Geological and geophysical constraints on Itokawa’s past spin periods

How to cite:

© 2020 Elsevier Inc.

https://creativecommons.org/licenses/by-nc-nd/4.0/

Version: Accepted Manuscript

Link(s) to article on publisher’s website:
Geological and geophysical constraints on Itokawa’s past spin periods

Hannah C. M. Susorney\textsuperscript{a,b}, Lydia C. Philpott\textsuperscript{b}, Ronald L. Ballouz\textsuperscript{c}, Catherine L. Johnson\textsuperscript{b,d}, Benjamin Rozitis\textsuperscript{e}, Erica R. Jawin\textsuperscript{f}

\textsuperscript{a}School of Earth Sciences, University of Bristol, Bristol, United Kingdom.
\textsuperscript{b}Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada.
\textsuperscript{c}Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ., USA.
\textsuperscript{d}Planetary Science Institute, University of Arizona, Tucson, AZ., USA.
\textsuperscript{e}School of Physical Sciences, Open University, Milton Keynes, United Kingdom.
\textsuperscript{f}Smithsonian National Museum of Natural History, Washington D.C., USA.

Abstract

Itokawa has two distinct terrain types, rough highlands, and smooth lowlands. The lowlands formed by the movement of fine-grained materials from the highlands into topographic lows, covering up large boulders and producing a smooth surface. The topography of asteroids is a function of the shape, interior density, and spin rate. Itokawa, like many near-earth objects, may have experienced changes in its spin period due to YORP. Changes in spin period compared with the current 12.13 hour period, may result in changes in the location of topographic lows and thus the concentration of fines in the lows. Under faster spin periods, $\sim 8$ hours or less, the northern topographic low, currently Sagamihara, changes location, but the southern lowland, Muses-Sea, stays in the same location. Above $\sim 8$ hours the topographic lows match the current geographic extent of the fine-grain lowlands. Current estimates of the timescale of regolith migration based on seismic shaking span several orders of magnitude. However, if these can be further
refined, the location of the northern lowlands could be used as a constraint on the past spin rates of Itokawa. The methods used in this study could be applied to other asteroids and may place an independent constraint on past spin periods.

Keywords: Asteroids, Topography, 25143 Itokawa, YORP

1. Introduction

Small Near-Earth Objects, in particular asteroids, are often irregular in shape and can be affected by the Yarkovsky-O’Keefe-Raszievskii-Paddack, YORP, effect (Rubincam, 2000), which can rapidly change their rotation rate via their asymmetric reflection and re-emission of impinging sunlight. As topography, height above the geoid, is a function of the asteroid’s shape, the acceleration due to gravity, and the rotational acceleration due to spin, changes in rotation rate will affect surface topography. Downslope motion on asteroids results in the movement of regolith due to local topographic gradients and affects resurfacing, regolith distribution, and surface geology. Large changes in rotation rate may, in turn, affect topographic gradients and can change the distribution of regolith due to downslope motion.

25143 Itokawa, hereafter called Itokawa, is a 535 x 294 x 209 m (Demura et al., 2006) S-class asteroid (Binzel et al., 2001) visited by the Hayabusa spacecraft in 2005 (Fujiwara et al., 2006). Itokawa’s size and distance from the Sun are such that its spin period is affected by YORP (e.g., Scheeres et al., 2007; Lowry et al., 2014). The material covering the surface of Itokawa exhibits a bimodal sorting of grain sizes, with the larger grains concentrated in the topographic highs, the highlands, and fine-grained material concentrated
in topographic lows, the lowlands, (Fujiwara et al., 2006; Abe et al., 2006; Saito et al., 2006; Yano et al., 2006; Miyamoto et al., 2007; Barnouin-Jha et al., 2008; Susorney et al., 2019). The size-sorting has been proposed to result from granular processes that filter the fine-grain particles through the boulder-sized particles of the highlands and concentrate them in the lowlands (e.g. Miyamoto et al., 2007; Barnouin-Jha et al., 2008; Susorney et al., 2019). The concentration of fines occurred either during re-accumulation (Shinbrot et al., 2017) or at some point after the re-accumulation that followed the cataclysmic collision of Itokawa’s parent body over a billion years ago (Terada et al., 2018). Noble-gas measurements indicate a surface exposure lifetime of fine grains of 3–8 million years for the grains collected from the surface, but this was only at the Hayabusa landing site and may not be reflective of large-scale re-surfacing (Nagao et al., 2011). Some studies have investigated the relationship between slope, density, and spin rate using the assumption that asteroid slopes will always be minimized by surface processes. Under this assumption, Richardson & Bowling (2014) found that Itokawa is not in erosional equilibrium, i.e., the slopes of Itokawa are not minimized at its current spin state, and Richardson et al. (2019) raised the possibility that Itokawa’s topography evolved under a different spin period.

