MODELING MOMENTUM ENHANCEMENT FROM IMPACTS INTO RUBBLE PILE ASTEROIDS. A. M. Stickle[1], E. S. G. Rainey[1], J. M. Owen[2], S. D. Raducan[3], M. Bruck Syal[2], G. S. Collins[3], T. M. Davison[3], P. L. Miller[2], and the DART Impact Modeling and Simulation Working Group, [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA (angela.stickle@jhuapl.edu), [2]Lawrence Livermore National Laboratory, Livermore CA, [3]Imperial College, London UK

Introduction: The Double Asteroid Redirection Test (DART) is a NASA mission concept to test the kinetic impact deflection of an asteroid. DART would target the moon of the binary system Didymos ("Didymoon"), impacting at ~6 km/s to change the moon's orbital period. DART represents the first direct test of the kinetic impactor theory for planetary defense. The momentum enhancement of Didymoon from the DART spacecraft is parameterized by β and depends on the initial spacecraft momentum ($p_{spacecraft}$) and the momentum of ejecta excavated during crater formation (p_{ejecta}): $\beta=1+(p_{ejecta}/p_{spacecraft})$, with momenta tracked in the direction of intended deflection. An important part of mission development is determining the expected outcome of the impact, including crater formation and momentum enhancement from the impact. Impact modeling is one of the primary tools to be used to interpret the results of the kinetic impact deflection, to infer the physical properties of the target asteroid, and to advance our understanding of impact processes on asteroids. Here, we summarize results of impact modeling examining the effects of target properties on momentum enhancement, including the internal structure of the asteroid.

Methods: Several numerical models are currently in use to model the putative DART impact, including CTH [1], iSALE [2,3], and adaptive SPH [4-9]. These codes have the ability to consider multiple materials and rheologies using a wide variety of material models and equations of state (EOS).

CTH. CTH is a 2-step Eulerian code developed by Sandia National Laboratories [1]. Microporosity was simulated by a p-α porosity model using a crush curve for pumice from [10]. Macroporosity was simulated in two ways: 1) generating large, arbitrarily shaped boulders in a 3D geometry and reading them in as one object made up of many parts (**Fig. 3D**), or 2) utilizing the "Particle Pack" program developed by LLNL [11] to generate a user-defined particle size distribution of spheres, which was then used as a starting condition for a 2D model (**Fig 3C**). Adaptive Mesh Refinement (AMR) [12] allows for high resolution over the areas of interest while minimizing computational time.

iSALE. The iSALE-2D shock physics code [2] is based on the SALE hydrocode solution algorithm [3]. To simulate hypervelocity impact processes in solid materials SALE was modified to include an elasto-plastic constitutive model, fragmentation models, various EOS, and multiple materials [13-14]. More recent improvements include a modified strength model [15] and a porosity compaction model [2,16].

Adaptive SPH. ASPH is a meshfree method based on Smooth Particle Hydrodynamics (SPH) [17], generalized to allow directional adaptivity in the resolution [4] and enforce exact energy conservation [5]. The ASPH results in this study employ the open source code Spheral, using a variety of equations of state and the ε-α microporosity model of [2]. Rubble piles are generated using a power-law distribution; boulders are sorted inversely by size before being settled into the desired asteroid volume in order to preferentially place larger boulders deeper in the asteroid (see **Fig. 1**).

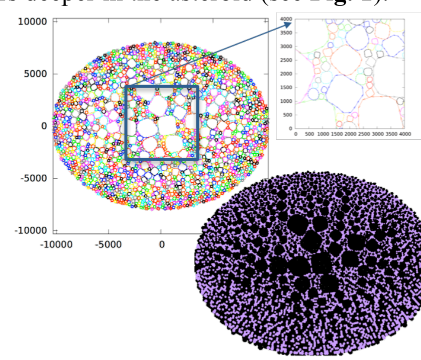

Fig. 1. Examples of 2D rubble piles generated using Spheral. This example shows 1900 boulders with 75% fill in the volume. 3D models tend to include more boulders, but a lower overall fill fraction.

Results and Discussion: Simulations suggest that results for impacts into rubble piles are likely to differ from impacts into solid body targets, even those with similar microporosity. Further, the impact location will have significant influence on the amount of ejecta produced and resultant momentum transfer. Though some material properties are important, specifics of material composition appear to have little effect of the overall expected momentum transfer [e.g., 18]. Indeed, initial statistical analyses [19] and modeling efforts suggest that the yield strength of the material, porosity, target cohesion and internal friction, and internal structure are the most important parameters to consider.

Porosity Effects. Material porosity can come in the form of "microporosity" where there is void space among grains in the material, or "macroporosity" where the void space is along large-scale cracks or between large boulders if the asteroid is a "rubble pile". Both of these porosity types will affect the ejecta generated following impact [e.g., 18, 20], and thus the eventual momentum enhancement from the kinetic impact. In general, as microporosity in the target increases, simulations show that the crater becomes increasingly narrow and deep, and that the shape of the subsurface damage zone is altered (**Fig. 3**). The ejecta is launched at higher angles for increasingly high porosities. 2D iSALE simulations of DART-scale impacts into solid targets with various levels of microporosity give results largely consistent with numerical scaling laws for analogous materials (**Fig. 2**) [21]. When an equivalent amount of macroporosity is included in the target instead, the crater tends to be larger with an increased amount of ejecta (**Fig. 3**).

