Deflection by Kinetic Impact: Sensitivity to Asteroid Properties

Megan Bruck Syal^{a,*}, J. Michael Owen^a, Paul L. Miller^a

^a*Lawrence Livermore National Laboratory, Livermore, CA 94551, USA*

Abstract

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 to 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 ($P = 2.5$ hr) 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

*Corresponding author, 1-925-423-0435

Email address: syal1@llnl.gov (Megan Bruck Syal)

principal uncertainties associated with the kinetic-impact deflection strategy.

Keywords: Impact processes; Asteroids; Cratering; Asteroids, dynamics; Asteroids, rotation

1 1. Introduction

2 Asteroids posing a threat to Earth may be deflected off of an Earth-impacting trajectory
3 by standoff nuclear bursts (Bruck Syal et al., 2013; Howley et al., 2014) or kinetic impactors
4 (Asphaug et al., 1998; Holsapple and Housen, 2012; Jutzi and Michel, 2014). Among the
5 range of concepts for asteroid threat mitigation, these two methods are considered to be the
6 most technologically mature, as discussed in the report by the National Research Council
7 (2010). While nuclear devices may represent the only viable option to prevent Earth im-
8 pacts for large asteroids or those detected with little warning time (Dearborn and Miller,
9 2014), under conditions where a kinetic impactor will be effective, it is the preferred strategy
10 (National Research Council, 2010). Hence, studies which quantify the effectiveness, risks,
11 and uncertainties for the kinetic-impactor method, under a range of initial conditions, are
12 advisable. Full-scale experiments to test the efficacy of kinetic impactors have been and will
13 be rare; these valuable opportunities must be complemented by extensive numerical treat-
14 ment of the problem. The Deep Impact mission successfully deployed a 370 kg impactor
15 to remotely excavate the surface of Comet Tempel 1 in 2005 (A’Hearn et al., 2005; Schultz
16 et al., 2007), providing the first demonstration of kinetic-impact technology on a small body.
17 While the large size of Tempel 1 precluded a measurement of the body’s change in velocity,
18 future asteroid-defense-focused missions will aim to directly measure the momentum transfer
19 imparted by kinetic impactors. In particular, the AIDA mission, a joint ESA and NASA
20 venture, seeks to provide the first quantitative test of asteroid deflection, using the DART
21 spacecraft to impact the secondary of asteroid Didymos (Cheng et al., 2015).

22 A spacecraft impacting in line with an asteroid’s center of mass will transfer all of its
23 momentum, $p_i = m_i v_i$, to the body, changing the asteroid’s translational velocity by $\Delta v_a =$
24 $m_i v_i / (m_a + m_i) \approx m_i v_i / m_a$. An additional transfer of momentum is achieved in the cratering
25 process, as material is ejected above escape speed. This additive effect to the momentum

26 transfer can be expressed as:

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

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

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

47 Prior numerical studies of kinetic-impact deflection have focused on planar target ge-
48 ometries (Jutzi and Michel, 2014), or a limited number of cases to simulate the relatively
49 low-speed (~ 6 km/s) AIDA mission impact (Stickle et al., 2015). Both of these studies
50 used modest impactor masses (300-400 kg), similar to the planned mass to be delivered by
51 the DART impactor during the AIDA impact event. Additionally, Asphaug et al. (1998)
52 modeled very energetic, disruptive impacts, finding a strong dependence on internal struc-
53 ture 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 Michel et al. 2015; Asphaug et al. 2015; Jutzi 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 et al., 1998; Owen, 2010). 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 ~ 10 - 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 ($\sim 10^6$ - 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

112 Spherical calculations using radar-derived shape models, which are briefly discussed in Section
113 3.5 and will be presented in detail in a forthcoming paper.

114 2.2. Asteroid model

115 Target asteroids were represented by a single, uniform composition (SiO_2), modeled using
116 a variety of equations of state, including Tillotson (Tillotson, 1962), ANEOS (Thompson and
117 Lauson, 1972; Melosh, 2007), and Livermore Equation of State (LEOS) tables (Fritsch, 2011).
118 While asteroids are not comprised of pure SiO_2 , this material can be described by a relatively
119 well-constrained equation of state (Melosh, 2007; Kraus et al., 2012) and is commonly used for
120 planetary impact modeling. Exploring the effects of variable asteroid composition, including
121 variations introduced by heterogeneous, rubble-pile structures, remains a priority for later
122 studies. A nominal spherical shape was used to model each asteroid, for straightforward
123 comparison across a range of parameters. However, as discussed in Section 3.5, asteroid shape
124 introduces non-trivial changes to the imparted deflection velocity and should be accounted
125 for in uncertainty assessments.

126 Most asteroids for which bulk-density information is available are believed to contain
127 significant porosity, in the form of microporosity (at the grain level), macroporosity (larger
128 voids between boulders and rubble-pile fragments), or some combination of the two (Britt
129 and Consolmagno, 2000; Britt et al., 2002; Lindsay et al., 2015). Here we focus on microporosity; investigating the effects of macroporous structures is reserved for future calculations.
130 Spheral uses a strain-based approach, defined in Wünnemann et al. (2006), to include asteroid microporosity. The strain-based porosity method, termed the $\epsilon - \alpha$ model, contains an
131 elastic regime, an exponential-compaction regime, and a power-law compaction regime; only
132 the initial porosity ϕ , elastic-plastic transition strain ϵ_e , power law transition strain ϵ_X , and
133 exponential compaction rate κ need to be defined (Wünnemann et al., 2006). Values used
134 for these parameters are listed in Table 1.

135 Asteroid strength was included using either a von Mises yield criterion (constant strength)
136 or a pressure-dependent model for strength:

$$Y_i = Y_0 + \frac{\mu_i P}{1 + \mu_i P / (Y_M - Y_0)} \quad (2)$$

139 where Y_0 is shear strength at zero pressure (cohesion), μ_i is the coefficient of internal friction,
 140 and Y_M is the von Mises plastic limit of the material (Lundborg, 1968; Collins et al., 2004).
 141 Recent work highlights the importance of including pressure-dependent constitutive models
 142 (i.e., friction) when calculating the outcomes of asteroid collisions (Jutzi, 2015); hence, most
 143 simulations reported here used a pressure-dependent strength model. As direct measure-
 144 ments of asteroid strength are not yet available, a range of values for asteroid cohesion, Y_0
 145 (yield strength at zero pressure), were explored: $Y_0 = 1$ kPa - 100 MPa. The lower end of this
 146 range corresponds to typical values for weak soils (e.g., lunar regolith), while the upper end
 147 is representative of strong, competent rock. However, strength is size-dependent; while 1-cm
 148 samples of Allende meteorite crush at 25-50 MPa, these strengths decrease to ~ 1 MPa when
 149 extrapolated to 5-m sample sizes (Cotto-Figueroa et al., 2015). In the absence of available
 150 yield-strength data on asteroidal materials at high pressures, a constant value of $Y_m = 1.5$
 151 GPa was assumed (Collins et al., 2004). A value of $\mu_i = 1.2$, consistent with the 50° angle
 152 of internal friction determined for lunar soil samples (Mitchell et al., 1972), was used for all
 153 simulations.

