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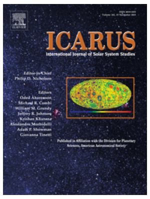

Deflection by kinetic impact: Sensitivity to asteroid properties

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Impacting an asteroid with a spacecraft traveling at high speed delivers an impulsive change in velocity to the body. In certain circumstances, this strategy could be used to deflect a hazardous asteroid, moving its orbital path off of an Earth-impacting course. However, the efficacy of momentum delivery to asteroids by hypervelocity impact is sensitive to both the impact conditions (particularly velocity) and specific characteristics of the target asteroid. Here we numerically model asteroid response to kinetic impactors under a wide range of initial conditions, using an Adaptive Smoothed Particle Hydrodynamics code. Impact velocities spanning 1–30 km/s were investigated, yielding, for a particular set of assumptions about the modeled target material, a power-law dependence consistent with a velocity-scaling exponent of $\mu = 0.44$. Target characteristics including equation of state, strength model, porosity, rotational state, and shape were varied, and corresponding changes in asteroid response were documented. The kinetic-impact momentum-multiplication factor, β, decreases with increasing asteroid cohesion and increasing porosity. Although increased porosity lowers β, larger porosities result in greater deflection velocities, as a consequence of reduced target masses for asteroids of fixed size. Porosity also lowers disruption risk for kinetic impacts near the threshold of disruption. Including fast ($P = 2.5$ h) and very fast ($P = 100$ s) rotation did not significantly alter β but did affect the risk of disruption by the impact event. Asteroid shape is found to influence the efficiency of momentum delivery, as local slope conditions can change the orientation of the crater ejecta momentum vector. These results emphasize the need for asteroid characterization studies to bracket the range of target conditions expected at near-Earth asteroids while also highlighting some of the principal uncertainties associated with the kinetic-impact deflection strategy.

1. Introduction

Asteroids posing a threat to Earth may be deflected off of an Earth-impacting trajectory by standoff nuclear bursts (Bruck Syal et al., 2013; Howley et al., 2014) or kinetic impactors (Asphaug et al., 1998; Holsapple and Housen, 2012; Jutzi and Michel, 2014). Among the range of concepts for asteroid threat mitigation, these two methods are considered to be the most technologically mature, as discussed in the report by the National Research Council (2010). While nuclear devices may represent the only viable option to prevent Earth impacts for large asteroids or those detected with little warning time (Dearborn and Miller, 2014), under conditions where a kinetic impactor will be effective, it is the preferred strategy (National Research Council, 2010). Hence, studies which quantify the effectiveness, risks, and uncertainties for the kinetic-impactor method, under a range of initial conditions, are advisable. Full-scale experiments to test the efficacy of kinetic impactors have been and will be rare; these valuable opportunities must be complemented by extensive numerical treatment of the problem. The Deep Impact mission successfully deployed a 370 kg impactor to remotely excavate the surface of Comet Tempel 1 in 2005 (A'Hearn et al., 2005; Schultz et al., 2007), providing the first demonstration of kinetic-impact technology on a small body. While the large size of Tempel 1 precluded a measurement of the body's change in velocity, future asteroid-defense-focused missions will aim to directly measure the momentum transfer imparted by kinetic impactors. In particular, the AIDA mission, a joint ESA and NASA venture, seeks to provide the first quantitative test of asteroid deflection, using the DART spacecraft to impact the secondary of asteroid Didymos (Cheng et al., 2015).

A spacecraft impacting in line with an asteroid's center of mass will transfer all of its momentum, $p_i = m_i v_i$, to the body, changing the asteroid's translational velocity by $\Delta v_a = m_i v_i/(m_a + m_i) \approx m_i v_i/m_a$. An additional transfer of momentum is achieved in the cratering process, as material is ejected above escape speed. This additive effect to the momentum transfer can be expressed as:

$$m_a \Delta v_a = m_i v_i + m_{ej} v_{ej} = \beta m_i v_i \tag{1}$$

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where β denotes the multiplication factor applied to the impactor's momentum by crater ejecta. The value of β is one of the primary uncertainties associated with the use of kinetic impactors. It is known to be dependent on both target material properties and impactor velocity (Asphaug et al., 1998; Holsapple and Housen, 2012; Jutzi and Michel, 2014; Stickle et al., 2015); thus, β may vary substantially between different deflection scenarios. Impacts occurring off-axis from the asteroid's center of mass present further complications, as the ejecta flow field is affected by impact angle and the body's rotational state will be altered. The AIDA mission will provide a critical first measurement of β for an actual asteroid-deflection event.

There is a great diversity of near-Earth asteroids which may threaten Earth in the future. Numerical study of kinetic-impact deflection – including variability in details such as composition, porosity, strength, internal structure, shape, and rotation – can provide guidelines for kinetic-impactor mission design, including pre-impact reconnaissance of a threatening asteroid. Even in the absence of known near-term threats, information on the sensitivity of various deflection methods to specific asteroid characteristics can inform priorities for future small-body characterization missions. Additionally, numerical simulations, performed for a range of conditions, help define the current limitations of the kinetic-impact approach. Advance knowledge of scenarios where other mitigation methods would be necessary (or provide lower cumulative risk) could speed the response of decision makers in the event of an emergency.

