Developing space weathering on the asteroid of 25143 Itokawa

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There has been a long-standing problem that the parent bodies of ordinary chondrites, the most abundant type of meteorites, do not seem abundant among asteroids. One explanation is that surfaces of such ordinary chondrite parent bodies become optically altered to become the S-type asteroids which are abundant in the main asteroid belt. The process is called 'space weathering' which makes the visible and near-infrared reflectance spectrum of a body darker and redder[1]. The result of recent survey of small, near-Earth asteroids suggests that the surfaces of small S asteroids may present developing stages of space weathering[2]. Here we report a discovery that a dark region on a small (550-meter) asteroid 25143 Itokawa is significantly more space-weathered than a nearby bright region. Spectra of both regions show the 1-μm absorption band shape consistent with those of LL5-6 chondrites after continuum removal[3]. A simple calculation based on Hapke's space weathering model[4] suggests that the dark area has a shorter mean optical path length and about 0.04 volume % more nanophase reduced iron ($npFe^0$) particles than the bright area. This discovery clearly shows a process of accumulating space-weathered materials on small asteroids, which is likely to be an immediate parent body of LL chondrites. Because LL chondrites are the smallest in abundance among ordinary (H, L, and

LL) chondrites, the discovery of an S asteroid having an LL-chondrite composition strongly suggests that there are many S asteroids having ordinary-chondrite compositions in the near-Earth orbits.

The Japanese Hayabusa spacecraft was launched on May 9, 2003 and made a successful rendezvous with the asteroid 25143 Itokawa on September 12, 2005. During its three-month rendezvous and sampling period until early December 2005, the Near-Infrared Spectrometer[3] (NIRS) onboard Hayabusa took continuous point-target near-infrared reflectance spectra covering an effective wavelength range of 0.76~2.1 μm. Although the footprint positions for the majority of NIRS observations are not accurately located due to failures of two reaction wheels of the spacecraft, some positions are reasonably known based on simultaneous observations of the Asteroid Multiband Imaging Camera[5] (AMICA) also onboard the spacecraft. AMICA images clearly show large variations in both brightness and color correlated to each other over the entire surface of Itokawa[6]. Such evidence of space weathering can be addressed more precisely using NIRS data. Based on the preliminary study[3] deriving the likely surface composition of Itokawa as the LL5 or LL6 chondrite meteorite, this study concentrates on the aspect of space weathering derived from NIRS observations near Tsukuba and Sagamihara on October 25 shown in Fig. 1. Shown in Fig. 2 are variations in reflectance and the 1-μm band continuum slope in the time sequence during the above NIRS observations. It is clearly seen that there is a good correlation between reflectance and the continuum slope: the darker, the redder. Two data points each from the bright and blue area and the dark and red area near Tsukuba and Sagamihara are chosen for analyses.

Reflectance spectra of the above chosen points are photometrically corrected[3] to 30° incidence and 0° emergence angles and averaged by each region. The spectra are plotted in Fig. 3 and compared with an LL5 chondrite spectrum after continuum removal. Consistent with earlier studies[3,9], these NIRS spectra exhibit similar band features around 1.0, 1.25, and 1.95 μm to those of this LL5 chondrite. After continuum removal, all three spectra look very similar to one another except the depths of absorption bands. The mismatch around 1.7 μm in wavelength is due to the known calibration error. This suggests that they are made of the same material similar to LL5 or LL6 chondrite with different degrees of space weathering and/or mean optical path length (MOPL). The MOPL can be the effective grain size if the material is particulate, monomineralic grains, but the MOPL of a rock may depend not only the mineral grain sizes but also the physical conditions such as porosity.

