COMPARISON OF SPACE WEATHERED LUNAR OLIVINES OF VARYING MATURITY, RECENT EXPOSURE, AND CURATION TEMPERATURE. B. A. Cymes[1], K. D. Burgess[2], R. M. Stroud[3], and The ANGSA Science Team, [1]NRC Postdoctoral Research Associate, U.S. Naval Research Laboratory, Washington, DC 20375 (brittany.cymes.ctr@nrl.navy.mil), [2]U.S. Naval Research Laboratory, Washington, DC 20375, [3]Arizona State University, Tempe, AZ 85287.

Introduction: Space weathering refers to the physical and chemical alteration of the surfaces of airless bodies (e.g. the Moon, asteroids) in response to solar wind irradiation and micrometeorite bombardment. The characteristic features of space weathering are thin (<200 nm) veneers on space-exposed soils grains which can contain nanophase metallic iron particles ($npFe^0$), vesicles, vapor deposits, melt splashes, and amorphous zones [1-3]. Analyses of both natural lunar soil grains [e.g., 4-5], asteroid Itokawa grains [e.g., 6-7] and experimental lunar analogues [e.g., 8] have revealed that differences in response to space weathering are present among different mineral phases. In the interest of understanding how other parameters such as maturity and exposure influence the development of space weathering features in natural samples, we are using scanning transmission electron microscopy (STEM), electron energy loss spectroscopy (EELS), and energy dispersive spectroscopy (EDS) to analyze olivine grains from mature, sub-mature, shaded, and exposed lunar soils. Additionally, to understand the influence of curation temperature on the retention of solar-wind implanted volatiles, frozen aliquots of the two shaded samples were analyzed.

Methodology: Six ~10-20 µm olivine grains were selected and prepared for analysis in the STEM using a FEI Helios G3 Dual Beam focused ion beam-scanning electron microscope (FIB-SEM) equipped with an Oxford EDS detector. The olivines chosen are summarized in Table 1. The surfaces of selected olivine grains were first protected with 1.5 µm of amorphous carbon and thinned to ~1 µm with a 30 keV Ga^+ ion beam. After Pt-welding the sample lamellae to Cu TEM half-grids, the samples were thinned to 80-100 nm using progressively lower beam currents. The samples were held under vacuum at room temperature for 24 hours to drive off adsorbed water prior to introduction into the ultra-high vacuum STEM. The STEM data were acquired using an aberration-corrected Nion UltraSTEM200-X, operated at 200 keV and 40 pA with a ~0.1 nm probe. The EDS data were collecting using a Bruker X-Flash windowless silicon drift detector and the EELS data were collected using a Gatan Enfinium ER Dual EELS spectrometer equipped with a MerlinEELS direct electron detector (Quantum Detectors).

Results: The olivine grains from 72321, 72320, 72501, and 76241 have similar space weathered rims, characterized by a 50-150 nm thick layer of ~3 nm $npFe^0$. The rims in these grains contain laterally-continuous lenticular vesicles near the surface (e.g. Fig. 1a). Such vesicles are similar to those observed in low-Ca pyroxene in asteroid Itokawa samples [9]. Interspersed with the lenticular vesicles are flat- and linear-shaped vesicles, oriented parallel to the surface or at a ~30° glancing angle (Fig. 1b). Both the lenticular and flat vesicles contain $npFe^0$ within their volume or length. The olivine from 76241 had melt splashes present on the surface. Interestingly, under most of the splashes, the rim does not differ in thickness or content from those areas without melt; however, one area under a melt splash had a thinner rim, potentially indicating that it is an older melt splash (Fig. 1c).

The olivine from soil 76261 is texturally distinct from the others, its rim being comprised of a ~200 nm thick layer of ~3 nm $npFe^0$ particles (with a few larger $npFe^0$) and lacking in the vesicles present in the other olivines rims (Fig. 1d). The olivine from 76261 does however have $npFe^0$-bearing linear vesicles beneath the main $npFe^0$ layer, extending up to ~300 nm beneath the rim surface and oriented nearly perpendicular to the surface. Also present both within and beneath the $npFe^0$ rim are small, irregular to round-shaped vesicles without $npFe^0$ in their volume.

The STEM-EDS data show variations in olivine chemistry of Fe:Mg=0.1-0.5; such variation in Fe content does not correlate strongly with rim thickness (e.g. 76261 Fe:Mg=0.3). Preliminary STEM-EELS data show that vesicles from the room-temperature curated olivine are devoid of H or He [10].

