Global mapping of the degree of space weathering on asteroid 25143 Itokawa by Hayabusa/AMICA observations

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Abstract—We obtained color images of near-Earth asteroid 25143 Itokawa by the Hayabusa multi-band imaging camera to characterize the regional color properties. Images were obtained for the whole disk from the gate position (GP) and home position (HP) at a spatial resolution of 0.8–3.7 m/pixel. Whole-disk spectra are adjusted to the telescopic data obtained by the University of Hawai’i’s 88-inch telescope using the Eight Color Asteroid Survey (ECAS) system. The disk-resolved measurements show large variations in the three visible channels. We present a map of an index related to the degree of space weathering, which has been newly developed based on laboratory measurements. We find large variations in the degree of space weathering on Itokawa. Fresh materials are observed in regions of steep slopes and craters, whereas mature materials are ubiquitously distributed. This result suggests that pristine ordinary chondrite-like materials have been exposed through weathered layers by excavation. By also examining close-up images obtained during touchdown rehearsal, we find that most rocks in Itokawa’s rough terrains are weathered. Instead of a regolith blanket, the surface of this small asteroid is covered with weathered rocks and gravels.

INTRODUCTION

Remote sensing is an essential approach to learning about the nature of asteroids. Multi-band observations by cameras on board spacecraft provide detailed information regarding chemical and physical properties on the surface of target bodies. As a result of previous asteroid missions, colorimetric studies were reported. Galileo spacecraft images revealed a 5–10% albedo contrast and ~10% color (0.76 μm/0.41 μm) variation on S-type asteroids 951 Gaspra and 243 Ida (Helfenstein et al. 1994; Veverka et al. 1996; Chapman et al. 1996). The color and albedo heterogeneities were correlated...
AMICA MULTI-BAND OBSERVATIONS AND THE COLOR MAP OF ITOKAWA

One of the optical navigation cameras (ONC-T) was developed to acquire scientific data as well as for engineering purposes (Nakamura et al. 2001). The Asteroid Multiband Imaging Camera (AMICA) is equipped with a broad-bandpass filter and seven narrow band filters. The narrow-band filter system is nearly equivalent to that of the Eight Color Asteroid Survey (ECAS) system (Tedesco et al. 1982; Zellner et al. 1985); that is, the designed effective wavelengths (and the full width of half-maximum) for solar incident light are $0.38 (0.05) \, \mu m$ (ul-band), $0.43 (0.11) \, \mu m$ (b-band), $0.55 (0.07) \, \mu m$ (v-band), $0.70 (0.07) \, \mu m$ (w-band), $0.86 (0.08) \, \mu m$ (x-band), $0.96 (0.08) \, \mu m$ (p-band), and $1.01 (0.07) \, \mu m$ (zs-band), respectively. During the nearly 3-month observation period in approaching phase and mission phase, AMICA took approximately 1400 images of Itokawa at solar phase angles between 0 and $35^\circ$ (Fig. 1). About 60% of Itokawa images are obtained for the purpose of shape modeling and topography with lossy compression, and about 40% are for photometric studies with lossless compression.

Global mapping was done from a distance of about 20 km in the gate position (GP) and about 7 km in the home position (HP), a region roughly on a line connecting the Earth with the asteroid on the sunward side. The solar phase angle during GP and HP was small (typically $10^\circ$). After substantial observations, the spacecraft left the HP and made a tour (Fujiwara et al. 2006) to observe Itokawa at various attitude and solar phase angles ($0–35^\circ$; see Fig. 1). The data taken during the tour period is useful not only for the topography and scattering properties of Itokawa’s surface, but also for the calibration of camera data using the ground-based data because of the limited conditions of the ground-based observations (most telescopic studies were performed at solar phase angles of 15–90° (see e.g., Lederer et al. 2005).

Most of the color mapping data was obtained in GP and HP when the spacecraft was at an altitude of 8–23 km. The $1 \times 1$ or $2 \times 2$ pixel binning, which is the combination of the observed flux of adjacent $1 \times 1$ or $2 \times 2$ detector in the CCD, were applied according to the total data amount. A total of 37 sets of multi-color observations were scheduled, but v-band images in 9 sets were found to be useless due to an incorrect
Space weathering map of Itokawa

Table 1. Images used for this study.

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largely independent of incident and emergence angle. In Fig. 3, we show the emergence angle dependence of $R_w/R_b$ color ratio in four terrains, which show negligible change up to ~60°. We can ignore the phase reddening (reddening with increasing phase angles) because the data presented here were taken at narrow-phase angle range (Fig. 1). Accordingly, space weathering is possibly a process that can explain the color and albedo variation on Itokawa.

