HYPERVELOCITY IMPACTS ONTO SMALL ASTEROIDS: DISRUPTION THRESHOLDS, MOMENTUM TRANSFER, AND THE EFFECT OF ROTATING TARGETS.
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Introduction: Asteroid collisions constitute a key mechanism for the evolution of the asteroid belt, with outcomes ranging from local cratering to full disruption and asteroid family formation [1,2]. Potentially hazardous asteroids also may be deflected off an Earth-bound trajectory by means of a kinetic impactor, an idea that will be examined in the first space experiment of kinetic impact within the Asteroid Impact & Deflection Assessment (AIDA) mission [3]. Therefore, an, understanding of the fundamental physical processes that occur during an asteroidal impact event is crucial for predicting the outcomes of impacts at velocities, timescales, and lengthscales beyond those achieavable in a lab setting.

Hybrid numerical techniques have typically been employed to bridge across the two widely varying timescales of an impact event: a hydrocode such as SPH for the short-timescale mechanical response (microseconds up to some tens of seconds), and an *N*-body gravity code for the long-timescale gravitational response (few hours up to several days) [1,2,4]. In a previous work [5], we presented a novel framework consisting of a modified Tonge-Ramesh material model [6] implemented in the Material Point Method (MPM), coupled with a hand-off to an *N*-body gravity code (pkdgrav) for the late-stage gravity response. The hand-off to pkdgrav is facilitated by means of the Lagrangian-Eularian nature of MPM, alievating some of the ad-hoc assumptions used in an SPH-based hand-off [7]. The model was compared to previous results from Michel et al. [8], showing that 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.

In this work, we examine the parameter space of impacts near the disruption threshold for different impact angles. We then model the case of initially rotating asteroids, where targets are given an initial angular momentum corresponding to a period of rotation of a few hours. We examine the fate of the ejected regolith, including the high-speed ejecta from near the impact site, the momentum enhancement factor (β), the change in angular momentum of the targets, and the final shape of the largest remant.

Model Outline: We first discretize the materials into a set of material points (particles) overlayed by a background grid. An MPM implementation [9] captures the mechanical response following the first few seconds of impact. Then, a consistent hand-off to pkdgrav is performed once the stress waves incurred by the impact have dissipated and the lithostatic pressure in the entire target becomes comparable to the gravitational overburden pressure.

Mechanical Response: In the Tonge-Ramesh material model, stress waves probe the material's microstructure to activate sub-scale internal flaws that interact and grow. The extent of crack growth within a material point is characterized by an internal damage build-up, which degrades the elastic properties. After a critical damage threshold is reached, the heavily fragmented material becomes granular, and follows a granular viscoplastic flow with a pressure-dependent yield surface. Porosity can therefore be developed by the shearing of granular material, and is crushed by pore compaction due to pressure.

Gravity Response: We hand-off the MPM particle data through an interpolation with the background grid that is consistent with the numerical integration of MPM. This process conserves mass and momentum, and gives a set of well-aligned non-overlapping paricles corresponding to the same numerical resolution used in MPM. The gravitational evolution of the fragments is then tracked in pkdgrav for a simulated time of 5 hours, using a fixed timestep of a few microseconds. In this work, we use the soft-sphere formulation as implementated in the latest version of pkdgrav [10], which includes inter-particle rolling and twisting friction.

Material Model Validation: We validate the Tonge-Ramesh material model by comparing predicted strengths against dynamic brazil disk experiments [11,12]. These experiments are often used to calibrate numerical codes [12]. Instead, we here use these experimental measures for validation by demonstrating the model's capability of reproducing the reported strain-rate dependence through an independent calibration of crack growth parameters (particularly the critical stress intensity factor and its effect on the crack growth velocity).

