islands. The islands become more rounded (equilibrium shaped) after irradiation via autocoalescence.

Results and discussion: Pronounced differences in the products of electron and ion irradiation were observed in this simulation. Electron irradiation produces larger islands that are fairly homogeneous in size. Ion irradiation does the same, but with production of an "atoll" structure, with rings of smaller islands surrounding large islands. The islands remain crystalline throughout the process [8,9]. Ion irradiation should generate some sputtering of islands, with possible *re-deposition of sputtered atoms on preferred sites* and *secondary nucleation* leading to some islands growing while others are consumed. However, electron irradiation should not have such pronounced sputtering effects. The differences in the results of electron and ion irradiation can be explained in terms of the migrational coalescence model in an ensemble of interacting islands [9]. The random migration of the islands occurs as a result of a fluctuating external force, which varies unpredictably in both direction and magnitude, and is a result of the electrostatic interaction between the charged islands on charged substrate. It is necessary to distinguish between the action of the whole system on a given island and that due to the local action of the nearest neighbours to the island; the first action is a slowly varying function of position and time, while the second is a rapidly varying function. The influence of the nearest surroundings on the given island will vary with time owing to the change in the number of islands and fluctuations in the distribution of the nearest islands and their charges.

The features of ion beam exposure in comparison with an electron beam can be explained as follows [9,10]:

(1) Inadequate charging of Au/SiO_x system under ion irradiation. In the ensemble of identically charged islands, even after ion exposure, the small islands have deficiency of charging to get over the repulsed forces;

(2) Weak effect of charging onto self-diffusion in consequence of decreasing Laplace's pressure by repulsive action of captured charges inside the island;

(3) Trapping of islands by the point defects that were created by ion irradiation;

(4) Redeposition of sputtered atoms onto preferred sites that were formed by ion beam exposure, in consequence of which the smaller islands undergo preferential sputtering compared to larger ones.

Within this model, it is possible to calculate the Brownian surface diffusivity (D_b) of islands. Based on our images and the duration of irradiation, we find that for the Au/SiO_x system under ion irradiation D_b is about~$10^{-16}cm^2 \times s^{-1}$, which is one order of magnitude higher than D_b under thermal annealing ($10^{-17}cm^2 \times s^{-1}$) and one order of magnitude lower than surface diffusivity D_b under electron irradiation of~$10^{-15}cm^2 \times s^{-1}$.

The total irradiation dose in our experiment was estimated to be about ~10^{18} electrons cm^{-2} for electron irradiation and ~10^{17} ions cm^{-2} for ions. This approximates the doses of ~10^{19} ion cm^{-2} for H^+ and ~10^{18} ion cm^{-2} for He^{++} estimated for surface residence times of 5000-150,000 years for lunar regolith grains (1-50 μm in diameter) [11].

A final issue is whether all the $npFe^0$ produced in space weathering is produced by impact processes, as suggested by the experiments of *Sasaki et al.* [12] and subsequently subjected to migrational coalescence of vapor- and sputter-deposited Fe islands by irradiation, or whether the $npFe^0$ is also a immediate product of irradiation created on mineral surfaces. It was noted [13] that the formation of islands of metal on the surface of ionic crystals occurs by migrational coalescence in an ensemble of identically charged defects/islands of colloid metal under the action of irradiation (via stimulated desorption and capturing of electrons). According to the surface defect formation mechanism [13], irradiation ejects oxygen atoms preferentially, producing anionic vacancies (v_a^+), then, gradually, various types of defects including F-...F_n-centers and, finally, the stabilization of small islands of colloidal metal which can transform into negatively charged aggregates whose structure is different from the structure characteristic of bulk metal (up to R>10nm).

It is thus possible that space weathering is significantly, perhaps largely, governed by irradiation by solar wind and (to a much lesser degree) galactic cosmic rays, rather than micrometeorite bombardment. Meteorite and micrometeorite impacts are still important as they expose new mineral grains and bury previously exposed grains, and redistribute grains on the surface, but it is possible that their role is limited, except for the largest impactors which can produce large volumes of melt and vapor.

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