CRATERING PROCESSES ON RUBBLE-PILE ASTEROIDS: INSIGHTS FROM LABORATORY EXPERIMENTS AND NUMERICAL MODELS S. D. Raducan[1], J. Ormö[2], M.I. Herreros[2], K. Wünnemann[3,4], Y. Zhang[6], R. Luther[3], C. Hamann[3], G.S. Collins[5], P. Michel[6], M. Jutzi[1], [1]Space Research and Planetary Sciences, Physikalisches Institut, University of Bern, Switzerland; sabina.raducan@space.unibe.ch; [2]Centro de Astrobiologia (INTA-CSIC), Torrejon de Ardoz, Spain; [3]Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science, Germany; [4]Freie Universität Berlin, Germany; [5]Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, UK; [6]Université Côte d'Azur, Observatoire de la Côte d'Azur, Laboratoire Lagrange, France.

Keywords: *DART, Hera, rubble-pile, SPH*

Introduction: NASA's Double Asteroid Redirection Test (DART) will impact the moon of Didymos, Dimorphos, and alter its orbital period around the primary, thus demonstrating the controlled deflection capabilities of near-Earth asteroids by a kinetic impactor [1, 2]. ESA's Hera mission [2] will arrive at Dimorphos several years after the DART impact and provide a detailed characterisation of the impact outcome, including the morphology of the impact crater. Recent impact experiments and numerical studies [3–5] have shown that the kinetic impact efficiency strongly depends on the target properties, and is non-unique (i.e., impacting asteroids with different properties can result in the same deflection). Moreover, small asteroids, of less than about 10 km in diameter, are believed to be rubble-pile objects, aggregates held together only by self-gravity or small cohesive forces [6]. It is likely that Dimorhpos is not homogeneous at the scale of the DART.For a successful interpretation of the DART impact outcome, it is important to understand the influence of asteroid properties and structure on the cratering process. Efforts to model rubble-pile geometries in the context of DART are undertaken (e.g., [7]), however these results have not yet been validated against laboratory experiments.

Here we present new modelling results aimed at assessing the momentum transfer and the crater morphology resulted from DART-like impacts on rubble-pile asteroids.

Laboratory experiments: To increase the confidence in our numerical model, we first performed validation tests of impacts into heterogeneous targets, against recent laboratory experiments performed at the Experimental Projectile Impact Chamber (EPIC) at Centro de Astrobiología CSIC-INTA in Spain [8, 9]. The EPIC facility was used to perform a vertical shot into a rubble-pile like target, at about 400 m/s. The projectile, a 20 mm in diameter Delrin sphere, that disrupts upon impact. The ceramic balls are ≈2.25 cm in diameter and have a compressive strength of about 1 MPa and a porosity of about 50%. This material is considered to be a good mechanical analogue for the boulders found on the rubble-pile asteroids Ryugu or Bennu [10]. The experiment was performed into a quarter-space beach sand target with 4 layers of embedded boulders, which had one ball diameter spacing between each ball in the x, y and z directions. All layers were identical and were placed on top of each other with one ball-diameter thick sand layer in between. The uppermost layer was covered by sand.

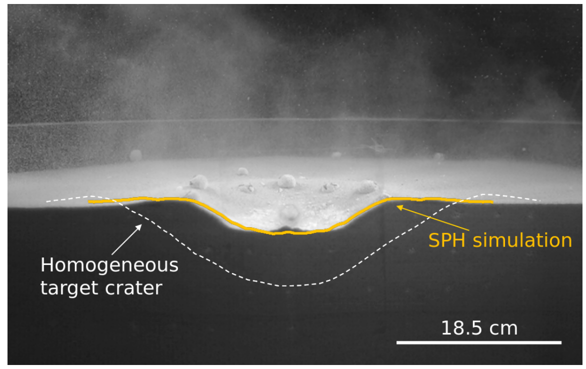

Figure 1: Crater profile from a ≈400 m/s impact into a heterogeneous target, compared with the profile obtained from an SPH simulation. The crater profile from a similar impact into a homogeneous target is plotted for comparison.

Validation of the SPH model: We used Bern's Smoothed-particle hydrodynamics (SPH) shock physics code [11, 12] to reproduce the EPIC impact experiment. SPH is well suited to model high velocity impacts on heterogeneous asteroids. The code includes material models relevant for geological materials, various equations of state and a porosity compaction model, the $P-\alpha$ model.

The target matrix was modelled using the Tillotson EoS for SiO_2 and the Drucker-Prager strength model, with a coefficient of internal friction, f = 0.56. The porosity of the matrix was about 30%. The boulders were modelled using the Tillotson EoS for basalt [13] and a tensile strength and fracture model as described in [12].

