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The distribution and source of boulders on asteroid 4179 Toutatis

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Abstract. Boulders are ubiquitous on the surfaces of asteroids and their spatial and size distributions provide information for the geological evolution and collisional history of parent bodies. We identify more than 200 boulders on near-Earth asteroid 4179 Toutatis based on images obtained by Chang'e-2 flyby. The cumulative boulder size frequency distribution (SFD) gives a power-index of -4.4 $\pm$ 0.1, which is clearly steeper than those of boulders on Itokawa and Eros, indicating much high degree of fragmentation. Correlation analyses with craters suggest that most boulders cannot solely be produced as products of cratering, but are probably survived fragments from the parent body of Toutatis, accreted after its breakup. Similar to Itokawa, Toutatis probably has a rubble-pile structure, but owns a different preservation state of boulders.

Keywords. Minor planets, asteroids; planets and satellites: individual (4179 Toutatis)

1. Introduction

On 13 December 2012, Chang'e-2 successfully flew by asteroid 4179 Toutatis after the spacecraft accomplished its primary scientific objective of lunar exploration and an extended mission of space-environment exploration at the Sun-Earth Lagrangian point. This flyby, with the closest distance $\sim$ 770 m, captured a series of optical images displaying detailed geology and morphology of Toutatis (Huang *et al.* 2013; Zou *et al.* 2014; Zhu *et al.* 2014; Jiang *et al.* 2015; Zhao *et al.* 2015). Previous investigations show that most of boulders on relatively large asteroids are connected with impact craters like the Shoemaker crater on the surface of Eros, whereas for much smaller bodies like Itokawa most boulders are likely to originate from the disruption of its larger parent body (Thomas *et al.* 2001; Fujiwara *et al.* 2006). Toutatis owns an intermediate size as described above. Herein, we identify boulders on its imaged surface and investigate their spatial and size distributions, in order to dig out important clues for the formation and evolution of Toutatis.

2. Results

About 222 boulders are counted over the imaged area ($\sim$ 6.68 km^2), with geometric mean sizes from 10 to 61 m, with an average of 22 m (Fig. 1). Approximate 90% of boulders are less than 30 m in size. As far as the number density of boulders ($>$ 20 m) is concerned, Toutatis ($\sim$ 17/km^2) has higher surface density of boulders than Eros

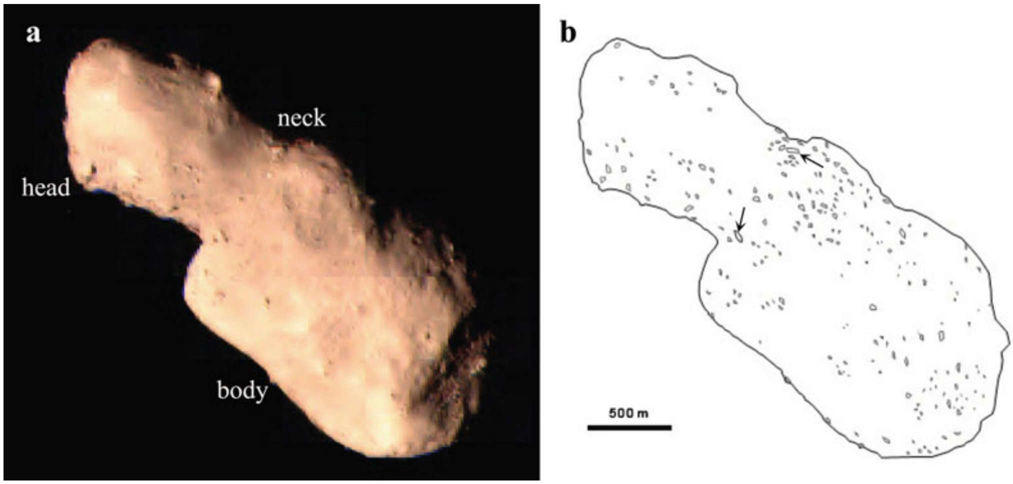

Figure 1. The distribution of boulders on the surface of Toutatis. a. The first panoramic image of Toutatis captured by Chang'e-2. b. The sketch map shows Toutatis' outline, where a total of 222 boulders identified is marked up, with two largest boulders (black arrows) near the neck region.

