Ejecta flux estimation after an impact crater: a methodology

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This work is part of the Horizon-2020 MSCA project CRADLE (Collecting Asteroid-Orbiting Samples) and it is based on the study of novel concepts for asteroid exploration and sample collection missions. Specifically, the objective of the project is to assess the feasibility of performing in-orbit sample collection. To this aim, in this work, we present a methodology to estimate the number of particles the spacecraft would be able to collect by generating an ejecta cloud releasing a small kinetic impactor onto the asteroid surface. The methodology estimates the fluxes of particles around the asteroid using the concept of representative fragments. As the spacecraft moves within these particle fluxes, we estimate the impact rate of the particles on the spacecraft and the cumulative number of impacts. We apply this methodology to a spacecraft hovering around asteroid Ryugu.

I. Introduction

Asteroids carry fundamental information on the evolution of our Solar System and they are rich in valuable resources such as metals, silicates, and water. The resources they contain can be exploited, via future asteroid mining, to extract rare metals and water to enable the self-sustainability of long-duration missions. Having a better knowledge of asteroids' composition can enable such future missions; in fact, their physical composition is varied and, in most cases, poorly understood. By collecting samples from asteroids we can vastly improve our knowledge of their composition and, thus, we can better target them for scientific, safety, and economic purposes. This can be achieved through sample collection missions. Several missions have visited asteroids and other small bodies; however, only few have orbited, landed, or impacted on them. Examples are JAXA missions Hayabusa and Hayabusa2 [1–3], ESA Rosetta, and NASA OSIRIS-REx. One of the most challenging aspects of such missions is to collect and sample asteroids material by means of an on-ground collection, involving landing (or touchdown). In a context of future asteroid exploration missions, within the Collecting Asteroid-Orbiting Samples - CRADLE project, we envision the possibility to perform in-orbit collection as an alternative to landing or touchdown operations [4, 5]. Such a collection mechanism relies on the knowledge of the dynamical behaviour of small particles orbiting the asteroid, which is influenced by the third body effect, solar radiation pressure and the gravitational potential of the asteroid.

In this work, we present e methodology to estimate the fluxes of fragments around an asteroid, generated by an impact cratering event. The knowledge and prediction of such fluxes can enable the collection of samples in orbit and direct the mission planning towards areas around the asteroid that are expected to have higher fluxes of fragments. In this way, a more effective collection can be performed. In addition, the knowledge about the fluxes as a function of the particle size can help the design of the size and characteristics of the sampling mechanism to be used during the collection phases. The methodology is then applied to a test case of a Hayabusa2-like impact on asteroid Ryugu.

II. Methodology

The methodology to estimate the ejected fragments fluxes is based on the sampling and propagation of selected samples from the ejecta distribution and the discretization of the space around the asteroid in order to estimate the

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density and the fluxes of particles. To obtain an estimate of the flux, first a set of samples is drawn from the ejecta distribution [6], as described in Section II.B. Then, the samples are propagated according to the desired dynamical model (Section II.A) and the results saved at specific snapshots in time. For each of the saved snapshots, the fluxes are estimated on a spherical grid around the asteroid (in right ascension, declination, and radius) by estimating the density and average velocity of the fragments in each bin.

A. Dynamical model

The adopted dynamical model is the Photo-gravitational Hill Problem that is the extension of the classical Hill problem to a radiating primary [7]. The equations of motion are expressed in non-dimensional form in a synodic reference frame centred in the asteroid. The x-axis is along the Sun-asteroid direction, pointing outwards, the z-axis is along the direction of the angular momentum of the asteroid orbit, and the y-axis completes the right-hand system.

$$\begin{cases} \ddot{x} - 2\dot{y} = -\frac{x}{r^3} + 3x + \beta \\ \ddot{y} + 2\dot{x} = -\frac{y}{r^3} \\ \ddot{z} = -\frac{z}{r^3} - z \end{cases} \tag{1}$$

where x, y, and z are the non-dimensional particle positions with respect to the centre of the asteroid in the synodic frame, and $r = \sqrt{x^2 + y^2 + z^2}$ is the particle's distance from the centre of the asteroid. The lightness parameter β can be expressed as follows [8]:

$$\beta = \frac{P_0}{c} \frac{AU^2}{\mu_a^{1/3} \mu_{\mathrm{Sun}}^{2/3}} \frac{3(1 + c_{\mathrm{R}})}{2\rho_{\mathrm{p}} d_{\mathrm{p}}}. \tag{2}$$