Thermophysical modeling of Itokawa using the shape model generated from images during close encounter (Gaskell et al., 2008b) and assuming a homogenous interior density indicates that Itokawa should be spinning down (rotation period increasing, Fig. 1, Scheeres et al., 2007). In 2014, light-curve observations found that Itokawa was accelerating in the opposite direction, i.e., spinning up (Fig. 1, Lowry et al., 2014). The Lowry et al.
light-curve observations could have been affected by surface roughness variations (Statler, 2009; Rozitis & Green, 2012), however, models of the surface roughness variations required to produce the observed spin acceleration (Lowry et al., 2014) do not reflect the global surface roughness of Itokawa (Susorney et al., 2019), but the Susorney et al. (2019) study measures the surface roughness at a larger scale than is relevant for YORP.

The contradiction between theory and observations can be explained by a center-of-figure center-of-mass offset due to a density difference between the head and body (Scheeres & Gaskell, 2008; Lowry et al., 2014). Recently, work using the location of the lowlands of Itokawa, found that Itokawa’s head may be more dense than the body (Kanamaru et al., 2019) using the assumption that surface slopes will always be minimized by surface processes. Alternatively, this contradiction can also be explained, at least partially, by the tangential-YORP effect, which only causes an asteroid to spin-up (Golubov & Krugly, 2012). Unlike the previously discussed normal-YORP effect, the tangential-YORP effect is caused by east-west temperature asymmetries induced in rocks by the asteroid rotation, and Itokawa has many rocks and boulders that could contribute to this effect (Ševeček et al., 2015). However, current models of the tangential-YORP effect are idealized, and as such it is unclear whether it is the dominant YORP component on Itokawa.

Although, the observations of Itokawa points towards Itokawa currently spinning up, this may have not always been the case in the past. Itokawa has a current YORP-timescale (i.e., the time for its spin rate to be doubled/halted) of ∼1 Myr ago (Rozitis & Green, 2013) Before ∼1 Myr ago, the spin acceleration and resulting spin rates of Itokawa are unknown due to the
spin due to Itokawa having zero spin at \( \sim 1 \) Myr ago (Rozitis & Green, 2013). However, coupled simulations of asteroid shape deformations and YORP spin evolutions demonstrate that the YORP effect could be rather self-limiting on non-rigid bodies, such that a fairly constant spin rate is maintained over an asteroid’s dynamical lifetime (Cotto-Figueroa et al., 2015). Therefore, in this study, we investigate how the topographic lows on Itokawa change under different spin periods to understand both the geologic history of the asteroid and the surface changes that might be expected in the future as Itokawa’s spin evolves.

We used the high-resolution shape model of Itokawa to investigate the relationship of the observed surface geology to Itokawa’s past spin rates using the location of topographic lows under different spin periods. We focused our investigation on the two largest topographic lowlands, Muses-Sea and Sagamihara, which are the locations of the largest concentrations of fine-grain material on Itokawa. In the following sections, we summarize how we used the shape model and two interior density models to calculate the topography of Itokawa. We then show these topographic maps with an emphasis on the locations of the lowlands on Itokawa and evaluate how the locations of the lowlands could have changed through time. We discuss what our topographic maps imply for the geologic history of Itokawa and how modeling asteroid topography could be used to investigate the spin history of other asteroids that have size-sorting of regolith.
2. Methodology

