Regolith Properties on the S-type Asteroid Itokawa Estimated from Photometrical Measurements.

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Introduction: Photometry is a powerful tool that can be used through remote sensing to understand the surface regolith properties of an asteroid, especially prior to direct observations by spacecraft. The details of asteroid regolith properties, prior to the arrival of a spacecraft, is critical for planning the scientific program and observations that will take place by the spacecraft. Photometric analysis from telescopic observations (ground-based or spacecraft-based) is a very effective way to estimate mechanical and structural properties of the regolith remotely.

In 2018, JAXA's Hayabusa2 spacecraft and NASA's OSIRIS-REx spacecraft will arrive at their target asteroids, Ryugu and Bennu, and will return regolith samples from the surfaces. It is important to know the surface conditions, such as grain size and porosity, before sampling surface materials because surface conditions may greatly influence the safety of touch down and sample yield. Thus, estimating the surface conditions of Ryugu based on photometric observations will be extremely useful.

To test how effectively we can predict the surface conditions of a small asteroid based on photometry, we investigated Itokawa data. The Hayabusa spacecraft observed Itokawa at phase angles 0.7˚ – 37˚; the detailed opposition observations (phase angles < 5˚) help constrain regolith grain size and porosity. In this study, we analyzed the disk-integrated photometry of Itokawa compiled from both ground-based telescope observations [1] and spacecraft observations and discuss what the photometry implies about the surface regolith properties. Further, our results are compared with other remote-sensing observations and the returned-sample analyses.

Data and Methodology: We used the ground-based telescopic data obtained by [1] and the images obtained by AMICA (Asteroid Multi-band Imaging Camera) onboard Hayabusa [2]. The AMICA dataset includes 6 color filters (ul: 381 nm, b: 429 nm, v: 553 nm, w: 700 nm, x: 861nm, p: 960nm) with phase angles between 0.7˚ - 37˚. The telescopic dataset includes 5 color filters (U: 360nm, B: 440nm, V: 540nm, R: 630nm, I: 850nm) with phase angles between 4˚ - 139˚. However, only the spacecraft b-, v-, w-, and p-filter data included near 0˚ phase images for analyzing the opposition region in detail. The images were calibrated using the method by [2]. The difference in filter transmissions between the two systems was taken into account by using the reflectance spectral shape [3]. The agreement between the telescopic and spacecraft phase curves indicates that the AMICA images are well calibrated. The resulting disk-integrated phase curve for each filter was modeled using Hapke's model [4] using a least-squares grid search after equally weighting all regions of each phase curve [5].

Table 1. Disk-integrated Hapke parameters of Itokawa.

Hapke Parameters	Lederer et al. (2008)	This Study
w	0.7 ± 0.04	0.57 ± 0.05
B_{S0}	0.02 ± 0.1	0.98 ± 0.06
h_s	0.141 ± 0.1	0.05 ± 0.02
b	0.59 ± 0.04	0.35 ± 0.04
c	0.87 ± 0.04	0.56 ± 0.08
θ	40° ± 5°	40° ± 3°
χ	6.2387e-5	9.30e-7

Results: The Hapke model parameters for the V-band are shown in Table 1 in comparison with earlier ground-based derived parameters [1]. There are large differences in single-scattering albedo (SSA) w and shadow hiding opposition effect (SHOE) parameters B_{S0} and h_s due to the additional observations in the opposition region obtained by AMICA (Fig. 1) that cannot be constrained by the higher phase-angle ground-based data.

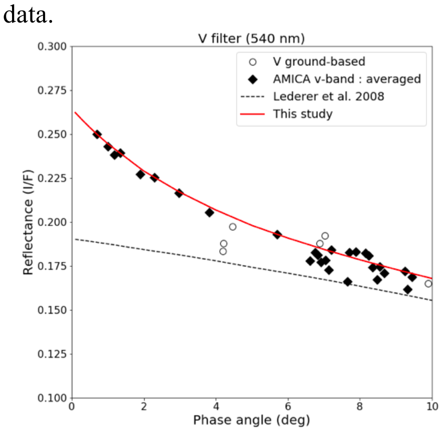

Figure 1. Hapke models of Itokawa constrained only by the ground-based observations [1] (dotted black) and this study by the ground-based and Hayabusa observations (red solid).

Itokawa Regolith Properties: The Hapke parameters are theoretically connected to the properties of the surface regolith. Using these theoretical relationships, we estimated several properties of Itokawa's regolith and compared them with another S-type asteroid, Eros, which was observed in detail by the NEAR spacecraft.

