Overviews of the Hayabusa2 mission and its integrated science

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The asteroid explorer Hayabusa2 performed its proximity operation around Cb-type asteroid (162173) Ryugu from June 2018 to November 2019, and returned to Earth with the surface sample in December 2020. More than 5 g of the particles in the sample catchers were successfully retrieved and the initial description and initial analysis were performed. The formation of the Solar System and the subsequent history of asteroid Ryugu will be discussed based on the proximity observations of Ryugu and analysis of the return sample.

From the initial analysis, the Ryugu sample was confirmed to be similar to CI (Ivuna-type) chondrites in terms of mineral assemblages and composition, and isotopic ratios [1–4]. Some differences were attributed to the effects of weathering and contamination on the ground suffered by CI chondrites, so that the Ryugu sample is considered to preserve the chemical and isotopic state of CI chondrites as they were in space. The presence of grains having large anomalies in the stable isotope ratios of H, C, and N was confirmed [5], suggesting that these particles were produced in the low-*T* environment of the solar parental molecular cloud and retained without undergoing isotopic equilibrium on the parent body. The organic carbon of the Ryugu sample is comparable to that of CI chondrites, whereas the carbonate content is significantly higher, and therefore the total carbon content is somewhat higher. The presence of CO_2-bearing aqueous fluid inclusions in a large iron sulfide (phyrrhotite) crystal [3], the IR absorption of NH in ammonium salts or organic nitrogen compounds [6], and the very low content of chondrules and CAIs [3] suggest that the parent body of Ryugu may have originated outside the snow lines of CO_2 and NH_3 (presumably outside Saturn's orbit). Near infrared spectrometer NIRS3 found a global 2.72 μm absorption on Ryugu, indicating omnipresence of Mg-rich phyllosilicates [7]. Return sample analyses clarified that aqueous alteration in the parent body had progressed in alkaline water with a temperature of ~310 K [1] generated by the decay heat of ^{26}Al in the interior of an about 100-km sized icy body at 5-6 million years after the formation of CAIs in the protosolar disk [3]. The presence of less altered grains in Ryugu particles suggests the difference in temperature between the near-surface and interior of the icy parent body at the stage of aqueous alteration [3]. Some of these less altered grains have particularly high micro-porosity, suggesting the formation of planetesimals from fluffy ice and stone particles. It is noteworthy that franboidal magnetite grains with a remanent magnetization of ~100 μT were found in several Ryugu particles [3], suggesting that the parent body had moved from the outer Solar System to the asteroid belt, where disk magnetic field is expected to have been strong enough, before/during a period of aqueous alteration.

These results are consistent with the scenario that carbonaceous chondrites' parent bodies are icy planetesimals with diameters of ~100 km that formed in the outer Solar System and were brought to the inner Solar System through scattering by giant planets. However, based on the reflection spectra and orbital analysis of Ryugu, its parent body is considered to be one of the collisional families in the inner asteroid belt [8]. Therefore, it is necessary to verify whether the scattering by giant planets could bring planetesimals to such an inner region of the asteroid belt. In any case, it is a great discovery that the parent bodies (at least one of them) of CI chondrites are collisional families in the inner asteroid belt.

Contrary to the parent body processes, the sample analysis information about the formation and evolution of Ryugu itself is rather little and the results from remote sensing observations are important. Low bulk density and abundant large boulders indicate that Ryugu is a rubble-pile object formed through re-accumulation of fragments produced by catastrophic disruption or cratering of the parent body [9]. Surface mean visible spectrum of Ryugu is similar to that of (495) Eulalia, and spectrum of the largest boulder Otohime is similar to (142) Polana, both asteroids are the largest members of the Polana-Eulalia collisional families. Assuming the collision frequency model for the asteroid main belt, the surface age of Ryugu is about 10 Myr based on crater chronology using crater-to-impactor size ratio of 130 after the SCI experiment [10]. The surface age is much younger than the estimated ages of the parent collisional family of Ryugu, either the Polana or Eulalia family. Thus, the surface age is considered to correspond to the top shape formation, probably global resurfacing events [9, 11], induced by the YORP spin-up long after the formation of Ryugu.

Much has also been learned about the post-formation history of Ryugu. From the analysis of the YORP effect using the shape models, Ryugu is now slowly spinning down and had a fast rotation in the past (~10 Ma) [12]. The analysis of the tilt angle distribution on the surface of Ryugu suggests that the top shape was formed by surface landslides when the rotation period was 3.5 to 3.75 hours [9]. Following a previous study [13], which suggested that the east-west asymmetry of the crater rims on Ryugu was caused by the Coriolis forces acting on crater ejecta during a high-speed rotation era, the analysis with precise topographic correction revealed that three large craters on Ryugu have significant higher rims both on the west and equatorial sides [14]. These craters are more susceptible to the Coriolis force than other craters at the stage of high-speed rotation, and the average tilt angle of each surrounding terrain is larger than that of other craters. These results as well as numerical simulations of top-shape formation [15] suggest that the top shape of Ryugu was formed during high-speed rotation era about 10 million years ago, and that the crater formation and space weathering were proceeded during the spin-down phase.

Several bluer (negative spectral slope in visible wavelengths) craters are sccattered in red (flat spectral slope) areas on Ryugu. Stratigraphic relationship between craters reveals that bluer craters are younger in this region, suggesting primordial material of Ryugu is bluer and distributed underground [16]. Suface reddening of the bluer material occurred by space weathering due to solar wind [17]. On the other hand, on (101955) Bennu, the OSIRIS-REx target, redder, flat spectral slope craters are scattered in blue areas, and the craters changed from red to blue due to space weathering, so younger craters are redder on Bennu [18]. This means that space weathering progressed in the opposite direction on the two bodies from the similar flat-spectral material.

The thermal infrared imager (TIR) onboard Hayabusa2 revealed flat diurnal brightness temperature profiles caused by surface roughness and derived global thermal inertia of 225 ± 45 J m^{-2} $s^{-1/2}$ K^{-1} [19, 20], indicating higher porosity of boulders on Ryugu than that of carbonaceous chondrites. In situ measurement by the Mobile Asteroid Surface Scout (MASCOT) also found low thermal inertia of 295 ± 18 J m^{-2} $s^{-1/2}$ K^{-1} [21]. In contrast, return sample measurement showed that the thermal inertia of a Ryugu particle with the thickness of < 1 mm is 890 J m^{-2} $s^{-1/2}$ K^{-1} [3], which is higher than the values on the asteroid surface. The thermal skin depth for the diurnal temperature change of Ryugu is about 10 mm, so that mm-scale cracks may be responsible for the thermal shielding effect on the surface layer of Ryugu. Some dark boulders on Ryugu have thermal inertia lower than 100 J m^{-2} $s^{-1/2}$ K^{-1}, which correspond to porosity >70% [22]. These boulders are considered to be the least processed materials on Ryugu and may preserve the structure of grain aggregates on the parent porous planetesimal.

References

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