Discussion: The olivine grains from the five samples studied thus far have similar space weathering features regardless of maturity or exposure, suggesting that olivines have a characteristic weathering profile on the Moon distinct from other phases. The anisotropic vesicle structures and their attitude to the surface and to one another suggest that a structural control to rim development may exist. Additionally, the linear vesicles extending hundreds of nanometers into the grain interior are far beyond the theoretical stopping range of H^+ and He^+; however, because these and other vesicles are decorated with $npFe^0$, we conclude that H^+

and He^+ have diffused deeper into the grain in these areas, potentially along defects. In the future, the rim compositions of these olivines will be determined to further constrain how solar wind irradiation produces $npFe^0$ in olivine (i.e., whether by volatile implantation or sputtering), but further systematic studies into the crystal structure effects of solar wind ion implantation should be undertaken in light of these results.

Conclusions: In this investigation, we preliminarily find that lunar olivine grains varying in maturity and recent exposure history share similar space weathering characteristics. We also conclude that the presence of H and He in the frozen-curated samples indicate that cold-curation makes a meaningful difference in retention of solar wind volatiles. Further supporting data from olivine in sample 76240 will provide further information. Though natural samples vary in bulk composition to a degree, these results are important as they provide a detailed picture of how olivine responds to space weathering. These results are useful for interpreting the space weathering features of other mineral phases and supporting data in the form of experimental analogues of lunar olivines and other phases will provide an even clearer picture.

Acknowledgements: This work has been supported by NASA award 80HQTR19T0057 and 80NSSC19M0215.

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Table 1. The six lunar soils olivine grains were selected from, their maturity, storage conditions, and exposure history.

Soil	I_S/FeO[1]	Storage	Exposure
72320	73	Frozen	Partially shaded
72321	73	Ambient	Partially shaded
72501	81	Ambient	Exposed
76240	56	Frozen	Permanently shaded
76241	56	Ambient	Permanently shaded
76261	58	Ambient	Exposed

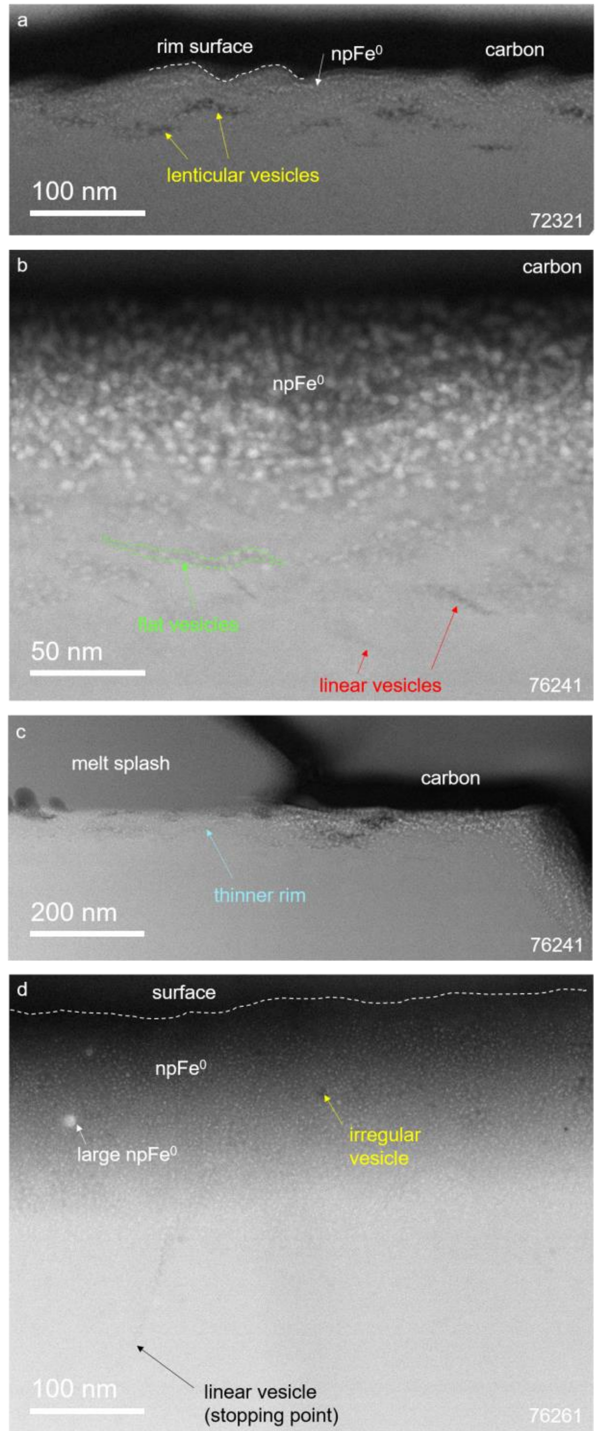

Figure 1. HAADF-STEM images of the lunar olivine grains analyzed. **(a)** olivine from 72321 showing space weathered rim and characteristic lenticular vesicles; **(b)** olivine from 76241 showing flat and linear vesicles; **(c)** olivine from 76241 showing rim thickness under a melt splash; **(d)** olivine from 76261 showing mostly vesicle-free rim and linear vesicles.