154 Meteorites can provide clues to the strength properties of asteroids; however, consid-
 155 eration should be given to: (1) scaling of strength from laboratory-scale measurements to
 156 bodies hundreds of meters in scale, including possible micro- and macro-structural differ-
 157 ences between solid meteorite specimens and asteroids (many of which may have rubble-pile
 158 structures); (2) whether available meteorite samples are representative of near-Earth aster-
 159 oids (samples are biased towards compositions likely to survive atmospheric entry and be
 160 recognized by meteorite hunters); and (3) changes in physical properties introduced by the
 161 reentry process. Regardless, strength measurements from meteorites, particularly at high
 162 pressures and a variety of strain rates, are valuable for asteroid impact studies. While there
 163 has been little data published on the mechanical properties of meteorites (Petrovic, 2001),
 164 interest in planetary defense applications has spurred new efforts. Measurements of an L5
 165 chondrite by Kimberley and Ramesh (2011) demonstrated increased compressive strength
 166 from ~ 50 MPa to ~ 200 MPa with increasing strain rate. Efforts are underway to obtain
 167 both compressive and tensile strength data from a variety of chondrite samples at a wide
 168 range of strain rates (Cotto-Figueroa et al., 2015; Sears et al., 2015).

169 Damage, which is accumulated through strain-rate-dependent, dynamic-fracture mecha-
 170 nisms, reduces the strength of rocky materials; therefore, asteroid strength is coupled to a
 171 damage model, which tracks the strain history of each particle and calculates the extent of
 172 damage sustained throughout the impact event. The damage model employs a statistical
 173 representation of flaw-activation strains, initially described by Grady and Kipp (1980) and
 174 later applied to SPH calculations by Benz and Asphaug (1994, 1995). These (and subse-
 175 quent) SPH implementations of the Grady-Kipp fracture model used a scalar representation
 176 for damage, D ; here we use a similar approach, with the damage variable generalized to
 177 a tensor form, $D_{\alpha\beta}$ for each ASPH node (Owen et al., 2015). The eigenvalues of $D_{\alpha\beta}$ are
 178 bounded in the range $[0,1]$, and represent the fraction of damage in the direction of their as-
 179 sociated eigenvector. $D_{\alpha\beta}$ represents the history of the damage (including directionality) for
 180 each ASPH node, and follows that node throughout the evolution of the simulation. Weibull
 181 parameters used to describe the initial flaw distributions are listed in Table 1.

Figure 1: Comparison of two different methods for calculating the momentum multiplication factor, β : tracking the asteroid's center of mass (black) and summing the momentum of ejecta exceeding escape velocity (blue). The two methods yield very similar results throughout the simulated time; final values for β are nearly identical ($< 0.2\%$ difference). Results are from run 21 (Table 2).

182 2.3. Calculation of β

183 Calculation of the total momentum delivered to an asteroid is carried out using two
184 separate methods, as a check on consistency. The first method sums the vertically-directed
185 momentum of ejecta exceeding escape velocity (e.g., $v_{esc} = 4.71$ cm/s for a 100-m asteroid
186 with 40% porosity). The time evolution of this momentum is followed until the impulse
187 converges (typically, 0.1-0.5 s after impact). For the asteroid sizes considered here (50-100
188 m), kinetic energy lost to material that is escaping from the asteroid’s gravity is negligible.
189 For example, accounting for the change in final velocity from gravitational effects, $v_{inf}^2 =$
190 $v_{ej}^2 - v_{esc}^2$, for a 5 km/s impact into a 40% porous, 100-m asteroid, reduces the calculated β
191 by $< 0.1\%$. As a result, we report β values without including energy losses to gravity.

192 The second β calculation method tracks the center-of-mass velocity of the asteroid after
193 impact, by summing the momentum of all material remaining below escape velocity. This
194 method requires modeling the entire asteroid, as was done for nearly all calculations in this
195 study but, depending on asteroid size and desired resolution, may not always be possible.
196 Direct comparison of the two β calculation methods shows very good agreement, as shown
197 for a test case in Figure 1. This provides enhanced confidence in using either approach
198 to calculate momentum transfer. Note that β decreases from initially larger values during
199 the impact event, owing to the early-time, instantaneous velocities of material that remains
200 bound to the asteroid. The full list of simulation results is provided in Table 2.

201 3. Results

202 3.1. Equation of State

203 Perhaps the most fundamental material property choice is which equation of state should
204 be used to represent the target asteroid. The time evolution of the momentum-transfer
205 multiplier, β , for 10 km/s impacts into 50 m-diameter asteroids, modeled using three different
206 SiO₂ equations of state, is shown in Figure 2. Strength and damage models were not included
207 for the purposes of this comparison. Strength (as evidenced in the results for Tillotson with
208 strength shown in Figure 2 and discussed in detail in Section 3.2) can significantly reduce
209 β . Calculated values for β , measured by either the momentum of ejecta exceeding escape
210 velocity or the asteroid’s center-of-mass velocity, converge within ~ 0.2 seconds post-impact.

Figure 2: Momentum multiplication factor, β , plotted as a function of time for kinetic-impact simulations, using three different SiO_2 equations of state: Tillotson (Tillotson, 1962), LEOS (Fritsch, 2011), and ANEOS (Thompson and Lauson, 1972; Melosh, 2007). To simplify comparison, no strength or damage models were initially included (blue, red, black lines). Including strength (cyan line) reduces β significantly. Momentum delivery converges to a final value within the first ~ 0.2 s. While Tillotson is a simpler analytic equation of state and useful under a range of lower-velocity impact conditions, LEOS and ANEOS capture melting and vaporization processes more accurately. ANEOS is used for most impact simulations in this paper. Figure shows results from runs 1-4 (Table 2).

211 The Tillotson model is among the simplest analytic equations of state, and it predicts
 212 somewhat larger β values than the more sophisticated LEOS (Fritsch, 2011) and ANEOS
 213 models. The LEOS tabular equation of state and the ANEOS semi-analytical equation of
 214 state include accurate treatment of melt and vapor transitions, unlike Tillotson; lower values
 215 of β for these cases are attributed to more impact energy being partitioned into melting
 216 and vaporizing target material, with less energy partitioned into crater ejecta. The ANEOS
 217 package, which tracks regions of mixed melt and vapor in a thermodynamically consistent
 218 way (Thompson and Lauson, 1972; Benz et al., 1989; Melosh, 2007) and is already used
 219 extensively within the planetary-impacts community, is used for the bulk of simulations

220 reported in this paper.

221 3.2. *Strength and Damage Model*

222 The presence of strength, coupled with a damage model, results in the dissipation of
223 impact energy by additional mechanisms, as material is plastically deformed and existing
224 flaws in the rock are activated, leading to crack growth, failure, and fragmentation. Figure 3
225 compares the β values for asteroids with 40% porosity but with different values of cohesion,
226 Y_0 , for 10 km/s impacts. A pressure-dependent strength model was used (Equation 2) for
227 all but one of the cases, where a simple von Mises yield criterion (constant strength) was
228 implemented. The difference between these two strength models is small: β is calculated to
229 be $< 2\%$ greater for the constant strength case than for the pressure-dependent model (for
230 $Y_0 = 100$ MPa). Prior calculations of β by Jutzi and Michel (2014) used pressure-dependent
231 strength for all simulations.