LABORATORY MEASUREMENTS

Itokawa’s surface has an olivine-rich mineral assemblage and is potentially related to LL5 or LL6 chondrite materials (Abe et al. 2006a; Hiroi et al. 2006b). We thus focus on LL chondrites here. A broad comparative study of space-weathering indices with other materials is beyond the scope of this application, but will be discussed elsewhere. Harleton...
(L6) and Cherokee Springs (LL6) ordinary chondrites were prepared in different forms, that is, a chip and powder-size fractions (125–500 and <125 μm). An Alta’ameem (LL5) sample was prepared into a <125 μm size fraction, and powder samples (<250 μm) of Northwest Africa (NWA) 1799 (LL5) were prepared and pressed into pellets. The pellets were irradiated with a pulsed laser at 5 and 15 mJ as a space-weathering simulation (Sasaki et al. 2001) at National Astronomical Observatory of Japan. Bidirectional reflectance spectra of the meteorite samples were taken at various incidence and emergence angles between 0 and 60° at the NASA Reflectance Experiment Laboratory (RELAB) at Brown University, the University of Tokyo, or JAXA/ISAS. It is well known that space weathering strongly alters the visible reflectance spectra of airless planetary surface materials, namely by darkening and reddening (Pieters et al. 1993). It is not as well known that space weathering also causes changes in spectral inflections around 0.42 and 0.55 μm in wavelength. In Fig. 4, we show the normalized reflectance in order to see the change in the inflection. In laboratory experiments, we used a laser beam to simulate the processes of space weathering caused by micrometeorite bombardments. We assume that increasing laser energy corresponds to higher degrees of space weathering (Sasaki et al. 2001). We observe that as the degree of space weathering progresses, inflections at 0.42 and 0.55 μm decrease toward a smoother spectrum. With AMICA multiband spectroscopy, we can quantify the inflections (Hiroi et al. 2006a):
where \( R_x \) and \( \lambda_x \) indicate reflectance and effective wavelength for a band \( x \), respectively.

From our experiments, it is found that 1) both \( C_v \) and \( C_b \) show a good correlation to the amount of irradiated pulse-laser energy in NWA 1799 LL5 chondrite sample (Fig. 5); 2) \( C_v \) and \( C_b \) values for the Alta’ameem LL5 sample show negligible change up to 50° of phase angle and up to 60° of incident angle (Figs. 6a and 6b); and 3) \( C_v \) for both Cherokee Spring LL6 and Harleton L6 samples is largely independent of the grain size (Fig. 6c; see also Hiroi et al. 2006a). In Figs. 4 and 5, we plot the reflectance and \( C_v \) in the fresh-looking Kamoi crater and the matured Tsukuba basin (surrounding area of Tanegashima boulder), two terrains that differ strongly in color properties. (Note that Tsukua is a tentative name used in previous papers; see, e.g., Demura et al. 2006). Both the reflectance and \( C_v \) of the bright blue crater Kamoi is similar to that of a fresh ordinary chondrite sample.

**RESULTS**

**Space Weathering Map**

We apply the \( C_v \) index to AMICA data; the results are shown in Fig. 7. The boundary of the solar incident angle of 60° is delineated to delimit the effective region of the \( C_v \) index by applying Itokawa’s shape model (Gaskell et al. 2006). Most fresher (bluer) areas in Fig. 7 correspond with brighter and bluer regions in Fig. 2. Thus, we could conclude that a plausible explanation for the color and albedo effects observed on Itokawa is space weathering. No significant difference has been observed in space weathering between “head” and “body.” The overall degree of freshness is greater for the western (Tsukuba) side than the eastern (MUSES-C Regio) side. This might be related to the difference in general appearances of large boulders; the eastern side has a rougher surface due to larger numbers of big boulders (Fujiwara et al. 2006). While differences in the degree of space weathering are limited between two smooth terrains (MUSES-C Regio and Sagamihara Regio), significant variations are observed in rough (boulder-rich) terrains. Although most rough terrains are weathered, pristine areas are found specifically in regions of steep slopes (e.g., Shirakami region, edge of Little Woomera) and crater rims (e.g., Kamoi crater). In addition, big boulders (e.g., Yoshinodai, Pencil, and Tanegashima boulders) are found to be immature.
The circular area surrounding the Tanegashima boulders is reddish in $R_{w}/R_{b}$ (Fig. 2b) and also dark red in the $C_{v}$ index (Fig. 7b). This area may have a mature fine-material deposit. A similar trend is observed in Little Woomera Regio (Fig. 2c). There are, however, some regions that show unusual relationships between $R_{w}/R_{b}$ and $C_{v}$. In Fig. 2d, MUSES-C Regio appears to gradually change from brighter and bluer on the western (Yatsugatake region) side to darker and redder on the eastern (boulder-rich) side on the $R_{w}/R_{b}$ map. However, on the $C_{v}$ map, MUSES-C Regio appears to be mostly space-weathered. The east-west variation in color and brightness of MUSES-C Regio may be caused by grain size, roughness of particles, or freshness change. Yano et al. (2006) reported that 1) MUSES-C Regio is filled with size-sorted regolith, mostly ranging from millimeter to centimeter scales; 2) no spectral variations in MUSES-C Regio were found by XRS or NIRS; and 3) MUSES-C Regio has the minimum potential over the entire surface of Itokawa. Their results suggest that particle segregation from the eastern side to Yatsugatake side (Yano et al. 2006; Miyamoto et al. 2007) may be explained by the color variation in Fig. 2d. In the case of freshness change, the change may be too subtle to detect using the $C_{v}$ index. In all cases, it can be said that samples collected at touchdown probably include weathered surface materials, as the $C_{v}$ map shows that the whole surface of MUSES-C Regio is weathered. Yoshinodai boulder looks fresh in both $R_{w}/R_{b}$ and $C_{v}$ maps. Half-buried boulders Tanegashima and Pencil look neutral or redder in the $R_{w}/R_{b}$ map, but they are less matured in the $C_{v}$ map. The accumulation process of rubble-pile asteroid might cause the immaturity of half-buried big boulders. Larger boulders, which formed the core of the asteroid in the early stage of the formation, were embedded in a blanket of smaller boulders (Britt and Consolmagno 2001), and have recently come to the surface due to external forces (e.g., seismic shaking or tidal force by planetary encounter). Another possibility is that a spallation of boulders on the surface could cause the freshness changes (Nakamura et al., Forthcoming). In this case, freshness heterogeneity on boulders can be expected. Further analysis using higher resolution color maps are needed.

