DENSITY DISTRIBUTION ESTIMATION OF ASTEROID ITOKAWA BASED ON DISTRIBUTION OF SMOOTH TERRAIN.

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Introduction: Small solar system bodies have a wide variety of sizes and bulk densities (or macroporosities) [1]. These fundamental physical properties encode crucial information for investigating asteroid interiors and their evolutions. Asteroids larger than 100 km generally have more spherical shapes and higher bulk densities. It is also possible that a size of a few hundred km is large enough to fully or partially differentiate their interiors [2]. On the other hand, smaller asteroids of several km to sub-kilometer in size are likely to be more primitive bodies. Their shapes and internal structures are more directly affected by impact events and disruption of their parent bodies and subsequent accumulation processes.

In spacecraft missions targeting a small body, a detailed 3D shape model can be obtained by stereo photogrammetry. However, it is difficult to measure variations in the gravity field precisely enough to investigate whether the interior density distribution is homogeneous or not. In this study, we propose a new method to estimate interior density distribution within a small body, which will help us shed light on the formation process of a rubble-pile asteroid.

Our estimation method is based on a fitting between a simulated gravity field and the surface topography observed by a spacecraft camera. We applied this method to asteroid 25143 Itokawa, a rubble-pile asteroid visited by Japan's spacecraft Hayabusa, which has two distinctive lobes, a "head" and a "body" (Figure 1) [3]. There exists also three flat and smooth regions on Itokawa, named "MUSES-C Regio", "Sagamihara Regio" and "Uchinoura Regio". This smooth terrain is associated with low areas of the gravity potential and is considered to be formed by mass movement and accumulation of fine gravels [4]. We assumed that these small particles will move down slope, and accumulate in regional gravitational lows, analogous to water on Earth. We extracted the smooth terrain from a 3D shape model of Itokawa and varied the interior density distribution such that these regions approach an equi-potential surface.

Table 1. Physical properties of Itokawa [3, 6]

Dimension	535 × 294 × 209 m
Rotation period	12.1324 hours
Mass	$(3.58 \pm 0.18) \times 10^{10}$ kg
Volume	$(1.84 \pm 0.09) \times 10^{7}$ m^3
Density	1,950 ± 140 kg/m^3
Macroporosity	~ 40 %

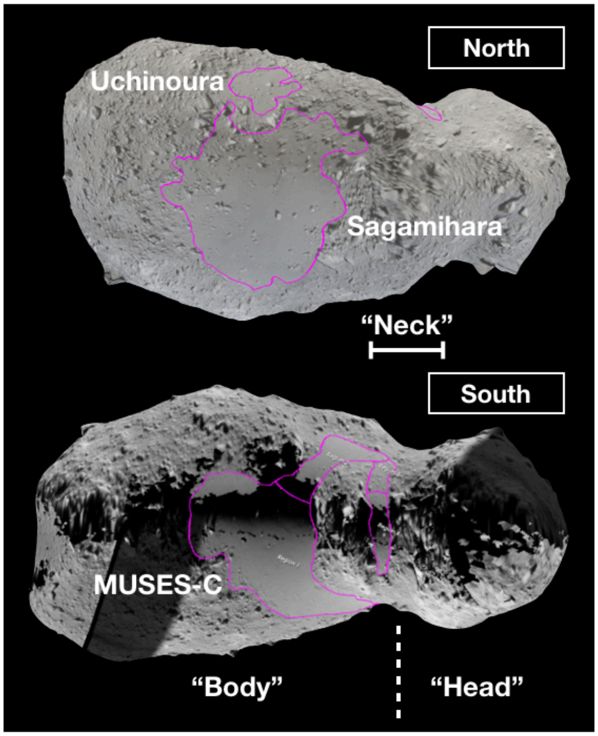

Figure 1. Smooth terrain extracted from Itokawa imagery using the Small Body Mapping Tool [7].

Mascon Gravity Modeling: In order to simulate the gravity field of Itokawa taking density heterogeneity into account, we filled up its shape with numerous point masses (or mascons). We utilized the Netgen Mesh Generator to generate tetrahedral meshes inside a Gaskell shape model that was composed of 786,432 surface facets [5]. The numerical mesh model used in this study has 3,613,429 volume elements and 173,974 surface elements. Every volume element was approximated by a point mass, and the gravity potential and acceleration were calculated on the surface elements by summing the contribution from each point mass. The centrifugal potential and force due to rotation at a rate of 12.1324 hours were then combined with the gravitational term.

Table 1 shows the physical properties used for the gravity modeling. The re-meshed shape model has a volume of 1.77×10^7 m^3, and thus a mean density of the asteroid is 2,020 kg/m^3, which is within the uncertainty of the spacecraft measurement [6].

