A NEW APPROACH TO SIMULATION OF ASTEROIDAL IMPACT EVENTS: FROM DAMAGE TO DISRUPTION AND GRAVITATIONAL ACCUMULATION. C. El Mir[1], K. T. Ramesh[1], and D. C. Richardson[2], [1]Johns Hopkins University, Hopkins Extreme Materials Institute, 3400N Charles Street, Malone Hall Suite 140, Baltimore, MD 21218, [2]Department of Astronomy, University of Maryland, College Park, MD 20742

Introduction: Asteroidal impacts, ranging from small-scale cratering events to catastrophic disruption, have played a crucial role in the evolution of the asteroid belt. These collision events lead to a series of surface modification processes [1], as well as the evolution of new asteroid and binary families [2,3]. The consequences of impacts are also important in assessing asteroid impact hazard mitigation (some of these issues will be examined in the first space experiment of kinetic impact within the Asteroid Impact & Deflection Assessment (AIDA) mission [4,5]).

The outcome of an asteroidal impact event can be typically grouped into three categories: a cratering event that affects only the target's surface, a shattering event that breaks an initially coherent parent into many fragments, and a disruption event that generates fragments from an initially intact parent, with some of those fragments escaping from the parent [6]. The extent of the response reached during an impact event depends on many factors, including the target asteroid's initial composition (internal structure and material properties), the sizes of the target and impactor, as well as the properties of the impactor (composition, velocity, and angle of impact). Impact speeds may vary from about 5 km/s in the Main Belt to about 20 km/s for Near-Earth Asteroids (NEAs).

To be able to accurately predict the outcome of a high-speed impact on small airless bodies, two regimes with drastically different timescales must be considered in the simulations: the material mechanical response (from a few microseconds up to some tens of seconds), and the gravity response (from hours to months). Hybrid numerical methods have been used to bridge these widely-spread timescales: these typically consist of a hydrocode coupled with an *N*-body code. For example, Michel et al. [2] and Durda et al. [3] used a smoothed particle hydrodynamics (SPH) code, a Lagrangian code, to model the mechanical response for the first few seconds following an impact, and then an *N*-body gravity code (pkdgrav) was used to calculate the gravity response. This hybrid approach allowed for the investigation of the formation of asteroid families and binaries. Leinhart et al. [7] used an Eulerian shock physics code, CTH, coupled with the same *N*-body gravity code to investigate the catastrophic disruption of Kuiper belt objects. One of the features of many of the early particle-based simulations was that essentially every particle became a fragment during large impacts, so that subsequent gravitational re-accumulation dominated the final fragment distribution.

More recently, Tonge et al. [8] have used the Material Point Method (MPM), a numerical scheme that uses Lagrangian particles with an Eulerian mesh to simulate the impact history of asteroid (433) Eros. MPM implementations are well suited for simulating extreme events such as impact. Tonge et al. [8] were able to demonstrate impact-induced lineament formation and porosity growth on Eros using this approach. The associated Tonge-Ramesh material model is now available in the public domain. In this work, we demonstrate the ability to couple the strength and gravitational timescales in asteroidal impact events by combining the Tonge et al. MPM numerical method with the *N*-body code pkdgrav, using the Tonge-Ramesh material model [8]. This approach is efficient, produces fragment size distributions from both the strength and gravitational domains, and demonstrates the development of residual damage structures in the target asteroid. Our simulations consider a 1.21-km diameter impactor hitting a 25-km diameter target at 5 km/s, initial conditions similar to those in [2].

We choose a numerical resolution that translates to more than 1 million material points. We use material properties corresponding to basalt, and we populate the initial bodies with a Pareto distribution of initial flaws. The damage profile at 30 seconds after the impact is shown in Fig. 1. Contrary to previous observations [2], damage is built up throughout the entire target, but it is not fully shattered down to the resolution of the simulation.

Mechanical Response: We have reformulated the Tonge-Ramesh material model to incorporate a Tillotson Equation of State (EOS). In the Tonge-Ramesh model, stress waves probe the material's microstructure to activate sub-scale internal flaws that interact and grow, resulting in an increase in the internal damage level. This damage build-up is manifested in the degradation of the material's elastic properties. Once a material point reaches a critical damage threshold, the material becomes granular, and follows a granular viscoplastic flow with a pressure-dependent yield strength.

