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Investigating the Response of Sulfides and Fe- Oxides Under Space Weathering Conditions Through the Analysis of Returned and Experimental Samples

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Space weathering is the progressive spectral, microstructural, and chemical alteration of grains on the surfaces of airless bodies caused by micrometeoroid impacts and solar wind irradiation [1]. Space weathering results in the development of multiple microstructural and chemical characteristics for exposed mineral grains on planetary surfaces, including vesiculation, amorphization, ion implantation, comminution, melt and vapor deposits, and Fe-bearing nanoparticles. Specifically, the presence of Fe nanoparticles alters the optical properties of airless bodies by causing reddening (increasing reflectance with increasing wavelength) and/or darkening (lower reflectance) [2], making it difficult to properly interpret regolith mineralogy from remote sensing datasets. Most space weathering studies of returned samples and laboratory analogs [3, 4] have focused on understanding the response of silicate minerals that are the predominant phases in lunar materials, which comprise the bulk of our returned sample collection. However, the effects of space weathering on other mineral phases that are present in other planetary bodies (e.g., S-type and C-type asteroids) are still understudied. Some of these unexplored minerals include sulfides (e.g., pentlandite $(Fe,Ni)_9S_8$, pyrrhotite $Fe_{(1-x)}S$) and Fe-oxides (e.g., magnetite Fe_3O_4) that are relevant accessory minerals in the samples returned from asteroid Itokawa by the Hayabusa mission [5] and from asteroid Ryugu by the Hayabusa2 mission [6]. Further, remote sensing observations identified the presence of magnetite on the surface of asteroid Bennu, indicating this mineral may be an important component of the returned samples from the OSIRIS-REx mission [7]. To explore the response of sulfides and Fe-oxides to micrometeoroid bombardment and solar wind irradiation, we performed coordinated analyses of a sulfide-bearing Itokawa regolith particles and simulated space weathering for magnetite powders in the laboratory.

First, we examined the effects of space weathering on grains from asteroid Itokawa. The regolith particle RC-MD01-0025 was embedded in epoxy and ultramicrotomed in sections with an approximate thickness of 50 nm using a Leica EM UC7. The electron transparent sections were analyzed using a 200 keV FEI Talos transmission electron microscope (TEM) equipped with a Super-X energy dispersive X-ray spectroscopy (EDS) detector at Purdue University and a 200 keV Hitachi HF5000 aberration corrected TEM at University of Arizona. High resolution transmission electron microscopy (HRTEM) analyses show a 5-10 nm nanocrystalline rim on the surface of a pentlandite grain. EDS analyses show that the rim is depleted in sulfur and nickel and enriched in iron and oxygen. The formation of the Ni and S depleted rim could result from different mechanisms, including diffusion of S and Ni in response to a thermal event caused by a micrometeoroid impact, as these elements have been shown to segregate to the surfaces of thermally treated minerals [8, 9] and subsequent sputtering of Ni and S, or only by the preferential sputtering or these elements from the pentlandite structure. We will conduct experimental efforts to simulate micrometeoroid impacts and solar wind irradiation on pentlandite to identify the cause driving the formation of the S and Ni depleted rim.

To better understand the effects of space weathering on Fe-oxides we simulated space weathering conditions on powdered magnetite pressed pellets. We performed pulsed-laser and ion irradiation experiments to simulate the conditions associated with high-velocity micrometeoroid impacts and solar wind irradiation, respectively. We conducted pulsed laser irradiation experiments using an Nd-YAG laser at 10^{-8} Torr with short pulses (6-8 ns). For our solar wind irradiation experiments, we performed 4 keV He^+ and 1 keV H^+ irradiation experiments using a flux of ~1 x 10^{13} ions/cm^2/s to total fluences equivalent to ~750 years on Bennu: 3.6×10^{16} He/cm^2 and 5.3 x10^{17} H/cm^2. For each analog sample we used a Thermo Scientific Helios G4 UX Dual Beam FIB secondary electron microscope (SEM) to prepare electron transparent samples to be analyzed using the FEI Talos TEM at Purdue.

SEM observations show the presence of melts on the surfaces of the pulsed-laser irradiated magnetite grains. However, compared to sulfide and silicate minerals that have been subjected to similar irradiation experiments [10, 11], the extent of melt production appears to be more limited in magnetite. Preliminary TEM and EDS analyses of the pulsed-laser irradiated pellets do not show any significant microstructural or chemical changes in the samples suggesting that magnetite could be more resistant to space weathering compared to silicates and sulfides. Those phases often develop amorphous or disordered rims, vapor deposits, chemically distinctive layers, and S depleted rims. More analyses are underway to identify the mechanisms driving these discrepancies.

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