AIDA: Test of Asteroid Deflection by Spacecraft Impact.

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Introduction: The impact of a Near Earth object as large as 30 m in diameter occurs every few centuries, releasing an energy of at least a megaton of TNT. The impact of a larger object, which would occur less often, would be even more hazardous. To protect the Earth from a potential asteroid impact, various mitigation methods have been proposed, including deflection of the asteroid by a spacecraft impact.

The Don Quijote mission study performed by ESA in 2005-2007 had the objective of demonstrating the ability to modify the trajectory of an asteroid and to measure the trajectory change. Although Don Quijote was not funded, the mitigation technique using asteroid deflection by spacecraft impact remains of interest [1]. However, the magnitude of the resulting deflection is highly uncertain, owing to the contribution of recoil momentum from impact ejecta.

Previous models of the momentum transfer [e.g., 2-3] are extended to account for target properties via crater scaling relations, as well as velocity distributions and ballistic trajectories of ejecta. Results are relevant to ongoing studies of the Asteroid Impact & Deflection Assessment (AIDA) mission [4] which are jointly undertaken by the Johns Hopkins Applied Physics Laboratory and the European Space Agency with support from NASA centers including Goddard, Johnson and Jet Propulsion Laboratory.

AIDA Mission: The AIDA mission is a first demonstration of asteroid deflection and a characterization of the kinetic impact effects. AIDA consists of two independent but mutually supporting missions, one of which is the asteroid kinetic impactor and the other is the characterization spacecraft. These two missions are, respectively, DART and the European Space Agency's Asteroid Impact Monitoring (AIM) mission. DART will be the first ever space mission to deflect the trajectory of an asteroid and measure the deflection to within 10%. This will be done using a binary asteroid target with accurate determinations of orbital period by ground-based observations. AIDA will return vital data to determine the momentum transfer efficiency of the kinetic impact [1-3].

AIDA follows the previous Don Quijote mission study performed by ESA in 2005 - 2007, whose objectives were to demonstrate the ability to modify the trajectory of an asteroid, to measure the trajectory change, and to characterize physical properties of the asteroid. Don Quijote involved an orbiter and an impactor spacecraft, with the orbiter arriving first, measuring the deflection, monitoring the impact and making additional characterization measurements. Unlike Don Quijote, DART envisions an impactor spacecraft to intercept the secondary member of a binary near-Earth asteroid, with ground-based observations to measure the deflection. In the joint AIDA mission, DART combines with the ESA AIM mission which will rendezvous with the asteroid. Each of these missions has independent value, with greatly increased return when combined.

The DART mission will use a single spacecraft to impact the smaller member of the binary Near-Earth asteroid [65803] Didymos in October, 2022. The impact of the >300 kg DART spacecraft at 6.25 km/s will change the mutual orbit of these two objects. DART will use ground-based observations to make the required measurements of the orbital deflection, by measuring the orbital period change of the binary asteroid. The DART impact will change the period by 0.5% – 1%, and this change can be determined to 10% accuracy within months of observations. The DART target is an eclipsing binary [5], which enables accurate determination of small period changes by ground-based optical light curve measurements.

ESA's Asteroid Impact Mission (AIM) mission will: determine binary asteroid orbital and rotation state; analyze size, mass and shape of both binary components; analyze geology and surface properties; observe the impact crater and derive collision and impact properties (requires the DART mission). AIM will be a small spacecraft mission to rendezvous with Didymos. The strawman payload for the characterization of the asteroid, which satisfies the minimum requirements, consists of a Narrow Angle Camera, a Micro laser Altimeter, a Thermal IR Imager and a NIR spectrometer. On arrival, the spacecraft would perform continuous observations from a serious of "station points" fixed point relative to the asteroid inertial frame and at a safe distance, out of the sphere of influence of both Didymos components. In order to be able to image the two bodies for precise measurements of the orbital state, distances of 13.5 to 17 km were considered for the 1st characterization point. If the AIM spacecraft arrives at the target before the DART spacecraft, the impact of the DART spacecraft will be observed from a second characterization point of 100 km to avoid any damage by impact debris.

The present study parameterizes the principal effects governing momentum transfer efficiency from an incident spacecraft to an asteroid target. To date, no asteroid deflection experiment has ever been performed, and it is not possible to predict accurately the result of such an experiment, owing to uncertainties in asteroid surface properties. Results of laboratory experriments [7] and models of momentum transfer efficiency [7,8] will help to understand the science value of a future asteroid deflection experiment and will help to design such a mission.