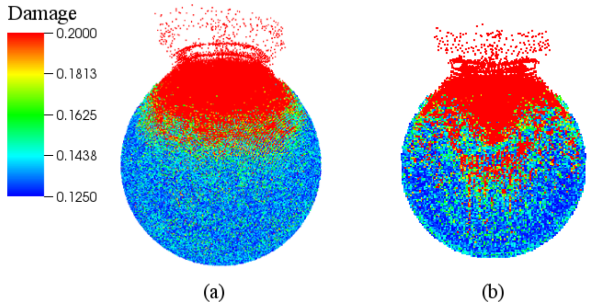

Fig. 1: Damage profile at t=30s after impact for a) the full 3D representation and b) the asteroid cross-section.

Gravity Response: After the initial 30 seconds, the stress waves incurred by the impact event have dissipated, and the underlying physics can then be well captured by the *N*-body gravity code, pkdgrav.

To hand-off the material points from MPM to pkdgrav, we make use of the Lagrangian-Eulerian nature of MPM. We first interpolate the data from the material points onto the background grid nodes. The information in each numerical cell is then interpolated back onto a single material point located at the cell's centroid, wherein the grid is initially set up to have cubical cells. The centroid is then represented as a discrete sphere with a diameter corresponding to the length of the cubical cell. This procedure allows us to have a well-formed and non-overlapping set of spheres that trace the material's geometry. Material information such as damage and granular flow, which are not natively supported in pkdgrav, are recorded at the generated material points for later analysis.

In pkdgrav, the inter-particle gravity is calculated for the ~1 million spheres, with a timestep of ~2 seconds, and the calculation is run for a simulated time of 6 days.

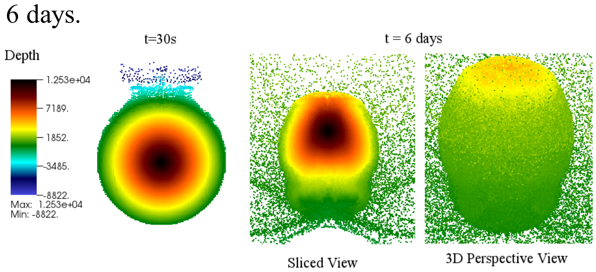

Fig 2: The particle initial depth relative to the center (depth=0 corresponds to the surface of the target) at t=30s and t=6 days. A relatively unaltered aggregate is observed at a depth of ~ 5km, whose surface is freshly exposed under the impact site. A large amount of surface material is re-accumulated at the opposite end of the impact and leads to the burial of the initial surface material at that end.

Preliminary Results: The initial impact onto the 25-km target accumulated damage throughout the entire asteroid (Fig. 1), but did not completely shatter it. The development of heavily fractured regions and fracture ligaments is observed. The gravity calculation using pkdgrav shows that a relatively coherent core remains as an intact aggregate over which material that is ejected from the surface gets re-accumulated. The excavation and exposure of fresh surface (corresponding to an initial depth of ~4 km) is observed under the impact site. Furthermore, the far-end of the sphere, opposite to the impact site, gets buried under the re-accumulated particles. After 6 days, a total of 88% of the original material mass remains as the biggest remnant of the impact event.

Summary: We present the initial results from the collision of two basaltic asteroids, using a new hybrid approach that uses the Tonge-Ramesh constitutive model implemented in an MPM code for calculating the material's mechanical response, coupled with the *N*-body gravity code pkdgrav for examining the fate of the fractured particles in the gravity regime.

Our approach incorporates the benefits of the Lagrangian-Eulerian nature of MPM, as well as the experimentally-informed Tonge-Ramesh material model, which includes sub-scale flaw evolution and pressure-dependent granular flow of material.

The constitutive model and the hybrid approach are able to simulate a variety of impact events that may not necessarily lead to the complete fragmentation of the target, which makes this method desirable for examining scenarios similar to the kinetic impactor on the AIDA mission. In addition, a subsequent hand-off from pkdgrav back to MPM can also be performed to simulate additional damage build-up due to secondary impacts.

References: [1] Oberbeck, V.R. et al. (1967). *JGR 72*, 4697–4704. [2] Michel, P. et al. (2001), *Science 294*, 1696-1700. [3] Durda, D.D. et al. (2000), *Icarus 145*, 220-229. [4] Cheng, A. F. et al. (2016) *P&SS 121*, 27-35. [5] Michel, P. et al. (2016). *Advances in Space Research 57(12)*, 2529-2547.[6] Leinhardt, Z. M. et al. (2008), *The Solar System Beyond Neptune* 1, 195-211. [7] Leinhardt, Z. M., et al. (2009). *Icarus*, *199*(2), 542-559. [8] Tonge, A. L. et al. (2016) *Icarus*, *266*, 76-87.

Acknowledgements: This work was supported by the Solar System Exploration Research Virtual Institute (SSERVI) NASA Cooperative Agreement NNA14AB02A and by the Hopkins Extreme Materials Institute (HEMI).