DIRECT DETERMINATION OF THE SPACE WEATHERING RATES IN LUNAR SOILS AND ITOKAWA REGOLITH FROM SAMPLE ANALYSES. L. P. Keller[1], E. L. Berger[2], R. Christoffersen[3] and S. Zhang[4]. [1]ARES, Code XI3, NASA/JSC, Houston, TX 77058 (Lindsay.P.Keller@nasa.gov). [2]GeoControl Systems, Inc./JETS, Houston, TX 77058. [3]Jacobs, NASA Johnson Space Center, Mail Code XI, Houston, TX 77058 [4]Texas Materials Institute, Univ. Texas, Austin, TX 78712.

Introduction: Space weathering effects on airless bodies result largely from micrometeorite impacts and solar wind interactions. Decades of research have provided insights into space weathering processes and their effects, but a major unanswered question still remains: what is the rate at which these space weathering effects are acquired in lunar and asteroidal regolith materials? To determine the space weathering rate for the formation of rims on lunar anorthite grains, we combine the rim width and type with the exposure ages of the grains, as determined by the accumulation of solar flare particle tracks. From these analyses, we recently showed that space weathering effects in mature lunar soils (both vapor-deposited rims and solar wind amorphized rims) accumulate and attain steady state in 10^6-10^7 y [1].

Regolith grains from Itokawa also show evidence for space weathering effects, but in these samples, solar wind interactions appear to dominate over impact-related effects such as vapor-deposition [2,3]. While in our lunar work [1], we focused on anorthite, given its high abundance on the lunar surface, for the Itokawa grains, we focused on olivine. We previously studied 3 olivine grains from Itokawa and determined their solar flare track densities and described their solar wind damaged rims [3]. We also analyzed olivine grains from lunar soils, measured their track densities and rim widths, and used this data along with the Itokawa results to constrain the space weathering rate on Itokawa. We observe that olivine and anorthite have different responses to solar wind irradiation.

Materials and Methods: We analyzed <20 μm olivine grains in microtome thin sections from several different lunar soils showing a range of maturity: 67701, 71501, 10084, and 64501. The sections were analyzed using a JEOL 2500SE scanning and transmission electron microscope (STEM) equipped with a Thermo-Noran thin window energy-dispersive X-ray (EDX) spectrometer. We also measured the amorphized rim width and track density in olivine from the surface of rock 64455. We used our recent calibration of the solar flare track production rate in lunar anorthite and olivine determined by [4] to estimate exposure ages.

Results and Discussion: The solar wind damaged rims on anorthite are amorphous, lack inclusions, and are compositionally similar to the host grain. The width of solar wind amorphized rims on anorthite increases as a smooth function of exposure age until it levels off at ~180 nm after ~20 My (Fig. 1). Solar wind damage can only accumulate if the grain has a direct line of sight to the Sun, whereas solar flare particles can penetrate mm of regolith. Thus, tracks can accumulate while the particle is not directly exposed at the lunar surface. To assess whether the track density accurately predicts surface exposure, we measured the amorphized rim width and track density in anorthite from the surface of rock 64455 [4] that was never buried, and has a well constrained surface exposure age of 2 My based on isotopic measurements [5]. The 60-70 nm rim width from 64455 plots within error of the well-defined trend for solar wind amorphized rims in Fig. 1, indicating that the measured solar flare track densities are accurately reflecting the surface exposure of the grains.

Space-weathered olivines from Itokawa show solar wind damaged rims that are not amorphous, instead the rims are nanocrystalline with a high dislocation densities and sparse inclusions of nanophase Fe metal [2,3,6]. In addition to the structural damage, natural Fe-bearing olivine undergoes chemical changes during solar wind irradiation with partial reduction of Fe^{2+} to Fe^0. In this regard, the olivine rims resemble lunar soil ilmenite grains which also do not amorphize and also show partial Fe reduction. The Itokawa olivine grains, with nanocrystalline rims, have track densities indicating surface exposures of ~10^5 years [7]. Even much longer exposures, up to ~10^7 years do not amorphize the rims, as evidenced by lunar soil olivines with high track densities (up to 10^{12} cm^{-2}). Measurements are underway to determine if the damaged rims become more chemically reduced with increasing exposure age. In Figure 1 we plot the solar flare track exposure age of olivine grains (both Itokawa and lunar) versus the width of their solar wind damaged rims. Also plotted in the figure is the measurement from olivine in 64455, which anchors the curve (100 nm width damaged rim with a 2My exposure). From the combined data, it is clear that olivine is damaged (but not amorphized) more rapidly by the solar wind compared to anorthite. The olivine damaged rim width rapidly approaches ~120 nm in ~10^6 y and then saturates at that width with longer exposure time.

