NUCLEAR AND KINETIC APPROACHES TO ASTEROID DEFENSE: NEW NUMERICAL INSIGHTS.

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Introduction and Motivation: Kinetic impactors and nuclear devices represent the only mature technologies for mitigation of hazardous asteroids and comets [1]. With sufficient warning time before Earth impact, an impactor or standoff nuclear device may be deployed to impart a modest velocity change (deflection) to a threatening body and achieve a comfortable miss distance of the Earth. However, for bodies exceeding ~300 m in diameter, or for short warning times, the momentum transfer from a kinetic impactor would not be sufficient to offer protection. In these scenarios, the mass limitations of current launch vehicles demand a nuclear approach for successful mitigation.

Understanding the limits of applicability for kinetic impact deflection is critical for developing optimal response strategies and mission design in the event of an impending impact threat. In addition to limitations imposed by the maximum mass transportable to a near-Earth asteroid (NEA) and achievable spacecraft encounter velocities, the risk of unintentional disruption (producing a poorly-dispersed fragment field) provides another constraint. In situations where the required deflection velocity is a significant fraction (~10%) of the body's escape velocity, v_{esc}, risk of fragmentation becomes a concern.

In particular, recent work highlighting the delicate cohesive strength of rapidly rotating asteroids questions under what conditions a kinetic impactor may destabilize the body and induce accidental disruption [2]. Rotational state is a key asteroid parameter which may affect the boundary between deflection and disruption, yet rotational effects on impulsive mitigation strategies have not yet been investigated. Probing the boundary between deflection and disruption requires modeling full-body response to an impulse.

Here we report on full-body asteroid response to a range of kinetic impactor masses (1000 kg to 10,000 kg) and encounter velocities (up to 30 km/s) for asteroids 50 – 300 m in diameter, in order to determine the safety limits and efficacy of the kinetic impactor approach. Uncertainty in asteroid composition, structure, and rotation, and the sensitivity of the impact process to each of these variables, motivates simulations incorporating a wide range of initial conditions. We use a nominal spherical shape for comparison across a suite of different material properties with the knowledge that shape effects will introduce additional variability in delivered momentum impulse [3]. This effect can be accounted for through the use of various asteroid shape models, as described in [3].

Numerical Approach: Three-dimensional simulations are carried out in Spheral [4,5], an open source, Adaptive Smooth Particle Hydrodynamics (ASPH) code. Key features of the code, including accurate modeling of anisotropic strain fields through adaptive node sampling, well-benchmarked damage models, self-gravity, an array of built-in equations of state and constitutive models, and user-extendibility to new physics packages, make Spheral particularly well-suited to probing the disruption/deflection limit for impulsive asteroid mitigation scenarios. Spheral has been used to model both standoff nuclear burst and kinetic approaches to asteroid deflection, particularly for asteroid Bennu [6] (Fig. 1).

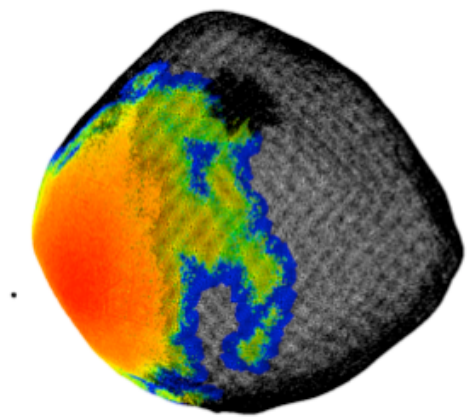

Fig. 1. Stand-off nuclear energy deposition onto a Bennu shape model, using Spheral [6]. Spheral is used to model asteroid deflection and/or disruption through both kinetic and nuclear surface ablation simulations.

We investigate sensitivity to numerical resolution, equations of state (e.g., ANEOS [7], Tillotson, LEOS tabular), porosity (strain-based, implemented as described in [8]), strength (e.g., constant strength, Drucker-Prager, and more sophisticated models as described in [9]), damage models, macro-structure (e.g., macroscopic porosity in the form of voids between boulders; layered and/or heterogeneous compositions), and rotational state. A commonly used metric for kinetic impact deflection is the momentum multiplication factor or so-called "β-factor" [10], where an asteroid's change in momentum, Δp, can be represented as:

$$\Delta p = \beta m v \quad (1)$$

where m is impactor mass and v is impact velocity. The efficiency with which impact ejecta is driven to above escape velocity (in surface normal direction) during the cratering process determines the value of β.