In order to estimate the degrees of space weathering in these two regions, Hapke's space weathering model[4] is employed. He proposed a formula for the absorption coefficient $\alpha(\lambda)$ of a material containing nanophase metallic iron ($npFe^0$) particles:

$$\alpha(\lambda) = \alpha_{\mathrm{h}}(\lambda) + \frac{36\pi}{\lambda} \phi\, z(\lambda) \,, \tag{1}$$

$$z(\lambda) = \frac{n_{\mathrm{h}}^3 n_{\mathrm{Fe}} k_{\mathrm{Fe}}}{(n_{\mathrm{Fe}}^2 - k_{\mathrm{Fe}}^2 + 2n_{\mathrm{h}}^2)^2 + (2n_{\mathrm{Fe}} k_{\mathrm{Fe}})^2} \,, \tag{2}$$

where α_{h} is the absorption coefficient of the host material, λ is the wavelength of light, n_{h} is the real part of refractive index of the host material, n_{Fe} and k_{Fe} are the real and imaginary parts of refractive index of iron, and ϕ is the volume fraction of $npFe^0$ particles in the host material. If we assume that the absorbance spectrum of the Alta'ameem sample and the surface material of Itowaka can be approximated with negative natural logarithm of its reflectance spectrum, we can obtain from Eq. (1),

$$\ln R(\lambda) \cong -\left\{ \alpha_{\mathrm{h}}(\lambda) + \frac{36\pi}{\lambda} \phi z(\lambda) \right\} d_{\mathrm{e}} \,, \tag{3}$$

where $R(\lambda)$ denotes reflectance at wavelength λ, and d_{e} the MOPL.

The absorption coefficient spectrum of the Alta'ameem sample (<125 μm) can be obtained using Eq. (3) with no $npFe^0$ ($\phi = 0$) from its laboratory reflectance spectrum by assuming its effective grain size to be the median 62.5 μm for example. Assuming the host material of Itokawa's surface has the same optical properties with those of the Alta'ameem sample, we use the above-obtained absorption coefficient as $\alpha_{\mathrm{h}}(\lambda)$ in Eq. (3).

Based on a previous study[10] that LL5-6 chondrites have mineral assemblages dominated by olivine (about 55 % in modal abundance as opposed to 25 % of pyroxene abundance) which has an average chemical composition of Fe / (Fe + Mg) ratio of about 0.4 (Fa 40), we can derive the real part of refractive index of the host material n_h as 1.76 at the visible wavelength (0.55 μm)[11]. The corresponding spectral shape is assumed to be $n_h(\lambda) = 1.6328 + 0.06998/\lambda$, where λ denotes wavelength in μm[12]. Then, the $z(\lambda)$ function in Eq. (3) can be calculated using Eq. (2) and adopting the data on the real and imaginary parts of refractive index of metallic iron[13] extrapolated to the longer wavelength as was done in Hapke's space weathering model[4].

We are now ready to estimate the volume % of $npFe^0$ (ϕ) and MOPL (d_e) in Eq. (3) for the natural log reflectance spectra of the Dark and Red area and the Bright and Blue area by optimizing these two parameters for the best fit between the measured spectrum for each region on the left hand and the model spectrum calculated on the right hand of Eq. (3). The results are shown in Fig. 4. As is expected, both areas require some amounts of $npFe^0$ and smaller MOPL than those for the Alta'ameem sample, where the Dark and Red area having 0.069 vol% $npFe^0$ is more space-weathered than the Bright and Blue area having 0.031 vol% $npFe^0$. The average of these two amounts of $npFe^0$ is consistent with the result of a ground-based telescopic work[9], which estimated it as 0.05

vol%.

Note that the natural log reflectance values used in the optimization process and shown in Fig. 4 are offset to 0 at 1.54 μm in wavelength. Due to the surface roughness and incident angle variation, a wavelength-independent factor always makes the apparent reflectance spectrum different from the standard spectrum measured in a laboratory even if the material may be the same. Such a factor appears as an offset in the natural logarithm of reflectance spectrum. The above offsetting process cancels that factor. Also, there seems to be a clear calibration problem around 1.7 μm. However, the fact that the Dark and Red area is more space-weathered than the Bright and Blue area should still hold true.

Some may also suspect that similar optical effect (darkening and reddening) could take place by enrichment of metallic iron particles on the surface regolith. If Itokawa is made of LL5 or LL6 ordinary chondrite, metallic iron grains cannot be separated unless the regolith contains many fine particles less than 100 μm in size. However, close-up images of AMICA reveal that the entire surface of Itokawa is full of much larger pebbles and boulders. Therefore, it is highly unlikely that metallic iron or other opaque mineral grains separate from silicate grains and become concentrated on the surface.