Numerical modeling based on the SRIM code and experimental ion radiation data [8] predicts that the solar wind damaged rims on anorthite will be thicker than olivine at saturation, in agreement with the data for natural rims. However, the models also predict the

rapid development of amorphized layers for both anorthite and olivine that reach steady state widths in <10^3 y [9,10]. This result however, is 2-3 orders of magnitude shorter than the much slower (~10^6 y) development of amorphized layers in anorthite observed in the natural samples. The models also predict the efficient amorphization of olivine by ions with solar wind abundances and energies, but again, this is not observed in the natural samples. These point to a stark contrast between our results for natural solar wind damaged rims on olivine and laboratory irradiation experiments [8]. The latter show rapid formation of fully amorphous and blistered surfaces from simulated solar wind exposures [e.g. 9,11]. These results suggest that not just the ion fluence alone, but also the ion flux controls the type and extent of irradiation damage that develops in olivine. This flux dependence argues for caution in extrapolating between high flux laboratory experiments and the natural case, as demonstrated by [11].

Space Weathering Rate on Itokawa. In the absence of direct surface samples to study, constraints on asteroidal regolith evolution and space weathering timescales have relied upon remote spectroscopic studies. The fundamental question is: What is the timescale to alter the reflectance spectrum of an ordinary chondrite meteorite to resemble the overall spectral shape and slope of an S-type asteroid? One approach to answering this question has been to determine ages of asteroid families by dynamical modeling and determine the spectral properties of the daughter fragments [e.g., 12-14]. However, large disconnects exist between inferred space weathering rates and timescales derived from analysis of asteroid family spectra and the space weathering styles [e.g. 9,13,15]. Vernazza *et al*. [13] concluded that solar wind interactions dominate asteroid space weathering on rapid timescales of 10^4-10^6 years. Loeffler *et al.* [9] scaled the results of their laboratory H+ and He+ irradiation experiments to the solar wind fluence, where the alteration saturates, and obtained a characteristic timescale for solar wind weathering of 5000 years at 1 AU. Shestopalov *et al*. [16] suggested that impact-gardening of regolith particles and asteroid resurfacing counteract the rapid progress of solar wind optical maturation of asteroid surfaces and proposed a characteristic space weathering timescale of 10^5-10^6 years.

We place a hard constraint on the the space weathering rate through analysis of returned samples. Provided that the track densities and the solar wind damaged rim widths exhibited by the Itokawa grains are typical of the fine-grained regions of Itokawa, then the space weathering rate is on the order of 10^5 y.

Conclusions: Space weathering effects in lunar soils reach steady state in a few My of exposure while those in Itokawa regolith grains formed in ~10^5 y. Olivine and anorthite respond differently to solar wind irradiation. The space weathering effects in olivine are particularly difficult to reconcile with laboratory irradiation studies and numerical models. Additional measurements, experiments, and modeling are required to resolve the discrepancies among the observations and calculations involving solar wind amorphization of different minerals on airless bodies.

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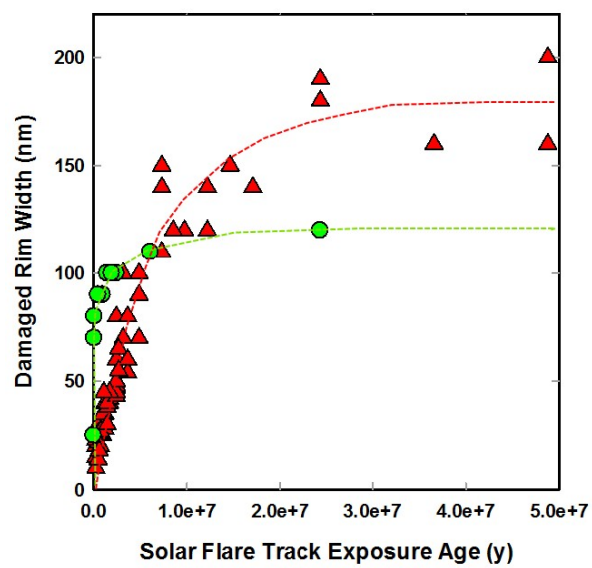

Figure 1. A plot of solar wind damaged rim width versus solar flare track exposure age for rims on lunar anorthite (red triangles) and Itokawa and lunar olivine (green circles).