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Unconsolidated boulders on the surface of Itokawa

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ABSTRACT

Numerous boulders have been identified on the 320 m-sized asteroid, Itokawa, which is puzzling especially due to its extremely low gravity environment (the escape-velocity is only ~20 cm/s). Through image analysis, we propose that gravels on the surface of this asteroid are likely unconsolidated and have been rearranged after their accumulation. The rearrangements of gravels may occur even now because the asteroid might be hit by meteoroids continuously. Although the possibility of rearrangement during the observational period of Hayabusa spacecraft is small, we scrutinize 19 pairs of high resolution images taken at different times to find if any surface modification occurs. As a result, no convincing evidence of surface modification is found. Thrusters of the Hayabusa spacecraft were activated at close range from the asteroid during its landing phases, which do not cause any identifiable changes. Nevertheless, this does not necessarily indicate that the gravels are consolidated because the observational period is too short to expect vibrations large enough to activate gravels into motion. A longer observational period, or an experiment of a carefully-arranged artificial impact, would be required to properly address why unconsolidated gravels exist on such a low gravity environment and whether this is a typical situation for a small asteroid.

1. Introduction

Asteroids are roughly defined as small bodies larger than dust-size particles, whose major components are not volatile. While several million asteroids are presumed to exist in the solar system, they are difficult to be resolved from ground-based observations due to their small-sizes. However, continuous observational efforts provide a sufficient amount of data to perform statistical study of their sizes and chemical distributions (e.g., Bottke et al., 2005; Usui et al., 2011). The importance of collisions in shaping asteroids has been recognized both through these observations as well as from analyses of meteorites and laboratory experiments (e.g., Cheng, 2004; Nakamura et al., 2008; Szabo and Kiss, 2008).

Recent and successful space explorations have significantly improved our knowledge of asteroids and the effects of their collisions (e.g., Asphaug, 2008; Thomas and Robinson, 2005). So far, 11 asteroids have been studied by spacecraft (Tables 1). Importantly, some asteroids are found to be rubble-piles held together by gravitational and cohesive forces (Scheeres et al., 2010). Their variety of sizes, shapes, and configurations are thus records of their complicated evolutionary histories, including repetitious collisions and accretion of particles, and deformation due to rotation, tidal, and the YORP effect.

In addition to the asteroids' irregular shapes (Barnouin-Jha et al., 2008; Demura et al., 2006; Sierks et al., 2011), craters (Hirata et al., 2008; Keller et al., 2010; Thomas and Robinson, 2005), and albedo contrasts (Ishiguro et al., 2007; Reddy et al., 2012), the regolith materials on the surface of asteroids provide important clues for unraveling the evolution of asteroids. Relatively large asteroids, such as Ida and Mathilde, have somehow homogenized regolith materials but when observed at higher resolution images, boulders are found on the surfaces (Chapman et al., 2002; Kuppers et al., 2012). In many cases, they have been associated with large impact structures; for example, most of boulders on asteroid Eros and Phobos are believed to originate from the Shoemakerand Stickney craters, respectively (Chapman et al., 2002), so regolith evolution would be a function of repetitious impacts.

In fact, when the surface gravity of an asteroid is as strong as that on Lutetia, boulders several tens of meters in size, or larger, remain on the surface, as expected from the scaling relationships for the size–velocity distribution (Kuppers et al., 2012). However, where gravity is much weaker, impact ejecta can easily escape and probably do not redeposit back onto the surface. Only 5 small (<10 km) asteroids have been visited by spacecraft: 5535 Annefrank of dimensions $6.6\times5.0\times3.4$ km^3 (Duxbury et al., 2004), 9969 Braille which is $2.1\times1\times1$ km^3 in size (Oberst et al., 2001), Dactyl which is $1.6\times1.4\times1.2$ km^3 in size (Veverka et al., 1996),

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25143 Itokawa which is 535 × 294 × 209 m^3 (Fujiwara et al., 2006), and 2867 Steins with dimensions of 6.67 × 5.81 × 4.47 km^3 (Keller et al., 2010). These asteroids are generally irregular in shape, and are covered with anomalous craters (Burchell and Leliwa-Kopystynski, 2010). The smallest asteroid, Itokawa, shows the unique appearance covered by numerous boulders. This indicates that Itokawa is composed of gravel deposits on the order of tens of meters and less, while spin-rate statistics imply that objects on the order of 100 m can spin at rates much faster for collection of self-gravitating boulders (Pravec and Harris, 2000). Itokawa may be significantly different from other small asteroids, as the only one observed at high resolution sufficient to resolve the presence of boulders, but it may also be the most typical small asteroid. Thus, in this work, we scrutinize the close-up images to examine the current condition of boulders on the surface of Itokawa as an only example of a small asteroid for such study.

Importantly, gravitational and morphological studies reveal that boulders on Itokawa have been gravitationally segregated, which has been proposed to results from gravel migration induced by impacts (Miyamoto et al., 2007). Other than craters, micrometeorite collisions down to submicron scales have been found on dust grains of returned samples obtained from Itokawa (Nakamura et al., 2012). Occurrences of the sub- to several μm-sized craters are believed to be due to hypervelocity collisions of micrometeorites at nm scales, as suggested from size distributions and chemical compositions of adhered particles. This indicates that collisions over a wide range in scale would have affected the evolution of the asteroid and that rearrangements of gravels might still happen periodically on the surface of Itokawa. Also, the Hayabusa spacecraft used thrusters during two touch downs, which might modify the surface. Therefore, in this paper, we critically study high-resolution images to ascertain whether any changes occurred during the Hayabusa's observation.