In the experiment, the impact generated a crater about half the diameter of a reference crater in a homogeneous beach sand target [8]. SPH simulations were able to accurately reproduce the crater profile from this impact scenario (Fig. 1). The im-

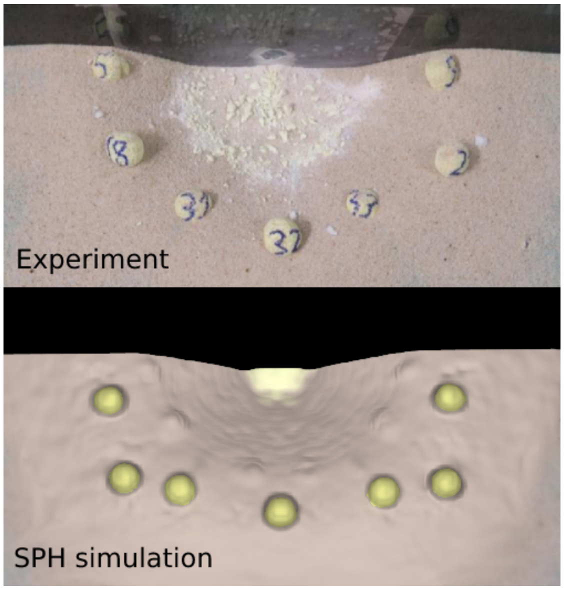

Figure 2: **Distribution of boulders after the impact in the EPIC experiment compared to the SPH simulation.**

pactor and the boulder placed at the point of impact got fragmented, while the boulders placed in immediate proximity to the impact point were ejected. Boulders placed more than three boulder diameters away from the impact point remained intact and were displaced towards the crater rim (Fig. 2). Boulders also affected the sand ejection to form rays in the ejecta blanket. The SPH simulation was able to closely reproduce these observations.

Applications to DART: Our validated SPH rubble-pile structure model can then be applied to simulate the global scale effects caused by DART-like impacts on small asteroids with heterogeneous interiors. We considered SPH simulations of 500 kg projectiles impacting 140 m rubble-pile asteroids, at 6 km/s. The matrix material was modelled using the Tillotson EoS for basalt [13]. To describe the shear response, we used the Drucker-Prager strength model, with f = 0.6. The initial target porosity was kept constant at 40%. The boulders were modelled the same as in the validation test described above.

We considered rubble-pile asteroids with three different distributions of boulders: a) grid distribution of 2.5 m in diameter boulders, with one boulder diameter spacing between each boulder in x, y, and z directions; b) random distribution of 2.5 m boulders; c) Random distribution of boulders with random sizes between 2 and 10 m (Fig. 3).

Due to the very large cratering efficiencies occurring in the low strength-low gravity regime, end-to-end models of these impacts are computationally expensive. Initial simulation results revealed that due to the presence of the boulders in the target, the efficiency of the DART impact can decrease by

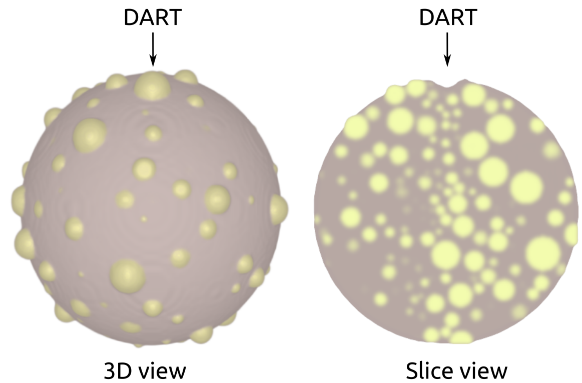

Figure 3: **3D and slice view from an SPH simulation showing the early stages of a DART-like impact on a 140 m rubble-pile asteroid with random distribution of boulders (T = 1 s).**

up to 40% compared to an impact into a homogeneous target [14].

Conclusion and outlook: The work presented here represents the first step towards modelling impacts into realistic rubble-pile asteroids, using well validated codes, against laboratory experiments that have been purposely developed for code validation. These impacts are challenging to model and only limited number of impact scenarios have been studied so far. Future work aims to explore the effects of DART-like impacts on heterogeneous asteroids with different boulder distributions and target shapes, also using model asteroid shapes derived from N-body models [15].

References:[1] Cheng, A. F. et al. (2018) *Planet Space Sci*, 157:104–115. [2] Michel, P. et al. (2018) *Adv Space Res*, 62:2261–2272. [3] Housen, K. R. & Holsapple, K. A. (2011) *Icarus*, 211:856–875. [4] Jutzi, M. & Michel, P. (2014) *Icarus*, 229:247–253. [5] Raducan, S. D. et al. (2019) *Icarus*, 329:282–295. [6] Richardson, D. C. et al. (2002) *Asteroids III*, 501–515. [7] Stickle, A. M. et al. (2018) *LPSC*, 49:1576. [8] Ormö, J. et al. (2015) *Meteorit Planet Sci*, 50:2067–2086. [9] Ormö, J. et al. (2021) *LPSC*,1965. [10] Ballouz, R.-L. et al. (2020) *Nature*,1–5. [11] Jutzi, M. et al. (2008) *Icarus*, 198:242–255. [12] Jutzi, M. (2015) *Planet Space Sci*, 107:3–9. [13] Benz, W. & Asphaug, E. (1999) *Icarus*, 142:5–20. [14] Raducan, S. D. & Jutzi, M. (2021) *LPSC*,1900. [15] Zhang, Y. et al. (2021) *Icarus*, 362:114433.

Acknowledgements: This project received funding from the EU's H2020 research and innovation programme, NEO-MAPP, grant agreement No.870377. JO was supported by grants ESP2014-59789-P, ESP2015-65712-C5-1-R and ESP2017-87676-C5-1-R from the MINECO and FEDER. JO and MIH were supported by the AEI Project No.MDM-2017-0737 INTA-CSIC and the CSIC support for international cooperation: I-LINK project LINKA20203.