Smooth Terrain Extraction: We used the Small Body Mapping Tool to visualize the shape model and

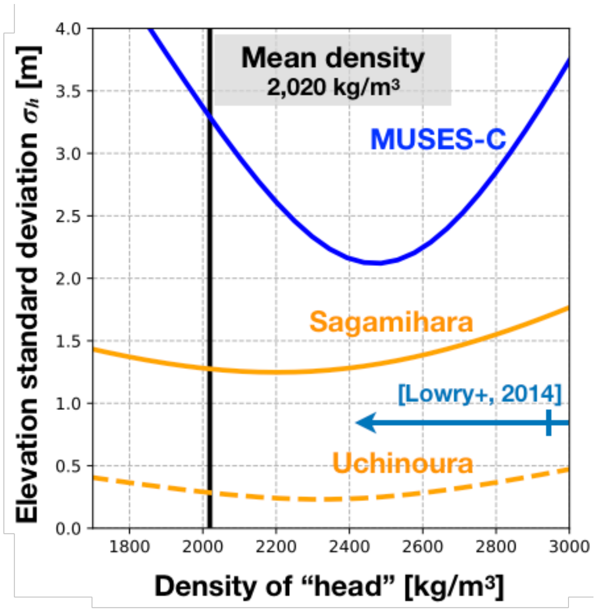

Figure 2. Standard deviations of the smooth terrain elevations as a function of the density of the "head".

extracted smooth terrain [7]. Spacecraft camera images and a global mosaic map were projected onto the shape model and smooth terrain was manually selected in polygons as shown in Figure 1. As a criteria for identifying the smooth terrain, we also used the surface roughness in meters scale, as calculated from the shape model.

Inversion technique: An "elevation" at a certain place $\boldsymbol{r}$ is here defined as the distance above or below a reference equi-potential surface [8].

$$h(\boldsymbol{r}) = \frac{U(\boldsymbol{r}) - U_{mean}}{g(\boldsymbol{r})}$$

where U and g are the local potential and acceleration at $\boldsymbol{r}$, respectively. The mean potential in each smooth terrain was used as the reference potential when computing the elevations.

Our misfit criteria is defined to be the standard deviation of the smooth terrain elevations:

$$\sigma_h = \sqrt{\sum_{i=1}^{n_S} A_i (h_i - h_{mean})^2 \Big/ \sum_{i=1}^{n_S} A_i}$$

where A_i and h_i are the area and elevation of ith surface element, and n_s is the total number of surface elements in each smooth terrain.

In modeling the density distribution of Itokawa, we assumed different densities for the "head" and "body". We changed the density of the "head" under the condition that the total mass of Itokawa was fixed to 3.58×10^{10} kg, and then repeatedly computed the standard deviation of the elevations in each extracted region. The best fitting density distribution is given by the minimum standard deviation.

Results: Elevation standard deviations were minimized in all three regions when Itokawa's "head" was of a higher density than the mean density 2,020 kg/m^3 (Figure 2). MUSES-C Regio is located closer to mass concentration in the "head" and is hence more sensitive to density variation between the two lobes. When modeling only MUSES-C Regio, the best fitting density of the "head" is 2,440 kg/m^3 and the density of the "body" is 1,930 kg/m^3. The other two regions give similar results, but the flatness of the misfit curves demonstrates that these regions are less sensitive to lateral variations in the interior density.

Discussion: Our best fit implies that there is a density heterogeneity between the two lobes of Itokawa, which corresponds to an offset of its center-of-mass from its center-of-figure toward the "head" by 9.7 m. Similarly, using a detected YORP spin-up of Itokawa, Lowry et al. (2014) estimated the center-of-mass offset to be 21 ± 12 m, also directed toward the "head" [9]. Our estimation is within the stated 1-sigma uncertainty of their measurement.

Assuming that Itokawa is composed of LL-chondritic materials with a grain density of 3,190 kg/m^3 [10], the macroporosity of the "head" corresponds to approximately 25 %, contrast to about 40 % for the "body". These porosities are representative of a coherent asteroid such as 433 Eros and a rubble-pile asteroid, respectively [11]. It is possible that the "head" of Itokawa has a more coherent and monolithic structure than the "body", or contains large blocks of fewer cracks derived from its parent body.

Our estimation method can be applied to an arbitrary density distribution such as the presence of a higher density core at the center of a small body, or the presence of a compressed region with lower porosity in the "neck" between the two lobes. This technique could be applied to any small body that possesses flat regions that might be expected to approximate an equi-potential surface.

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