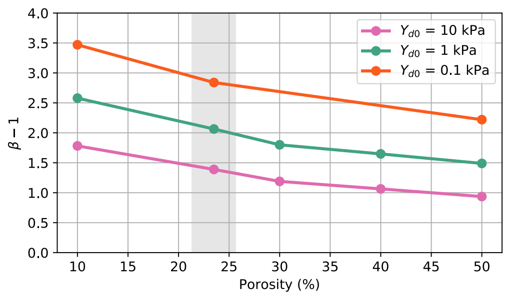

Fig. 2. Results from 2D iSALE simulations of a 1.6 m sphere impacting rock at 7 km/s. Total ejected momentum for in z direction (*β*-1*) v.*target porosity for three different strengths.

Effects of Internal Structure. Some care must be taken when modeling macroporous targets. Depending on the structure of the target (e.g., amount, size, and location of large boulders), impact outcomes can vary significantly. If the spacecraft were to impact onto a large, strong boulder, for instance, the cratering process and ejecta flow field will be significantly different than if the spacecraft were to impact into weaker granular matrix between boulders. Craters for impacts into boulders tend to be shallower and wider than for those into matrix material. Initial Spheral simulations of impacts into rubble piles show that the momentum enhancement factor can also depend on the impact site to a large degree. For various boulder realizations, the total calculated *β* scatters around the value for impact into the equivalent microporous and monolithic target. In general, ejecta material (and thus, *β*) are dominated by boulder material and whether the impactor strikes matrix or boulder material first. The internal damage propagation within the target is also sensitive to the presence of boulders, which may imply that disruption behavior is different.

Conclusions: Target properties, including cohesion, porosity and internal structure, may have significant effects on the momentum enhancement from a kinetic impact used to deflect an asteroid. Simulations of impacts into rubble piles show a wide range of momentum enhancements depending on the particulars of the internal structure and where the impact occurs. Further simulations are underway in order to fully explore this parameter space and map out the possible outcoms for the DART impact, and to estimate *β* from the measured deflection of Didymoon.

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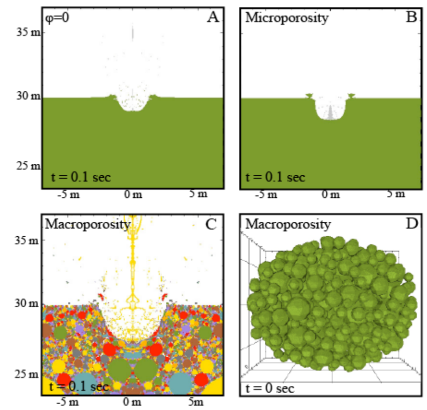

Fig 3. 2D models of a 30-cm aluminum sphere at 6 km/s into A) coherent, basalt target with no porosity; B) coherent basalt target with 20% microporosity; C) rubble pile target with equivalent 20% macroporosity; D) Example of a 3D rubble pile asteroid to model impacts into matrix with boulders and a variety of subsurface structures.

References: [1] McGlaun, J.M., S.L. Thompson ety al. (1990), *Int. J. Impact Eng.*, 10, 351-360; [2] Wünnemann, K. et al. (2006). *Icarus*, 180:514-527; [3] Amsden, A., et al (1980) LANL Report, LA-8095:101p.; [4] Owen, J. M., Villumsen, J. V., Shapiro, P. R., & Martel, H. (1998). *The Astrophys. J. Suppl. Ser.*, *116*(2), 155–209; [5] Owen, J. M. (2014) *Int. J. for Num. Meth. in Fl.*, *75*(11), 749–774; [6] D. E. Grady & M. E. Kipp, (1980) *Int. J. Rock Mech. Min. Sci. Geomech*., 17, 147-157. [7] Benz, W & E. Asphaug, (1995) *Computers Phys. Comm.*, 87, 253-265. [8] Benz, W. and E. Asphaug (1999) *Icarus 142,* 5-20; [9] Owen, J. M. (2010).). Presented at the Proceedings of the 5th International SPHERIC Workshop, Manchester, UK. [10] Jutzi et al. (2009) *Icarus 201*, 802-813; [11]Friedman, G. (2013) LLNL-SM-649196; [12] Crawford, D.A. (1999) Paper presented at 15th US Army Symposium on Solid Mechanics, April 12-14; [13] Melosh, H. J., et al (1992). *J. Geophys. Res.,* 97(E9):14735-14759; [14] Ivanov, B. A., et al. (1997) *Int. J. Imp. Eng.*, 20:411-430; [15] Collins, G. S., et al. (2004). *Met. & Planet. Sci.*, 39:217--231. [16] Collins, G., et al. (2011) *Int. J. Imp. Eng.*, 38:434-439; [17] Monahan, (2005), *Reports on Progrsss in Physics,* 68, 1703--1759; [18] Syal, M. B., et al. (2016). *Icarus*, 269, 50-61; [19] Rainey, E. et al. (2017) *IAA Planet. Defense Conf.*; [20] Jutzi, M., and P. Michel (2014), *Icarus* 229, 247-253; [21] Housen, K, and Holsapple, K. (2011) *Icarus*, *211*(1), 856-875