Results: Consistent with prior work [11], incorporation of porosity and damage models results in decreased momentum transfer efficiency. These material properties offer some protection from disruption, through shock wave attenuation and lower risk of spallation off the back side of the asteroid. We actively benchmark material property inputs using a range of experimental data on geological materials.

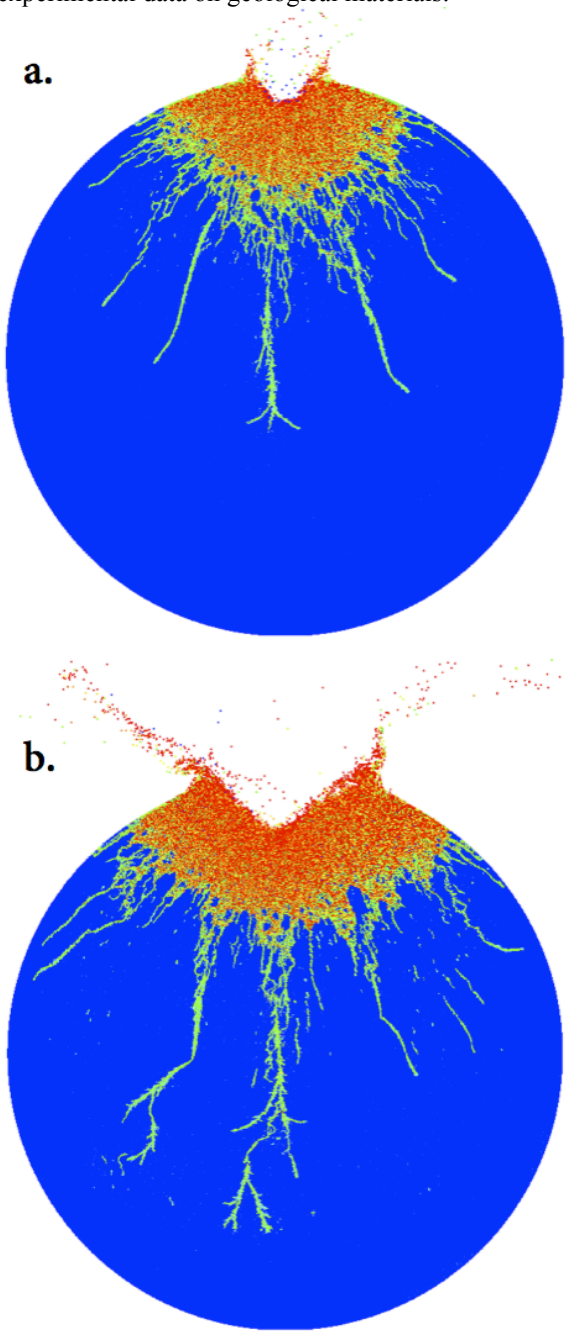

Fig. 2. Damage trace at 0.2 seconds for 10-ton masses impacting 500 m, SiO_2 asteroids at 20 km/s (blue: undamaged, red: devastated/strengthless) (**a**) porosity of 0.2 (**b**) porosity of 0.6

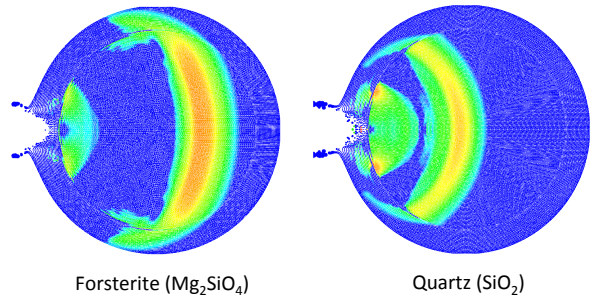

Fig. 3. Pressure plots for 12 km/s impactor into layered target asteroids (100 m diameter, porous regolith over crystalline interior). Material response and shock propagation depend upon composition (and EoS implemented; ANEOS used here [7,12,13]).

Implications: By investigating material sensitivities and disruption limits for the kinetic impactor strategy, we determine when a deflection attempt may be likely to fail or carry significant risk. In such cases, robust asteroid fragmentation and dispersion by a nuclear device may be a lower risk option. In any case, applying the same shock physics code to calculate asteroid response to both kinetic and nuclear impulses provides a clear advantage for making informed decisions on which strategy to pursue under a range of possible threat conditions.

References:

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