232 Low-cohesion asteroids result in larger values of β ; however, there is little difference
233 between 1 kPa (very weak soils), 10 kPa (weak soils), and 100 kPa (weak rocks). This range
234 brackets the size-dependent strength values for all but the strongest meteorite types. At
235 somewhat larger values of cohesion (>1 MPa), β declines more noticeably. The strengthless
236 example produces a significantly larger momentum-transfer efficiency ($\beta \sim 5.5$) than the
237 lowest-cohesion case. Assuming that powdery lunar regolith represents a minimum value
238 of cohesion for an airless silicate asteroid, a value of $Y_0 = 1$ kPa is used for many of the
239 comparative simulations, as it represents an approximate lower limit of the shear strength
240 at zero pressure for an asteroid and can be viewed as an “upper limit” for enhancing β in a
241 deflection scenario.

242 3.3. *Porosity*

243 Asteroid microporosity decreases the augmentation of momentum transfer from a kinetic
244 impactor, as impact energy is consumed in the crushing of pore spaces, leaving less energy
245 available for the ejection of target material. Figure 4 illustrates the effect of microporosity
246 on the momentum-enhancement factor, β , using two different values for asteroid cohesion:
247 $Y_0 = 1$ kPa and $Y_0 = 100$ MPa. In the case of weaker material ($Y_0 = 1$ kPa), momentum
248 transfer decreases sharply between the nonporous and slightly porous ($\phi = 0.05$) cases and

Figure 3: Increasing values of cohesion for asteroid material decreases the momentum enhancement factor, β , for kinetic deflections. Modeling the asteroid as strengthless results in a significant over estimate: $\beta \sim 5.5$. Cohesion values representative of weak soils (1 kPa) to weak rocks (100 kPa) produce similar deflection velocities, while somewhat larger values of cohesion (1-100 MPa, representative of stronger rocks), lead to increasingly smaller values for β . Use of a constant (von Mises criterion) strength for the 100 MPa case produced a slightly larger β value than the pressure-dependent strength model; the latter is considered more accurate and used in the majority of the simulations. Data from runs 5-13 (Table 2).

249 then decreases more gradually with increasing microporosity. Porosity effects are more subtle
 250 for the stronger material ($Y_0 = 100$ MPa).

251 However, asteroid porosity also reduces total target mass for a fixed-size asteroid, lowering
 252 the momentum necessary to achieve a desired change in velocity. Prior to a deflection mission,
 253 a likely scenario may include information on an asteroid's surface composition and diameter
 254 from remote sensing data but little or no direct information on mass or bulk density. In this
 255 situation, the uncertainty in asteroid density/porosity will result in two competing effects:
 256 larger porosities will reduce β but a corresponding lower asteroid mass will also lead to a
 257 larger Δv for a given momentum impulse. Figure 5 illustrates how the sum of both effects
 258 actually results in larger total Δv for more porous asteroids. Greater asteroid porosity is thus

Figure 4: The presence of microporosity decreases the total momentum of target material ejected during an impact, reducing β . The effects of varying asteroid porosity on delivered momentum impulse are shown for different values of cohesion: $Y_0 = 1$ kPa and $Y_0 = 100$ MPa. For the low-cohesion cases, there is an abrupt decrease in β between nonporous and slightly porous ($\phi = 0.05$) material and a more gradual decrease with further increasing microporosity. For the high-cohesion cases, porosity effects on momentum transfer are less prominent. Data from runs 12, 14-24 (Table 2).

259 helpful for achieving larger deflection velocities. In the case shown, the impacts are near the
 260 disruption limit of a 100-m asteroid, so that more significant porosity also results in deflection
 261 velocities nearer to the asteroid’s escape speed. While porosity will help reduce the risk of
 262 disruption through attenuation of the impact-generated shock wave, when the required Δv
 263 is near to an asteroid’s escape speed, another mitigation method may be required.

264 The risk of disruption can be assessed by tracking the post-impact center-of-mass velocity,
 265 v_{COM} , and evaluating the fraction of asteroid material (other than ejecta) for which the
 266 speed difference, $\|\delta v\| = \|v_{\text{COM}} - v\|$ exceeds escape speed. The disrupted fraction of 100-
 267 m asteroids with different initial porosities is shown in Figure 6. Even a small amount of
 268 porosity lowers disruption risk; cases with $\phi = 0.1$ -0.5 approach a disrupted fraction of $\sim$
 269 0.003, while a much larger fraction (0.184) of the non-porous case is disrupted at 0.1 s after

Figure 5: The final change in velocity, Δv , for 100-m asteroids of different porosities with low (1 kPa) and high (100 MPa) cohesion. Asteroid escape speed is plotted for reference. As porosity increases, total target mass decreases, producing larger deflection velocities for a given momentum impulse. This effect dominates over the decrease in β with increasing porosity (Fig. 4), causing more porous asteroids to receive larger changes in velocity.

270 impact.

271 3.4. Rotation

272 Pre-impact spin periods of 100 seconds and 2.5 hours were used to assess rotational effects
 273 on both momentum delivery and disruption risk. These spin rates correspond to some of the
 274 fastest known rotators ($P = 100$ s) and to rotators just above the 2.2 hour “spin limit” for a
 275 cohesionless gravitational aggregate (Statler et al., 2013; Pravec and Harris, 2000). Impact
 276 locations were placed at the equator, to maximize rotational effects on ejecta velocities. In
 277 both cases, rotation did not significantly affect the final β value calculated for the asteroids.
 278 Results for the time evolution of β for the $P = 100$ s asteroids are plotted in Figure 7. In both
 279 the strengthless and with-strength cases, the difference in calculated β values were $< 2\%$.
 280 Similar results were found for the asteroids with 2.5 hr rotation periods: including rotation

Figure 6: For kinetic-impact scenarios near the asteroid’s disruption limit, tracking the fraction of non-ejecta material that is mobilized above escape speed provides a measure of the disruption risk. For the high cohesion ($Y_0 = 100$ MPa) examples shown, even a small amount of porosity, ϕ , is protective against disruption, lowering the fraction of disrupted mass from 0.184 to ~ 0.003 (at 0.1 s post-impact). Data is from runs 12, 20-24 (Table 2).

increased β by only 0.16% (run numbers 27 and 28 in Table 2). As expected (and documented in Section 3.2), strength reduces the efficiency of momentum transfer for spinning and non-spinning asteroids. In order to search for maximal rotation-related perturbations, relatively low impact velocities ($v_i = 5$ km/s) were used, so that the time scale of crater formation was nearer to the timescale of rotation.

In contrast, the risk of disruption is found to be affected by pre-impact rotation. Figure 8 shows non-rotating (a) and rotating (b) asteroids ($D = 100$ m) impacted by 5000 kg masses at 5 km/s, at at time 0.12 seconds after impact. Blue color indicates material bound to the asteroid, while other colors represent material exceeding the asteroid’s escape velocity. Material that is not part of the crater ejecta curtain but is mobilized above escape speed can contribute to unintentional disruption. Along the equator of the rotating asteroid, significant material appears to be dislodged by the impact. The fraction of target mass that

Figure 7: Time evolution of β for a fast-rotating asteroid ($P = 100$ s), with and without strength, compared to a non-rotating asteroid. While, at early times, the spinning asteroid appears to receive a slight enhancement in momentum transfer, both the rotating and non-rotating cases converge to the same β values at later times. Results from runs 25-28 (Table 2).

will escape (apart from the desirable escape of material within the ejecta curtain), relative to the asteroid’s center-of-mass velocity, is found to be 0.029 for the rotating case, a significant increase from the 0.007 found in the non-rotating example. In situations where the required Δv corresponds to impact conditions that approach an asteroid’s disruption threshold, this enhanced disruption risk warrants extra caution, particularly for fast-rotating asteroids.

