Two kinds of "space weathering process" on the surface of asteroid Itokawa.

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Introduction:

A variety of processes on the surface of asteroid Itokawa have been elucidated by the preliminary examination of Itokawa particles recovered by the Hayabusa spacecraft [1-9]. Three-dimensional (3D) shapes of forty-eight Itokawa particles were determined by x-ray micro-tomography [1-3]. The shape distribution with respect to the three-axial ratios indicates that the particles are consistent with mechanical fragments by impact probably on Itokawa's surface. Most of the particles (~75%) have sharp edges, which are also consistent with the fragments. However, some of them (~25%) have rounded edges at least on a part of the particle surfaces. These rounded edges should be formed from sharp edges by abrasion probably due to particle motion by impact-induced seismic waves and/or sputtering by solar wind irradiation.

TEM and STEM observation on cross sections close to the particle surfaces revealed so-called "space weathering" on the asteroid [4]. Three types of surface modifications, which are mainly due to solar wind irradiation, were recognized in the rims a few - ~80 nm thick of twelve particles [5,6]: Type-1: thin amorphous rims, Type-2: nanoblob-bearing rims, and Type-3: nanoblob-bearing vesicular (blistering) rims. The degree of space weathering increases from Types-1 to -3.

Implantation of solar wind noble gases was also detected by noble gas isotopic measurements of three Itokawa particles [5]. The time needed for solar Ne exposure into the particles is 150-550 years. The upper limit of the residence time of the particles in the regolith layer by an estimate on cosmic-ray exposure is ~3 Myr. Release profiles of the noble gases indicate multiple implantations of solar wind particles.

Surface morphologies of eight particles were examined by a field emission scanning microscope (FE-SEM) [6]. Two types of surfaces were recognized: one has distinct structures such as sharp fine steps, which correspond to cleavage steps and growth (or evaporation) steps, and the other has faint structures such as ambiguous steps. The former and later types of surfaces can be regarded as "fresh" and "matured" surfaces, respectively. Structures probably due to blisters caused by solar wind implantation were also observed [9]. On "matured" surfaces, micron-scale glassy objects that look like melt splash as a result of micrometeorite impact were observed [8,10] although large scale impact melting textures were not observed [1].

In these previous studies, individual processes were discussed based on the results of the different analyses, but comprehensive understanding has not yet been made. In the present study, comprehensive approach for understanding processes on Itokawa's surface was made by comparing the results of the different analyses.

Comparison between surface morphologies and rim structures:

Two kinds of surface morphologies with different spatial resolution have been observed: one is 3D morphology by micro-tomography with the maximum resolution of a few μm [1-3], and we will call this "surface micro-morphology". The other is observed by FE-SEM with the maximum resolution of a few tens nm [8,9], and we will call this "surface nano-morphology". Eight Itokawa particles were commonly observed by these two methods. There is clear correlation between the angularity of edges in the micro-morphology and the sharpness of steps in the nano-morphology: four particles with angular edges always have sharp steps on fresh surfaces, three particles with angular and rounded edges always have sharp and ambiguous steps on fresh and matured surfaces, respectively, and one particle with rounded edges always has ambiguous steps on a matured surface.

The surface modifications observed by TEM and STEM has the spatial resolution of a few nm [4-6], and we will call this "rim nano-structure". The surface micro-morphology and the rim nano-structure of eight particles were directly compared. There seems to be no correlation between the angularity of edges and the rim types: two particles with Type-1 rims have angular edges, three particles with Type-2 rims have angular edges (one particle) or rounded edges (two particles), and three particles with Type-3 rims have angular edges (two particles) or rounded edges (one particle).

Only one particle was observed by micro-tomography, FE-SEM and TEM/STEM. This particle has rounded edges, ambiguous steps and Type-3 rim.

We cannot compare the noble gas data with the surface morphologies and the rim structures because the destructive noble gas isotope measurements [7] were made without any observation by micro-tomography and FE-SEM to minimize contamination from the Earth's atmosphere.

Discussion:

Space erosion:

There is clear correlation between the surface micro- and nano-morphologies. It is reasonable to consider that "matured" particles with rounded edges and ambiguous steps were formed by abrasion from "fresh" fragmental particles with angular edges and sharp steps. However, there seems to be no correlation between the surface sharpness and the rim types. In particular, two particles with angular edges (and probably sharp steps) have Type-3 rims, where Fe-rich nanoblebs are present in an amorphous layer with vesicles (blisters). Therefore, this most weathered type rim should form in a short duration before particles will be distinctly abraded. In fact, the time scale for the formation of Type-3 rims is relatively small (~10^3 yr. based on solar flare track density in a particle with Type-3 rim [6] and ~500-5000 yr. based on the blister formation by solar wind He^+ implantation [9]). The solar wind irradiation time scale based on the noble gas isotopes (150-550 yr.) [7] is also consistent with the short time scale for the surface modifications by solar wind irradiation [6].

The above discussion shows that the abrasion process has longer time scale than the surface modifications by solar wind irradiation. This abrasion process can also be regarded as a kind of space weathering in a broad sense and is called "space erosion" here. The space erosion might occur due to (a) particle motion due to seismic waves induced by small body impact, (b) sputtering by solar wind particles and (c) sputtering by micrometeoroid bombardments. The process (b) may be effective for modifying the surface nano-morphologies but probably not for the micro-morphologies. The process (c) may not be effective on relatively young Itokawa's surface [6]. Therefore, the process (a) might be effective although the abrasion rate by this process is unknown.

Two kinds of space weathering process:

As discussed above, it is reasonable to consider that the two kinds of space weathering process on Itokawa's surface are present: one is the surface modifications (formation of rim nano-structures) by so-called "space weathering" in a short time scale (<~10^3 yr.) [4-6], and the other is space erosion in a longer time scale (<~10^6 yr.). If we consider space weathering processes comprehensively, regolith particles were evolved on Itokawa's surface probably by the following processes. (1) Formation of fine particles (~100 μm in size) by impact of small bodies onto Itokawa. A small amount of fine particles that have relatively low velocities could survive although most of fine particles escaped from Itokawa [1,7]. (2) Formation of "space weathered" rims from Types-1 to -3 by solar wind irradiation to particles that were exposed on Itokawa's surface for <~10^3 yr. (3) Space erosion probably due to seismic-induced particle motion in a regolith layer for sufficiently longer duration than ~10^3 yr. Ablation of the "space weathered" rims by the particle motion might occur effectively.

The processes (2) and (3) might be repeated during residence time scale of particles in a regolith layer (<~3 Myr.). Some particles might be formed in a rough terrain of Itokawa's surface, suffered by the "space weathered" rim formation, and eroded during transportation to the smooth terrain [11].

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