SPECTRAL EVOLUTION TRACKS OF S-TYPE ASTEROIDS SUGGESTED BY PRINCIPAL COMPONENT ANALYSIS OF MULTI-BAND IMAGES OF ITOKAWA. S. Koga[1], S. Sugita[1], S. Kamata[2], M. Ishiguro[3], T. Hiroi[4], S. Sasaki[5], [1]Dept. of Complexity Sci. and Engr., Univ. of Tokyo, Chiba, 277-8561, JAPAN (koga@astrobio.k.u-tokyo.ac.jp), [2]Dept. of Earth and Planetary Sci., UC Santa Cruz, Santa Cruz, CA 95064, U.S.A., [3]Dept. of Phys. and Astr., Seoul National Univ., Seoul, 151-742, Korea, [4]Dept. of Geological Sci., Brown Univ., Providence, RI 02912, U.S.A., [5]Dept. of Earth and Space Sci., Osaka Univ., Osaka, 560-0043, Japan.

Summary: Spectral types of asteroids are often defined in a principal component (PC) space of their spectra [1,2], but how asteroids evolve with space weathering in the PC space is unknown. We used high resolution multi-band images of asteroid Itokawa, which is estimated to be covered with materials of the same initial material with different degree of space weathering [3,4], taken by Hayabsa´s AMICA (Asteroid Multi-band Imaging CAmera) and performed PCA on the spectra with main-belt asteroids spectra observed in the ECAS porgram [5]. Itokawa surface spectra span over a very wide rage along a line in the ECAS-defined PC space, ranging perhaps from around Q-type region to S-type region. The distribution of this linear trend seen in Itokawa surface spectra turned out to be very similar to spectral change of meteorite samples in space weathering simulating experiments (RELAB, [6-8]), strongly suggesting that the spectral distribution of Itokawa represents a spectral evolution track due to space weathering. Such an evolutionary track of asteroid spectra may provide important clues for understanding relationships among different spectral types.

Introduction: As an astreroid receives space weathering, the location in the PC space of the asteroid spectrum is expected to move, but the direction and the rate of such movement are still unknown. Previous studies have shown that both pulse laser irradiation, simulating micrometeorite bombardment, and heavy-ion irradiation, simulating solar wind bombardment, can cause spectral change in both pure minerals and chondrites, reproducing space weathering [9,10]. However, it is not clear if the real asteroids spectra develop in the PC space in the same way as observed in laboratory experiments. To examine this, we analyzed the spectra of asteroid Itokawa, whose surface is estimated to be covered globally with materials evolved from the same material similar to LL5 or LL6 chondrite with different degree of space weathering [4,5]. More specifically, we conducted principal component analyses (PCA) on high-resolution multi-band images of asteroid Itokawa taken by Hayabusa´s AMICA.

Analysis method: PCA was performed for multi-band visible spectra of 540 main-belt asteroids observed in the ECAS program [3], and each Itokawa surface spectrum was superimposed on the ECAS-defined PC space. Because the central wavelengths of AMICA filter bands are approximately the same as those of ECAS, we can compare the Itokawa surface in the PC space defined by ECAS dataset. If we have a continuous spectra, we can sample the ECAS filter band wavelengths and plot them in the same PC space. We use this latter approach for spectra of samples space weathered in laboratories. We used 4 sets of Itokawa images of 6 bands taken by AMICA covering the entire Itokawa surface. Each set of images were taken from the approximately same spacecraft positions with different filters. The images were calibrated following the method by [11], in which camera sensitivities are calibrated to make disk-integrated intensity to match spectrum of Itokawa observed with ground-based telescope [12,13] and coregistation procedures were conducted with translation sub-pixel shifting.

Meteorites spectra: We used the spectra of nine laser-irradiated ordinary (H, L, LL) chondrites given in the RELAB database and [6,7] and one Ar^{++}-irradiated H5 chondrite shown in [8]. The reflectance spectra of Ar^{++}-irradiated meteorite samples for the shorter wavelengths were not available for two intermediate spectra. Because the change in reflectance spectra in the missing wavelengths is very small, we linearly interpolated these missing data to complete the PCA. Thus, the direction of the movement of the two intermediate may not be very accurate, but the rate of movement would be relatively accurate.

PCA results: The spectra of the Itokawa surfaces are distributed along a line in the main-belt asteroids PC space (i.e., ECAS-defined PC space), extending widely from Q-type area to a high-population density area in the S-type cluster (Fig. 1). We also performed PCA for Itokawa surface alone. We call the obtained PCs as Itokawa-defined PCs and are shown in Fig. 2. Itokawa-defined PCs are different from ECAS-defined PCs. However, when a composite spectrum is made from ECAS-defined PC1 and PC2 with the weighing ratio of 1:0.75, which is based on the Itokawa spectra distribution trend in the ECAS PC1-PC2 space, resulting spectrum produce Itokawa-defined PC1 spectrum very well. Their correlation is >0.9. The variance contribution of Itokawa PC1 was 65-80% for the 4 sets of the Itokawa images. Fig. 3. is a map of Itokawa PC1 score and shows that PC1 score is higher in regions with regolith coverage and lower inside possible craters. This trend is consistent with the map of space weathering with spectral inflection method by [14].

The direction of movement of meteorites spectra irradiated by laser more than 20 mJ and heavy ions turned out to be very similar to that of the distribution trend of Itokawa surface spectra in the ECAS PC space. We also found that some ordinary chondrite spectra are located in an area very different from others in the PC space, but they tend to converge to the same trend line (Fig. 1). We further performed PCA for lunar soil samples with three different degrees of weathering [15] given in the RELAB database. They lie in an area different from the asteroids clusters, but trend of their distribution is very similar to that of meteorites. Furthermore, the histogram of the Itokawa surface spectra as a function of PC1 in the ECAS PC space exhibits a longer tail in the fresh side. (Fig. 4).