Here $P_0 = 1367\ \mathrm{W\,m^{-2}}$ is the solar flux at 1 AU, c is the speed of light, AU is the astronomical unit, μ_{Sun} and μ_a are the gravitational parameter of the Sun and the asteroid, respectively, ρ_{p} is the particle density and d_{p} the particle diameter. The reflectivity coefficient, c_{R}, is a number between 0 and 1, where 1 is for fully reflective surfaces. Eclipses are taken into account using a cylindrical shadow model via a modified lightness parameter, β^*:

$$\beta^* = \begin{cases} \beta & \text{if } x \leq 0 \\ \beta \cdot f(\sigma) & \text{otherwise} \end{cases}, \tag{3}$$

where $f(\sigma) = (1 + e^{-s \cdot \sigma})^{-1}$ is a sigmoid function with steepness parameter s, which, in this work is equal to 8 [8]. The variable $\sigma = r_x - R_a$, with $r_x = \sqrt{y^2 + z^2}$ distance to the x-axis, and R_a mean radius of the asteroid.

B. Ejecta model

The ejecta model describes the characteristics of the ejected particles after a kinetic impact and is used to generate the initial conditions of the propagation. The ejected particles are defined by their size, ejection location, ejection speed, and launch direction. Specifically, we will use the ejecta model to describe the effect of an impact with a small kinetic impactor, comparable to the one of the Hayabusa2 mission. The ejecta model is defined using a density function of the form:

$$p(\mathbf{x}) = p(s, r, \xi, \psi) = p_s(s) \cdot p_\xi(\xi) \cdot p_{\psi|r}(\psi|r) \cdot p_r(r), \tag{4}$$

where s is the particle radius, r the ejection location (i.e., distance from the centre of the crater), ξ and ψ are the in-plane and out-of-plane ejection angles relative to a normal impact (i.e., an impact perpendicular to the surface of the target) (Fig. 1). We observe that, even for a normal impact, the out-of-plane ejection angle, ψ, depends on the launch position, r [9]; therefore, we represent it with a conditional distribution. A detailed description of the expressions of the different probability distribution functions can be found in [4, 6].

The ejection speed can be directly obtained from the ejection location, r, using a correlation. In this work, we use the one derived by Housen et al. [10, 11], which has the following expression:

$$u(r) = C_1 \cdot U \cdot \left[\frac{r}{a} \cdot \left(\frac{\rho}{\delta}\right)^{\nu}\right]^{-\frac{1}{\mu}} \cdot \left(1 - \frac{r}{r_{\max}}\right)^{p}, \tag{5}$$

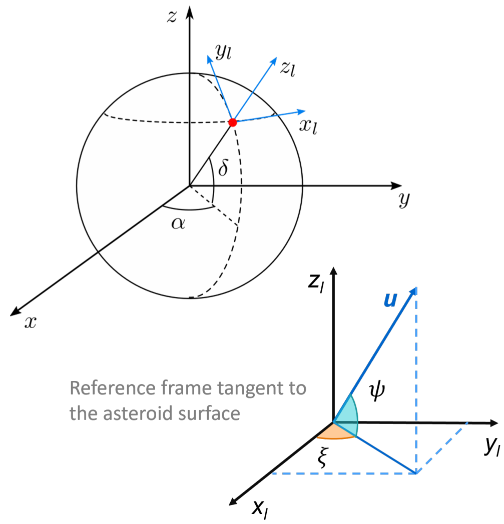


Figure 1 Representation of the ejecta model reference frame.

where C_1, μ, ν, p, and n_2 are coefficients depending on the target material, δ is the density of the impactor and U is the impactor speed.

The ejecta model is used to sample the distribution following the procedure described in [6], where to each sample is associated a number of *representative fragments*, which represent the amount of fragments each sample carries. In this way, we can better characterise the evolution of the entire ejecta cloud. The representative fragments are obtained integrating the propability distribution function of Eq. (4) on a grid as defined by the user and such that at least one sample is with each bin of the grid [6].

C. Flux estimation

In order to estimate the fluxes of ejected fragments on a spacecraft, we first obtain the position and velocity of the propagated samples at each snapshot in time and, with that, the information on the representative fragments carried by each sample. Subsequently, for each snapshot, we subdivide the volume around the asteroid using a spherical grid as in Fig. 2.

