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Solar wind-induced space weathering on asteroid Itokawa

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Abstract

A lesson learned from space weathering studies of Hayabusa-returned regolith particles is that laboratory experiments and expectations are hard to transfer to nature. Time, temperature and small body-dynamics are important factors to consider.

1. Introduction

Orbital perturbations of near-Earth asteroids (NEAs) occur on time scales of several hundreds to thousands of years. Asteroid 25143 Itokawa sampled by JAXA's Hayabusa spacecraft is an Apollo-type NEA with a chaotic orbital evolution [1]. A (partial) record of collisions, tidal strain, changes of spin, and thermal cycling connected to this evolution is potentially preserved in the regolith samples recovered from such bodies, which offer insight beyond remote sensing and numerical modeling.

Space weathering and erosion on atmosphere-less, rocky asteroids are complex processes involving multiple mechanisms that act on different temporal and spatial scales. 'Space weathering' *sensu strictu* as defined by [2] can be understood as the sum of surface modifications that change the optical spectral of individual regolith particles on relatively short time scales (~10^2-10^3 years).

The irradiation of directly exposed mineral surfaces by ions of the solar wind (~1 keV/nucleon, mostly H and He) has been recognized as one important mechanism of space weathering on asteroids [3]. The stopping of energetic ions within dielectric solids leads to structural damage via knocking of atoms from their regular, ordered crystal lattice sites into disordered, interstitial positions. Based on laboratory experiments with silicate minerals, this process should start with the disordering of cations while the anionic sublattice (i.e., SiO_4 tetrahedra) maintains structural coherency for longer time, resulting in partially amorphous rims with preserved crystallographic orientations of crystalline remnants. On the contrary to laboratory experiments and Monte-Carlo simulations predicting rapid amorphization in <10^3 years, the study of Hayabusa-returned samples has shown that ion-induced damage develops at much slower rates [4]. In the case of olivine significant amorphization does not occur even on time scales of ~10^5 years. Instead, olivine develops polycrystalline rims with very little, if any, amorphous material between crystallographically rotated, nanocrystalline olivine domains [5].

2. Samples and Methods

Since 2013 we have studied multiple Hayabusa-returned regolith particles by focused ion beam (FIB) sectioning and analytical transmission electron microscopy (TEM), including the largest particle recovered (RA-QD02-0136, ~310 µm). The sample suite includes all the principal minerals of the LL-chondritic assemblage (Table 1), in order to better understand the behavior of all relevant phases.

3. Results

Seven out of eight particles studied by TEM show rim structures on mineral surfaces that indicate exposure to the solar wind.

Table 1: Hayabusa particles studied at FSU Jena.

Sample	Minerals
RB-QD04-0042	Ol, (Di)
RA-QD02-0115	Ol, Tro, Ap, Mer, Met, (Hx)
RA-QD02-0265	Di, (Ol)
RA-QD02-0136	Ol, Plag, (Di)
RA-QD02-0286	Ol, Tro
RA-QD02-0292	Ol, Tro, (OPx)
RA-QD02-0325	OPx, Tro
RB-QD04-0092	OPx, Ol

Ap: apatite, Di: diopside, Hx: haxonite, Mer: merrillite, Met: metal, Ol: olivine, OPx: orthopyroxene, Plag: plagioclase, Tro: troilite. ( ): present but not exposed.

The silicates olivine, orthopyroxene, and diopside show disordered, polycrystalline rims with crystallographic misorientations on the order of a few degrees. Only albitic plagioclase in RA-QD02-0136 acquired a fully amorphous rim without any evidence of polycrystallinity. The phosphate merrillite developed a marginally discernible rim, while Cl-rich apatite did not develop TEM-visible radiation damage. Both minerals were exposed with olivine which developed a ~35 nm wide polycrystalline rim.

Rim widths range from ~25 to ~110 nm. First signs of vesiculation or blistering due to segregation of implanted gases appear within the polycrystalline rims of olivine and orthopyroxene at rim thicknesses of 50-65 nm in the form of thin, crack-like structures parallel to the original surface (Fig. 1). Only the thickest rim observed (~110 nm in orthopyroxene of RA-QD02-0325) shows well-developed vesicles and a top-most layer with significant amorphous material and nanoparticulate metallic iron ($npFe^0$, ~5 nm).

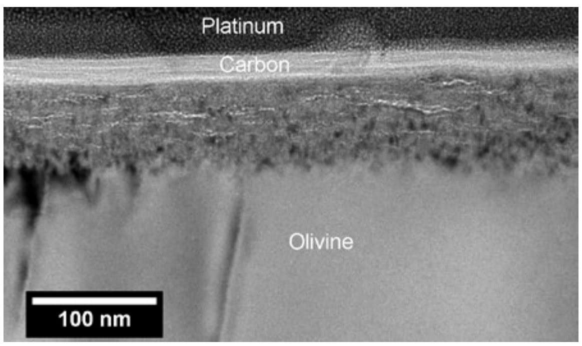

Figure 1: TEM image of crack-like structures in the polycrystalline damage layer of olivine suggesting incipient vesicle/blister formation (RA-QD02-0292).

Rims developed differently on different parts of the particles, indicating that surface were shadowed from the solar wind for some time and that regolith particles experienced movement on the time scales of rim formation. Vapor-deposited coatings are present but usually very thin (few nm).

4. Discussion and Conclusions

The development of polycrystalline rims in nature as opposed to amorphous ones expected from experiments suggest that the ferromagnesian silicates undergo thermally induced recovery of ionization damage while still being irradiated by the solar wind (i.e., thermal activation moves interstitial atoms back to their positions within the preserved anionic sublattice [5]). Nonetheless, this process appears to produce stress - possibly due to implanted gases - which leads to nanoscale subgrain rotation and eventual formation of vesicles. Due to structural aspects plagioclase and phosphates show contrastingly low and high annealing rates, which leads to enhanced and hindered radiation damage, respectively. Plagioclase seems to be particularly vulnerable due to its relatively open framework structure, which may hinder thermal recovery of the original lattice. Besides the realization that irradiation rates are more relevant than doses [4, 5] the surface temperature of asteroids certainly has an important influence on the development of solar wind-induced space weathering.

Acknowledgements

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