Laboratory Simulations of Troilite Space Weathering by Solar Wind Ion Irradiation: Surface, Composition, and Spectral Effects.

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Introduction: Space weathering by solar wind ion irradiation has long been acknowledged as one of the main processes altering the surfaces of airless planetary objects such as the Moon and stony asteroids [1,2] through the chemical alteration of surfaces e.g. production of nanophase iron [3,4]. With missions now exploring worlds with novel compositions such as 16 Psyche [5], it is critical to determine the behavior of additional materials in solar wind. Troilite (FeS) is the most abundant sulfide in carbonaceous chondrite and iron meteorites [6], as well as an anticipated major mineral component of 16 Psyche [5]. Investigations of troilite solar wind ion space weathering at 433 Eros [7,8] and 25143 Itokawa [9,10] have identified the production of a metallic iron and iron-rich sulfide layer and sub-micron surface structures. Here we report results of new ion irradiation experiments to identify differences between effects of H$^+$ and He$^+$ bombardment, and to investigate the possibility that irradiation-induced surface roughening may affect the detectability of weathering via reflectance spectrum alteration

Experiment: We carried out four ion irradiation experiments on three troilite samples provided by the ASU Center for Meteorite Studies: thick section slabs (x3) taken from troilite nodule inclusions in the Canyon Diablo and Toluca iron meteorites and a pressed troilite powder pellet. We used electron-bombardment-type ion guns on a PHI Versaprobe III and a highly-customized PHI-560 X-ray Photoelectron Spectrometer (XPS) at the University of Virginia. All four irradiations occurred at room temperature (~295K) and were designed to reach a total ion fluence >10^{18} ions/cm^2, determined to achieve equilibrium S-depletion and simulating ~10^4 years of solar wind bombardment at 16 Psyche [8]. Solar wind consists of ~96% 1 keV H$^+$, ~4% 4 keV He$^+$, and <0.1% heavier ions, with a total ion flux at 1 AU of ~2×10^{18} ions/cm^2/s [11]. For two of the irradiations we used a combination of 1 keV H$^+$ and 4 keV He$^+$ ions approximating this solar wind ratio, while the other two used exclusively 1 keV H$^+$ or 4 keV He$^+$. Ion fluxes were ~10^{13} ions/cm^2 for both H$^+$ and He$^+$.

Table 1: summary parameters of the four irradiations.

Sample	Surface	Instrument	H$^+$ cm^2	He$^+$ cm^2
Canyon Diablo	Rough	PHI-560	1.40 $\times10^{18}$	0
Pressed Pellet	Rough	PHI-560	1.33 $\times10^{18}$	7.00 $\times10^{16}$
Canyon Diablo	Polished	Versaprobe	0	3.00 $\times10^{18}$
Toluca	Polished	PHI-560	2.80 $\times10^{18}$	1.20 $\times10^{17}$

Before and after each irradiation we obtained visible to near-infrared (VNIR) optical reflectance spectra using apparatus at ASU, survey and high-resolution XPS spectra, and Scanning Electron Microscope (SEM) imaging using the FEI XL-30 at ASU's Center for High Resolution Electron Microscopy. During the last two irradiations, we took additional XPS spectra at multiple intermediate fluences to better track surface elemental abundance changes as the irradiation progressed and to monitor the presence of a ~15 nm oxide layer formed during sample storage in atmosphere. Atomic Force Microscopy (AFM) measurements of surface roughness were also made using the Bruker Dimension 3000 at ASU's Eyring Materials Center. We also modeled the FeS compositional evolution using SDTrimSP to better understand the sulfur depletion mechanism(s) at work, as described in [12].

Results:

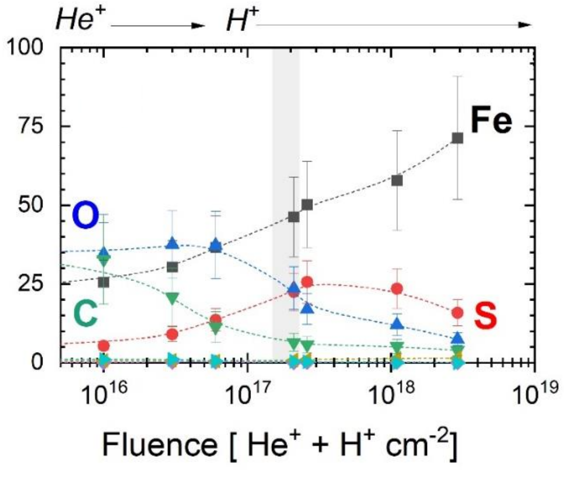

Fig. 1: XPS-derived elemental abundances of Fe, S, O, and C with respect to ion fluence for the Toluca irradiation. Results for the other 3 experiments are similar.