3.5. Shape

As an investigation into the effects of local asteroid topography on delivered momentum impulse, simulated impacts were carried out into asteroid Golevka, using a radar-derived shape model. Approximately 500 m across, Golevka represents the upper size range that a kinetic impactor could deflect off of an Earth-impacting orbit, even with decades of warning time (Dearborn and Miller, 2014). The asteroid’s unusual shape, including many concave regions, serves as an interesting test case. Adequately resolving a 10,000-kg impactor while

Figure 8: Rotational effects on the disruption risk to asteroids: top (a) depicts a non-rotating asteroid, while bottom (b) shows an asteroid rotating with a period of 2.5 hours. Blue material is below asteroid escape speed. The green regions along the equator of the rotating case represent asteroid material that has been unfavorably dislodged by the impact: it is not part of the crater ejecta curtain yet has been mobilized above escape speed. The fraction of unfavorably dislodged material is 2.9% for the rotating case, significantly more than the 0.7% calculated for the non-rotating case. Results from runs 29-30 (Table 2).

305 modeling an entire 500-m asteroid is computationally expensive, so the problem domain was
 306 confined to a region extending 80 meters from the chosen impact site.

307 The extent of damage produced by a 10 km/s impact into asteroid Golevka (modeled
 308 as 20% porous SiO_2) is shown in Figure 9. While the impactor collides along one of the
 309 asteroid's principal axes, the final direction of push is not through the asteroid's center of
 310 mass, as the ejecta momentum vector is directed 7 degrees off axis. Variations associated
 311 with local topography can thereby degrade the efficacy of the kinetic-impactor approach,
 312 leading to a smaller effective β (where β is defined as the momentum multiplication along

Figure 9: A shape model for asteroid Golevka is impacted by a 10,000-kg mass traveling at 10 km/s along a principal axis of the asteroid. Colors denote the trace of the damage tensor, shown at 0.074 s after impact. The ejecta’s momentum vector is directed approximately 7 degrees off axis from the impactor’s trajectory. Asteroid topography can thus affect the resulting direction of push by a kinetic impactor, in practice introducing undesirable variation into the delivered momentum impulse. The final change in asteroid velocity for this example is ~ 1 mm/s. The modeled region is confined to 80 m from the impact site (colored volume), while the entirety of the shape model is included for context.

the impact trajectory). In this case, the final β calculated is 2.33, which corresponds to a modest change in velocity of $\Delta v \sim 1$ mm/s.

3.6. Velocity Scaling

While a nominal impact velocity of 10 km/s was employed for most simulations in this study, we investigated the velocity scaling for momentum transfer, for comparison with analytical models and available experimental data (Holsapple and Housen, 2012). Experiments are necessarily limited to smaller impact sizes and lower velocity regimes (< 6 km/s). Numerical modeling allows the full range of likely encounter velocities to be investigated at the

321 impact-size regime of interest for asteroid deflection.

322 Based upon point-source scaling relations, the velocity scaling for the momentum of
 323 escaping ejecta, P , relative to impactor momentum, mU , should follow a power law:

$$\frac{P}{mU} = \beta - 1 \sim U^{3\mu-1} \quad (3)$$

324 where μ is the velocity-scaling exponent of the impact coupling parameter from point-source
 325 solutions (Holsapple and Schmidt, 1987; Holsapple and Housen, 2012). The value of μ is
 326 material dependent and may vary between the limits imposed by pure momentum scaling
 327 ($\mu = 1/3$) and pure energy scaling ($\mu = 2/3$). Experiments using geological materials find
 328 that μ generally ranges from 0.35 to 0.55 (Housen and Holsapple, 2011).

Figure 10: Velocity scaling of β for 1 - 30 km/s impacts into 40% porous, low-cohesion ($Y_0 = 1$ kPa) asteroid targets ($D = 100$ m). Momentum delivery is approximated by a power-law slope of 0.39 ($\mu = 0.44$). This value of μ is consistent with impact experiments that exhibit values of μ ranging from 0.35 (perlite-sand mixture) to 0.55 (competent rock) (Housen and Holsapple, 2011). Results from runs 6, 31-35 (Table 2).

329 Results from impact velocities ranging from 1 km/s to 30 km/s are plotted in Figure 10.
 330 This set of simulations used low-cohesion ($Y_0 = 1$ kPa) and 40% porous material. A power-

law fit to the data yields $\mu = 0.44$, intermediate between experimentally determined values of μ for sand and competent rock (Holsapple, 1993; Housen and Holsapple, 2011). Although prior numerical study by Jutzi and Michel (2014) found impacts 5-15 km/s to be described by $\mu = 0.62$, closer to pure energy scaling, this difference is partly attributed to the higher value of cohesion used in that study, $Y_0 = 100$ MPa, representative of relatively strong rock. The weaker material used to derive μ in the present work more closely approximates the idealized, “perfectly porous” case described in Holsapple and Schmidt (1987), for which μ is predicted to be closer to momentum scaling ($\mu = 0.37$ - 0.40). Differing values for numerically-computed μ may also arise from other subtle differences in the modeled material properties, including the internal friction coefficients used and the yield strength at large pressures.

3.7. Numerical Resolution

For under-resolved simulations, as numerical resolution increases, the velocity change imparted to an asteroid by a kinetic impact decreases (Owen, 2014) and the extent of damaged target material also decreases (Owen et al., 2015). Simulations at a range of resolutions are necessary to determine under what conditions the results exhibit numerical convergence. To investigate resolution effects, we modeled a region extending 20 meters from the impact point on a 100-meter asteroid — confining the problem to this domain size allowed the highest-resolution simulations to be run on 512 processors or less. The changing damage patterns associated with higher-resolution models are shown in Figure 11. As the damaged region decreases in size, less mass is ejected above escape speed and β decreases. Resolution effects on the β value calculated for 5 km/s impacts are shown in Figure 12, exhibiting convergence at a spatial resolution of 15 cm. The lowest-resolution case (44.5 cm) overestimates β by approximately 12.25%. As most calculations reported in this study modeled the entire asteroid, some required somewhat lower resolution than the optimal 15 cm. The approximate errors in β attributed to resolution effects are noted in Table 2.

4. Discussion

The results presented demonstrate the wide breadth of asteroid characteristics affecting the impulse delivered to an asteroid by a kinetic deflection, even within the bounds of a

Figure 11: Increasing numerical resolution limits the extent of damage in kinetic-impact simulations: a. 44.5 cm, b. 22.25 cm, c. 14.83 cm. The trace of the damage tensor is plotted 0.05 seconds after a 5 km/s impact, after crack propagation has ceased for the two higher-resolution cases. The problem domain is confined to 20 meters from the impact site on a 100-meter asteroid to permit the calculation to be run on 512 processors or less. A quadrant is cut away from each image, so that damage accumulated internally to the asteroid can be visualized. Models employed 40% porous SiO₂, $Y_0 = 100$ MPa, and 1000-kg impactors.

uniform SiO₂ composition. While these calculations are not exhaustive for the range of initial conditions describing real near-Earth asteroids, they provide baseline information on relations between some of the most fundamental, unconstrained parameters and an asteroid's response.

