DIMORPHOS'S MATERIAL PROPERTIES AND ESTIMATES OF CRATER SIZE FROM THE DART IMPACT. A. M. Stickle[1], M. E. DeCoster[1], D. M. Graninger[1], K. M. Kumamoto[2], J. M. Owen[2], E. S. G. Rainey[1], M. B. Syal[2], O.S. Barnouin[1], N. L. Chabot[1], A. F. Cheng[1], G.S. Collins[3], R.T. Daly[1],T. M. Davison[3], E. Dotto[4], C.M. Ernst[1], E. G. Fahenstock[5], F. Ferrari[6], T. Hirabayashi[7], O. Karatekin[8], A. Lucchetti[9], R. Luther[10], S. Marchi[11], N. Mitra[12], M. Pajola[9], L. M. Parro[13,14], J. Pearl[2], K.T. Ramesh[12], A. S. Rivkin[1], A. Rossi[15], P. Sanchez[16], C.B. Senel[8], S. R. Schwartz[17], F. Tusberti[9], K. Wunnemann[10,18], Y. Zhang[19], and the DART Investigation Team, [1]Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD, 20723, angela.stickle@jhuapl.edu, [2]Lawrence Livermore National Laboratory, Livermore CA; [3]Imperial College, London, US; [4]INAF-OAR; [5]Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA; [6]Politecnico di Milano, Milan, Italy; [7]Auburn University; [8]Royal Observatory of Belgium; [9]INAF-OAPd; [10]Museum für Naturkunde - Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany; [11]Southwest Research Institute;[12]Johns Hopkins University, Baltimore MD; [13]Lunar and Planetary Laboratory, University of AZ, USA; [14]Universidad de Alicante, Spain;[15]IFAC-CNR; [16]CU Boulder;[17]Planetary Science Institute;[18]Freie Universität Berlin, Germany; [19]University of Maryland, College Park.

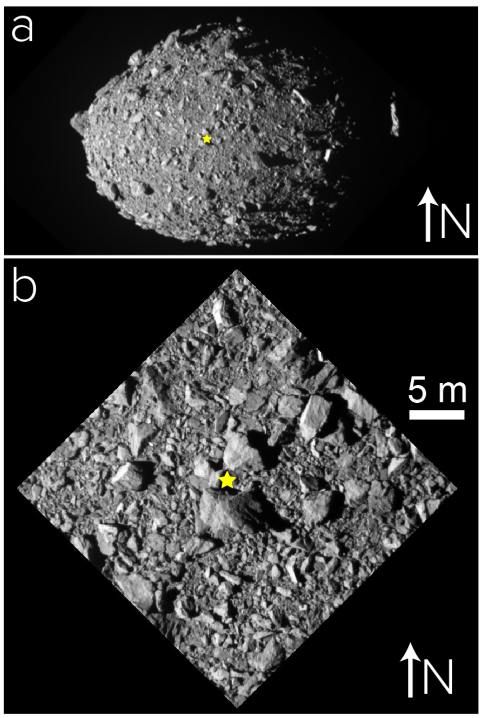

Figure 1. (a) The last full image of Dimorphos taken by the DRACO camera on the DART spacecraft, I-11.447 sec, 68 km distance; ~35 cm/pix. (b) The last full frame of the DART impact location, I-1.8 sec, 5.5 cm/pix. The yellow star indicates the impact location [1] Credit: NASA/JHUAPL

Introduction: On September 26, 2022, the Double Asteroid Redirection Test (DART) spacecraft intentionally collided with Dimorphos, the moon of the binary asteroid system 65803 Didymos. This collision provided the first full-scale test of a kinetic impactor for planetary defense. Images from DART's DRACO camera revealed Dimorphos to be a rubble-covered oblate spheroid (**Fig. 1**) [1].

The DART collision changed the orbital period of Dimorphos around Didymos by 33 minutes [2], which translates to an orbital velocity change of ~2.7 mm/s and a momentum enhancement factor, β, of ~3.6 assuming the density of Dimorphos is 2400 kg/m^3 [3]. Follow-on images from the ASI-led cubesat LICIAcube, and Earth- and space-based telescopes, revealed spectacular ejecta streamers immediately following impact, with a complicated ejecta structure and potentially ejected boulders (**Fig. 2**).

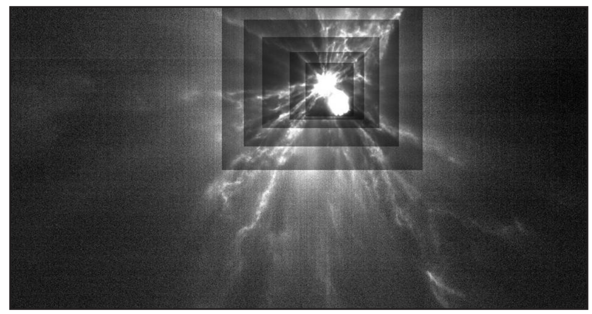

Figure 2. Image from ASI's LICIACube showing the plumes of ejecta streaming from the asteroid Dimorphos after DART impacted. Each rectangle represents a different level of contrast in order to better see fine structure in the plume. Credit: ASI/NASA/JHUAPL

Pre-impact Predictions: Very little was known about Dimorphos prior to DART's impact, including its shape, structure, and material properties. This made predicting the outcome challenging, because material properties affect crater size, ejecta processes, and the resulting deflection velocity and momentum enhancement following an impact. As such, a large parameter space was investigated by the DART Impact Modeling Working Group (IWG) in advance of the impact. These simulations covered a wide range of potential material properties, including strength, porosity, friction coefficient, etc. Compiling nearly 10 years of simulations provided predictions that β would be between 1–5, depending on material properties [4]. These simulations provided intuition leading up to the DART impact and suggested that the material properties that have the largest effects on deflection velocity and β are material cohesion (yield strength at zero pressure) and material porosity. The internal friction of the material, and whether or not the asteroid structure was a rubble pile also could play a significant role in the resulting crater formation and deflection efficiency.

