

**UNDERSTANDING THE EFFECTS OF SPACE WEATHERING ON MAGNETITE THROUGH EXPERIMENTAL SIMULATIONS.** L. C. Chaves<sup>1</sup>, M. S. Thompson<sup>1</sup>, B. Horgan<sup>1</sup>, C. A. Dukes<sup>2</sup>, B. Richards<sup>2</sup>, L. Honts<sup>2</sup>, M. J. Loeffler<sup>3</sup>. <sup>1</sup> Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN, 47907 (lchavesm@purdue.edu) <sup>2</sup> Laboratory for Astrophysics and Surface Physics, University of Virginia, 351 McCormick Road, Charlottesville, VA 22904, <sup>3</sup> Department of Physics and Astronomy, Northern Arizona University, 527 S. Beaver St, Flagstaff, AZ, 86011.

**Introduction:** The progressive chemical, microstructural, and spectral changes of airless planetary surfaces, known as space weathering [1], are caused by energetic particles from the solar wind and high-velocity micrometeoroid impacts. Together, these processes may result in ion implantation, comminution, amorphization, melting, vaporization and subsequent recondensation, and the formation of iron-bearing nanoparticles in grains on the surfaces of airless bodies. For the Moon in particular, the occurrence of metallic iron nanoparticles alters the visible-near infrared (VNIR) reflectance spectrum of surface materials producing reddening, darkening, and attenuation of absorption bands [2,3]. These spectral changes complicate our understanding of the surface composition of airless bodies as interpreted from remote sensing data.

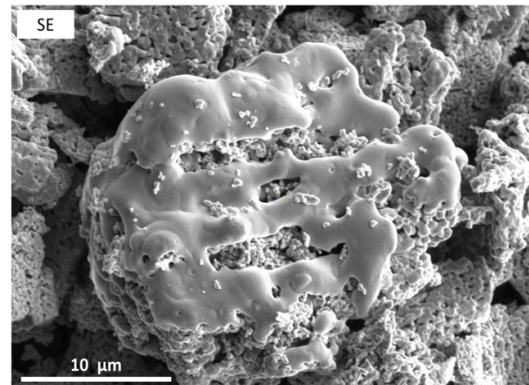
Traditionally, space weathering research has focused on silicate minerals which are the most abundant components of lunar and ordinary chondritic samples, with only a nascent understanding of how other mineral phases respond to weathering processes. Among the understudied and unexplored mineral groups are sulfides [4,5] and Fe-oxides like magnetite ( $\text{Fe}_3\text{O}_4$ ). These mineral phases are common accessory minerals in CM and CI chondrites [6,7], which are possible compositional analogs for asteroids Bennu and Ryugu [8,9]. In addition, magnetite has been identified on the surface of asteroid Bennu [10]. These opaque minerals are spectrally dominant at visible to near-infrared wavelengths even at minor abundances, so understanding their response to space weathering is critical for understanding the spectral properties of asteroids. To evaluate the response of magnetite under space weathering conditions, we simulated micrometeoroid bombardment and solar wind irradiation on synthetic magnetite powders.

**Methodology:** Magnetite powders with grain sizes  $<45 \mu\text{m}$  were pressed to pellets at 1500 psi. To simulate micrometeoroid bombardment, we performed pulsed-laser irradiation experiments (6-8 ns per pulse) using a Nd-YAG laser at  $10^{-8}$  Torr. The pellet was subjected to different number of laser pulses (1x, 2x, 5x) to simulate progressive space weathering exposure time. To replicate solar wind irradiation conditions, we performed nominal 1 keV  $\text{H}^+$  and 4 keV  $\text{He}^+$  irradiation experiments using fluxes  $\sim 1 \times 10^{13}$  ions/ $\text{cm}^2/\text{s}$ , with total fluences of  $5.3 \times 10^{17}$  H/ $\text{cm}^2$  and  $3.6 \times 10^{16}$  He/ $\text{cm}^2$  comparable to exposure times of 440 years and 750 years at

1 AU, respectively. The ion irradiation was accompanied by X-ray photoelectron microscopy (XPS) to analyze the chemical changes produced during irradiation. We used a Thermo Scientific Helios G4 UX focused ion beam scanning electron microscope (FIB-SEM) at Purdue University to analyze textural characteristics and prepare electron transparent samples for transmission electron microscopy (TEM) analyses. We performed TEM analyses of the laser-irradiated samples using the aberration corrected Hitachi HF 5000 TEM at the University of Arizona, which is equipped with two Oxford 100-mm<sup>2</sup> silicon-drift energy dispersive X-ray spectroscopy (EDS) detectors. To compare the spectral properties of the pulsed-laser and the ion irradiated pellets, we acquired reflectance spectra in the visible near-infrared region (0.35 – 2.5  $\mu\text{m}$ ) using a ASD FieldSpec Pro3 reflectance spectrometer at Purdue University.

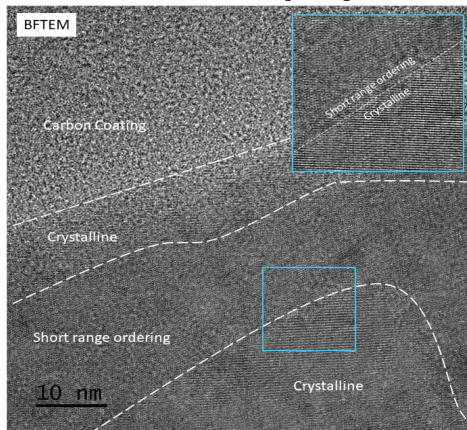
**Results:** We identified diverging spectral, morphological, and chemical characteristics between the laser- and ion- irradiated magnetite samples.

