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Asteroid Impact & Deflection Assessment mission: Kinetic impactor

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ABSTRACT

The Asteroid Impact & Deflection Assessment (AIDA) mission will be the first space experiment to demonstrate asteroid impact hazard mitigation by using a kinetic impactor to deflect an asteroid. AIDA is an international cooperation, consisting of two mission elements: the NASA Double Asteroid Redirection Test (DART) mission and the ESA Asteroid Impact Mission (AIM) rendezvous mission. The primary goals of AIDA are (i) to test our ability to perform a spacecraft impact on a potentially hazardous near-Earth asteroid and (ii) to measure and characterize the deflection caused by the impact. The AIDA target will be the binary near-Earth asteroid (65803) Didymos, with the deflection experiment to occur in late September, 2022. The DART impact on the secondary member of the binary at ~7 km/s is expected to alter the binary orbit period by about 4 minutes, assuming a simple transfer of momentum to the target, and this period change will be measured by Earth-based observatories. The AIM spacecraft will characterize the asteroid target and monitor results of the impact in situ at Didymos. The DART mission is a full-scale kinetic impact to deflect a 150 m diameter asteroid, with known impactor conditions and with target physical properties characterized by the AIM mission. Predictions for the momentum transfer efficiency of kinetic impacts are given for several possible target types of different porosities, using Housen and Holsapple (2011) crater scaling model for impact ejecta mass and velocity distributions. Results are compared to numerical simulation results using the Smoothed Particle Hydrodynamics code of Jutzi and Michel (2014) with good agreement. The model also predicts that the ejecta from the DART impact may make Didymos into an active asteroid, forming an ejecta coma that may be observable from Earth-based telescopes. The measurements from AIDA of the momentum transfer from the DART impact, the crater size and morphology, and the evolution of an ejecta coma will substantially advance understanding of impact processes on asteroids.

1. Introduction

On February 15, 2013, the small, 30 m asteroid 367943 Duende (2012 DA14) made an exceptionally close approach to Earth and passed inside the geosynchronous orbit radius, after having been discovered in February 2012. However, February 15, 2013 is remembered for an entirely different reason, as another, still smaller asteroid unexpectedly hit the Earth near Chelyabinsk, Russia on that same day without warning. The Chelyabinsk impact (Popova et al., 2013; Brown et al., 2013), of a roughly 20 m object, released 500 kton TNT of energy, injured over 1500 people, and caused extensive property damage.

The Chelyabinsk impact served as a dramatic reminder of the asteroid impact hazard and re-emphasized the importance of discovering hazardous asteroids and learning how to mitigate them. NASA was tasked in 1994 with identifying potentially hazardous asteroids greater than 1 km (0.62 miles) in diameter, and the NASA Authorization Act of 2005 required the agency to detect at least 90% of Near-Earth Objects (NEOs, small bodies with perihelia $\leq$ 1.3 AU) of 140 m or larger. Following an OSTP letter to the US Congress (Holdren, 2010), NASA has undertaken the lead in the analysis and simulation of asteroid mitigation and deflection, as well as the assessment of applicable technologies. In Europe, the NEOShield Project has been funded by the European Commission (EC) in its FP7 program since 2012 (Harris et al., 2013), to analyze asteroid mitigation options and address the scientific and technical issues. A continuation of this project, called NEOShield 2, funded by the EC program Horizon 2020 and focused on NEO

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physical characterization as well as space mission technologies started in March 2015 for 2.5 years.

There are many unknowns with respect to how an incoming NEO might best be deflected (Ahrens and Harris, 1994; Harris et al., 2013; Michel, 2013). Strategies to deflect an asteroid include impacting it with a spacecraft (a kinetic impactor), pulling it with the gravity of a massive spacecraft (a gravity tractor), using the blast of a nearby nuclear explosion, and modifying the surface or causing ablation by various means including lasers or particle beams. The impulsive methods to change an asteroid's orbit, kinetic impact and blast deflection, achieve immediate effects, whereas the non-impulsive methods may require years of operation to accumulate a sufficient deflection, and hence they require the hazardous object to be discovered more years in advance of its threatened collision with Earth.

However, none of these strategies for asteroid hazard mitigation has ever been tested on a NEO, and deflection of a NEO has never been demonstrated. The unknowns, in assessing strategies for deflecting an incoming asteroid, begin with unknowns concerning the threatening object itself: how large is it, what are its physical properties, how certain is the NEO to hit the Earth, and where will it hit. Also, if energy and momentum are applied to the NEO, impulsively or non-impulsively, in various ways, how much deflection will result, and over how much time? The physical properties of the NEO are vitally important to address the latter questions (Michel, 2013). Questions of costs and risks – technical, programmatic, and political – are critical as well but are not addressed here.

