Impact Modeling Results of the Deflection Efficiency Resulting from the DART Impact. M. E. DeCoster[1], O. S. Barnouin[1], A. Cheng[1], R. T. Daly[1], E. Dotto[2], C. M. Ernst[1], D. M. Graninger[1], K. M. Kumamoto[3], A. Lucchetti[4], R. Luther[5], F. Marzari[6], J. M. Owen[3], M. Pajola[4], E. S. G. Rainey[1], A. Rossi[5], A. M. Stickle[1], F. Tisberti[4], and K. Wunnermann[5,7], [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723, Mallory.DeCoster@jhuapl.edu, [2]INAF-Rome, IT, [3]Lawrence Livermore National Laboratory, [4]INAF-Astronomical Observatory of Padova, Padova, IT, [5]Museum fur Naturkunde, Berlin, GE, [6]University of Padova, Padova, IT, [7]Freie Universitat Berlin, Berlin, GE

Introduction: The use of a kinetic impactor is one strategy to deflect objects that might be on an Earth impact trajectory. NASA's Double Asteroid Redirection Test (DART) is the first planetary defense test mission, which demonstrated a kinetic impactor technology on a non-threatening binary asteroid called (65803) Didymos. At 23:14 UTC on Sept 26, 2022, the 579-kg DART spacecraft impacted the secondary of the Didymos system, Dimorphos, at 6.14 km/s, within 25 m of the center-of-figure [1]. This impact resulted in massive streams of ejecta that contributed to a reduction in the binary orbital period by 33.0 +/- 1.0 (3σ) minutes, which was measured via ground-based telescopes and radar [2].

This work explores computing the momentum enhancement factor (β), which is a measurement of the effectiveness of the kinetic impact, and is the ratio of momentum transferred to the target (ΔP_T) to the impactor momentum (ΔP_i) via

$$\beta = \frac{\Delta P_T}{P_i} = \frac{m_T \Delta v}{P_i} = 1 + \frac{P_e}{P_i}. \quad (1)$$

Equation 1 shows the ideal equation of β for a vertical impact, and is a function of the target's mass (m_T), the change in velocity of the target (Δv), and the momentum of the ejecta (P_e), all of which can be constrained from DART observations. For hypervelocity impacts, β can be greater than 1 due to the excavated ejecta imparting its additional momentum to the system [3]. Despite efforts in numerical modeling, scaling rules, and laboratory-scale experiments, there exists significant quantitative uncertainty in predicting β for planetary-scale impacts.

Images from the DRACO camera leading up to impact, and from LICIACube after impact, offer vital information about Dimorphos's morphology. Specifically, DRACO images show that Dimorphos contains a boulder-strewn surface resembling a rubble pile (Figure 1) [1]. The DART Investigation Team used DRACO images to constrain the shape and volume of Dimorphos to provide a mass estimate of Dimorphos using an appropriate assumption for the density, which is an important component of β defined in (Eqn. 1) [1]. Note, however, DART did not directly measure the mass of Dimorphos. Ground-based observations supplement these data by providing measurements of Dimorphos's orbital period change, which also controls β (Eqn. 1). The instantaneous reduction in Dimorphos's along-track orbital velocity component (Δv) is 2.70 $\pm$0.10 mms^{-1}, so that the analytically derived β = 3.6. [4].

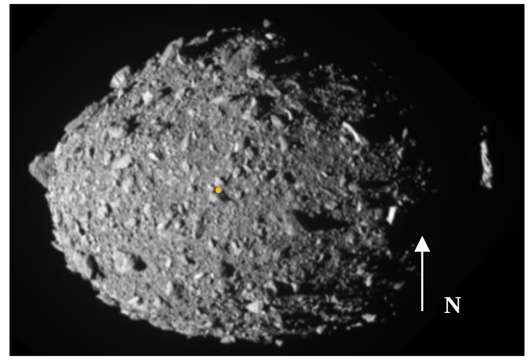

Figure 1: DART DRACO image of Dimorphos 11 s before impact, yellow dot shows the approximate impact site. Credit: NASA/Johns Hopkins APL

Since β is a nonlinear function composed of several input factors, numerical models also assist in filling the gaps of the large parameter space that controls β. Some of these parameters (material strength, internal friction, surface morphology) can be constrained from observations collected before and after impact, and some cannot (porosity, density, sub-surface morphology), but will be by ESA's Hera mission. These parameters are extremely important for determining the response of the asteroid to kinetic impact. We present the results from numerical simulations informed by observations of the DART impact to investigate the effects of target material properties and surface/subsurface morphology on β, ejecta mass-velocity distribution, and cratering.