Porosity is well known to dampen momentum transfer by impacts, both from experimental work (Holsapple and Housen, 2012) and numerical study (Asphaug et al., 1998; Jutzi and Michel, 2014). The present work has explored the trends associated with increasing porosity, under varied assumptions about the cohesion of asteroid-target material.

Figure 12: A graph of β , normalized by the highest-resolution result, as a function of numerical resolution (resolutions shown: 11.1, 14.8, 22.3, 44.5 cm). Convergence is achieved near 15-cm resolution; the lowest-resolution case over-predicts momentum-transfer efficiency by 12.25%. Results are for the impact conditions described in the caption of Figure 11.

367 As expected, β decreases with increasing porosity (Fig. 4). More interestingly, deflection
 368 velocities for increasingly porous asteroids are found to be greater, due to decreased aster-
 369 oid mass for fixed asteroid size (Fig. 5). Additionally, even moderate porosity is found to
 370 be helpful for preventing unintentional disruption of an asteroid (Fig. 6). Assessment of
 371 porosity effects was limited to the assumption of microporosity, using a strain-based $\epsilon - \alpha$
 372 model (Wünnemann et al., 2006); previous deflection calculations by Jutzi and Michel (2014)
 373 used the $P - \alpha$ porosity model (Herrmann, 1969). Ongoing development of microporosity
 374 models will enable future comparisons between approaches that account for the compaction
 375 of porous geological materials in different ways. For example, the microporosity model
 376 described in Herbold et al. (2015) was developed specifically for asteroidal materials and in-
 377 cludes poroelastic compaction, comminution of grains, and bulking. This thermomechanical
 378 constitutive model fully couples solid equation-of-state data for chondrites, porosity, yield
 379 surface, breakage/damage, and bulking response, so that each of these evolving variables are

interdependent throughout the simulation. Modeling porosity and strength/damage in such a manner benefits from improved thermodynamic consistency.

The high porosities inferred for most asteroids may be partially distributed in macroporous structures, including large voids between more competent boulders or fragments from previous collisions and subsequent gravitational reaccumulation. Investigation of kinetic impact deflection for asteroids with void space distributed using either a combination of micro- and macro-porosity, or only microporosity, has so far found minimal difference between the two scenarios (Jutzi and Michel, 2014). However, the effects of structural inhomogeneities, including larger voids and fragments of varying compositions and competency, remain to be studied in detail. The problem is intrinsically linked to asteroid-strength effects, as the constitutive models governing various possible structural components (e.g., granular regolith, crystalline rock fragments) are necessarily variable. The importance of internal structure in determining asteroid-mitigation outcomes is likely greater for situations when deflection is not a workable option (short warning times) but, rather, robust disruption and dispersal of the fragments is required for the mass to miss the Earth (Dearborn and Miller, 2014). The effects of asteroid structure on the outcomes of various mitigation options will be explored in detail in future calculations.

Rotation rates among the population of smaller asteroids ($D < 150$ m) can be particularly fast. During the past two decades, the number of known asteroids that rotate at periods less than ~ 2.2 hrs, has significantly increased (Harris, 1996; Pravec and Harris, 2000; Statler et al., 2013). Such spin rates indicate that some amount of cohesion is necessary to prevent disaggregation, although the amount of cohesion required may be small ($\sim 0.1 - 100$ kPa) in many cases (Holsapple, 2007; Rozitis et al., 2014). Recent optical light-curve surveys indicate that rotation rates are strongly correlated with size — while nearly all asteroids smaller than 60 m are categorized as fast rotators, very few bodies larger than 170 m are fast-rotating (Statler et al., 2013). Since smaller asteroids are least well-characterized by near-Earth asteroid surveys (Harris and D’Abramo, 2015), future detections of potentially hazardous asteroids will likely include greater numbers of small and fast-rotating bodies.

As a result, asteroid-mitigation measures should account for rotational effects on asteroid response. The work presented here does not find a significant increase in β , even for

410 very fast ($P = 100$ s) spin periods. This is attributable to characteristic ejecta velocities
 411 (those that significantly contribute to β) significantly exceeding the velocity introduced by
 412 rotation. However, spin remains important for assessing the boundary between deflection
 413 and unintentional disruption for cases when $\Delta v \sim v_{esc}$. Pre-impact rotation, particularly for
 414 weak, low-cohesion bodies, can increase the risk of generating a poorly-dispersed fragment
 415 field, depending on the size and velocity of the impactor. In cases when kinetic deflection
 416 creates such a fragment field, the end result could cause greater damage than electing to
 417 take no action. In situations where there is not sufficient warning time to gently deflect
 418 small, fast-rotating bodies without significant risk of undesired disruption, other, more en-
 419 ergetic options can be examined, e.g., intentional, robust disruption and fragment dispersal
 420 (Dearborn and Miller, 2014).

421 Rotation can also affect the impact point of a kinetic-deflection mission and, consequently,
 422 the uncertainty in momentum impulse introduced by shape effects. Targeting a specific
 423 impact point, even for asteroids well characterized by radar measurements or spacecraft
 424 data, is complicated by the rotational state. Hence, there may be uncertainty regarding the
 425 local topography at the impact point, which can compromise the effectiveness of crater ejecta
 426 in boosting the momentum impulse (as shown numerically in Section 3.5). The importance
 427 of shape in controlling the momentum vector of impact ejecta, while briefly highlighted here,
 428 will be described more fully in another paper, including detailed comparisons to the analytic
 429 model of Scheeres et al. (2015).

430 Off-axis impacts, which will arise from imperfect targeting and are also influenced by
 431 asteroid shape and rotational state, represent an additional source of variability in asteroid
 432 response. The idealized scenario of a vertical impact through a spherical asteroid’s center of
 433 mass, in the direction of intended deflection, represents a best possible case for maximizing
 434 the effective β . Any deviation from this scenario will result in an oblique impact, decreas-
 435 ing the delivered Δv as ejecta momentum is directed downrange (Anderson et al., 2003,
 436 2004). Furthermore, off-axis impacts introduce perturbations to the asteroid’s spin state. A
 437 significant percentage ($\sim 9\%$) of near-Earth asteroids can be described as contact binaries
 438 (Benner et al., 2006), while many more exhibit elongated geometries. In these cases, it may
 439 be particularly important to account for impact targeting variability — for instance, shock

440 wave interaction with the narrow, low-cohesion “neck” of a contact binary has been shown
441 to affect both the final Δv and the disruption of the impacted lobe (Asphaug et al., 1998).
442 More simulations are needed to fully evaluate how β decreases with increasingly oblique im-
443 pacts and to evaluate the range of outcomes for off-axis impacts on non-spherical asteroids;
444 this work is reserved for future contributions.

445 Impact velocity strongly influences asteroid response to kinetic deflections and may vary
446 considerably for different asteroid-intercept scenarios. It is therefore essential to have veloc-
447 ity scaling relationships for impacts into a variety of target types. Laboratory measurements
448 have provided important data on the velocity scaling of β for different geological materials at
449 somewhat lower velocities (< 6 km/s) (Holsapple and Housen, 2012), while numerical simu-
450 lations extend experimentally determined power laws to the higher possible impact velocities
451 for deflection missions (up to approximately 30 km/s). The calculations presented here are
452 the first to probe the full range of laboratory-to-deflection mission-relevant velocities (1- 30
453 km/s) and find that the power law describing the simulation results is consistent with avail-
454 able experimental data (Holsapple and Housen, 2012). While the velocity scaling exponent
455 μ will vary between different target types, our calculated value of $\mu = 0.44$ (for porous, low-
456 strength targets) provides a reasonable starting place for extrapolating momentum impulse
457 delivery to a range of encounter velocities, using Equation 3.