Once the grid is defined, we can estimate the particle density and average weighted velocity of the particles as follows:

$$\rho(r, \alpha, \delta) = \frac{\sum_i n_{f_i}(r, \alpha, \delta)}{\Delta V(r, \alpha, \delta)} \tag{6}$$

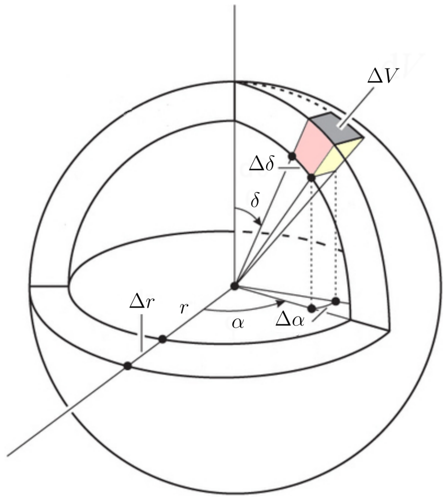
$$\mathbf{v}(r, \alpha, \delta) = \frac{\sum_i n_{f_i}(r, \alpha, \delta) \cdot \mathbf{v}_i}{\sum_i n_{f_i}(r, \alpha, \delta)} \tag{7}$$

where the subscript i indicates all the samples contained within the spherical bin centred in (r, α, δ), n_{f_i} is the number of representative fragments associated with each sample in the bin, ΔV is the volume of the considered spherical bin, and $\mathbf{v}_i$ is the velocity vector of each sample in the bin. As we can observe, the speed of each sample is weighted with the number of representative fragments associated to it. Fig. 3 shows an example of the density distribution around Ryugu, where a cut out of the distribution along the xy-plane is provided for a clearer representation.

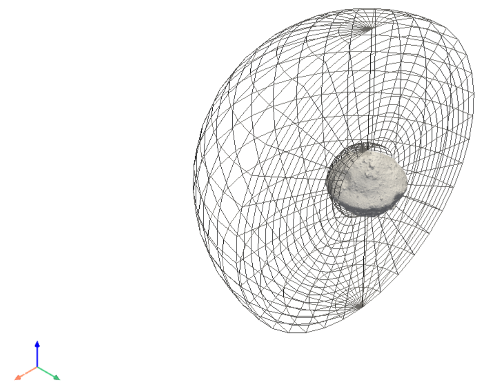
Finally, to compute the fluxes of particles onto a spacecraft traversing the ejecta cloud around the asteroid, it is necessary to know the relative velocity of the spacecraft with respect to the particles when i crosses one of the spherical bins. Therefore, if we know the position and velocity of the spacecraft, we can compute the impact rate as follows:

$$\dot{\eta}_{SC}(r, \alpha, \delta) = \rho(r, \alpha, \delta) \cdot |\mathbf{v}(r, \alpha, \delta) - \mathbf{v}_{SC}| \cdot A \,, \tag{8}$$

where A is the cross-section of the spacecraft (or of the collection instrument), $\mathbf{v}_{SC}$ is the velocity of the spacecraft when crossing the bin with coordinates (r, α, δ), and $\dot{\eta}_{SC}(r, \alpha, \delta)$ is the corresponding impact rate.



(a)



(b)

Figure 2 Representation of a spherical grid used to estimate the fluxes. a) elementary volume of the grid. b) wireframe representation of a section of the grid.

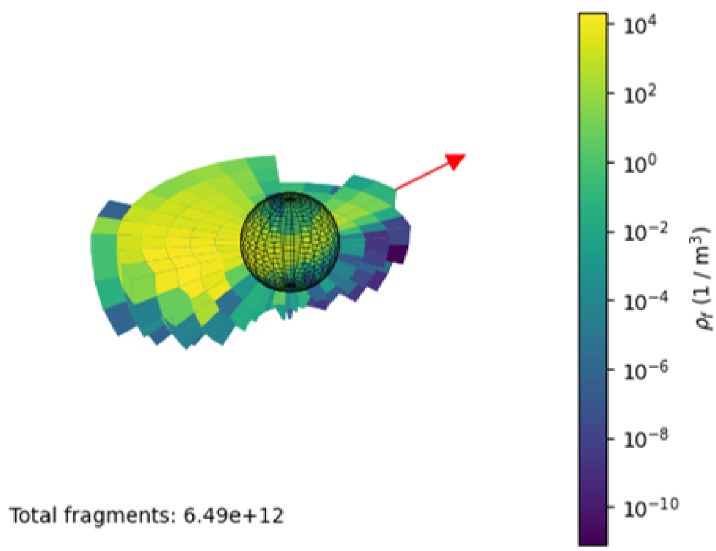


Figure 3 Example of density estimation on a spherical grid for a specific snapshot in time.