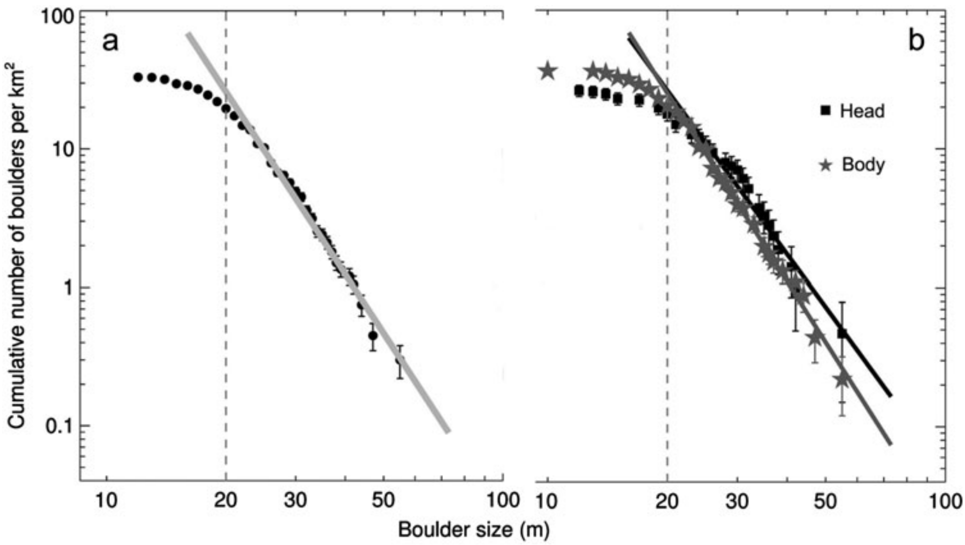

Figure 2. The cumulative SFD of boulders per unit area for Toutatis. a. All boulders give the power-law index of the best fit -4.4 $\pm$ 0.1 for boulders $>$ 20 m, since the distribution rolls over at less than 20 m due to incompletely counting. b. The boulders on head and body give the power-law index of -3.9 $\pm$ 0.2 and -4.5 $\pm$ 0.1, respectively.

($\sim 2/\text{km}^2$), but lower than Itokawa ($\sim 30/\text{km}^2$). The cumulative size-frequency distribution (SFD) per unit area exhibits a slope (power-index) of -4.4 $\pm$ 0.1 for boulders $>$ 20 m, since the distribution rolls over at $<$ 20 m due to incompletely counting. In addition, head and body give slopes of cumulative SFD of boulders above 20 m as -3.9 $\pm$ 0.2 and -4.5 $\pm$ 0.1, respectively (Fig. 2).

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3. Implications

Boulders distribution . For Toutatis, all boulders with sizes 20-60 m exhibits a cumulative SFD slope of -4.4 $\pm$ 0.1. This slope is significantly steeper than that of Eros (-3.2) boulders with sizes 15-80 m and that of Itokawa (-3.3 $\pm$ 0.1) boulders with sizes 6-38 m (Thomas *et al.* 2001; Mazrouei *et al.* 2014). After generation, boulders could be broken by subsequent impacts in which large ones may be destroyed but not replenished, leading to a steeper size distribution. The steep slope for Toutatis implies that boulders may have experienced high degree of fragmentation. The cumulative slope (-4.5 $\pm$ 0.1) of boulders on the body is relatively steeper than that on the head (-3.9 $\pm$ 0.2). The difference in the power index may imply that body has suffered heavier impacts than the head does. Thus, the resulting more impact fracturing of the body may lead to less dense internal structure than the head, which is consistent with the inference from moments of inertia (Busch *et al.* 2012).

Boulders source . Boulders on small rocky bodies are generally produced by impact cratering or/and catastrophic disruption of the parent body. During impact cratering, the ejected fragment is associated with the corresponding source crater, with one of the empirical relations expressing as $L \sim 0.25\ D^{0.7}$, with L (boulder size) and D (crater diameter) in meters (Lee *et al.* 1996). For Toutatis, the source crater for the largest boulder ($\sim$ 61 m) is $\sim$ 2570 m, which is four times larger than the largest impact crater ($\sim$ 530 m) identified on Toutatis. Moreover, the largest crater identified based on global radar model was only 750 m across (Hudson *et al.* 2003). Therefore, we infer that the largest boulder is not produced by the impact cratering. Further, the ratio of the total volume of boulders to the total excavated volume of craters on Toutatis is as high as $\sim$10%, which is a bit smaller than Itokawa (25%), but far more than Eros (0.4%). These results imply that most boulders cannot only be produced during impact cratering on Toutatis. Many boulders especially larger than 20 m ones are probably surviving fragments from the parent body of Toutatis, accreted after its breakup (Jiang *et al.* 2015; also see contribution by Ji *et al.* this volume).

Acknowledgements

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