Initial Results: We performed 2D axisymmetric and 3D rectilinear simulations using CTH and iSALE of rubble pile (boulders in a regolith matrix) and homogeneous 15-50% porous (ϕ) basalt targets with material properties informed from DRACO, LICIACube, and telescopic observations before and after impact [5]. We use multiple clustered spherical projectiles to model the DART spacecraft, which accurately represents the detailed spacecraft model while balancing computational efficiency [6]. We then compare these results to a simulation of the complete 3D DART spacecraft using the most likely target material properties. We individually vary the surface

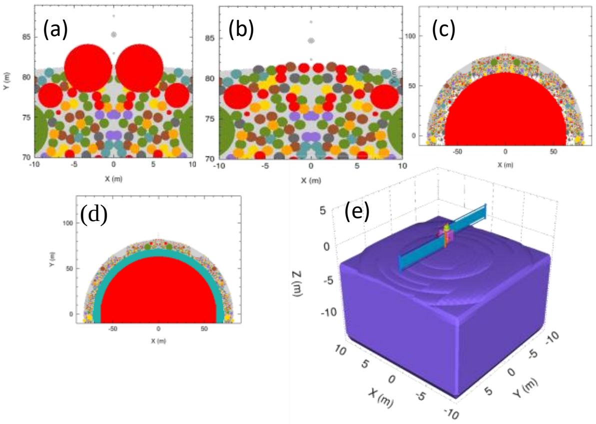

Figure 2: Initial conditions of the target morphologies simulated in CTH. (a) 2D rubble pile with large surface boulders at the impact site, (b) 2D rubble pile with small surface boulders at the impact site, (c) 2D rubble piles with a competent core ranging from 5-18 m from the surface, (d) 2D rubble pile with layered competent core, and (e) 3D homogeneous monolithic basalt target.

morphology (i.e., boulder size at the impact point), the subsurface morphology (i.e. addition of a competent or layered basalt core), and the cohesive and tensile strength of the regolith to understand their respective effects on β, ejecta mass-velocity distribution, and crater size. Figure 2 illustrates the target morphologies considered, and the target material parameters are listed in the legend in Figure 3 (a). Our initial results (Figure 3) indicate the subsurface effects are minor compared to the effects of surface morphology and regolith strength on modeling the DART impact, even when subsurface layers are close (5-10m) to the surface. We find that large boulders at the impact site reduce β, and the effects of regolith strength are greater than the effects of surface and subsurface morphology on β. We find that the homogeneous target (all regolith) results in ~50x more ejecta mass than the full rubble pile target. The effects of subsurface morphology on crater size become as important as regolith strength when the core is ≤ 10 m below the surface.

Summary: DART provided a unique opportunity to test our simulation capabilities against a full-scale experiment. To explore how variations in target material properties such as strength, porosity, and structure (layering, regolith, etc.) affect the impact, we model the observed momentum enhancement factor, ejecta evolution, and crater formation. Here, we present initial simulation results of the DART impact, quantifying how asteroid material properties and morphology affect the deflection efficiency. We then compare these results to a simulation of the complete DART spacecraft using the most likely target material properties.

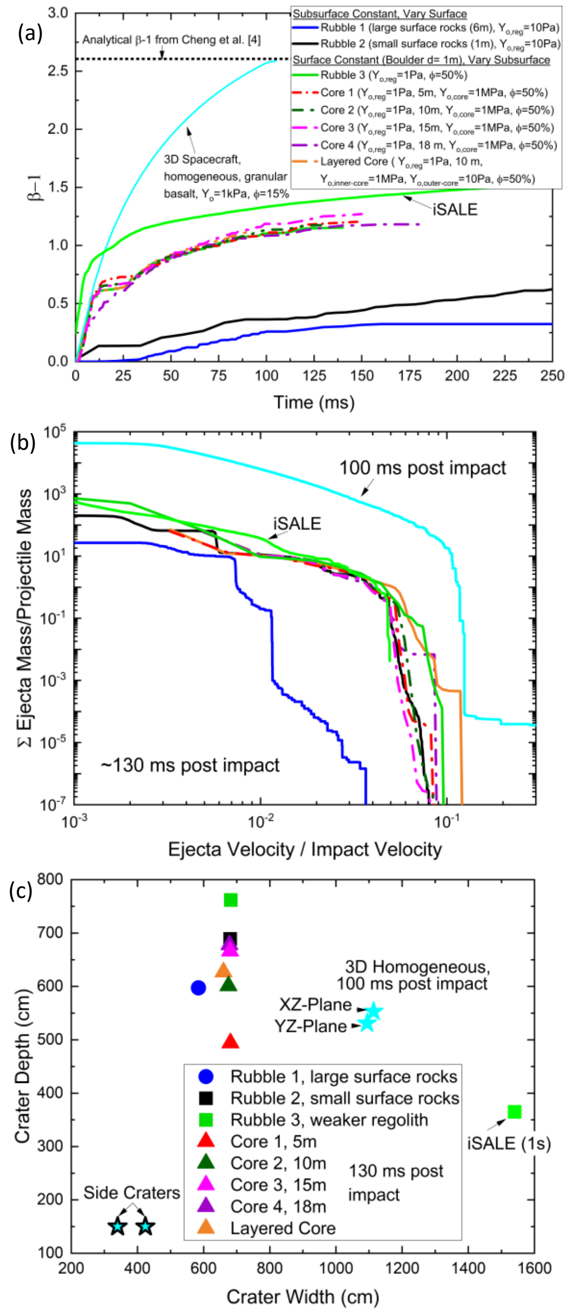

Figure 3: Initial results from CTH and iSALE simulations for (a) β - 1 (b) ejecta mass-velocity distribution, and (c) crater size, width is the diameter.

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