SPACE WEATHERING OF ITOKAWA PARTICLES: IMPLICATIONS FOR REGOLITH EVOLUTION.

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Introduction: Space weathering processes such as solar wind irradiation and micrometeorite impacts are known to alter the the properties of regolith materials exposed on airless bodies [1]. The rates of space weathering processes however, are poorly constrained for asteroid regoliths, with recent estimates ranging over many orders of magnitude [*e.g.*, 2, 3]. The return of surface samples by JAXA's Hayabusa mission to asteroid 25143 Itokawa, and their laboratory analysis provides "ground truth" to anchor the timescales for space weathering processes on airless bodies. Here, we use the effects of solar wind irradiation and the accumulation of solar flare tracks recorded in Itokawa grains to constrain the rates of space weathering and yield information about regolith dynamics on these timescales.

Samples and Techniques: Itokawa particles RA-QD02-0211 (0211) and RA-QD02-0125 (0125) were allocated by JAXA; particle RA-QD02-0192 (0192) was allocated by NASA. Multiple electron transparent thin sections of each of these samples were prepared via a hybrid ultramicrotomy-focused ion beam (FIB) technique [4], using a Leica EM UC6 ultramicrotome and an FEI Quanta 3D dual beam FIB-SEM. Transmission electron microscope (TEM) analyses were done on the JEOL 2500SE 200kV field emission STEM. All instruments are housed at NASA JSC. TEM analyses of FIB-prepared sections allow for accurate determination of solar flare particle track densities and rim characteristics (*e.g.*, width, crystallinity).

Results: Itokawa particles 0211, 0192, and 0125 are olivine-rich (Fo_{70}) with minor Fe-sulfides. They have continuous solar wind damaged rims that are structurally disordered, nanocrystalline, and compositionally similar to the cores of the grains [5]. All three have adhering mineral grains and melt particles, as well as solar flare particle tracks (tracks). The track densities and rim thicknesses vary across each particle. Particle 0211 exhibits a track density gradient across the grain that correlates with the rim thickness (Fig. 1). The widest solar wind damaged rim (~80nm) is on the side of the particle with the highest track density (3.4×10^9 tracks/cm^2), while the thinnest rim (~40nm) is on the opposite side of the particle (track density: 9.2×10^8 tracks/cm^2). Particle 0192 also shows a track density gradient (2.9×10^9 to 1.1×10^9 tracks/cm^2) and has similar rim widths to particle 0211. A plot of track density vs. depth is given in Fig. 2 for Itokawa particles 0211 and 0192 and for lunar rock 64455 for comparison [6]. Exposure ages, based on the track production rate of $4.1 \pm1.2 \times 10^4$ tracks/cm^2/year at 1AU [6] are: ~80,000 years for 0211, ~70,000 years for 0192, and ~24,000 years for 0125.

Discussion: *Cosmic-ray exposure:* Measurements of cosmic-ray exposure (CRE) ages of Itokawa particles [6-8] reveal that these grains are relatively young, ≤1−1.5 Ma, when compared to the distribution of exposure ages for LL chondrite meteorites (8−50Ma) [9]. The CRE ages for Itokawa grains are consistent with a stable regolith at meter-depths for ~10^6 years.

Solar flare particle tracks: Based on the solar flare particle track production rate in olivine at 1AU [6], the Itokawa grains recorded solar flare tracks over timescales of $<10^5$ years. Interestingly, the preservation of well-defined solar flare track gradients in two of the particles (fig. 2) indicates that they maintained a relatively stable orientation at mm to cm depths for ~10^4–10^5 years in the Itokawa regolith.

A comparison of the track density vs. depth relationships for the Itokawa particles and Apollo 16 sample 64455 shows that the track gradient slopes for the Itokawa particles are only slightly shallower. The 64455 sample is believed to have experienced little to no erosion, and remained stationary while exposed on the lunar surface [10]. A shallow slope or a truncated gradient is indicative of erosional processes [*e.g.*, 10-12]. However, the angular nature of our Itokawa particles shows that they are not eroded and that their track gradient slopes are more consistent with minor grain movement relative to zenith as evidenced by the heterogeneous thicknesses of solar wind damaged rims, as discussed below.

Solar wind damaged rims: Over timescales of a few 10^3 years, interactions with the solar wind produces ion-damaged rims on the outer ~100nm of grains that are exposed on the uppermost surface of lunar and asteroidal regoliths. The damaged rims on Itokawa grains are predicted to become amorphous and reach a steady state thickness of 80−100 nm within a few thousand years [13]. The rims observed on the Itokawa olivine grains are continuous indicating that all sides of the particle have had direct exposure to the solar wind. The varying rim thicknesses on the same particle indicate differing exposure times. As these rims are not amorphous and portions are thinner than 60−70nm, this suggests residence times of less than ~10^3 years. The uppermost surface of the Itokawa regolith was sufficiently dynamic that while grain rotation must have occurred, the particles were not lost to space.

Conclusions: Space weathering of particles results in a number of morphological changes, including cosmic ray exposure tracks, solar flare particle tracks and solar wind damaged rims. Each of these space-weathering effects yields information about particle histories at different depths and over multiple timescales. Together, they give us information about the regolith dynamics on asteroid Itokawa.

The heterogeneous distribution of the space weathering effects on two Itokawa particles is consistent with both particles maintaining a relatively fixed orientation in the Itokawa regolith throughout the time they were being irradiated by incoming solar flare ions. Solar flare particle tracks were formed over timescales of 10^4–10^5 years, during which the Itokawa particles were shielded, at mm to cm depths, from direct exposure to the solar wind. The presence of track gradients in the particles indicates that the regolith in the Muses-C region on Itokawa was relatively stable at millimeter to centimeter-depths for the last ~10^5 years, implying little overturn. We conclude that only late in their history (<10^3 years) were the particles exposed to the solar wind. The continuous nature of the damaged rims on the Itokawa particles however, requires grain movement on the uppermost surface of Itokawa in order to expose all sides of the particles to the solar wind.