This paper focuses on the kinetic impactor strategy and specifically on a first demonstration of asteroid deflection by kinetic impact. The kinetic impactor approach has attracted interest owing to its relevance to asteroid collisions and cratering processes, and the issue of momentum transfer efficiency (what is the ratio β of momentum transferred to the momentum incident?) has been the subject of analytical, experimental, and computational studies (Ahrens and Harris, 1994; Holsapple and Housen, 2012; Cheng, 2013; Jutzi and Michel, 2014; Cheng et al., 2015). The Don Quijote mission, proposed by ESA as an asteroid deflection experiment by kinetic impactor (Carnelli et al., 2006), was the subject of Phase A industry studies but did not reach implementation phase. The Deep Impact spacecraft impacted comet 9P/Tempel 1 in July, 2005, without causing any measurable deflection or intending to (A'Hearn et al., 2005).

When a kinetic impactor of mass m strikes a target at speed U, the impulse p transferred to the target exceeds mU because of momentum p_{ej} carried away by impact ejecta released back towards the incident direction, and the momentum transfer efficiency β is defined by

$$p = \beta m U = p_{ej} + mU \qquad (1)$$

where $\beta > 1$ unless there are ejecta released in the forward direction (a possible effect, not considered here). In this paper, we will discuss expectations for β based on crater scaling laws and on numerical computations.

This paper and its companion paper (Michel et al., submitted for publication) present science goals and objectives, payloads, measurements, and expected results of the Asteroid Impact & Deflection Assessment (AIDA) mission, which is an international collaboration between NASA and ESA (Cheng et al., 2015). AIDA will make the first demonstration of asteroid deflection by kinetic impact. In this paper, we describe the science of the kinetic impactor mission, which is one of the two independent but mutually supporting mission elements of AIDA. The NASA Double Asteroid Redirection Test (DART) is the asteroid kinetic impactor mission, and the ESA Asteroid Impact Mission (AIM) is the characterization spacecraft, for the joint AIDA mission.

The AIDA target will be the binary near-Earth asteroid (65803) Didymos, with the deflection experiment to occur in late September or October, 2022. The DART impact on the secondary member of the binary at $\sim$7 km/s will alter the binary orbit period. The change in the period will be measured to within 10% by Earth-based observations. Hence DART will determine directly the efficiency of impact kinetic energy transfer to the orbital energy, even without measurements from AIM. The impactor autonomously targets the asteroid centroid, to maximize the likelihood of successful kinetic impact. The AIM spacecraft will rendezvous with Didymos in advance of the DART impact to characterize the asteroid target and determine its key physical properties (Michel et al., submitted for publication). AIM will monitor results of the DART impact in situ and will make more precise measurements of the orbital speed change Δv induced by the kinetic impact and hence the momentum transfer, as well as another physical characterization of the target after the impact. Additional results of the DART impact, like the impact crater and the long-term evolution of impact ejecta, will be studied in detail by the AIM mission.

The combined mission AIDA will make the first measurement of momentum transfer efficiency from hypervelocity kinetic impact at full scale on an asteroid, where impact conditions of the projectile are known, and physical properties and internal structures of the target asteroid are also characterized. The two mission components of AIDA, namely DART and AIM, are each independently valuable, but together provide a greatly increased knowledge return. Supporting Earth-based optical and radar observations and numerical simulation studies will be an integral part of the DART mission.

Here we present the objectives, requirements and design of the DART mission as well as analyses of predicted outcomes from the kinetic impact including estimates of momentum transfer efficiency β from the DART impact on the Didymos secondary. The momentum transfer has been estimated using hypervelocity impact models based on crater scaling relations (Housen and Holsapple, 2011) and numerical simulations (Jutzi and Michel, 2014). We outline a simple method similar to that of Holsapple and Housen (2012) to estimate the momentum transfer efficiency using crater scaling law relations for a variety of target conditions and performing numerical integrations over ejecta mass versus velocity distributions.

The present model of momentum transfer in a kinetic impact is improved from previous work (Holsapple and Housen, 2012; Cheng et al., 2015) by incorporating more realistic ejecta velocity distributions fitted to laboratory experiments (Housen and Holsapple, 2011) instead of truncated power laws. The more accurate mass versus ejecta velocity distributions yield better estimates of momentum transfer efficiency and moreover enable direct comparisons with numerical simulation results (e.g. Jutzi and Michel, 2014). The present model also estimates the observability of ejecta from the kinetic impact, including the possibility that ejecta may form a dust coma observable by ground-based telescopes.

2. Objectives and requirements

The main objectives of the DART mission, which includes the spacecraft kinetic impact and an Earth-based observing campaign, are to:

- Perform a full-scale demonstration of the spacecraft kinetic impact technique for deflection of an asteroid, by targeting an object large enough to qualify as a Potentially Hazardous Asteroid (that is, larger than 100 m), which is large enough if an impact occurs to cause major damage on regional scales larger than a metropolitan area.