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Deflecting rubble-pile asteroids: Lessons learned from the DART impact on Dimorphos

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ABSTRACT

NASA's Double Asteroid Redirection Test (DART) impacted asteroid Dimorphos (the smaller component of the 65803 Didymos binary system) on September 26th, 2022 [1]. The impact altered the orbital period of Dimorphos around Didymos by ~33 minutes [2], demonstrating the capabilities of the kinetic impactor as a mitigation strategy for relatively small but therefore more numerous asteroids [3]. The response of an asteroid to a kinetic impact strongly depends on its surface, subsurface and internal properties [e.g., 4-6]. In the case of an incoming hazardous asteroid, a kinetic impactor would have to be designed to maximise the deflection, yet at the same time not disrupt the asteroid.

Using the material properties for Dimorphos that yield the best match to numerical simulations [7] done using Bern SPH [8, 9], numerical simulations of the DART impact outcome with LICIACube [10], and telescopic observations [11], we find that Dimorphos may be a rubble pile (i.e., aggregate held together only by self-gravity and/or small cohesive forces). This prediction will be verified by the ESA Hera mission during its investigation of the binary asteroid, which includes internal probing of Dimorphos with a low-frequency radar [12]. For this rubble-pile scenario, we compute the energy required to deform the shape or to catastrophically disrupt Dimorphos.

In the gravity regime (i.e., when the gravitational force of the target dominates over the tensile strength of the body), the specific impact energy required for a catastrophic disruption or shape deformation, Q, increases with target size, R, and impact speed, U, as described by the scaling relationship [13]: $Q = aR^{3\mu}U^{2-3\mu}$, where a is a constant, and μ is the coupling parameter to the target in the gravity regime. Q_{reshape} is defined as the specific impact energy required to displace 20% of the target material, while the catastrophic disruption threshold (Q^*_D) is defined as the specific impact energy required to disperse half of the target material mass.

We then use numerical simulations to quantify the sensitivity of Q_{reshape} and Q^*_D to the boulder size-frequency distribution (SFD) and boulder packing within the target, as well as other structures (e.g., layers). We compare our Q_{reshape} and Q^*_D for

Dimorphos-like targets with results obtained for other small asteroids, such as C-types (e.g., Ryugu/Bennu), and monolithic or homogeneous weak targets (e.g., [14]).

Our results allow us to determine the minimum asteroid size that can be deflected by a DART-scale kinetic impactor. Besides helping us design future kinetic impactor missions, our results can also be used to constrain the age of Dimorphos and the collisional evolution of such bodies.

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