We investigated how the topography of Itokawa changes for different spin periods, by generating surface topography using the global shape model of Itokawa derived from StereoPhotoClinometry, SPC, based on images from the Hayabusa mission (Gaskell et al., 2008b,a). The results presented in this paper are from the 196,608 plate shape model. We also computed the topography for the lower resolution 49,152 plate shape model and found no change in our results; we inferred that either of these shape models were of sufficient resolution for our study. Shape models with higher resolutions than the 196,608 plate shape model just refine the fine-scale detail of topography at spatial scales less than \( \sim 1.5 \) meters.

Using the Werner method for calculating an irregular object’s geopotential (Werner & Scheeres, 1997; Barnouin et al., 2020), we calculated the topography at spin periods of 6, 8, 10, 12.13, 14, 16, 18, 20, 22, 24 hours for two interior density distributions. The current observed spin period is 12.13 hrs and we identified 6-hours as the lower limit for our study based on work by Scheeres et al. (2007) and Hirabayashi & Scheeres (2019) who found structural failure at spin periods less than 6 hours. We used two different density models motivated by the internal structure models of thermophysical studies of Itokawa: a homogenous interior that resulted in the asteroid’s spin period increasing Scheeres et al. (2007), and a denser head with a less dense body that resulted in the asteroid’s spin period decreasing Lowry et al. (2014). We used a homogeneous internal density of 2.02 g cm\(^{-3}\) based on the mass of Itokawa (Abe et al., 2006) and the volume of the 196,608 plate shape model. For the inhomogeneous model, we used 1.93 g cm\(^{-3}\) for the body and
2.44 g cm$^{-3}$ for the head Kanamaru et al. (2019). The head was defined as
the portion of the shape model located at distances greater than 0.15 km
along the x-axis, where the x-axis is defined to run through the long-axis of
Itokawa (Lowry et al., 2014).

We mapped the two regions with the largest spatial extent of smooth
lowland material – Sagamihara and Muses-Sea – using a combination of the
slope map from the 196,608 plate shape model (with the current spin rate)
and images of the surface. The edges of Sagamihara and Muses-Sea were
identified as regions where the slope was lower than 10 degrees and images
showed a visually smooth region with few boulders. We also compared our
maps to the results of previous studies that have identified Sagamihara and
the Muses-Sea (Fujiwara et al., 2006; Miyamoto et al., 2007; Kanamaru et al.,
2019) and found that the outlines of the lowlands were consistent.

3. Results

As topography is sensitive to interior density distribution, we show the
topography of Itokawa for a homogenous interior distribution and inhomoge-
neous interior distribution for spin periods of 6, 12.13, and 24 hours (Fig 2).
When Itokawa is spinning more slowly than its current spin rate, i.e., when
the asteroid has larger spin periods, the spatial locations of the major topo-
graphic lows are the same as for the current spin period. In addition, at these
larger spin periods the absolute values of topography are similar to those for
the current spin rate. In the case where the asteroid spins more quickly
than currently, we observe changes in the spatial location of the northern
topographic low, Sagamihara, and an overall reduction in the difference in
topography from the lowlands to the highlands for the entire asteroid.

The topographic low associated with the Muses-Sea changes very little with different spin rates except for a reduction in the absolute value of the topographic low in the 6-hour spin case. In contrast, for Sagamihara we observe a more dramatic reduction of the absolute value of the topographic low from the 12 hour to the 6 hour spin period. Furthermore, the location of the northernmost topographic low changes from the current location of Sagamihara, to a thin curved region at the edge of Sagamihara that we call S2 (Fig. 3). To quantify these shifts in relative topography, we computed the difference of the mean topography in the highlands with the mean topography in the lowlands, and investigated how this changes for the spin periods studied here. Fig. 4 shows the difference in topography between the highlands and Sagamihara, Muses-Sea, and S2. At spin periods greater than 9 hours, for both the homogenous and non-homogenous interior density distributions, the topographic difference between the highlands and Sagamihara is larger than that between the highlands and S2. This implies that regolith is more likely to move to Sagamihara than S2 at these spin periods. At 8 hours for the homogenous case and 7 hours for the non-homogenous case, the situation is reversed, with fine-grains more likely to be concentrated in S2 instead of Sagamihara.