*Micrometeoroid bombardment simulations:* SEM imaging shows the development of melt textures on the surfaces of the magnetite grains after pulsed-laser irradiation (Fig. 1). However, the melts are not homogeneous across the entire irradiated surface, instead, they are localized on a few individual grains. Preliminary TEM analyses show that the melts have an approximate thickness of 200 nm and present crystalline and short range ordered regions (Fig. 2). The crystalline region presents d-spacing values of 0.24 nm similar to (222) magnetite. EDS analyses do not show a distinct chemical change between the melt and the interior of the grain.

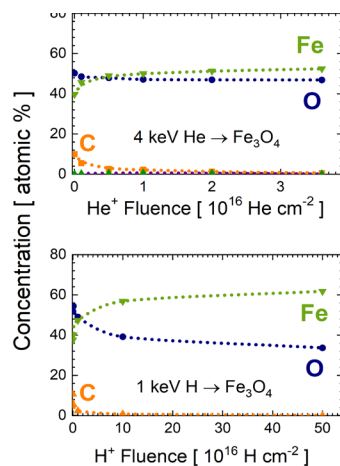


**Figure 1.** Secondary electron (SE) image of melt on the surface of a magnetite grain after pulsed laser irradiation.

**Solar-wind irradiation experiments:** SEM imaging of the ion irradiated grains did not show significant textural changes compared to the unirradiated grains. XPS data in both the  $\text{H}^+$  and the  $\text{He}^+$  irradiated pellets shows a decrease in the concentration (at%) of O and an enrichment of Fe with increasing fluence (Fig. 3). 4 keV  $\text{He}^+$  irradiation of the magnetite powders produced a 6.7% reduction of O and a 32.1% increase in the concentration of Fe, whereas the 1 keV  $\text{H}^+$  caused a 35% reduction of O and a 64% increase of Fe. A small amount of  $\text{N}_2$  (<5%) was identified as result of contamination of the  $\text{H}_2$  gas; similar compositional results were observed for subsequent pure H irradiation.

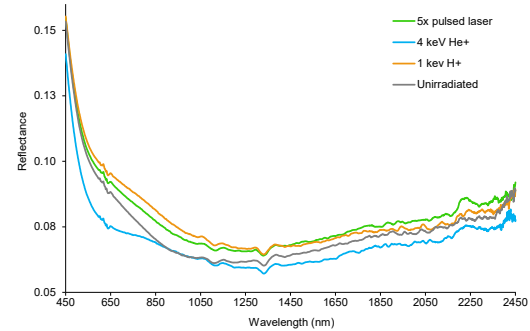


**Figure 1.** Bright field (BF) TEM image of 5x pulsed laser irradiated magnetite showing crystalline and short-range ordered areas in the melt.



**Figure 3.** XPS data showing the enrichment of Fe and depletion of O as a function of a)  $\text{He}^+$  and b)  $\text{H}^+$  fluence.

**Reflectance spectral measurements:** The 5x pulsed laser and the  $\text{H}^+$  ion irradiated samples are slightly brighter at wavelengths > 450 nm, and more red sloped compared to the unirradiated magnetite (Fig. 4), whereas the  $\text{He}^+$  irradiated sample exhibits a lower reflectance (except in the 850 nm to 1150 nm interval, where it presents similar reflectance) in comparison to the unirradiated magnetite.



**Figure 4.** Reflectance spectra of 5x pulses, 1 keV  $\text{H}^+$  and 4 keV  $\text{He}^+$  irradiated, and unirradiated magnetite.

**Discussion:** SEM imaging shows a contrasting response of the magnetite under pulsed-laser irradiation compared to ion irradiation. While the laser irradiation produces melts on the surfaces of the magnetite, the ion irradiation did not produce significant textural changes. The TEM data indicates that the melt has intermittent crystalline and short-range ordered regions, which is at odds with the amorphous melt produced on silicate minerals under similar irradiation conditions. The spectral analysis indicates that the  $\text{He}^+$  sample exhibits an overall darkening compared to the other studied samples, and we expect future TEM analyses may reveal which microstructural or chemical features are driving this alteration. The 5x pulsed laser and the 1 keV  $\text{H}^+$  irradiated samples exhibit a brighter spectrum and redder slopes compared to the unirradiated sample.

Bennu's surface exhibits a bright spectrum and a blue slope, characteristics which have been attributed to possible space weathering processes [11]. Moreover, the addition of "fresh" magnetite has been shown to effectively produce a blue slope on CM chondrites at shorter wavelengths (0.65-1.0  $\mu\text{m}$ ) [12]. Our space weathering experiments produced slightly reddened slopes for magnetite, suggesting that a bluing effect at shorter wavelengths may be achieved through fresh, but not weathered magnetite. Future work includes the simulation of space weathering conditions on other understudied phases including hematite, pentlandite, troilite, and pyrrhotite.

**References:** [1] Hapke B. (2001) *JGR* 106, 10039-10073. [2] Keller L. P. et al. (1998) *LPSC XXIX*. [3] Kohout T. et al. (2014) *Icarus* 237, 75-83. [4] Keller L. P. and Berger E. L. (2014) *EPS*, 66:71. [5] Matsumoto T. et al. (2020) *Nat. Commun.* 11, 1-8.. [6] Hyman M. and Rowe M.W (1979) *LPSC XIV*. [7] Bland P. A. et al (2004) *Meteoritics & Planet. Sci.*, 39, Nr 1, 3-16. [8] Clark B. E. et al (2011) *Icarus* 216, 462-475. [9] Kitazato K. et al (2019) *Science* 364, 272-275. [10] Lauretta D. S. et al. (2019) *Nature* 568, 55-60. [11] DellaGiustina D. N. et al (2020) *Science* 370, 1-12. [12] Izawa M. R. M. et al (2019) *Icarus* 319, 525-539.