2. Gravels on a small asteroid

Hayabusa spacecraft rendezvoused a ~320 m-sized asteroid, Itokawa, for about 3 months in 2005 (Fujiwara et al., 2006). Despite its small size, we find that the asteroid is covered by a considerable number of boulders (Saito et al., 2006), whose chemical compositions are similar to that of LL4 chondrite (Abe, M. et al., 2006; Okada et al., 2006) as confirmed by the analyses of the returned samples obtained from Itokawa (Nakamura et al., 2011). The nature and morphological characteristics of boulders have been studied in detail (Noguchi et al., 2010). The estimated bulk density of this asteroid is only 1950 kg/m^3 (Abe, S. et al., 2006), which implies a high bulk porosity (as large as ~40%), and thus indicates that Itokawa comprises a rubble-pile internal structure. Analyses of the returned samples support the view that a parent body more than 20 km in diameter was catastrophically disaggregated into small pieces, and then later re-accreted to form the current rubble-pile of Itokawa (Nagao et al., 2011; Nakamura et al., 2011; Noguchi et al., 2011; Tsuchiyama et al., 2011; Yurimoto et al., 2011).

The gravels found in high-resolution images of Itokawa range from several tens of meter-sized boulders to centimeter-sized pebbles, concentrated in smooth terrains at gravity lows (Miyamoto et al., 2007). This is difficult to reconcile with the very-low gravity environment of Itokawa, which has an escape velocity of typically only 20 cm/s. Much finer particles may exist on Itokawa, but these cannot be resolved in the Hayabusa's images which are upto 6 mm/pixel resolution. However, we do not observe smooth deposits whose particle size cannot be resolved. This implies no major accumulation of particles finer than pebbles on the surface. Powdery materials would be created through impacts onto the present surface of the asteroid, surface degradation due to micrometeoroid impacts, or from catastrophic disruption of Itokawa's parent body (Asada, 1985; Flynn and Durda, 2004; Nakamura et al., 1994). The deficiency in powdery materials might be explained by any individual, or combination, of the following scenarios: (1) no fine particles existed on Itokawa since gravitational accumulations of gravels, because of the much higher

Table 1
Sizes of asteroids visited by spacecraft.

Asteroid	Size (reference)
5535 Annefrank	6.6 × 5.0 × 3.4 km^3 (Duxbury et al., 2004)
9969 Braille	2.1 × 1 × 1 km^3 (Oberst et al., 2001)
Dactyl	1.6 × 1.4 × 1.2 km^3 (Veverka et al., 1996)
433 Eros	34.4 × 11.2 × 11.2 km^3 (Zuber et al., 2000)
951 Gaspra	18.2 × 10.5 × 8.9 km^3 (Belton et al., 1992)
243 Ida	53.6 × 24.0 × 15.2 km^3 (Thomas et al., 1996)
25143 Itokawa	0.54 × 0. 29 × 0.21 km^3 (Fujiwara et al., 2006)
21 Lutetia	121 × 101 × 75 km^3 (Sierks et al., 2011)
253 Mathilde	66 × 48 × 46 km^3 (Veverka et al., 1999)
2867 Steins	6.67 × 5.81 × 4.47 km^3 (Keller et al., 2010)
4 Vesta	572 × 557 × 446 km^3 (Russell et al., 2012)

Table 2
Image pairs used in this study.

	Area	Image pair		Time difference	Figure
1	Rough terrain, west of San Marco	ST_2420822891	ST_2559003068	51 days	
2	Rough terrain, west of San Marco	ST_2494934387	ST_2559003068	23 days	Fig. 3
3	Western side	ST_2421003158	ST_2494934387	28 days	
4	Eastern side	ST_2422985584	ST_2506733028	30 days	
5	Rough terrain near Komaba crater	ST_2474731509	ST_2558581440	30 days	Fig. 4
6	Rough terrain near Komaba crater	ST_2474731509	ST_2532629277	20 days	
7	Rough terrain near Komaba crater	ST_2474731509	ST_2539429953	23 days	
8	Rough terrain near Komaba crater	ST_2474731509	ST_2539423137	23 days	
9	Rough terrain near Komaba crater	ST_2474731509	ST_2495748476	7 days	
10	Rough terrain near Komaba crater	ST_2495748476	ST_2558581440	23 days	
11	Rough terrain near Komaba crater	ST_2532629277	ST_2539429953	3 days	
12	Rough terrain near Komaba crater	ST_2532629277	ST_2539423137	3 days	
13	Sagamihara	ST_2492225173	ST_2516129281	8 days	
14	Arcoona	ST_2492513077	ST_2530297837	14 days	
15	Near Muses-C	ST_2474731509	ST_2530286817	19 days	
16	Near Muses-C	ST_2493031594	ST_2530286817	13 days	Fig. 5
17	Muses-C	ST_2563607030	ST_2563537820	1 min	
18	Muses-C	ST_2563537820	ST_2563511720	2 min	
19	Muses-C	ST_2563607030	ST_2563511720	3 min	Fig. 6