Because space weathering process is believed to take a significantly longer time than the average surface lifetime of a small body such as Itokawa, the surface which can accumulate the effect of space weathering needs to be stable and have little new incoming materials over it. Sagamihara may be one of such places on Itokawa. Including Sagamihara, features on asteroid Itokawa observed by the Hayabusa spacecraft may present the first, clear look of an asteroid of an ordinary-chondrite composition in its developing stage of regolith formation and space weathering process.

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Author Contributions

T. H. contributed to the overall analyses and measurements of some meteorite samples in this work. M. A., K. K., and S. A. contributed to production and calibration of NIRS data as well as discussion on the NIRS data quality. K. K. and B. E. C. contributed to photometric correction of NIRS spectra. B. E. C. and O. S. B.-J. contributed to deriving footprint positions of NIRS observations. S. A. provided gravity information. M. I. contributed to choosing the target location on Itokawa to study in this work based on AMICA color image works. S. S. contributed to providing meteorite samples and space weathering discussions.

Figure Captions

Fig. 1. A monochromatic image of asteroid Itokawa with NIRS observation points indicated. This AMICA v-band image (Time ID: 2489416612) containing Sagamihara and Tsukuba was taken at 8:16:21 UT on October 25, 2005 at a solar phase angle of about 21° and 5.3 km distance from the asteroid. The NIRS footprint of about 6.6 m in size[7] when this image was taken is indicated as an open square, and its movement as an arrow. The location of the NIRS footprint requires very accurate spacecraft location information. This was achieved in a non-traditional manner by using data on the illuminated center of figure XY of the asteroid obtained by the Wide Angle Camera (WAC) aboard the Hayabusa spacecraft. Using knowledge of the alignment between NIRS, the Hayabusa Laser Altimeter (LA) and this WAC imager, we were able to use the XY information, the LA ranges, and the most recent shape model of Itokawa[14] to determine the spacecraft location at 10 min intervals. From the spacecraft attitude information and a simple spacecraft trajectory model, we determined the location of the spacecraft location within 10 m at every 1s interval each time the LA ranged to the surface of Itokawa. With this spacecraft location we were able to identify the location of the NIRS footprint in most instances to within 10 m.

Fig. 2. Variations in brightness and redness of NIRS spectra near Tsukuba and Sagamihara. The brightness is defined as reflectance at 0.76 μm (open and filled circles) and the redness as the 1-μm band continuum slope (1.54 μm / 0.76 μm) (open and filled triangles). Continuum slopes are plotted by scaling with a factor of 0.1. The NIRS observations were performed at every one minute seven seconds. Data points plotted in filled triangles and circles indicate spectra which are darker than 12.3 % and redder than 1.33 (Dark and Red area), or brighter than 15.2 % and bluer than 1.23 (Bright and Blue area) used for spectral analyses.

Fig. 3. Comparison of reflectance spectra of two areas on Itokawa with an ordinary chondrite spectrum. Plotted here are natural logarithm of average reflectance spectra of the Dark and Red area and the Bright and Blue area (filled markers), their continuum-removed spectra (open markers), and the continuum-removed and scaled spectrum of Alta'ameem (LL5) chondrite[8] powder sample (<125 μm). Both the NIRS spectra the Alta'ameem spectrum are for the same viewing geometry of 30° incidence and 0° emergence angles. Continuum (broken line) is defined as a linear-to-wavenumber curve which passes the shortest-wavelength data point (at 0.76

μm) and is tangential to the spectrum around 1.55 μm, connected with a constant (flat line) longward of that contact point. Continuum-removed Alta'ameem spectrum was scaled by factors of 0.43 and 0.63 to fit with the spectra of the Dark and Red area and the Bright and Blue area, respectively.

Fig. 4. Estimation of the degrees of space weathering of two areas on Itokawa. Natural log reflectance spectra of Dark and Red area and Bright and Blue area of Tsukuba are fit with the spectrum of Alta'ameem (LL5) <125 μm sample by optimizing the mean optical path length (MOPL) and volume percentage of nanophase metallic iron ($npFe^0$) particles. Considering the data quality and the importance of the 1-μm band feature as indicators of the degree of space weathering, grain size, and composition, only the NIRS data in the wavelength range from 0.76 to 1.00 μm are used in the optimization process with the data point at 1.54 μm always offset to 0.