We then assume that at a specific snapshot in time, the density and speed distribution of the particles can be considered approximately constant until the subsequent snapshot; therefore, we can estimate the total impact on the spacecraft as follows:

$$N_{\mathrm{imp}} \approxeq \sum_{t=1}^{N_T} \dot{\eta}_{\mathrm{SC}}^{t}(r_t, \alpha_t, \delta_t) \cdot \Delta T_t \ , \tag{9}$$

where the index t identifies the time snapshot considered, N_T is the total number of snapshots, ΔT_t is the duration of a snapshot (time between a snapshot and the next), and $\dot{\eta}_{\mathrm{SC}}^{t}$ is the impact rate on the spacecraft at snapshot t, when the spacecraft is within the bin centred in $(r_t, \alpha_t, \delta_t)$.

III. Results

We apply the methodology of Section II to the test case of a Hayabusa2-like impact onto asteroid Ryugu [12], considering a sand-like material [10, 11, 13]. The impactor has a speed of 2 $\mathrm{km\,s^{-1}}$ and a mass of 2 kg; the impact is assumed to be normal (perpendicular to the asteroid's surface) and the impact location has a right ascension (α) and declination δ with respect to a synodic frame centred in the asteroid of 200° and 10°, respectively. The particle size range is between 10 µm and 1 cm, and the maximum sampled speed is the escape speed from the asteroid.

To test the procedure, we assume our spacecraft can be approximated as a sphere with a 1 m diameter; in addition, we assume the spacecraft can occupy a position around the asteroid and maintain it hovering, with a zero relative velocity with respect to the asteroid in a synodic frame. We selected a series of test locations to estimate the impact rates and total impacts, uniformly distributed along the equatorial plane of the asteroid, as shown in Fig. 4. Here, we have highlighted the test location selected for further examination and to present the results for this work.

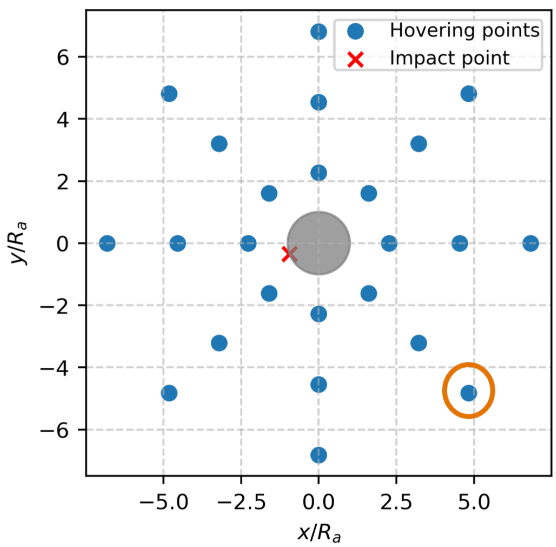


Figure 4 Hovering positions of the spacecraft used as test locations.

In Fig. 5 we show the overall impact rate and the total number of impacts at the selected location. As we can observe, the impact rate increases sharply in the first hours after the impact as the highest fluxes reach the hovering location. As shown by Fig. 7a, these fluxes are associated with the smallest ejected particles. As the time passes, the impact rate decreases exponentially as the majority of th particles is cleared from the neighbourhood of the asteroid by the effect of solar radiation pressure. Nonetheless, as we can observe hundreds of thousands of particles can potentially be collected in this location. Of these particles, the vast majority have sizes smaller than 0.1 mm and few hundreds between 0.1 and 1 mm. The particles greater than 1 mm, instead, have negligible numbers and would require a much larger area to be collected in sufficient quantity.

