**Impact consequences on rubble-pile asteroids and implications for NASA’s DART mission**

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**Introduction:** The fraction of the asteroid population that survived since the Solar System formation has experienced numerous collisional, dynamical and thermal events, which have shaped their structures and orbital properties.

NASA’s Double Asteroid Redirection Test (DART) impact [1, 2] on the smaller component of the 65803 Didymos asteroid system, Dimorphos, is an ideal study case because it may take place in the sub-catastrophic collision regime, a regime between cratering and catastrophic collisions [e.g., 3], that has been largely unexplored so far. The DART mission was successfully launched on November, 24th 2021, and is currently on its way to impact Dimorphos, in late September 2022 [1, 4]. The main goal of the mission is to alter the orbital period of the small satellite around Didymos, by an amount measurable from Earth [1]. A successful deflection of Dimorphos will demonstrate the capabilities of the kinetic impact as an asteroid mitigation strategy. ESA’s Hera mission [4] will be launched in 2024 and arrive at Dimorphos about four years after the DART impact. Hera will enable us to perform detailed characterisation of Dimorphos, including measurements of the crater volume and morphology resulting from the DART impact.

Past studies of the outcome of small-scale impacts on asteroid surfaces [e.g., 5–8] have shown that the impact effects strongly depend on the surface, subsurface and internal properties. Small asteroids are often considered to be rubble-pile objects, aggregates held together only by self-gravity or small cohesive forces [9]. Moreover, recent results from the SCI impact on Ryugu [10] suggest that impacts on its surface might be controlled to a large extent by its weak gravity rather than strength. These findings might also be applicable to the DART impact.

The aim of this work is to numerically simulate DART-like impacts on Dimorphos-like asteroids with varying realistic surface material properties and interior structures, in order to:

1) study the consequences of such impacts on the physical evolution of small asteroids;

2) make predictions of the outcome of the DART impact (e.g., deflection efficiency $\beta$, crater morphology or degree of global deformation).

**Numerical Model:** We use Bern’s parallel Smoothed Particle Hydrodynamics (SPH) impact code [11, 12] to model DART-like impacts ($\approx 500$ kg projectiles at 6 km/s) on spherical asteroid targets, and track the evolution of the target for up to 2 hours after the impact. Bern’s SPH code has been previously validated against laboratory experiments and benchmarked against other codes [e.g., 12, 13]. Recently, the code has been validated against laboratory experiments of impacts into heterogeneous, rubble-p ile-like targets [14].

To quantify the effects of the target properties and structures on the post-impact morphology, degree of shape change and on the momentum transfer efficiency, we considered the following target scenarios:

1) Homogeneous spherical targets with varying cohesion ($Y_0 = 0$ to 50 Pa) and varying coefficient of internal friction ($f = 0.4$ to 1.0); The target material was modelled using a simple pressure-dependent strength model typical of pre-damaged rock materials [15]. The initial target porosity was kept constant at 40%.

2) Rubble-pile spherical targets with different distributions of boulders, embedded into a cohesionless matrix material. In all rubble-pile target scenarios, the boulders were modelled using a tensile strength and fracture model as described in Jutzi2015 ($Y_T = 1$ MPa) and the matrix material was modelled the same as in (1), with $Y_0 = 0$ Pa and $f = 0.6$.

**Results and discussion:**

**Homogeneous asteroids:** We find that the mechanical strength properties of small asteroids are crucial for their physical evolution. The size and morphology of the DART crater is of paramount importance for determining the asteroid’s near-surface properties and structure. With decreasing target cohesion, more material is displaced or ejected above escape speed. Our results show that even a small amount of cohesion (10 Pa) can dramatically affect the outcome of an impact on a small body in terms of the post-impact target morphology and the production of low velocity ejecta. Fig. 1a shows the 3D model and the 2D slice view of an initially spherical asteroid target with $Y_0 = 10$ Pa and $f = 0.6$, $\approx 2$ hours after a DART-like impact. In this impact scenario, DART creates a well defined bowl-shaped crater and $\beta \approx 4.2$. In the case of a homogeneous cohesionless target (Fig. 1b), the post-impact morphology does not resemble an impact crater anymore and $\beta \approx 5.0$.

**Rubble-pile asteroids:** Fig. 1c shows the final target morphology from a DART-like impacts on a rubble-pile target with a random distribution of boulders. Similar to the homogeneous cohesionless target case (Fig. 1b), the DART impact produces a morphology that is dissimilar to cratering and it changes the global shape of the asteroid.
Before impact

DART

Homogeneous strong target

Diameter = 150 m

Homogeneous weak target

Rubble-pile target

After impact

a) 3D view

β = 4.2

b) 3D view

β = 5.0

c) 3D view

β = 3.8

Figure 1: Target morphology of an initially spherical body, 150 m in diameter, before (left) and 2 hours after a DART-like impact (right). The target was initially (a) homogeneous and strong ($Y_0 = 10$ Pa), (b) homogeneous and weak ($Y_0 = 0$ Pa) and (c) rubble-pile ($Y_0 = 0$ Pa (matrix) and $Y_{b0} = 1$ MPa (boulders)). In the case of a rubble-pile target, during the crater growth, large boulders are ejected from the surface and some land back on the target.

Our simulations also show that the presence of boulders close to the impact point can decrease the deflection efficiency, $\beta$, by up to 30% compared to a similar impact into a homogeneous target ($\beta \approx 3.8$). Moreover, impact simulations into targets with different initial boulder size-frequency distributions show that the initial boulder configuration also influences $\beta$.

Our initial results suggest that large boulders (up to a size of $\approx 10$ m, corresponding to $\approx 10^4 \times$ projectile’s mass) can be ejected from a rubble-pile asteroid, mostly intact. In the case of the DART impact on Dimorphos, such boulders then either leave the asteroid system, either orbit the system, or land on Didymos or back on Dimorphos. The ejection of large intact boulders by small scale sub-catastrophic collisions may have important implications for the structure of small asteroids (i.e., the abundance of rubble-pile vs. monolithic objects among the small asteroid population).

Our modelling results together with the future observations by the Hera mission will therefore provide constraints regarding the evolution of the shapes and structures of small asteroids by sub-catastrophic impacts.

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