The elemental abundances of major elements show similar trends across all four irradiations (Fig. 1). Oxygen is initially the most abundant element present due to the surficial nano-scale oxide layer, thicker than the sampling depth of XPS. As this oxide layer is removed by sputtering, the underlying FeS is exposed. Sulfur abundance maximizes around 10^{17} to 10^{18} ions/cm^2, before depleting. Notably, there does not appear to be a major difference in sulfur depletion between H^+ and He^+ irradiation; this was confirmed by our modeling [12]. All four irradiated surfaces ended with a S:Fe ratio in the range of 0.2 to 0.35.

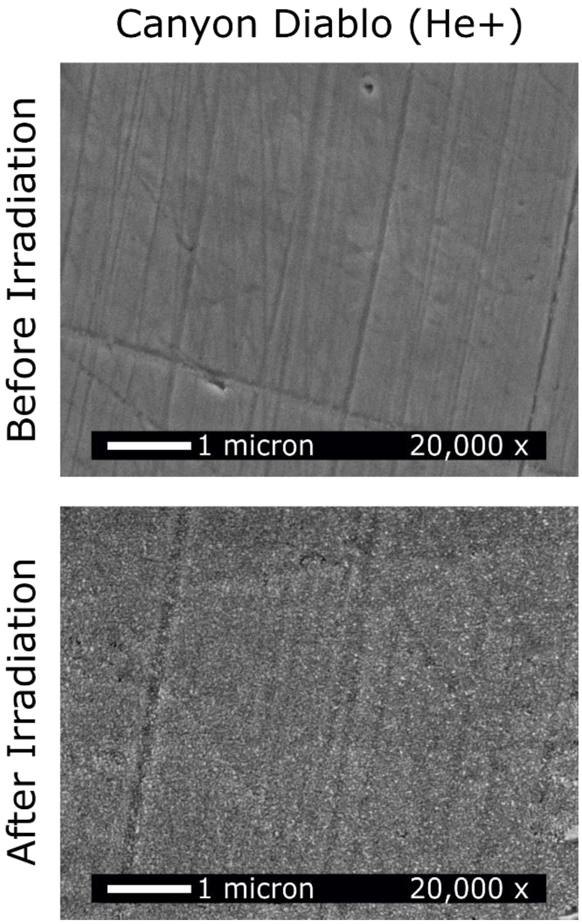

Fig. 2: SEM image of the polished surface of Canyon Diablo before irradiation and the same surface after He^+ *irradiation; similar textures are present on the Toluca surface.*

SEM imaging of the two polished surfaces after irradiation revealed ubiquitous nano-scale pitting and other roughness features (Fig. 2). Using AFM we measured the average height deviation of the irradiated regions as 5.5 +/- 0.4 nm, compared to 2.3 +/- 0.3 nm on the unirradiated polished surfaces. Any roughness increase on the two non-polished samples was obscured by preexisting roughness at larger length scales.

Preliminary assessment of the VNIR spectra (Fig. 3) shows that all of the irradiated surfaces are significantly darker and have shifted slopes as compared with unirradiated troilite. However, the degree of darkening and the final slopes vary between the irradiations, not necessarily correlated to surface chemistry.

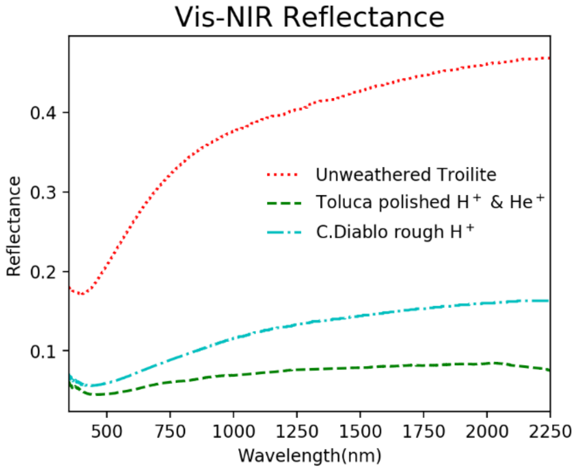

Fig. 3: Post-irradiation VNIR reflectance spectra.

Discussion: Though we cannot fully differentiate whether nanoscale roughening or chemical alteration is the dominant cause of the optical change we observe in reflectance spectra, it is nevertheless apparent that in both results, ion irradiation plays a role. It is therefore possible that even on materials which likely would not be chemically modified by solar wind ion irradiation, e.g. metallic nickel-iron, ion-induced roughening may still result in altered spectra. Further work will be necessary to quantify the precise relationship between surface roughness and reflectance, but we suggest that ion-induced roughness be considered an independent variable influencing laboratory and planetary optical spectra.

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