4. Discussion

Geophysical modeling of the topographic lows on Itokawa under different spin periods shows that the northern topographic low is sensitive to changes in the spin. As Itokawa is affected by YORP, it could have spun at a different
period when it formed in the main belt. Currently, the north and southern
topographic lows are colocated with the location of the smooth fine-grain
regions. However, our modeling shows that this may not have always been
the case.

For spin periods less than 7–8 hours, the topographic low in Itokawa’s
northern hemisphere would be at a different location from the current geo-
graphic location of the fine-grained material. Thus understanding the age of
Sagamihara and the time scale for migration of fines over the surface, is im-
portant for constraining the previous spin history. If Sagamihara was found
to be younger than the rest of Itokawa, it could mean that fine-grains have
migrated into Sagamihara from S2, erasing older craters and any evidence
for a previous spin period less than 7–8 hours. However, if the time-scale
of fine migration is longer than the expected spin period changes due to
YORP, then the current colocation of fines and lowlands would suggest that
Itokawa never spun below 7–8 hours as there would not have been time to
migrate grains from S2 to Sagamihara. The relative ages of different regions
of the surface has not previously been explored. Below, we investigate the
potential of dating the ages of Itokawa’s terrains, the potential timescales
of regolith migration, and geologic evidence of regolith migration. We also
briefly discuss the role of internal density in our results.

4.1. Craters on Itokawa

In Hirata et al. (2009), 37 potential craters were identified on Itokawa.
We first defined a confidence index to assess how likely it is that each of
the quasi-circular features is an impact crater. The confidence index was
based on a evaluation of each crater from Hayabusa Asteroid Multiband
Imaging CAmera, (AMICA, Nakamura et al., 2001) images, and from two topographic profiles (perpendicular to one another) across each feature from the SPC shape model. The evaluation criteria for low, medium, and high confidence candidate craters are outlined in the supplementary information. The criteria focus on the identification of a clear bowl-shape and crater rim, as all candidate craters on Itokawa are in the size range expected for simple-craters. We only use medium and high confidence craters (31 craters) for the analysis below, but our conclusions are unchanged if we use the entire crater population.

We generated size-frequency distributions for craters for the entire surface, Muses-Sea, Sagamihara, and S2 (Group, 1979), Fig 5. We observe no statistically different differences in population density for each of the regions on Itokawa. This is not completely unexpected due to the relatively small size of Itokawa and the few craters present. In particular, no differences in surface age are detectable between S2 and Sagamihara.

4.2. Timescales of regolith migration on Itokawa

We next explored the timescales of regolith migration to constrain the time it could take to move regolith from S2 to Sagamihara. Mechanisms that may contribute to down-slope motion in small bodies are seismic-shaking induced by impacts (Richardson et al., 2004; Michel et al., 2009), changes in the local slope due to asteroid spin-up (Jawin et al., 2020), or tidal interactions with planets (Ballouz et al., 2019). Here, we focused on impact-induced seismic shaking as this has been proposed to be the main mechanism leading to the concentration of fines in the lowlands of Itokawa (Miyamoto et al., 2007).
4.2.1. Theoretical Considerations

If material flowed from S2, which has a surface area $A_{S2} \sim 0.014 \text{ km}^2$, to Sagamihara, which has a surface area $A_{Sag} \sim 0.04 \text{ km}^2$, then this had to have happened within the time since Sagamihara became the local topographic low (i.e. since Itokawa was spinning at a period of 7 to 8 hours to the present). As observations show Itokawa is currently spinning up (Lowry et al., 2014), then any grain migration may have happened in the previous spin-down phase of Itokawa’s YORP cycle. However, we note that Nagao et al. (2011) find a resurfacing age of 8 Myr, providing a potential upper-limit to any potential material exchange between S2 and Sagamihara.

