RED-BLUE MATERIAL DISTRIBUTIONS ON RYUGU CAUSED BY THE PREVIOUS FAST ROTATION.

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Introduction: The color and reflectance of asteroids are the keys to understanding their surface structure, composition, and evolutionary history. These changes in spectral properties are brought about by differences in rock types and exposure to a process called space weathering (impact of meteoroids and solar wind ions). In S-type asteroids, space weathering (impact of meteoroids and solar wind ions) causes a darkening or reddening the spectral slope in the visible wavelength range. On the other hand, for carbonaceous (or C-complex) asteroids, the spectral changes due to space weathering are not well understood and its consequence may be reddening or bluing. Understanding these changes is necessary to decifer the origin and evolution of the surface units of primitive objects in the solar system.

Hayabusa 2 spacecraft reached asteroid Ryugu and revealed a top-shaped body, with higher potentials at its equator and both poles [1]. The equatorial cross-section of Ryugu is almost circular, and Ryugu has a short rotation period, which suggests that deformation due to rotation is envisaged [2]. However, the current rotation speed is too slow to cause significant deformation. Thus, Ryugu may have rotated much faster in the past and then slowed down to the current spin rate [1]. Regarding the top-shape body, Sabuwala et al. (2021) showed by numerical calculations that material uniformly attached to a rotating body tends to accumulate at both the poles and the equator because centrifugal force decreases with latitude [3].

The surface of Ryugu shows a red-blue distribution depending on its reflection properties. Morota et al. (2020) show that asteroid Ryugu has redder and bluer material distributions indicated on a map of the global spectral slope ranging from longitude 0° to 360° and latitude -80° to 80° [4]. Hirata and Ikea (2021) summarized that bluer units are observed in the following four features (1) the equatorial ridge (Ryujin dorsum), (2) near the north and south poles, (3) Tokoyo fossa, and (4) some small fresh craters [5].

Morota et al. (2019) interpreted origin of the bluer unit as a consequence of the red material near the equator being mass wasted to the mid-latitudes [4]. On the other hand, numerical studies show that bluer materials ejected from craters selectively deposited near the equator on Ryugu [5]. The feature (2) has been interpreted to remain bluish because they were not subjected to surface metamorphosis due to low solar irradiance and solar heating. The formation model of the feature (3) has not been well understood. The feature (4) can simply be interpreted as the exposure of flesh material inside Ryugu. Generally speaking, the blue material is assumed to be covered by the red material.

Mass westing and ejecta redeposition should affect the dynamical environment on Ryugu. This study aims to investigate in detail the relationship among the red-blue distributions of Ryugu and dynamic height and slope, changing of the rotation rate.

Method: As the observations and analysis of Ryugu have progressed, Ryugu's global red-blue distributions have been investigated. Yokota et al. (2021) show the normal albedo map of Ryugu, using the data of the opposition geometry from ~20 km distance. From the normal albedo ratio of x-band (0.86 μm) / b-band (0.48 μm), a false color map is produced with the simple cylindrical projection [6]. This figure not only represents a close resemblance to the color distributions presented in the previous study [4], but also represents large bluer units in the latitude ranges above 80 degrees and below -80 degrees.

In order to investigate what geophysical quantities correlated with the global red-blue distributions, the incident flux of sunlight, dynamic height, and dynamic slope were investigated, using the Ryugu shape model with 3,145,728 triangles and 1,579,014 vertices aggregated on the surface [1].

We investigated the correlation between the red-blue distributions and the dynamical environment on Ryugu. Computing the local gravitational potential (U), we divided the Ryugu shape model volumetrically into N (83,256) small triangular pyramids of volume Δv. Under the assumption of homogeneous bulk density value ρ (1.190 kgm^{-3}), U can be calculated:

$$U = G\rho \sum_{i=1}^{N} \frac{\Delta v_i}{r_i}$$

where G is the gravitational constant (6.67408 km^{3}kg^{-1}s^{-2}), and r_i is the distance from the center of mass to the ith mass element. From centrifugal and self-gravitational forces, the equation of motion is given as:

$$\ddot{r} = \nabla U(r) - \omega \times \omega \times r - 2\omega \times \dot{r}$$

where ω is the angular velocity of Ryugu. The dynamic slope is defined as the angle between the normal vector of a surface triangle polygon of the shape model and the surface acceleration vector at the triangle center point.