Prior numerical studies of kinetic-impact deflection have focused on planar target geometries (Jutzi and Michel, 2014), or a limited number of cases to simulate the relatively low-speed ($\sim$6 km/s) AIDA mission impact (Stickle et al., 2015). Both of these studies used modest impactor masses (300–400 kg), similar to the planned mass to be delivered by the DART impactor during the AIDA impact event. Additionally, Asphaug et al. (1998) modeled very energetic, disruptive impacts, finding a strong dependence on internal structure for the Δv imparted to the gravitationally bound portion of the asteroid. The present paper, in contrast, seeks to resolve the limitations and sensitivities of the kinetic-impactor approach within a somewhat broader context, by modeling entire asteroid bodies, using impactor masses representative of the approximate limits posed by current launch vehicle technology (1000–10,000 kg), and probing sensitivity to a range of asteroid characteristics. Specific asteroid-dependent parameters explored in this work include: equation of state, strength/damage, porosity, rotational state, and shape. In addition, we consider the effects of varying impactor velocity and numerical resolution. Our results are intended to serve as a guide for future simulations incorporating the details of specific asteroids or including additional variations in shape, composition, and internal structure of both the asteroid and impactor.

2. Numerical approach

Accurate calculation of the total momentum imparted to an asteroid through hypervelocity impact requires a shock-physics code that can resolve the mass and velocity of particles ejected during the cratering process. Meshless approaches, such as Smoothed Particle Hydrodynamics (SPH) codes (Monaghan, 1992), are particularly well suited to the problem, as mesh entanglement is avoided and tracking ejected mass through large displacements across the problem domain presents fewer complications than many grid-based methods. SPH codes have been used extensively to model impacts at asteroids (see Asphaug et al., 2015; Jutzi et al., 2015; Michel et al., 2015 for reviews of prior work), with Jutzi and Michel (2014) recently applying the method directly to artificial impacts for planetary-defense purposes.

An extension of the SPH method, called Adaptive Smoothed Particle Hydrodynamics (ASPH), generalizes the scalar (isotropic) smoothing length for each SPH particle to a tensor form of smoothing length (Owen, 2010; Owen et al., 1998). This generalization enables ASPH to more accurately define and resolve problems involving anisotropic distortions by allowing the smoothing length scale of each particle to vary with direction; characteristic smoothing lengths in the simulations described here range from $\sim$10 to 45 cm. For hypervelocity planetary impacts, the tensor generalization is particularly important for capturing the failure of geological materials subjected to large shear stresses. The open-source ASPH code, Spheral, was used to model the kinetic impacts presented in this paper. Unlike many standard implementations of SPH, Spheral exactly conserves energy, which presents advantages for demonstrating self-convergence in the simulation of kinetic deflection of asteroids (Owen, 2014). All simulations reported here are three dimensional and the number of particles modeled in each problem is substantial ($\sim 10^6$ to 10^7), requiring a significant number of processors (256–512 cpu) and one to four days of machine time per simulation.

2.1. Impactor model

As this paper is primarily concerned with the influence of asteroid characteristics, impactors were modeled simply as uniform aluminum spheres. Future work will examine the effects of impactor shape and mass distribution on deflection results. An extended, lower-density source, as opposed to a solid aluminum sphere, will change the impedance matching conditions and the timescale of momentum coupling, which may alter the ejecta velocity distribution and, hence, affect momentum delivery. Quantifying impactor effects will require simulations of sufficient resolution to describe the geometry of different impactors. For specific kinetic-impact missions, resolving the details of the impacting spacecraft may become important, as shown in calculations for the LCROSS impact event (Korycansky et al., 2009). Impact speeds are varied from 1 km/s to 30 km/s, representative of the full range of encounter velocities for spacecraft intercepting the orbits of near-Earth asteroids. While the power-law velocity dependence of β can be estimated analytically, using laboratory-scale experimental results (Holsapple and Housen, 2012), numerical simulations provide an opportunity to explore a greater range of velocities than is possible experimentally, at the impact-size regime of interest.

An additional uncertainty associated with the impactor is targeting – in an actual deflection attempt, the impact will, to some degree, be off axis from the asteroid's center of mass. This effect will decrease the Δv delivered to the asteroid in at least two ways: some momentum will be partitioned into modifying the asteroid's rotational state, and the obliquity of the impact will influence the direction of the momentum vector associated with the crater ejecta. This second effect is also related to variations in Δv introduced by the natural topography of asteroids; an analytical model for perturbations introduced by irregular asteroid shape is presented in Scheeres et al. (2015). These results are further supported by Spheral calculations using radar-derived shape models, which are briefly discussed in Section 3.5 and will be presented in detail in a forthcoming paper.

2.2. Asteroid model

Target asteroids were represented by a single, uniform composition (SiO_2), modeled using a variety of equations of state, including Tillotson (Tillotson, 1962), ANEOS (Melosh, 2007; Thompson and Lauson, 1972), and Livermore Equation of State (LEOS) tables (Fritsch, 2011). While asteroids are not comprised of pure SiO_2, this material can be described by a relatively well-constrained equation