Following Michel et al. (2009), we utilize Richardson et al. (2004)’s impact-induced seismic shaking model. However, instead of calculating the timescale for crater erasure, we use the calculated seismic diffusion constants, $K_i$, from Michel et al. (2009) for two different assumptions of the impact strength of the Itokawa surface (Nolan et al., 1996; Holsapple, 1993). We note that Barnouin-Jha et al. (2008) find a minimum regolith thickness, $h$ of 2.3±0.4 m in the Itokawa lowlands. Therefore, in order for the material from S2 to migrate to Sagamihara, the cumulative value of $K_i$ has to be equivalent to a total thickness of regolith in S2 that migrated to Sagamihara, $K_{S2}$, of regolith given by:

$$K_i = K_{S2} = \frac{h \times A_{Sag}}{A_{S2}} \sim 7 \text{ m}^3\text{m}^{-2}$$  \hspace{1cm} (1)

We match this value of $K_{S2}$ to the calculated values of $K_i$ that best match the crater erasure history of Itokawa (Michel et al., 2009), and find that an impactor with a diameter, $D_{\text{imp}}$, between 0.3 to 7.8 m could have induced seismic shaking that would have mobilized the necessary volume of material
from S2 to cover Sagamihara.

Finally, to determine a timescale for this to occur, we consider the rate of impacts on Itokawa during its residence time in the main belt as well as its current residence in near-Earth space. We first consider the cumulative size frequency distribution (CSFD), \( N_{C,\text{MBA}} \), of main belt asteroids (MBAs) calculated from observations of the MBA size distribution and models of their collisional evolution (Bottke et al., 2005). By numerically differentiating \( N_{C,\text{MBA}} \), we derive the incremental size frequency distribution \( N_{I,\text{MBA}} \) of MBAs with diameters \( D \):

\[
N_{I,\text{MBA}}(D_k) = N_{C,\text{MBA}}(\geq D_k) - N_{C,\text{MBA}}(\geq D_{k+1}) \tag{2}
\]

where \( k \) is the index of the logarithmically binned CSFD data and \( D_{\text{imp,k+1}} > D_{\text{imp,k}} \). Then, the number of impacts, \( N_{MBA} \), over a mean time interval, \( t_{coll} \), on Itokawa by an impactor with diameter \( D_{\text{imp}} \) is given by:

\[
N_{MBA} = N_{I,\text{MBA}}(D_{\text{imp}}) \times P_i \times \left( \frac{D_{\text{imp}}}{2} + \frac{D_{\text{ast}}}{2} \right)^2 \times t_{coll}, \tag{3}
\]

where \( P_i = 2.9 \times 10^{-18} \text{ km}^2 \text{ yr}^{-1} \) is the constant impact probability in the main asteroid belt (Bottke et al., 2005), and \( D_{\text{ast}} \) is Itokawa’s mean diameter.

The value of \( t_{coll} \) can then be found by setting \( N_{MBA} = 1 \), and finding \( N_{I,\text{MBA}} \) for values of \( D_{\text{imp}} \) between 0.3 to 7.8 m. We perform a similar analysis for Itokawa’s residence in near-Earth space, using the measured impact flux of near-Earth objects on Earth (Brown et al., 2002).

For Itokawa’s time in the main asteroid belt, we find the timescale for regolith migration from S2 to Sagamihara, \( t_{coll} \), is between 80 kyr to 300 Myr. For Itokawa’s time in near-Earth space, we find \( t_{coll} \) is between 4.6 Myr to 30 Gyr (Fig. 6). With a potential upper constraint to \( t_{coll} \) of 8 Myr.
given by Itokawa’s resurfacing age (Nagao et al., 2011), our analysis shows that impact-induced seismic activity may feasibly have caused migration of regolith from S2 to Sagamihara if this occurred during Itokawa’s residence in the main asteroid belt. The lower limit on the regolith migration timescale is consistent with Itokawa’s current YORP timescale of $\sim$1 Myr, but the upper limits would have to reflect a previous YORP cycle that lasted much longer. For instance, other YORP-detected asteroids have current YORP-timescales as long as $\sim$7 Myr (Rozitis & Green, 2013), which are compatible with these upper limits. Furthermore, self-limitation of the YORP effect (Cotto-Figueroa et al., 2015) could also allow for the longer regolith migration timescales.