Fig. 7 shows the types of orbits of the fragments that can be intercepted at the selected location, together with the estimated impact time, as a function of the particle size. We can observe that up to 1 mm particles, all the trajectories quickly escape the system due to the effect of SRP. For larger particles, instead, we observe that most of them remain in orbit around the asteroid for several hours.

IV. Conclusions and future work

In this work, we have presented the building blocks of a methodology to estimate the number of collectable fragments by a spacecraft around an asteroid as they are generated by a small kinetic impactor. The methodology is based on the estimation of the particle flux onto the spacecraft, which is obtained by sampling and propagating a set of representative fragments and using them to estimate the density and speed of the particles on a spherical grid around the asteroid.

The methodology is statistical in nature and further analysis are required to understand its sensitivity to the several parameters involved, such as the different realisations of the sampling routine, the selection of the grid to estimated the fluxes, and to the characteristics of the impact itself. Finally, the influence of operational constraints should also be

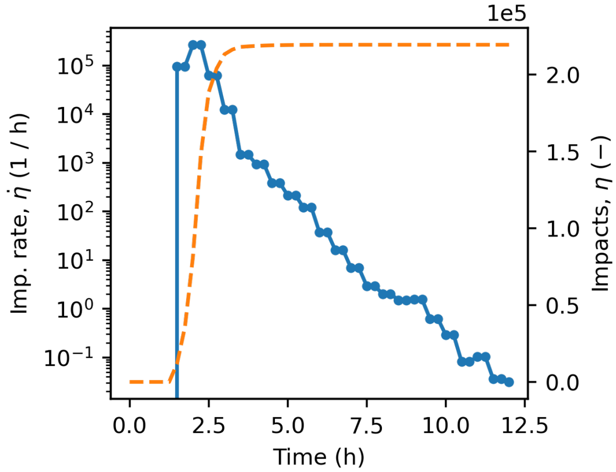


Figure 5 Impact rate and total number of impacts at the selected test point.

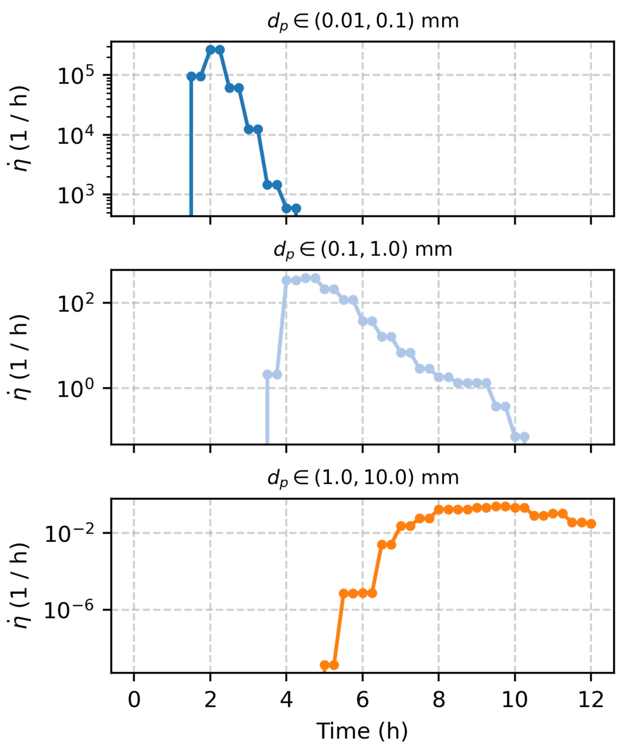


Figure 6 Impact rates as a function of the particle diameter at the selected test point.

included.

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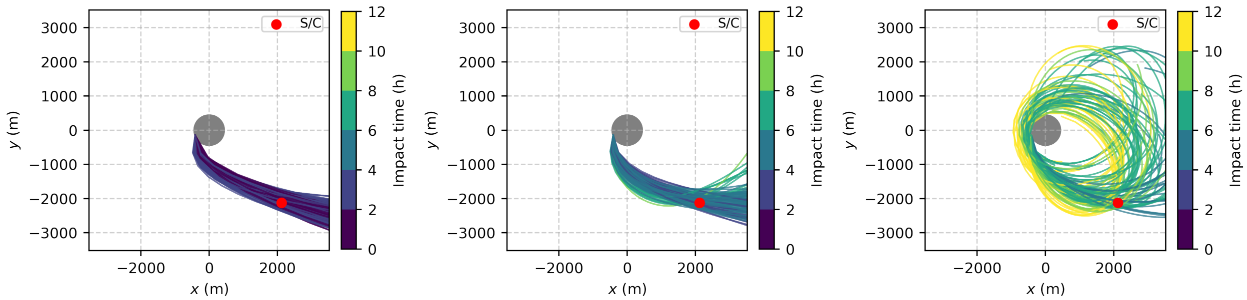