458 Lastly, demonstrating numerical convergence is found to be particularly important for
459 calculations of β — under-resolved simulations will yield β values that are too large. Mod-
460 eling entire asteroids at a resolution sufficient to avoid over-estimating momentum transfer
461 can be challenging. An alternative approach is to model a portion of the asteroid at higher
462 resolution. Depending on the scenario, such a problem set-up may or may not be adequate.
463 For example, when assessing the risk of disruption or large-scale damage and spallation
464 across the asteroid, it is necessary to model the entire body. Impacts of higher velocities
465 and larger masses can require larger domains (all or most of the asteroid) to avoid edge
466 effects. In either case, the effects of varying the domain size and increasing resolution should
467 be explored. Other strategies may include the use of finer-mass-resolution particles near
468 the impact site and coarser masses at greater radial distances. However, this requires use
469 of special node generators and must be thoroughly tested, to rule out introduction of error

470 from the variable node masses.

471 The dependence of damage extent and total momentum of ejecta on the node-mass
472 resolution also has implications for other asteroid-impact problems of interest. For example,
473 the generation of collisional asteroid families by catastrophic disruption events (Michel et al.,
474 2001, 2002, 2003, 2004) and calculations of the critical specific energy, Q_D^* , to disperse
475 small bodies in both the strength- and gravity-dominated regimes (Asphaug et al., 1998;
476 Benz and Asphaug, 1999; Leinhardt and Stewart, 2009) both rely upon SPH-type codes to
477 determine the final fragment distribution after the impact phase. Sensitivity of the damage
478 accumulation and ejected mass to numerical resolution may be an important consideration
479 for future extensions of such studies.

480 5. Conclusions

481 Kinetic impactors represent a relatively simple and mature technology useful for deflecting
482 asteroids when warning times are not too short and the bodies are not too large. However,
483 details of the method’s efficacy depend on a number of target parameters that may or may not
484 be well-characterized before a deflection mission is staged, including composition, strength,
485 porosity, rotational state, shape, and structure. It should be noted that these same asteroid
486 characteristics are of interest for determining the outcomes of natural hypervelocity collisions
487 and for understanding collisional histories.

488 We have systematically varied several asteroid properties expected to affect momentum
489 delivery by high speed impacts, using an Adaptive Smoothed Particle Hydrodynamics code
490 to model a range of deflection scenarios. Choice of equation of state, strength and damage
491 models, porosity, rotation rate, and shape are all found to affect asteroid response. The
492 momentum multiplier factor, β , decreases with increasing asteroid cohesion or with increas-
493 ing porosity. For target bodies of a given size, larger porosity values actually result in
494 greater deflection velocities, despite the decreased β values, as a result of decreased asteroid
495 mass. Calculations also reveal how porosity helps to mitigate disruption risk. Rotation, for
496 the range of spin rates explored ($P = 100 - 9000$ s), was not found to significantly affect
497 momentum transfer but does increase the risk of unintentional disruption. Local asteroid
498 topography at the impact point affects ejecta-momentum-vector direction, decreasing the

499 effective β calculated.

500 Velocity scaling of the momentum delivered to asteroids was found to follow a power law
501 described by $\mu = 0.44$, consistent with the range of values determined by laboratory-scale
502 impact experiments into geological materials ($0.35 < \mu < 0.55$). Impact velocities spanned
503 1-30 km/s, covering the regimes explored by laboratory work as well as the upper limits
504 of likely kinetic-deflection velocities. Our results provide a basis for extrapolating expected
505 momentum multiplication factors under a variety of asteroid intercept conditions, a useful
506 consideration for kinetic deflection mission design.

507 The results described here (1) highlight the importance of continued research to char-
508 acterize the properties of near-Earth asteroids and (2) illustrate uncertainties in asteroid
509 response that may remain before an actual kinetic deflection event. Although asteroids are
510 diverse, gathering data on the strength and internal structure of just one or a few aster-
511 oids (through a combination of in-situ and remote-sensing investigations by future missions)
512 would provide helpful information on some of the most poorly constrained geo-mechanical
513 parameters. Uncertainties in topography at the impact point, introduced by the rotation
514 and shape of individual asteroids, present complications for predicting the final momentum
515 impulse. However, the statistical degradation of momentum transfer by shape effects can
516 be accounted for during the planning stages of kinetic deflection missions. Opportunities to
517 mount realistic tests of the kinetic-impactor concept, such as the AIDA mission, are exceed-
518 ingly valuable, both for the new insight on an individual asteroid’s material properties and
519 for the experimental data for validation and verification of models within the impact-size
520 ranges of interest to planetary defense. In such experiments, observables are not limited to β
521 — crater shape and size, ejecta evolution, and other details of the impact event, in addition
522 to pre-impact reconnaissance, can be used to sort out the various effects that influence the
523 final state of the asteroid.

524 Acknowledgments

525 The authors thank Erik Asphaug and an anonymous reviewer for their comments, which
526 strengthened this paper. Part of this work was funded by the Laboratory Directed Research
527 and Development Program at LLNL under project tracking code 12-ERD-005, performed

528 under the auspices of the U.S. Department of Energy by Lawrence Livermore National Lab-
529 oratory under Contract DE-AC52-07NA27344. LLNL-JRNL-677415.

A'Hearn, M.F., Belton, M.J.S., Delamere, W.A., Kissel, J., Klaasen, K.P., McFadden, L.A., Meech, K.J., Melosh, H.J., Schultz, P.H., Sunshine, J.M., Thomas, P.C., Veverka, J., Yeomans, D.K., Baca, M.W., Busko, I., Crockett, C.J., Collins, S.M., Desnoyer, M., Eberhardy, C.A., Ernst, C.M., Farnham, T.L., Feaga, L., Groussin, O., Hampton, D., Ipatov, S.I., Li, J.Y., Lindler, D., Lisse, C.M., Mastrodemos, N., Owen, W.M., Richardson, J.E., Wellnitz, D.D., White, R.L., 2005. Deep Impact: Excavating Comet Tempel 1. *Science* 310, 258–264.

Anderson, J.L.B., Schultz, P.H., Heineck, J.T., 2003. Asymmetry of ejecta flow during oblique impacts using three-dimensional particle image velocimetry. *Journal of Geophysical Research (Planets)* 108, 13–1.

Anderson, J.L.B., Schultz, P.H., Heineck, J.T., 2004. Experimental ejection angles for oblique impacts: Implications for the subsurface flow-field. *Meteoritics and Planetary Science* 39, 303–320.

Asphaug, E., Collins, G., Jutzi, M., 2015. Global Scale Impacts, in: Michel, P., DeMeo, F.E., Bottke, W.F. (Eds.), *Asteroids IV*, University of Arizona Press.

Asphaug, E., Ostro, S.J., Hudson, R.S., Scheeres, D.J., Benz, W., 1998. Disruption of kilometre-sized asteroids by energetic collisions. *Nature* 393, 437–440.