4.2.2. Observational Evidence

We also searched within the S2 region for morphologic evidence of accumulated fine-grained material based on AMICA images with pixel scales 20-50 cm/pixel. The presence of fines within a region that is not currently the global topographic minimum (i.e., outside Sagamihara and within the S2 region) would indicate that: 1) Itokawa has previously experienced a spin period less than 7-8 hours, and 2) fine-grained material can travel across the surface of Itokawa with relative ease, following the shifting topography through spin period variations. However, much of the S2 region overlaps with the Sagamihara region (Figure 7); as such, the region outside Sagamihara, in which the presence of fines would be meaningful for our analysis, is relatively small—only 20 m wide (up to 50 m on the westernmost portion of S2). Within this S2 region, we did not find distinct evidence of past accumulations of fine-grained material. Several regions within S2 (outside of
Sagamihara) appear to contain fine-grained materials (red arrows in Figure 7), but these do not appear to be distinct from the surrounding terrains outside of either S2 or Sagamihara (yellow arrows in figure 7). These results are ambiguous—they could suggest that S2 used to host deposits of fine-grained material, which was efficiently transported into the present Sagamihara region (and/or the overlap between S2 and Sagamihara)—conversely, they may indicate that the spin period of Itokawa has never decreased past 7-8 hours.

4.3. Itokawa’s internal structure

Kanamaru et al. (2019) used the location of Itokawa’s smooth lowlands to constrain the interior structure of Itokawa and found that either the head should be more dense than the body or that there could be a very dense, compressed region between the head and body. We also investigated the relationship of the internal structure and the location of the lowlands, but we focused on changes in the geographic locations of topographic lows in response to changes in spin rates under two density models. We found that a denser head, the inhomogeneous case, does not affect the topographic difference between the highlands and the Muses-Sea but does affect the difference in topography between the highlands and Sagamihara/S2 as seen in Fig 4. Kanamaru et al. (2019) found that the Muses-Sea was more useful in constraining interior structure, but our work here shows that the northern lowlands are more sensitive to interior structure. Future modeling of the interior structure of Itokawa should consider the northern lowlands of Sagamihara as an important constraint on understanding Itokawa’s internal structure and spin history.
5. Conclusions

The location of Itokawa’s lowlands is sensitive to spin periods, especially at short spin periods. The smooth region on Itokawa corresponds to topographic lows for spin periods of 7–8 hours (for inhomogeneous or homogeneous interiors respectively) to 24 hours. For spin periods of less than 8–9 hours, the location of the lowland on the back of Itokawa shifts from Sagamihara to the S2 region. At short spin periods the overall topographic range of Itokawa is also reduced. As Itokawa posses few impact craters, we could not constrain the relative ages of Itokawa’s highlands and lowlands, or differences in age among the three lowland areas investigated here. Using the range of seismic shaking parameters previously suggested for regolith migration on Itokawa (Michel et al., 2009), we found a large range in possible migration timescales for the fine material. Specifically fines can migrate from S2 to Sagamihara in as little as 80 kyr; however, this had to have occurred in the main asteroid belt. In near-Earth space, the timescales for impact-induced seismic shaking to mobilize sufficient material from S2 to cover Sagamihara is in excess of 4.6 Myr. While the impact-induced seismic diffusion timescale is much larger in near-Earth space than in the main asteroid belt, it is still within the average dynamical lifetime of near-Earth asteroids. Furthermore, this minimum value of 4.6 Myr is smaller than Itokwa’s resurfacing age of 8 Myr (Nagao et al., 2011). Although we were not able to further elucidate the spin history of Itokawa, our approach demonstrates that improved understanding of regolith migration time scales on rubble-pile asteroids and / or observations of rubble pile asteroids with distinct variations in surface age, could be used to provide a record of past spin periods.
Acknowledgements