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Fig. 6. Effects of viewing geometry and grain size on the amounts of ul-b-v-w inflections $C_{b}$ and b-v-w inflection $C_{v}$. Effects of (a) phase angle and (b) incidence angle using an LL5 chondrite sample, and (c) the effect of grain size using LL6 chondrite chip and powder samples.
Fig. 7. Space-weathering index \((C_v, b-v-w\) inflection) map overlaying a w-band image. The solid line denotes the boundary of the incident angle of 60°; at less than this angle, the index accurately shows the degree of space weathering.

Fig. 8. Close-up images on the western side. Original lossless data were processed with the Lucy-Richardson image deconvolution algorithm in order to restore the blurred images. The spatial resolutions are 6 mm/pixel (left) and 9 mm/pixel (right). The left image (ST_2544579522) is of a ubiquitously rough area. The right image (ST_2544617921) is the boundary between a rough (boulder-rich) area and a brighter (fresher) area on the rim of LINEAR crater.
Comparison with Close-Up Monochromatic Images

In Fig. 8, we show high-resolution images of Itokawa rough terrains. These images were obtained during a touchdown rehearsal on November 12, 2005, using a v-band filter. Due to the Fourier image deconvolution process, the spatial resolutions of these two images are improved to the pixel resolutions, that is, 6 mm (Fig. 8a) and 9 mm (Fig. 8b). The left image (Fig. 8a) reveals that particles less than a centimeter in size are very limited, or even lacking, on the surface of this boulder-rich area. If the boulders are coated by finer particles, brightness heterogeneity caused by inhomogeneous thickness can be expected. Uniform darkness (the brightness difference is less than 10%) of the boulders and evidence of weathering in most boulder-rich terrain (e.g., rough terrain on the eastern side) suggests that the rocky surfaces are likely weathered in spite of the inefficiency of the processes there (Sasaki et al. 2006; Strazzulla et al. 2005). In close-up images, most bright (fresh) areas are observed to underlie dark boulders (Fig. 8b). This indicates that the brighter areas might reflect the subterranean fresh materials, which were exposed due to the removal of weathered boulders. While fresh material in craters can be explained by the excavation of the weathered layer by impact, freshness on steep slopes remains an open question. The lack of flow front and talus structure in Shirakami region cannot simply be explained by the removal of the superposed boulders (Saito et al. 2006). The existence of bright spots (Fig. 8a) and scars, which were probably produced by interplanetary dust particle bombardments, on dark boulders might support the assumption that the boulders on Itokawa are covered by thin weathered layers.

SUMMARY AND DISCUSSION

In this paper, we show the color images of the near-Earth asteroid Itokawa taken by Hayabusa’s multi-band imaging camera AMICA. The disk-resolved measurements show large variations in three visible channels. We present a map of an index related to the degree of space weathering, and find large variations in the degree of space weathering on Itokawa. Unlike the large asteroids (>10 km) studied by previous space missions, this small asteroid has little or no regolith blanket. Instead, most of the surface of Itokawa is covered by weathered rocks and gravel, which require considerable time to develop weathered layers. In fact, the space-weathering index obtained from ECAS Version 3.0 shows that the surfaces of Ida (C_v = 0.09 ± 0.11) and Gaspra (C_v = −0.38 ± 0.30) would be more mature than that of Itokawa (disk-averaged C_v = −0.49 ± 0.02).

Recent ground-based observations suggest that a color transition exists between ordinary chondrite-like objects and S-type asteroids over size range of 0.1–5 km, which implies that the surfaces of small asteroids are evolving toward the colors of larger asteroids (Binzel et al. 2004). The evidence arguing for less space weathering on small near-Earth asteroids obtained by ground-based observations implies that 1) these asteroids are young because collisions that generate new objects or fresh surfaces become much more frequent at small sizes (Bottke et al. 2005; O’Brien and Greenberg 2005), and 2) they do not have sufficient gravity to have a regolith blanket, which is susceptible to space weathering.

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Editorial Handling—Dr. Carlé Pieters