Preliminary Results: Given the wide parameter space made possible with this new hybrid formulation, we first focus on the cases that are near the disruption thresholds reported in [13,14]. We consider the cases of oblique impacts onto stationary and rotating targets, and explore the extent of damage and fate of the ejecta in each case. We consider the case of oblique impacts with an incident angle of 0°, 30° and 45°(Fig 1). We observe that oblique impacts lead to a smaller momentum enhancement factor, β, compared to a head-on impact. We also record an increase in angular momentum of the initially non-spinning target, giving the largest remnant an effective period of rotation. In addition, we note that a higher impact speed is required to damage the target when granular flow is activated, as some of the impact energy is dissipated by granular plasticity.

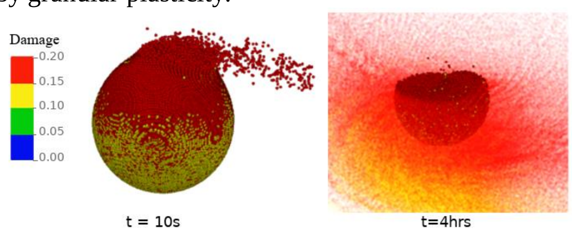

Fig 1: Damage profile in MPM (left) for a 45° disruptive impact at 3km/s of a 3.18km diameter basalt impactor on a 20km diameter non-rotating target. In the gravity phase (right), a granular core remains as the largest remnant (shown as opaque particles). Particles labeled with transparency have escaped the target's gravitational field, and may reaccumulate separately to form asteroid families.

Rotating Targets: We assign an initial period of rotation for the target and direct the impact at the equator. Angled impacts are considered along the direction of spin as well as opposing the spin direction. Initial results indicate that these rotating targets appear weaker than the stationary asteroids. In addition, we observe an increase in angular momentum leading to a decrease in the rotational period (from 6 hours to 5.5 hours) when impacted along the direction of spin (Fig 2).

Summary: We present the results from a range of impact parameters by varying the impact specific energy, the angle of impact, and the target's period of rotation. Each run is performed through a two-stage hybrid approach, based on the characteristic timescale of the dominant mechanism. In the small-timescale mechanical response, a Tonge-Ramesh material model implemented in MPM captures the crack growth, accumulation of damage, porosity growth, and granular flow of the material. A hand-off of the simulation parameters to pkdgrav is carried out, facilitated by the Eularian-Lagrangian nature of MPM. Finally, the long-timescale gravitational interaction of the fragmented particles is tracked in the *N*-body code. Using MPM, we do not note any of the difficulties reported with SPH-based codes in modeling the high speed fragments generated near the impact site.

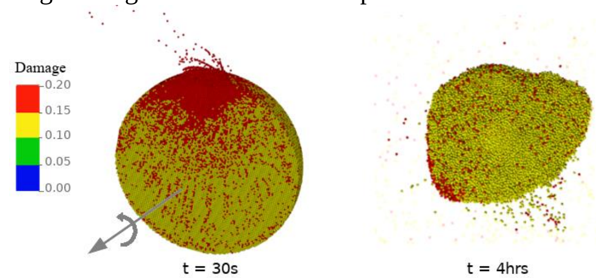

Fig 2: Damage profile for a non-disruptive 30° impact at 5km/s of a 1.21 km diameter impactor striking a 25km diameter target with an initial period of rotation of 6 hours (direction as shown). The impactor is placed at the equator, with an orientation following the target's spin direction. The fragment ejection and reaccumulation are tracked in pkdgrav (right) and an increase in angular momentum of the largest remnant is observed, reducing the effective period of rotation from 6h to 5.5h.

Our preliminary results highlight the importance of granular flow as a mechanism that increases the disruption threshold of asteroids by dissipating some of the impact energy. Even initially non-porous targets can develop significant porosity by means of the shearing of fragmented grains. For rotating targets, the final shape of the largest remnant is highly dependent on the impact direction and location. In addition, we observe an increased damage level (and a possible decrease in the disruption threshold) for initially spinning asteroids. We also capture the angular momentum enhancement in the targets following a non-disruptive oblique impact.

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