FORMATION OF BENNU AND RYUGU: MODELING THE CONTRIBUTION OF MATERIAL FROM THE PROJECTILE THAT DISRUPTED THEIR PARENT BODY.

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Introduction: In a previous study, we investigated by numerical simulations the disruption and reaccumulation process and its role in the formation of Bennu and Ryugu as rubble piles, including their top shapes, their porosity, and their level of hydration [1]. Due to the apparent spectral homogeneity observed on the surfaces of Bennu and Ryugu during the first observational campaigns, we performed reaccumulation simulations that only considered the fate of material originating from the parent body, assumed to be homogenous in composition. However, spectral data from both the OSIRIS-REx and Hayabusa2 missions show a small fraction of silicate-like material signatures on the surface of the two bodies [2, 3]. This can be explained by retention of a silicate projectile's material on either the original (~100 km) parent body or on the (~1 km) rubble pile itself after its formation. However, projectile retention efficiencies from impacts of silicate material on C-type material is still poorly constrained [4, 5] for expected impact speeds in the main asteroid belt (~ 5 km/s, [6]). Here, we investigate whether the family-forming catastrophic disruption can lead to the incorporation of impactor material in the reaccumulated family members, leading to the small fraction of apparently exogeneous material on their surface.

Disruption and Reaccumulation: Asteroids as small as Ryugu and Bennu are likely fragments formed from a larger body that was disrupted [7,8]. Numerical simulations of asteroid disruptions—including both the fragmentation phase during which the asteroid is broken up into small pieces and the gravitational phase during which fragments may reaccumulate due to their mutual attractions—lead to a family of rubble piles over a range of sizes down to 200 m [9]. Considering microporous parent bodies of 100 km in diameter, we found that their disruption (Fig. 1) can lead to rubble piles with oblate spheroidal or top shapes. Moreover, assuming that the parent body is hydrated, the various degrees of heating of its material at impact lead to rubble piles that can have different level of hydration as a result of a single parent body disruption [1].

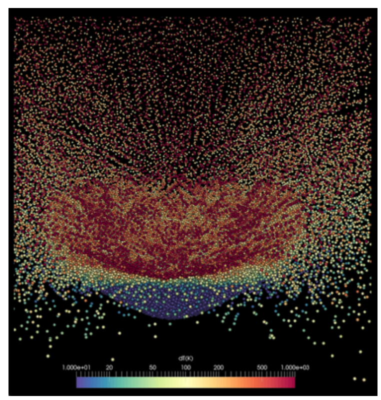

Fig. 1. Outcome of a SPH simulation of the disruption of a microporous 100-km-diameter parent body. Each particle is a fragment produced in this phase. Colors represent the various degrees of impact heating. This outcome is the starting point of the gravitational phase during which those fragments and their different level of impact heating reaccumulate to form rubble piles.

Approach: To assess the role of the projectile in the disruption/reaccumulation process at the origin of Bennu and Ryugu, we performed a series of numerical simulations of catastrophic disruption of 100-km-diameter microporous asteroids and account for both the parent body's material and the surviving projectile's material in the subsequent gravitational phase when fragments re-accumulate to form rubble piles. As in our previous works, the fragmentation phase was simulated using a Smoothed Particle Hydrodynamics

(SPH) hydrocode and the gravitational phase was computed using the *N*-body code *pkdgrav*, including the Soft-Sphere Discrete Element Method (SSDEM) [10]. We then track the surviving materials of both the projectile and the parent body, including their level of heating, that contribute to the formation of aggregates. For each of them, we measure their shapes, the fraction of materials of the projectile and the parent body that compose them, and their associated level of heating. One complexity is that the fraction of projectile's material contributing to each aggregate may be very small, which is a challenge for the simulations that require high resolution to track this small fraction.

Results and Perspectives: Our simulations show that oblate spheroids are a common product of large asteroid disruptions, and in some circumstances the formation of an equatorial ridge may be possible. Formation by this process of top shapes, or shapes than can quickly lead to top shapes through YORP spin-up (Fig. 2), provides an explanation to the apparent old age of the ridges of Ryugu and Bennu [11, 12].

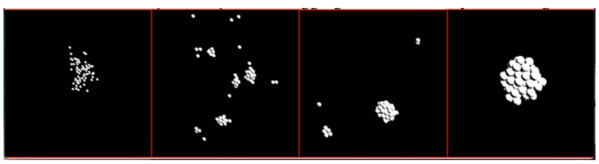

Fig. 2. Example of a forming aggregate during the reaccumulation phase that becomes a top shape. The final aspect ratios are c/a=0.86 and b/a=0.98, where a, b, c are the long, intermediate, and short axis, respectively, to be compared with those of Bennu (c/a=0.9 and b/a=0.96) and Ryugu (c/a=0.87 and b/a=0.96).

However, the detected signature of apparently exogeneous material poses a new challenge [2, 3]. While for large asteroids like Vesta, projectile material retention during impacts over its history may explain some observed surface features, this scenario poses some challenges for small asteroids like Bennu and Ryugu that may be easily disrupted. However, more work is needed to clarify how much of the projectile's material can survive on asteroid surfaces at typical impact speeds (~5 km/s).

Alternatively, contamination on Bennu and Ryugu may be a signature of the impact history of their parent bodies in the asteroid belt, either through multiple impacts on the parent body before a family-forming event, or in the catastrophic disruption of the parent body itself. Here, we study the latter scenario and simulations are still running. The previously neglected fate of projectile material during the catastrophic disruption of the parent body may provide an explanation regarding the small portion of apparently exogeneous material on the surfaces of Bennu and Ryugu. The projectile's material was neglected in the previous simulations of disruption/reaccumulation for the reason that asteroid families formed by this process looked spectrally homogeneous, suggesting that they are mostly made of the material of their parent body. But thanks to space missions and advanced performances of observational capabilities, we now discover that the situation is more complex than it seemed. The more we can measure the compositional properties of asteroids in detail, the more we may identify a greater or lesser fraction of material mixtures, like for 2008 TC3 and its Almahata Sitta meteorites [13]. If we find that the material of the projectile at the origin of a parent body disruption contributes to the material of reaccumulated rubble piles, implications will be huge and will go beyond the cases of these two fascinating bodies.

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References: [1] Michel, P. et al. (2019) *EPSC-DPS*, Abstract #2019-245. [2] DellaGiustina, D.N. et al. (2019) *EPSC-DPS,* Abstract #2019-1074. [3] Sugimoto, C. et al. (2019) Asteroid Science in the Age of Hayabusa2 and OSIRIS-REx Abstract #2051. [4] Avdellidou, C. et al. (2016) *MNRAS, 456*, 2957. [5] Daly, R.T., & Schultz, P. H. (2018) *M&PS, 53,* 1364. [6] Bottke, W.F. et al. (2005) Icarus, 179, 63. [7] Michel, P. et al. (2001) *Science, 294,* 1696–1700. [8] Walsh, K.J. (2018) *ARA&A 56*, 593. [9] Jutzi, M. et al. (2019) *Icarus 317,* 215. [10] Ballouz, R.-L. et al. (2019) *MNRAS 485,* 697. [11] Walsh, K.J., et al. (2019) *Nature Geoscience 12,* 242. [12] Sugita et al. (2019) *Science 364,* 252. [13] Goodrich, C.A. et al. (2019) *M&PS 54,* 2769.