Geometric albedo and SSA. The geometric albedos of Eros for UBVRI and p-filter are calculated as

0.21±0.05, 0.24±0.02, 0.27±0.02, 0.30±0.02, 0.32±0.02, and 0.30±0.02, respectively. The V-filter value is similar to the geometric albedo of Eros (0.29±0.02) at 550nm [5], even though Itokawa's SSA is much higher than that of Eros (0.43). Itokawa's higher SSA can be explained by either particles with higher albedos or by smaller regolith grain sizes than Eros. However, the Hayabusa images show that the average grain size distribution on Itokawa is larger than Eros, indicating that Itokawa may be covered with brighter particles. This suggests that Itokawa might be covered with materials less space weathered than Eros, as the compositions of both asteroids are consistent with LL chondrites [6,7].

Roughness. The surface roughness, θ, for Itokawa is comparable to that of Eros (36°±5°). This contradicts with roughness visually inferred from images of the two asteroids. One hypothesis is that the irregular macroscopic shapes of both asteroids is contributing to the roughness value since telescopic data treats both objects as point sources and the model assumes a spherical shape. Note that this value is larger than the roughness value derived by regional analysis using NIRS data [8].

Opposition effect. In the classic Hapke model, the opposition effect is modeled as a single-scattering phenomenon (SHOE). However, theoretically there is an alternative mechanism, namely coherent backscattering opposition effect (CBOE), which is due to multiply scattered light. We fitted the derived phase curves to the recently updated Hapke model [9], which includes both mechanisms. The modern Hapke model parameters in the V-filter are found to be B_{s0}=0.79±0.06, h_s=0.17±0.06, B_{c0}=0.27±0.06, and h_c=0.04±0.06. The amplitude of CBOE is smaller than that of SHOE, suggesting that SHOE may make a larger contribution to the opposition effect. This is supported by Itokawa's rough surface. The CBOE width h_c is related to microscopic structures, such that $h_c = \lambda/4\pi\Lambda_T$, where λ is the observational wavelength and Λ_T is the transport mean free path. The transport mean free path is estimated to be ~1 μm. This is much smaller than the typical particle size (10 – 100 μm) of the returned samples. This implies that the particle size may not cause the coherent backscattering. In fact, sample analyses suggest that sub-micron-sized features such as impact craters [e.g., 10] and polycrystalline materials [e.g., 7] could be contributing to the CBOE.

Simulation from the Hapke model: Simulated I/F images were created based on the geometrical and illumination conditions from the Hayabusa SPICE kernels, the shape model, and the Hapke modeling results. Figure 2 compares the observed image and the simulated image, which shows that the Hapke model underestimates the reflectance at the edges of the object, where incidence and emission angles are large (>70°). The differences across the surface indicate that that a single set of parameters may not fully describe the entire surface.

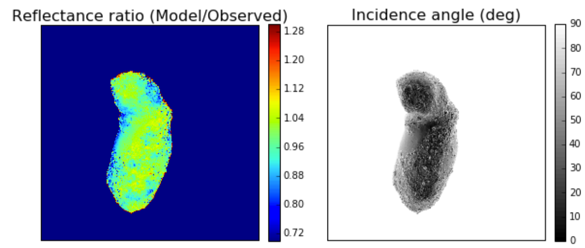

Figure 2. Comparison between the model reflectance and the observed reflectance: ST_2385578902_v at phase 8.1°.

Summary: Our photometric analyses of disk-integrated measurements of Itokawa, based on both ground-based telescopic data and Hayabusa imaging data, indicate the following conclusions:

1. The geometric albedo of Itokawa (0.27) is similar to that of Eros (0.29), but the SSA of Itokawa (0.57) is higher than Eros (0.43). This suggests that Itokawa is less space weathered than Eros, consistent with the young ages of the returned samples.
2. Regolith properties based on Itokawa's opposition effect, first directly observed by Hayabusa, are well constrained by the AMICA images.
3. Surface roughness for irregularly shaped objects may not be well constrained by disk-integrated observations alone. Disk-resolved measurements may be needed to adequately determine roughness.
4. Sub-micron sized features on larger regolith grains [8] may possibly contribute to the opposition properties of Itokawa's regolith.

References: [1] Lederer S.M. et al., (2008) *EPS, 60,* 49. [2] Ishiguro M. et al. (2010) *Icarus, 207,* 714. [3] Lowrys et al., (2005) *Icarus,* 408. [4] Hapke B., (1986) *Icarus, 67,* 264. [5] Domingue D. et al., (2002), *Icarus, 155*, 205. [6] Peplowski et al., (2015) *MAPS, 50,* 353. [7] Nakamura T. et al., (2011) *Science, 333*, 1113. [8] Kitazato et al., (2008) *Icarus, 194*, 137. [9] Hapke B., (2012) Cambridge Univ. press. [10] Matsumoto T. et al., (2018) *Icarus, 303*, 22.

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