Implication for asteroid spectral evolution: The above results suggest that PC1 of the Itokawa surface spectra may represent space weathering end-member spectrum. Moreover, the spectra movement of meteorite samples due to space weathering simulation experiments becomes slower as irradiation accumulates. This is also consistent with the asymmetric histogram of Itokawa surface spectra. This may be a manifestation of space weathering saturation. These findings suggest that the linear trend of Itokawa spectral distribution may be a space-weathering-induced spectral evolutionary track of S-type asteroids in the PC space. Knowledge of such spectral evolution tracks will help us understand the relation among different spectral classes and subclasses of asteroids. Furthemore, the fact the distribution of Itokawa surface spectra extends very far toward fresh meteorites in the PC space strongly suggests that either impact excavation or granular flow convection due to impact-induced seismic shaking [16] may be refreshing the Itokawa surface relatively frequently. Such spectral refreshing may also keep other asteroid surface rather fresh as proposed by (e.g., [17]).

The retrograde movement of some meteorites irradiated by laser against the Itokawa distribution in the ECAS PC space may be due to their composition, while it may be attributable to experimantal reasons such as surface condition of the samples. Further analyses of the spectra of experimentally simulated space weathered samples will be very useful for understanding of spectral evolutionary tracks of S-type asteroids.

References: [1] Tholen, D.J. (1984) Ph.D. thesis, Univ. of Arizona. [2] Bus, S.J. and Binzel, R.P. (2002) *Icarus,158,* 146. [3] Tedesco, E.F. et al. (1982) *Astron.J.87*, 1585. [4] Abe, M et al. (2006) *Sci.,312*, 1334. [5] Hiroi, T. et al. (2007) *Nature, 443,* 56. [6] Hiroi, T et al. (2007) *LPSC XXXVIII*, Abstract #1048. [7] Noble, S.K. et al. (2011) *LPSC*, Abstract #1382. [8] Strazzulla, G. et al. (2005) *Icarus,174,* 31. [9] Sasaki, S. et el. (2001) *Nature,410,* 555. [10] Brunetto, R. et al. (2006) *Icarus,180*, 546. [11] Ishiguro, M. et al., (2010) *Icarus,207*, 714. [12] Binzel, R.P., et al (2001) *MAPS,36,* 1167. [13] Lowry, S.C., et al. (2005) *Icarus,176 (2),* 408. [14] Ishiguro, M. et al. (2007) *MAPS,42*, 1791. [15] Fischer, E.M. and Pieters, C.M. (1994) *Icarus,111*, 475. [16] Miyamoto, H. et al., *Sci.,316*, 1011, [17] Shestopalov, D.I. et al. (2013) *Icarus,225,* 781.

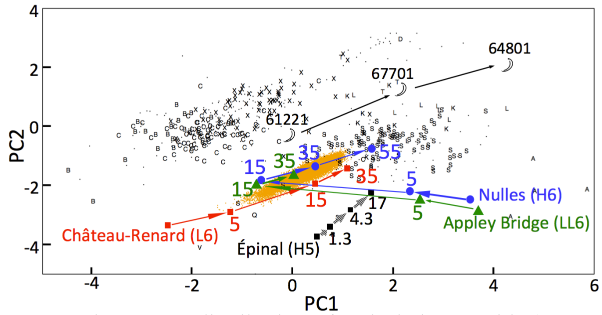

Fig. 1. The spectra distribution of main-belt asteroids (ECAS [3]), Itokawa surfaces (AMICA/Hayabusa), simulated space-weathered meteorite samples in laboratories and lunar soil samples. The black symbols and the orange points indicate main-belt asteroids and Itokawa surfaces, respectively. The colored and black points connected with arrows indicate laser-irradiated samples [6,7] and Ar^{++} -irradiated samples [8]. The numbers by the sample spectra points indicate laser intensity (mJ) or ion fluency (10^{15} /cm^2). Lunar samples 61221, 67701, 64801 are fresh, moderately weathered, highly weathered, respectively [15].

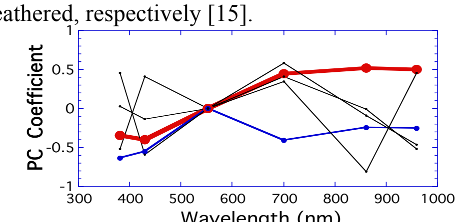

Fig. 2. Spectral pattern of principal components of 6 bands spectra of Itokawa surfaces. The thick red curve indicates the PC1, and the thinner blue curve is the PC2. The other PCs with much smaller variance contribution are shown with thin black curves.

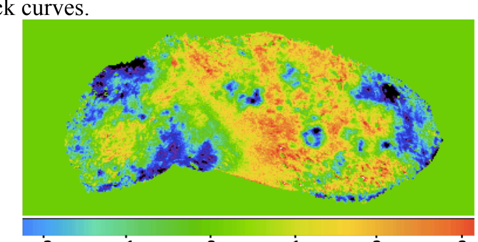

Fig. 3. The map of the PC1 of AMICA multi-band images of Itokawa surfaces. The redder color indicates higher values of PC1, corresponding to actually redder spectra.

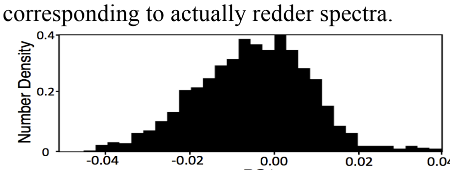

Fig.4. The histogram of Itokawa surface spectra as a function of PC1 in the ECAS PC space.