The total potential (P) was given as:

$$P = \frac{1}{2}\omega^2(x^2 + y^2) - U$$

Then, the dynamic height (*H*) was defined as:

$$H = \frac{P_0 - P}{g_0}$$

where g_0 is a reference gravity and P_0 is a mean gravitational potential. Changing the spin rate (T) in the four cases of 3.5, 3.7, 4.5, 5.5, and 7.36 h, we calculate the dynamic slope and dynamic height for each case.

Results and Discussions: We find that as the rotation speed becomes slower, the overall dynamic slope becomes smaller. Comparing the red-blue distribution map with the dynamic slope maps, we can see that the dynamic slope map, when the rotation speed is less than ~3.7 h, has the features (1), (2), and (4) of the red-blue distributions (Fig 1). However, the feature of (3) does not match. The geophysical quantities (*x-b* ratio and dynamic slope) in the blue region of both maps are different, but their distributions seems to be quite similar. The maps that seemed to correlate best with the red-blue distributions were, in order, the dynamic slope map at T of 3.7 h, the dynamic height map at T of 7.36 h, and the incidence angle map.

When the rotation speed is 3.7 h, there is a strong correlation between the x-b ratio of less than 0.97 and the dynamic slope map of less than 12 degrees. Thus, the bluer units are concentrated on the gentle slope of 12 degrees or less. On the other hand, when the rotation speed is 7.36 h, there is no correlation between the two. Furthermore, the difference of the dynamic slope between the rotation speed of 3.7 h and 7.36 h shows that the dynamic slope is almost unchanged around the equator and both polar regions. These results suggest that the blue material deposited in the slow-slope region during the period of high rotation velocity has remained on the Ryugu surface without significant movement.

We hypothesize an alternative evolution scenario of Ryugu based on this study. When the shape of Ryugu was almost formed, the basic internal structure of Ryugu was also formed, with the blue material inside and red material outside; when an impact event occurred in Ryugu, the blue material inside covered the surface of Ryugu. Later, when Ryugu was spinning at ~3.7 h, the blue material remained in the region with a gentle gradient of less than 12 degrees, while the blue material moved away on a steeper gradient, exposing the red material. This scenario explains features (1) and (2) of the blue distribution, but not (3), that Tokoyo fossa is blue. This may be due to the recent formation or deposition of blue material. The blue distribution feature (4) can be explained if we consider that the blue material was trapped in a local gently sloping area at mid-latitudes. In this scenario, the top-shape of Ryugu was formed in the early stage of formation, which is harmonious with the numerical results [3].

Conclusion: We find that the red-blue distribution map and the dynamic slope map at the rotation speed of ~3.7 h have quite similar characteristics. Considering that the dynamic slope conditions remain almost unchanged around the equator and both polar regions for the rotation rates of 3.7 h and 7.36 h, the red and blue material distributions on Ryugu were formed by the fast rotation of ~3.7 h, and its distribution have not changed much since then. The material on the surface of Ryugu may well retain information about its early history.

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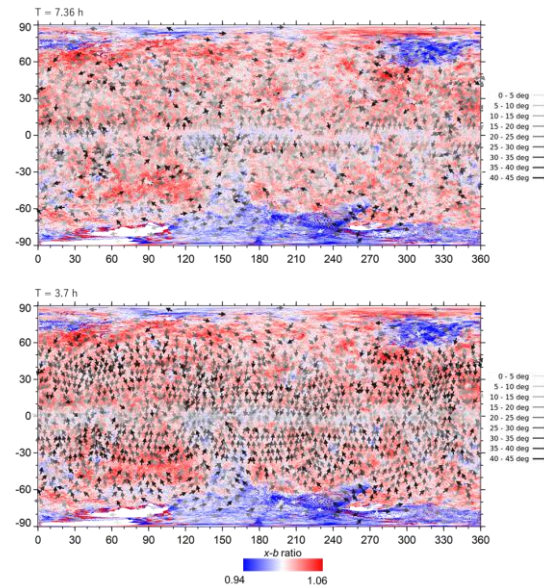
Figure 1. Dynnamic slope maps for the rotation rates of 7.36 h (top) and 3.7 h (bottom). The base map is the x-b slope map derived from the figure 10 of [6].