(a) **(b)** **(c)**

Figure 7 Examples of particles orbit impacting the spacecraft at the considered collection location for three different diameter ranges. a) $d_p \in$**(10** µm**, 0.1** mm**) b)** $d_p \in$**(0.1** mm**, 1** mm**) c)** $d_p \in$**(1** mm**, 1** cm**)**

References

[1] Tsuda, Y., Yoshikawa, M., Abe, M., Minamino, H., and Nakazawa, S., "System design of the Hayabusa 2—Asteroid sample return mission to 1999 JU3," *Acta Astronautica*, Vol. 91, 2013, pp. 356–362.

[2] Tsuda, Y., Yoshikawa, M., Saiki, T., Nakazawa, S., and Watanabe, S.-i., "Hayabusa2–Sample return and kinetic impact mission to near-earth asteroid Ryugu," *Acta Astronautica*, Vol. 156, 2019, pp. 387–393.

[3] Tsuda, Y., Saiki, T., Terui, F., Nakazawa, S., Yoshikawa, M., Watanabe, S.-i., and Team, H. P., "Hayabusa2 mission status: Landing, roving and cratering on asteroid Ryugu," *Acta Astronautica*, Vol. 171, 2020, pp. 42–54.

[4] Trisolini, M., Colombo, C., Tsuda, Y., et al., "Ejecta dynamics around asteroids in view of in-orbit particle collection missions," *72nd International Astronautical Congress (IAC 2021)*, 2021, pp. 1–10.

[5] Trisolini, M., Colombo, C., and Tsuda, Y., "Target selection for Near-Earth Asteroids in-orbit sample collection missions," *Acta Astronautica*, Vol. 203, 2023, pp. 407–420. https://doi.org/https://doi.org/10.1016/j.actaastro.2022.12.012.

[6] Trisolini, M., Colombo, C., and Tsuda, Y., "Ejecta cloud distributions for the statistical analysis of impact cratering events onto asteroids' surfaces: A sensitivity analysis," *Icarus*, Vol. 394, 2023, p. 115432. https://doi.org/https://doi.org/10.1016/j.icarus.2023.115432.

[7] Soldini, S., and Tsuda, Y., "Assessing the hazard posed by Ryugu ejecta dynamics on Hayabusa2 spacecraft," *26th International Symposium of Space Flight Dynamics*, 2017, pp. 1–11.

[8] Villegas-Pinto, D., Soldini, S., Tsuda, Y., and Heiligers, J., "Temporary Capture of Asteroid Ejecta into Periodic Orbits: Application to JAXA's Hayabusa2 Impact Event," *AIAA Scitech 2020 Forum*, 2020, p. 0221.

[9] Richardson, J. E., Melosh, H. J., Lisse, C. M., and Carcich, B., "A ballistics analysis of the Deep Impact ejecta plume: Determining Comet Tempel 1's gravity, mass, and density," *Icarus*, Vol. 191, No. 2, 2007, pp. 176–209.

[10] Housen, K. R., and Holsapple, K. A., "Ejecta from impact craters," *Icarus*, Vol. 211, No. 1, 2011, pp. 856–875.

[11] Holsapple, K. A., and Housen, K. R., "A crater and its ejecta: An interpretation of Deep Impact," *Icarus*, Vol. 191, No. 2, 2007, pp. 586–597.

[12] Arakawa, M., Saiki, T., Wada, K., Ogawa, K., Kadono, T., Shirai, K., Sawada, H., Ishibashi, K., Honda, R., Sakatani, N., et al., "An artificial impact on the asteroid (162173) Ryugu formed a crater in the gravity-dominated regime," *Science*, Vol. 368, No. 6486, 2020, pp. 67–71.

[13] Holsapple, K. A., and Housen, K. R., "Momentum transfer in asteroid impacts. I. Theory and scaling," *Icarus*, Vol. 221, No. 2, 2012, pp. 875–887.