References: [1] Hapke, B. (2001) *JGR* 106:10039-10073. [2] Willman et al. (2010). *Icarus* 208:758-772. [3] Vernazza *et al.* 2009. *Nature* 458:993-995. [4] Berger and Keller (2015) *Microscopy* Today, in press. [5] Keller and Berger EPS [6] Berger and Keller (2015) *this volume.* [6] Meier et al. (2014) *LPSC XLV,* #1247. [7] Nagao et al. (2013) *LPSC XLIV,* #1247. [8] Nagao et al. (2011) *Science* 333:1128-1131. [9] Graf & Marti (1994) *Meteoritics*: 29, 643-648. [10] Blanford *et al.* (1975) *Proc. 6th Lunar Sci. Conf.,* 3557-3576. [11] Walker & Yuhas (1973) *Proc. 4th Lunar Sci. Conf.,* 2379-2389. [12] Crozaz et al. (1974) *Proc. 5th Lunar Sci. Conf.,* 2475-2499. [13] Christoffersen & Keller (2015) *this volume.*

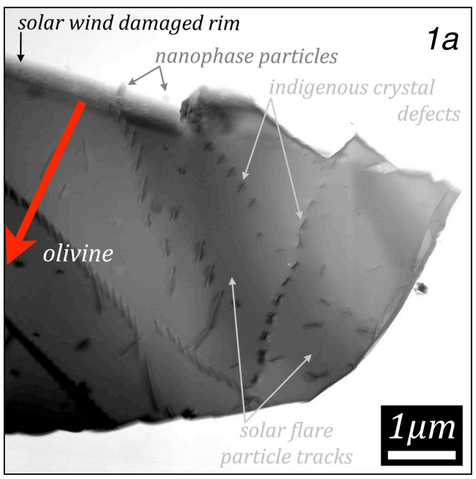
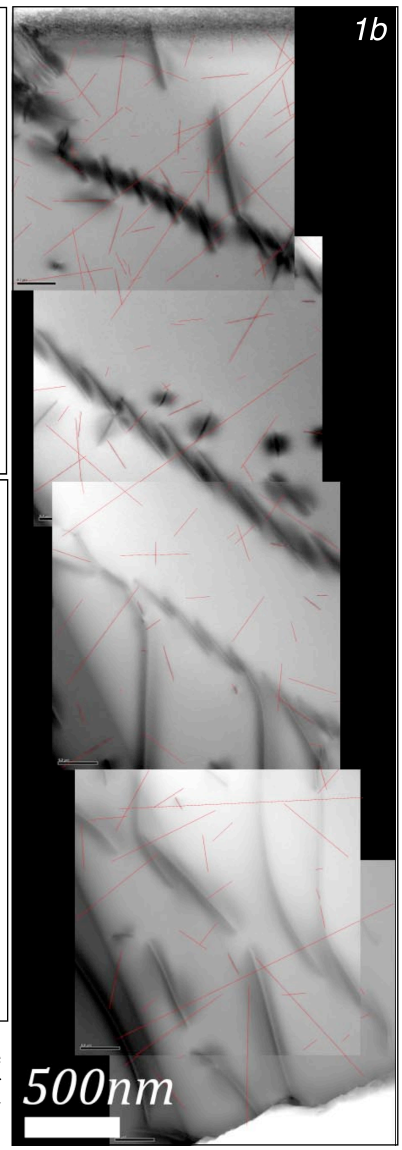


Fig.1a. Bright field image (BFI) of Itokawa 0211, FIB section 1. *1b.* BFI mosiac from 0211, sect. 1 (indicated by the red arrow in fig. 1a). The thickest rim and highest track density are at the top, while the thinnest rim and lowest track density are at the bottom (red arrow in above image). Tracks are highlighted in red for ease of viewing. Track densities are plotted as red squares in figure 2.



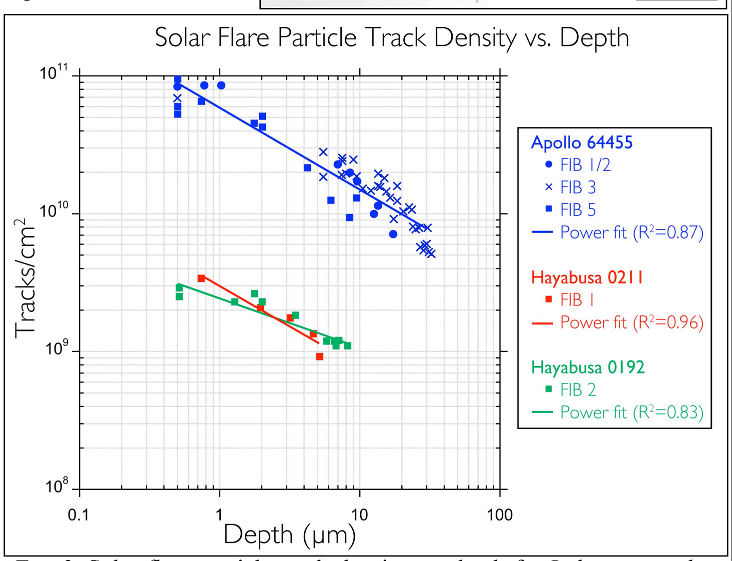


Fig. 2. Solar flare particle track density vs. depth for Itokawa samples; 64455 data is plotted for comparison. The trend line slopes for the Itokawa particles are only slightly shallower than that for the lunar sample; this is consistent with the Itokawa particles experiencing only mild tumbling while exposed on the surface of the asteroid.