Benner, L.A.M., Nolan, M.C., Ostro, S.J., Giorgini, J.D., Pray, D.P., Harris, A.W., Magri, C., Margot, J.L., 2006. Near-Earth Asteroid 2005 CR37: Radar images and photometry of a candidate contact binary. *Icarus* 182, 474–481.

Benz, W., Asphaug, E., 1994. Impact simulations with fracture. I. Method and tests. *Icarus* 107, 98–116.

Benz, W., Asphaug, E., 1995. Simulations of brittle solids using smooth particle hydrodynamics. *Comput. Phys. Commun.* 87, 253–265.

- Benz, W., Asphaug, E., 1999. Catastrophic Disruptions Revisited. *Icarus* 142, 5–20.
- Benz, W., Cameron, A.G.W., Melosh, H.J., 1989. The origin of the Moon and the single impact hypothesis. III. *Icarus* 81, 113–131.
- Britt, D., Yeomans, D., Housen, K., Consolmagno, G., 2002. Asteroid density, porosity, and structure, in: Bottke, W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), *Asteroids III*, University of Arizona Press.
- Britt, D.T., Consolmagno, G.J., 2000. The Porosity of Dark Meteorites and the Structure of Low-Albedo Asteroids. *Icarus* 146, 213–219.
- Bruck Syal, M., Dearborn, D.S., Schultz, P.H., 2013. Limits on the use of nuclear explosives for asteroid deflection. *Acta Astronaut.* 90, 103–111.
- Cheng, A., Atchison, J., Kantsiper, B., Rivkin, A., Stickle, A., Reed, C., Galvez, A., Carnelli, I., Michel, P., Ulamec, S., 2015. Asteroid impact & deflection assessment mission. *Acta Astronaut.* 115, 262–269.
- Collins, G.S., Melosh, H.J., Ivanov, B.A., 2004. Modeling damage and deformation in impact simulations. *Meteoritics and Planetary Science* 39, 217–231.
- Cotto-Figueroa, D., Asphaug, E., Garvie, L., Morris, M., Rai, A., Chattopadhyay, A., Chawla, N., 2015. Scale-Dependent Measurements of Meteorite Strength and Fragmentation: Tamdakht (H5) and Allende (CV3), in: *AAS/Division for Planetary Sciences Meeting Abstracts*.
- Dearborn, D.S.P., Miller, P.L., 2014. Deflecting or Disrupting a Threatening Object, in: Pelton, J.N., Allahdadi, F. (Eds.), *Handbook of Cosmic Hazards and Planetary Defense*, Springer.
- Fritsch, F.N., 2011. LIP: The Livermore Interpolation Package, Version 1.4. LLNL-TR-406719-REV-3 Lawrence Livermore National Laboratory, Livermore, CA.
- Grady, D.E., Kipp, M.E., 1980. Continuum modelling of explosive fracture in oil shale. *International Journal of Rock Mechanics and Mining Sciences* 17, 147–157.

- Harris, A.W., 1996. The Rotation Rates of Very Small Asteroids: Evidence for ‘Rubble Pile’ Structure, in: Lunar and Planetary Science Conference, p. 493.
- Harris, A.W., D’Abramo, G., 2015. The population of near-Earth asteroids. *Icarus* 257, 302–312.
- Herbold, E., Owen, J., Swift, D., Miller, P., 2015. Simulations of Defense Strategies for Benu: Material Characterization and Impulse Delivery. *Procedia Engineering* 103, 173–180.
- Herrmann, W., 1969. Constitutive equation for the dynamic compaction of ductile porous materials. *Journal of Applied Physics* 40, 2490–2499.
- Holsapple, K., Schmidt, R., 1987. Point source solutions and coupling parameters in cratering mechanics. *J. Geophys. Res.-Sol. Ea.* 92, 6350–6376.
- Holsapple, K.A., 1993. The scaling of impact processes in planetary sciences. *Annu. Rev. Earth Pl. Sc.* 21, 333–373.
- Holsapple, K.A., 2007. Spin limits of Solar System bodies: From the small fast-rotators to 2003 EL61. *Icarus* 187, 500–509.
- Holsapple, K.A., Housen, K.R., 2012. Momentum transfer in asteroid impacts. I. Theory and scaling. *Icarus* 221, 875–887.
- Housen, K.R., Holsapple, K.A., 2011. Ejecta from impact craters. *Icarus* 211, 856–875.
- Howley, K., Managan, R., Wasem, J., 2014. Blow-off momentum from melt and vapor in nuclear deflection scenarios. *Acta Astronaut.* 103, 376–381.
- Jutzi, M., 2015. SPH calculations of asteroid disruptions: The role of pressure dependent failure models. *Planet. Space Sci.* 107, 3–9.
- Jutzi, M., Holsapple, K., Wünneman, K., Michel, P., 2015. Modeling asteroid collisions and impact processes, in: Michel, P., DeMeo, F.E., Bottke, W.F. (Eds.), *Asteroids IV*, University of Arizona Press.

- Jutzi, M., Michel, P., 2014. Hypervelocity impacts on asteroids and momentum transfer I. Numerical simulations using porous targets. *Icarus* 229, 247–253.
- Kimberley, J., Ramesh, K.T., 2011. The dynamic strength of an ordinary chondrite. *Meteorit. Planet. Sci.* 46, 1653–1669.
- Korycansky, D.G., Plesko, C.S., Jutzi, M., Asphaug, E., Colaprete, A., 2009. Predictions for the LCROSS mission. *Meteoritics and Planetary Science* 44, 603–620.
- Kraus, R., Stewart, S., Swift, D., Bolme, C., Smith, R., Hamel, S., Hammel, B., Spaulding, D., Hicks, D., Eggert, J., et al., 2012. Shock vaporization of silica and the thermodynamics of planetary impact events. *J. Geophys. Res.-Planet.* 117.
- Leinhardt, Z.M., Stewart, S.T., 2009. Full numerical simulations of catastrophic small body collisions. *Icarus* 199, 542–559.
- Lindsay, S.S., Marchis, F., Emery, J.P., Enriquez, J.E., Assafin, M., 2015. Composition, mineralogy, and porosity of multiple asteroid systems from visible and near-infrared spectral data. *Icarus* 247, 53–70.
- Lundborg, N., 1968. Strength of rock-like materials. *International Journal of Rock Mechanics and Mining Sciences* 5, 427–454.
- Melosh, H., 2007. A hydrocode equation of state for SiO_2 . *Meteorit. Planet. Sci.* 42, 2079–2098.
- Michel, P., Benz, W., Richardson, D.C., 2003. Disruption of fragmented parent bodies as the origin of asteroid families. *Nature* 421, 608–611.
- Michel, P., Benz, W., Richardson, D.C., 2004. Catastrophic disruption of pre-shattered parent bodies. *Icarus* 168, 420–432.
- Michel, P., Benz, W., Tanga, P., Richardson, D.C., 2001. Collisions and Gravitational Reaccumulation: Forming Asteroid Families and Satellites. *Science* 294, 1696–1700.