This research was supported by the Canadian Space Agency and the Natural Sciences and Engineering Research Council of Canada (HCMS, LCP, CLJ) and by the UK Science Technology Facilities Council (BR). HCMS was additionally supported by the European Unions H2020 Marie Sklodowska-Curie Individual Research Fellowship. We thank the developers of the Small Body Mapping Tool and the OSIRIS-REX Altimetry Toolkit which were used in this study. Both software packages are available at sbmt.jhuapl.edu.
References


Ballouz, R.-L., Baresi, N., Crites, S. T., Kawakatsu, Y., & Fujimoto, M. 2019, Nature Geoscience, 12, 229

Barnouin, O. S., Daly, M. G., Palmer, E. E., et al. 2020, Planetary and Space Science, 180, 104764


17

Group, C. A. T. W. 1979, Icarus, 37, 467


Jawin, E., Walsh, K., McCoy, T., Ballouz, R.-L., & Connolly Jr., H. 2020, JGRR Planets

Kanamaru, M., Sasaki, S., & Wieczorek, M. 2019, Planetary and Space Science


18
Richardson, J. E., Graves, K. J., Harris, A. W., & Bowling, T. J. 2019, Icarus, 329, 207


Rozitis, B. & Green, S. F. 2013, Monthly Notices of the Royal Astronomical Society, 430, 1376

Rubincam, D. P. 2000, Icarus, 148, 2


Scheeres, D. J. & Gaskell, R. W. 2008, Icarus, 198, 125


Yano, H., Kubota, T., Miyamoto, H., et al. 2006, Science, 312, 1350
Figure 1: The spin evolution of Itokawa for the past 400,000 years and predictions for the next 400,000 years from Scheeres et al. (2007) and Lowry et al. (2014) with the width of the lines showing the associated error bars. The results from Lowry et al. (2014) reflect observations of Itokawa’s spin change, while the Scheeres et al. (2007) results are due to modeling alone. The black horizontal line denotes the current spin period.
Figure 2: The topography on Itokawa for spin periods of six hours, 12.13 hours (current value) and twenty-four hours. The left column depicts the asteroid from a north polar perspective and the right column is a south polar perspective. The color scale is the same for all spin periods. Red outlines denote the three regions discussed in the paper and are identified in the twenty-four hour spin row.
Figure 3: Two maps of the six hour topography of Itokawa looking down onto the south pole for two different scale bars. The right hand map is the same scale bar as Fig 2, but with the red outline of just Sagamihara. The left map has a stretched color scale to show that the topographic low is now in the region we call S2.
Figure 4: The difference in the mean topography between the lowlands identified in Fig. 2 and the highlands of Itokawa for both a homogenous interior density model (solid line) and heterogenous density model (dashed lines). The highlands were identified as all of Itokawa outside of Muses-Sea, Sagamihara, and S2. The dashed black line is partially obscured by the solid black line as the interior model has little effect on the topography of the Muses-Sea.
Figure 5: The size-frequency distributions of the medium and high confidence craters (see supplemental information) from the list of candidate features in Hirata et al. (2009) for different regions of Itokawa’s surface. Error bars are one standard deviation following the methodology outlined in Group (1979). The error bars for S2 and Sagamihara overlap at the smallest crater size bin.
Figure 6: The time to migrate material from S2 to Sagamihara in millions of years for impact-induced seismic activity driven by different impactor diameters. The impactor diameter is related to a seismic diffusion constant calculated in (Michel et al., 2009). An upper-limit on the timescale is set by the resurfacing age (~ 8 Myr) as determined from laboratory analysis of the returned samples (Nagao et al., 2011).
Figure 7: An annotated AMICA image (st2481442195v, pixel scale: 40-45 cm, S/C: 4.3 km) show regions of visually smooth terrains inside and outside S2. The blue outline is S2 and the pink outline is Sagamihara. The red arrows are smooth patches with S2 and the yellow arrows are smooth patches outside S2.