ASTEROID DEFLECTION BY SPACECRAFT IMPACT. A. F. Cheng[1], [1]The John Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd, Laurel, MD 20723 (andrew.cheng@jhuapl.edu).

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., 2-4] 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 mission concept studies of asteroid deflection 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.

Momentum Transfer Model: The objective of the present study is to obtain a parameterization of 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. The simple model of momentum transfer efficiency developed here is intended to help interpret the results of a future asteroid deflection experiment and to help design such a future mission.

I consider an impactor mass M_i and velocity v_i incident on a much larger target of mass M and radius R. Both objects are assumed to be spherical, and the impact is assumed to be along the centerline. The impulse transferred to the target p exceeds M_i v_i because of momentum p_{ej} carried away by impact ejecta, and the momentum transfer efficiency β is defined by $p = \beta M_i v_i = p_{ej} + M_i v_i$ where β >1 unless there are ejecta released in the forward direction (a possible effect, not included here).

The total ejecta mass is written M_{ej} and is given by crater scaling relations [5] giving the usual crater efficiency $\pi_V = M_{ej}/M_i$ in the gravity and the strength regimes, with the key parameters being the target surface gravity g (for the gravity regime) and impact strength Y for the strength regime. The ejecta velocity distribution is taken to be of the power law form $M(>v) = M_{ej}(v/v_{min})^{-n}$ where the index n is empirically 1.22 (or 2) in the gravity (or strength) regime. The minimum ejecta velocity v_{min} is written $v_{min} = max\left(0.5\sqrt{gR_c}, 0.24\sqrt{Y/\rho}\right)$ with R_c the crater radius and ρ the target density. The escape velocity is $v_{esc} = \sqrt{2G\,M/R}$. The ejecta momentum becomes $p_{ej} = -\int_{v_{min}}^{\infty} dv\, n\, M_{ej}(v/v_{min})^{-n}\left(v_{inf}/v\right)\cos\theta$ with θ the angle between the asymptotic velocity and the incidence direction and with v_{inf} the ejecta speed at infinity. With the dimensionless parameter $u = v/v_{esc}$ the ejecta momentum becomes

$$p_{ej} = f M_{ej} v_{esc} \tag{1}$$

$$f = -n(v_{esc}/v_{min})^{-n}\int_{u_{min}}^{\infty} du\, u^{-n-1}\sqrt{u^2-1}\cos\theta$$

Here $u_{min} = max(v_{min}, v_{esc})/v_{esc}$ and $\cos\theta$ is expressed in terms of u assuming ejection at 45° to the incidence direction onto ballistic trajectories.

This model accounts for the ejecta velocity distribution, the need to escape from the target, and the ballistic slowing and bending of ejecta. It can be shown that in the gravity regime $u_{min} = 1$; although the total ejecta mass is large, much of it does not escape the target and does not contribute. In the strength regime, again $u_{min} = 1$, if the strength satisfies $Y < 61\text{ kPa }(\rho/2.5\text{ g/cc})^2 {R_{km}}^2$. If $u_{min} = 1$ is adopted, then numerical integrations show that in the gravity regime $f = 3.602(v_{min}/v_{esc})^{1.22}$, while in the strength regime $f = 1.018(v_{min}/v_{esc})^2$ determining ejecta momentum in eq. [1] and then β. However, in the strength case even Y values as low as for lunar regolith, for small targets, can lead to $u_{min} > 1$. An asteroid deflection experiment can yield unique information on physical properties and internal structure.

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] D. Izzo et al. ESA ACT-PUB-AF0501, 61-68, 2005 [5] K. Holsapple. Ann. Rev. Earth Plan. Sci. 21:333-73, 1993