BOULDER MOTIONS ON ASTEROID RYUGU INDUCED BY THRUSTER GAS DISTURBANCE BY HAYABUSA2

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Introduction: On asteroid Ryugu, both spectral and morphological evidence supports that boulders and regolith have experienced extensive motion from equatorial ridge toward mid latitude regions and that the motions may have been triggered by de-spinning of Ryugu [1,2]. Hayabusa2 spacecraft performed touchdown and sampling on asteroid Ryugu. At the transition phase from the descent to ascent after the sampling, many surface materials were found to be ejected from the surface due to physical contact of the sampler horn and powerful thruster jets onto the surface. Similar surface disturbance also occurred during TAGSAMP sampling event on asteroid Bennu by OSIRIS-REx [3]. Mass movement in these events caused resurfacing and resultant spectral change [2]. However, the great dynamical disturbance and optically-thick dust cloud make us difficult to investigate the detailed motion and dynamical properties of the surface materials.

In this study, we focused on low-altitude descent operations without touching the Ryugu surface. Our investigation revealed that many surface boulders were in motion after the thruster injection for spacecraft ascending. The image data were enough quality to examine the motion of individual boulders.

Observation data: Hayabusa2 performed a total of five descent operations to altitudes below 25 m, excluding two touchdowns and sample collection, in its proximity phase around Ryugu from June 2018 to November 2019 [4]. During the ascending sequence, continuous imaging was performed with the optical navigation camera ONC-T and the mid-infrared camera TIR.

Our detailed analysis of these image data revealed that the boulders on Ryugu's surface moved in four decent operations (TD1-R3, DO-S01, PPTD-TM1A, and PPTD-TM1B). In particular, observation by ONC-T over a long period was made during the DO-S01 operation conducted on March 8, 2019, allowing us to observe the motion of individual boulders. In TD1-R3, PPTD-TM1A, and PPTD-TM1B operation, TIR imaged the surface at a time around thruster injection. Some boulder motions were found also in the thermal infrared images. However, detailed investigation of the boulder motion was difficult in TIR data since the field of view changed significantly near the lowest point.

We used 24 images taken by ONC-T during the ascending phase. The delta-V thruster injection was 03:24:12 UTC, and the ONC-T imaging was started from 03:26:04 (about 3 minutes later after the thruster injection) at the altitude of 75 m, resulting in the pixel resolution of 8 mm/pixel. The images are registered each other to identify the moving boulders. Finally, we find 74 moving boulders in DO-S01 operation. An example of the moving boulder is shown in Fig. 1.

Boulder Motion Analysis: To analyze the boulder motion quantitatively, we define a 2D coordinate fixed on the local surface where +y direction is northward. All ONC-T images were projected on this plane, and we investigated the temporal change of the boulder coordinates. Using these datasets, we evaluated the motion speed, direction, and mode, as well as the comparison with stationary boulders.

Direction of the motion (Fig. 2) is defined by the angle between northward (++) and the least-square linear fitting vector of the coordinates of each boulder. We found that 54 boulders fell within the range of -90 to +90 degrees in the direction of the movement. This means that most of the boulders moved in the direction toward the north (high-latitude direction). This is preliminary explained by the facts that the thruster gas pressure had northward component and that the local gravity at this region (northern side of equatorial ridge) has also northward.

On the motion speed, it ranges from 0.4 mm/s up to 17.4 mm/s, with mean speed of 2.8 mm/s. The motions were activated by the thruster gas, whose pressure on the surface is estimated to be 0.24 Pa. In addition, the northward gravitational acceleration also affects the motion speed. The sum of the reachable speeds induced by the thruster gas pressure and gravity is higher than the observed velocities for all moving boulders. The observed lower velocity could be due to the deceleration by the friction with ground.

We examined the relationship between the boulder’s minor axis direction and the direction of the motion. We found that they have positive correlation, showing that the boulders tend to move along with the
minor axis, which supports that the rolling about the major axis (with lower moment of inertia) is the primary mode of the mass movement. Whether the boulders always contacted with the surface was unknown. It is plausible that the boulders bounce concomitant with impacts on surface irregularities, leading to brief detachment. For instance, if a boulder vertically jumps at a typical surface movement speed of 2.8 mm/s, it could reach an altitude of approximately 33 cm — similar to the size of a typical moving boulder. This indicates that boulders possess sufficient kinetic energy for saltation. Thus, we infer here that saltation, which involves jumping and rotation, may be the dominant mode of transport of centimeter to decimeter scale pebbles and boulders on the Ryugu surface.

It was evident that thruster gas pressure induced movement of boulders, but the majority of boulders remained stationary. In this context, we counted boulders that did not move. The result indicates that the slope of the size-frequency distribution for moving boulders larger than 17.5 cm is approximately the same as that for stationary ones and the number of the moving boulders is ~3% of the number of the stationary ones. Conversely, for rocks smaller than 17.5 cm, the number of moving boulders is relatively low. We infer that the small boulders should come to a stop earlier than larger boulders through collisions with the rough surface. The trend for larger boulders to stay in motion for longer periods might be important for interpreting surface features on Ryugu, such as large boulder deposit on the base of large/old craters [5].

**Conclusion:** In this study, we made a notable observation that surface materials undergo displacement due to the injection of thruster gas over the asteroid. This marks the first confirmation of movement induced by remote disturbance from thruster gas.

These observational findings regarding rock movement on asteroids hold significance for the future operational planning of OSIRIS-APEX [6], which aims to unveil the resurfacing of asteroid Apophis through a similar thruster injection operation. It is crucial to comprehend not only the kinetic excitation by gas pressure but also the dynamic behavior of small-body materials, including mass flow due to high-speed rotation during the creation of the equatorial ridge of Ryugu, subsequent mass movement from the ridge, and resurfacing by micro-meteorite impacts.

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