- Michel, P., Richardson, D.C., Durda, D.D., Jutzi, M., Asphaug, E., 2015. Collisional Formation and Modeling of Asteroid Families, in: Michel, P., DeMeo, F.E., Bottke, W.F. (Eds.), *Asteroids IV*, University of Arizona Press.
- Michel, P., Tanga, P., Benz, W., Richardson, D.C., 2002. Formation of Asteroid Families by Catastrophic Disruption: Simulations with Fragmentation and Gravitational Reaccumulation. *Icarus* 160, 10–23.
- Mitchell, J.K., Scott, R.F., Houston, W.N., Costes, N.C., Carrier, W.D., Bromwell, L.G., 1972. Mechanical Properties of Lunar Soil: Density, Cohesion, and Angle of Internal Friction, in: *Lunar and Planetary Science Conference*, p. 545.
- Monaghan, J.J., 1992. Smoothed particle hydrodynamics. *Annu. Rev. Astron. Astrophys.* 30, 543–574.
- National Research Council, 2010. *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies*, National Academies Press, Washington, DC.
- Owen, J.M., 2010. ASPH modeling of material damage and failure, in: *Proceedings of the Fifth International SPHERIC Workshop*, pp. 297–304.
- Owen, J.M., 2014. A compatibly differenced total energy conserving form of sph. *Int. J. Numer. Meth. Fl.* 75, 749–774.
- Owen, J.M., Miller, P., Rovny, J., Wasem, J., Howley, K., Herbold, E.B., 2015. Asteroid diversion considerations and comparisons of diversion techniques. *Procedia Engineering* 103, 466–474.
- Owen, J.M., Villumsen, J.V., Shapiro, P.R., Martel, H., 1998. Adaptive Smoothed Particle Hydrodynamics: Methodology. II. *Astrophys. J. Suppl. S.* 116, 155–209.
- Petrovic, J., 2001. Review mechanical properties of meteorites and their constituents. *J. Mater. Sci.* 36, 1579–1583.
- Pravec, P., Harris, A.W., 2000. Fast and Slow Rotation of Asteroids. *Icarus* 148, 12–20.

- Rozitis, B., MacLennan, E., Emery, J.P., 2014. Cohesive forces prevent the rotational breakup of rubble-pile asteroid (29075) 1950 DA. *Nature* 512, 174–176.
- Scheeres, D.J., McMahon, J.W., Jones, B.A., Doostan, A., 2015. Variation of delivered impulse as a function of asteroid shape, in: *Aerospace Conference, 2015 IEEE*, pp. 1–7.
- Schultz, P.H., Eberhardy, C.A., Ernst, C.M., A’Hearn, M.F., Sunshine, J.M., Lisse, C.M., 2007. The Deep Impact oblique impact cratering experiment. *Icarus* 191, 84–122.
- Sears, D., Sears, H.W., Ostrowski, D., Bryson, K., Dotson, J., Bruck Syal, M., Swift, D., 2015. A meteorite perspective on planetary defense. *Planet. Space Sci.* (under review).
- Statler, T.S., Cotto-Figueroa, D., Riethmiller, D.A., Sweeney, K.M., 2013. Size matters: The rotation rates of small near-Earth asteroids. *Icarus* 225, 141–155.
- Stickle, A., Atchison, J., Barnouin, O., Cheng, A., Crawford, D., Ernst, C., Fletcher, Z., Rivkin, A., 2015. Modeling momentum transfer from kinetic impacts: Implications for redirecting asteroids. *Procedia Engineering* 103, 577–584.
- Thompson, S., Lauson, H., 1972. Improvements in the Chart D Radiation Hydrodynamic Code III: Revised Analytical Equation of State. SC-RR-710714 Sandia National Laboratory, Albuquerque, NM.
- Tillotson, J.H., 1962. Metallic equations of state for hypervelocity impact. Technical Report. General Atomic Report GA-3216.
- Wünnemann, K., Collins, G., Melosh, H., 2006. A strain-based porosity model for use in hydrocode simulations of impacts and implications for transient crater growth in porous targets. *Icarus* 180, 514–527.

Table 1: Computational Parameters

Parameter	Value
$\rho_{target}(\phi = 0)$	2.65 g/cm ³
$\rho_{impactor}$	2.70 g/cm ³
Y_0	1 kPa - 100 MPa
Y_m	1.5 GPa
μ_i	1.2
G	22.7 GPa
m^a	9.5
k^a	8×10^{37} cm ⁻³
ϕ	0.0 - 0.5
ϵ_e	0.0
ϵ_X	-0.4
κ	0.8

^aWeibull parameters from Jutzi (2015)

Table 2: List of Kinetic Impact Simulations

No.	v_i^a	m_i^b	D_a^c	EOS ^d	Y_0^e	Porosity ^f	P^g	Resolution (cm) ^h	β
1	10	10	50	T	NS	0.4	-	32.1	3.507
2	10	10	50	L	NS	0.4	-	32.1	3.087
3	10	10	50	A	NS	0.4	-	32.1	2.898
4	10	10	50	T	VM, 3.5 GPa	0.4	-	32.1	2.243
5	10	1	100	A	NS	0.4	-	44.5	5.432
6	10	1	100	A	1 kPa	0.4	-	44.5	3.695
7	10	1	100	A	10 kPa	0.4	-	44.5	3.693
8	10	1	100	A	100 kPa	0.4	-	44.5	3.569
9	10	1	100	A	1 MPa	0.4	-	44.5	1.917
10	10	1	100	A	10 MPa	0.4	-	44.5	1.301
11	10	1	100	A	50 MPa	0.4	-	44.5	1.196
12	10	1	100	A	100 MPa	0.4	-	44.5	1.094
13	10	1	100	A	VM, 100 MPa	0.4	-	44.5	1.112
14	10	1	100	A	1 kPa	0.0	-	44.5	5.230
15	10	1	100	A	1 kPa	0.05	-	44.5	4.159
16	10	1	100	A	1 kPa	0.1	-	44.5	4.096
17	10	1	100	A	1 kPa	0.2	-	44.5	4.000
18	10	1	100	A	1 kPa	0.3	-	44.5	3.898
19	10	1	100	A	1 kPa	0.5	-	44.5	3.571
20	10	1	100	A	100 MPa	0.0	-	44.5	1.249
21	10	1	100	A	100 MPa	0.1	-	44.5	1.155
22	10	1	100	A	100 MPa	0.2	-	44.5	1.138
23	10	1	100	A	100 MPa	0.3	-	44.5	1.101
24	10	1	100	A	100 MPa	0.5	-	44.5	1.077
25	5	10	50	T	NS	0.4	100	32.1	3.022
26	5	10	50	T	NS	0.4	-	32.1	2.965
27	5	10	50	T	VM, 3.5 GPa	0.4	100	32.1	1.822
28	5	10	50	T	VM, 3.5 GPa	0.4	-	32.1	1.858
29	5	5	100	L	100 MPa	0.4	9000	38.1	1.225
30	5	5	100	L	100 MPa	0.4	-	38.1	1.223
31	1	1	100	A	1 kPa	0.4	-	44.5	2.494
32	3	1	100	A	1 kPa	0.4	-	44.5	3.330
33	5	1	100	A	1 kPa	0.4	-	44.5	3.567
34	20	1	100	A	1 kPa	0.4	-	44.5	4.654
35	30	1	100	A	1 kPa	0.4	-	44.5	5.945

^aimpact velocity (km/s)

^bimpactor mass (10^3 kg)

^casteroid diameter (m)

^dT: Tillotson, L: LEOS, A: ANEOS

^eStrength takes form of Equation 2, except NS: no strength, VM: von Mises

^f $\rho_0 = 2.65$ g/cm³

^gRotation Period (s)

^hConvergence occurs near 15 cm; 44.5-cm resolution may over-estimate β by $\sim 12.25\%$