Method: The model [8] considered an impactor of mass M_i and velocity v_i incident on a target of mass M and radius R:

- Impact along centerline
- Spherical objects

- Impulse to target p exceeds $M_i v_i$ because of momentum p_{ej} carried away by crater ejecta
  - Defines β by $p = \beta M_i v_i = p_{ej} + M_i v_i$
  - Predicts $\beta > 1$ (magnitude of impulse increased)
- Total ejecta mass is M_{ej} and is given by crater scaling in relation to projectile mass M_i
- Define $\pi_V = M_{ej}/ M_i$ given by point-source scaling laws with the usual definitions [6]

$$\pi_V = K_1\left[\pi_2\left(\frac{\delta}{\rho}\right)^{1/3} + \bar{\pi}_3^{(2+\mu)/2}\right]^{-3\mu/(2+\mu)}.$$

$$\pi_2 = \frac{ga}{U^2}, \quad \bar{\pi}_3 = \frac{\bar{Y}}{\rho U^2},$$

- Power law cumulative ejecta mass above velocity v is written $M(>v)= M_{ej}\,(v/v_{min})^{-n}$ for index $n > 0$ where n=1.22 (gravity scaling) or n=2 (strength scaling)
- The minimum ejecta velocity v_{min} is

$$v_{min} = \max(0.5\sqrt{gR_c}, 0.24\sqrt{Y/\rho})$$

$$R_c = 1.3\left(M_{ej}/\rho\right)^{1/3}$$

- To escape the system, need

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

Results: The ejecta momentum p_{ej} becomes

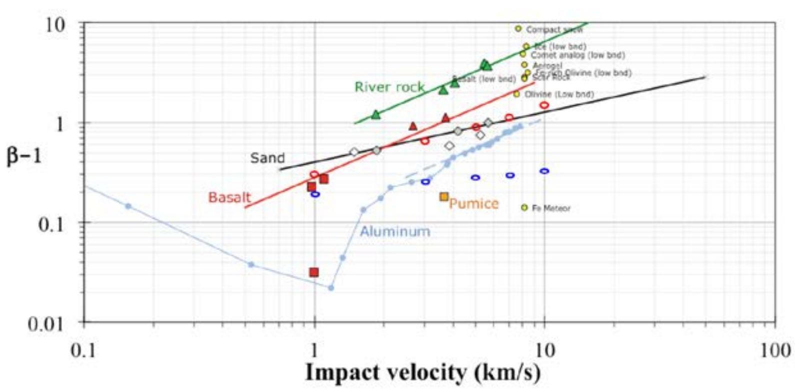
$$p_{ej} = f\, M_{ej} v_{esc}$$

$$f = n\left(v_{esc}/v_{min}\right)^{-n}\int_{u_{min}}^{\infty} du\, u^{-n-1}\left(\frac{v_{inf}}{v_{esc}}\right)\cos\theta$$

$$u = v/v_{esc} \quad \text{and} \quad u_{min} = \frac{\max(v_{min}, v_{esc})}{v_{esc}} \geq 1$$

The resulting β values from this model are compared to data [7] yielding reasonable agreement. The results of a deflection experiment, yielding a β value and a measured crater size, will provide important new information on the asteroid's physical properties.

References: [1] NRC Committee, *Defending Planet Earth*. Nat. Acad. Press, 2010. [2] T.J. Ahrens and A.W. Harris. Nature, (360): 429–433, 1992. [3] T.J. Ahrens and A.W. Harris. In Hazards Due to Comets & Asteroids, Univ. Az Press, 897–927, 1994. [4] www.esa.int/Our_Activities/Technology/NEO/Asteroid_Impact_Deflection_Assessment_AIDA_study [5] Pravec, P., et al. Photometric survey of binary near-Earth asteroids. Icarus, 181, pp. 63–93, 2006. [6] K. Holsapple. Ann. Rev. Earth Plan. Sci. 21:333-73, 1993 [7] Housen, K.R. & Holsapple, K.A. Deflecting Asteroids by Impacts: What is Beta? In LPSC Abstracts 43, 2012. [8] Cheng, A.F. Asteroid Deflection by Spacecraft Impact, ACM Conf. Paper 6414, 2012.



Open ovals are results of model calculations for case 3 (red) and for case 1 (blue); 350 kg impactors into 150 m target. Data from Housen and Holsapple (2012).

Incident 6000 m/s	case	Ybar [MPa]	density [g/cc]	mu	alpha	K	Mej [kg]	Rc [m]	beta
dry soil	1	0.18	1.7	0.41	0.510	0.132	9.10E+05	9.28	1.28
wet soil	2	1.14	2.1	0.55	0.647	0.095	5.92E+05	8.04	2.52
soft rock	3	7	2.65	0.55	0.647	0.105	1.34E+05	4.91	1.90
hard rock	4	18	2.65	0.55	0.647	0.12	7.72E+04	4.08	1.79
transition	5	9.00E-05	1.7	0.36	0.458	0.132	1.25E+07	22.24	1.31