Post-impact Understanding: Approach observations and those following the DART impact provided crucial knowledge to narrow the parameter space relevant to Dimorphos. Early post-DART simulations by the DART IWG suggest that multiple combinations of material properties (e.g., strength and porosity) and target structure (e.g., rubble pile, boulder arrangement and packing, subsurface structure) can match critical DART observations. No single simulation has yet, or is likely to without further data, uniquely explain every key observation from DART because many properties remain currently unconstrained (subsurface structure, etc.) or highly uncertain (e.g., density and mass of Dimorphos).

Numerical Simulations: Despite remaining uncertainties, initial models of DART's kinetic impact provide important information about the results of DART (e.g., potential crater size and morphology, ejecta mass) and the properties of Dimorphos. For instance, the images of a rubble-strewn surface, abundant ejecta, and the magnitude of the period change rule out strength properties for Dimorphos similar to low-porosity competent rock (e.g., strength of 100s of MPa), which would have resulted in a β that is too low.

Using constraints provided by direct observations of the Didymos system and resulting ejecta, a set of impact simulations is used to place bounds on crater size and material properties. The DART IWG uses a variety of impact codes to perform these simulations, which were benchmarked and validated against each other as part of the DART project preparations [5]. These simulations assume:

1. Bulk density of Dimorphos is 2400 kg/m^3 ± 300 (1σ) [3],
2. Dimorphos is made up of rubble with a size frequency distribution (SFD) consistent with the global boulder SFD on Dimorphos (**Fig. 1**, **3**),
3. The boulder shear strength is: 1 MPa (based on estimates from Bennu of boulder strengths ranging from 0.44-1.7 MPa [6]), with an intact tensile strength of: 1 kPa,
4. Boulder porosity is intermediate between average porosity of high-reflectance boulders on Bennu [7] and LL chondrites,
5. The intact matrix material of Dimorphos, in the simulations, has strength properties similar to lunar regolith. The damaged strength (e.g., cohesion) is a free parameter,
6. Dimorphos's bulk porosity is consistent with chosen grain density boulder volume fraction,
7. The DART spacecraft is represented by three aluminum spheres, following [8], with an impact velocity and orientation to represent the actual DART spacecraft at impact.

Output from these simulations is compared to the direct observations of the DART impact, specifically: the measured period and orbital velocity change of Dimorphos, the calculated momentum enhancement factor, β, the morphology of the ejecta, and the estimated ejecta mass, to determine potential best-fit properties for Dimorphos.

Summary: Following from the predictions of the DART IWG, we will discuss how the observations following the DART impact (e.g., period change, ejecta, surface morphology) combined with the insights gained from impact simulations can help reduce the uncertainty in Dimorphos's material properties. Synthesizing results from a variety of simulations provides one of the best ways to evaluate potential "best-fit" properties of Dimorphos, and estimate ejecta mass and crater size. The constraints from the simulations will also provide additional information regarding how data from Hera can further constrain Dimorphos's material properties after it arrives at the Didymos system.

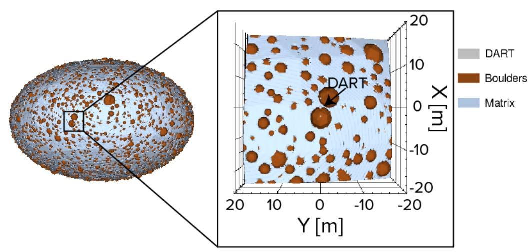

Figure 3. Initial setup of 3D simulations, using a rubble pile structure for Dimorphos. Here, shown using the CTH code. (left) whole asteroid, (right) zoom in on impact site. Impact is into the page. Brown material represents boulders, grey material shows matrix.

Acknowledgments: This work was supported by the DART mission, NASA Contract No. 80MSFC20D0004 and by the Italian Space Agency (ASI) within the LICIACube project (ASI-INAF agreement AC n. 2019-31-HH.0). Portions of this work were performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-843785.

References: [1] Daly, R.T. et al. (2023) *Nature*, in revision. [2] Thomas et al. (2023) *Nature,* in revision. [3] Cheng, A.F. et al. (2023) *Nature*, submitted. [4] Stickle, A.M. (2022) *Planet. Sci. J.*, 3(11), 248. [5] Stickle, A.M. et al. (2020) *Icarus, 338*, 113446. [6] Ballouz, R. L., *et al.* (2020) *Nature* **587**, 205–209. [7] Rozitis, B. et al (2020). *Sci. Adv.*, *6*(41), eabc3699. [8] Owen, J. M., (2022). *The Planet. Sci. J.*, *3*(9), 218.