

Surface Exposure Ages of Space-Weathered Grains from Asteroid 25143 Itokawa

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Abstract

We use the observed effects of solar wind ion irradiation and the accumulation of solar flare particle tracks recorded in Itokawa grains to constrain the rates of space weathering and yield information about regolith dynamics. The track densities are consistent with exposure at mm depths for 10^4 - 10^5 years. The solar wind damaged rims form on a much faster timescale, $<10^3$ years.

1. Introduction

Space weathering processes such as solar wind ion irradiation and micrometeorite impacts are widely known to alter the properties of regolith materials exposed on airless bodies. The rates of space weathering processes however, are poorly constrained for asteroid regoliths, with recent estimates ranging over many orders of magnitude [e.g., 1, 2]. 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.

1.1 Samples and Analysis Methods

Itokawa particles RAQD02-0211 (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 using an ultramicrotome and a FEI Quanta 3D dual-beam FIB-SEM [3]. Transmission electron microscope (TEM) analyses were acquired with a JEOL 2500SE 200kV field emission STEM.

2. Results

Itokawa particles 0211, 0192, and 0125 are olivine-rich (Fo₇₀) 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. All three particles have adhering mineral grains and melt particles, as well as solar flare particle tracks (tracks). Compared to lunar soil grains with a similar exposure history, the Itokawa grains are notable for a relative lack of abundant melt spherules and vapor deposits. Particle 0125 shows a track density of 9.8×10^8 tracks/cm² and a solar wind damaged rim thickness of ~50nm. Interestingly, the track densities and rim thicknesses vary across the other two particles. Particle 0211 exhibits a track density gradient across the grain that correlates with the rim thickness. The widest solar wind damaged rim (~80nm) is on the side of the particle with the highest track density (3.4×10^9 tracks/cm²), while the thinnest rim (~40nm) is on the opposite side of the particle (track density: 9.2×10^8 tracks/cm²). Particle 0192 also shows a track density gradient (2.9×10^9 to 1.1×10^9 tracks/cm²) and has similar rim widths to particle 0211.

Solar flare energetic particles (mainly Fe-group nuclei) have a penetration depth of a few millimeters and leave trails of ionization damage in insulating materials that are readily observable by TEM imaging. The density of solar flare particle tracks is used to infer the length of time an object was at or near the regolith surface (i.e., its exposure age), but requires the accurate determination of a track production rate in order to convert track density into years of exposure. We used FIB-TEM techniques to obtain such a calibration using the track density/exposure age relations for lunar rock 64455. The 64455 sample was used earlier by [4] to

determine a track production rate by chemical etching of tracks in anorthite. Lunar rock 64455 had a stable orientation during its exposure on the lunar surface and displays a well-developed track density gradient in both anorthite and olivine. We measured a maximum track density at the sample surface of $8.2 \pm 2.4 \times 10^{10}$ tracks/cm². Based on the measured track density and the Kr-Kr exposure age (2×10^6 y) for the splash glass on 64455 [4], we calculate a track production rate at 1 AU of $4.1 \pm 1.2 \times 10^4$ tracks/cm²/y for a 2π exposure. Applying this track production rate to the Itokawa particles gives surface exposure ages of ~80,000 years for 0211, ~70,000 years for 0192, and ~24,000 years for 0125.

3. Discussion

Based on the solar flare particle track production rate in olivine at 1AU, 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 indicates that they maintained a relatively stable orientation at mm to cm depths for $\sim 10^4$ – 10^5 years in the Itokawa regolith. Plots of track density vs. depth for the two particles showing track gradients reveal no changes or breaks in slope suggesting the particles experienced little or no erosion of their surfaces.

Over timescales of a few 10^3 years, interaction 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 [5]. As the rims are not amorphous and portions are thinner than 60–70nm, this suggests their direct exposure to the sun was less than $\sim 10^3$ years. Although rims are generally continuous around the grain circumference, their thickness varies in a manner suggesting different sides of the grain had different solar wind exposure times. This indicates the Itokawa regolith was sufficiently dynamic for the grains to rotate, but not so dynamic that the grains become lost to space.

5. Summary and Conclusions

Space weathering of regolith particles on airless bodies 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 $\sim 10^5$ 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.

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