FATE OF THE DART IMPACT EJECTA: INTERPRETATION OF THE TAIL MORPHOLOGY UNDER THE EFFECT OF THE SOLAR RADIATION PRESSURE ACCELERATION.

S. Soldini[1], F. Ferrari[2], J-Y Li[3], S. Raducan[4], M. Jutzi[4], Y. Zhang[5], A. Rossi[6], F. Marzari[6], F. Moreno[7], A. Campo-Bagatin[8], A. Cheng[11], D. Hamilton[5], S. Ivanovski[9], G. Fahnestock[10], O. S Barnouin[11], R. T. Daly[11], C. M. Ernst[11], E. Palmer[12], A. S. Rivkin[11], N. L. Chabot[11] and the DART Investigation Team, [1]University of Liverpool, Liverpool L3 5TQ, United Kingdom (stefania.soldini@liverpool.ac.uk), [2]Department of Aerospace Science and Technology, Politecnico di Milano, Italy, [3]Planetary Science Institute, [4]Space Research and Planetary Sciences, University of Bern, Switzerland, [5]University of Maryland, College Park, MD, USA, [6]IFAC-CNR, Italy, [7]Instituto De Astrofisica De Andalucia, Spain, [8]IUFACyT, Universidad da Alicante, Spain, [9]National Institute for Astrophysics, Italy, [10]JPL, [11]Johns Hopkins University Applied Physics Laboratory, USA, [12]Planetary Science Institute, Tucson, AZ, USA

Introduction: On 26th September 2022, the NASA's DART spacecraft intentionally impacted Dimorphos, the secondary member of the Didymos system, successfully demonstrating the first planetary defense test in space [1]. ESA's Hera mission will then visit the Didymos system in late 2026 for a thorough evaluation of the aftermath of NASA's DART impact [2]. DART's impact exceeded the expectations of the kinetic-impactor technique, showing that the ejecta generated from the impact enhanced the momentum exchange, making this technique an effective deflection method for rubble-pile asteroids [1]. Extensively observed by the Italian CubeSat (LICIACube) [3] and several ground-based telescopes [4], the tail has lasted for several months. On the basis of observations made on December 28th, 2022 [4], it appears to have started to fade. In this study, the N-Body planetary code goNEAR [6,7] is used to simulate the ejecta dynamics. The tail's morphology and geometry are highly dependent on the acceleration effects of Solar-Radiation Pressure (SRP).

goNEAR N-Body Planetary Code: The evolution of the ejecta particles analyzed here is driven by the dynamical environment of Didymos, i.e., the gravitational fields of the asteroids, the Sun, and planets, and SRP acceleration. A subset of initial conditions provided by SPH simulations [5] is used here as representative of the range of velocities within the ejecta cone for fragments 0.18-57 mm in radius. The goNEAR tool is written in J2000 equatorial coordinates with a reference frame centered at Dimorphos, was developed and validated in real time for the Hayabusa2 mission [6,7] and extended to the case of a binary asteroid system [5]. The goNEAR tool makes use of NASA's SPICE Toolkit package to import the ephemeris of Didymos, Dimorphos, the solar system planets, Earth, the Moon, and the Sun. The effect of the SRP acceleration is also implemented. In this case, a simple cannonball model, where an object is assumed to be spherical, is used to compute the SRP acceleration of the ejecta particles.

The N-body planetary equations are given as in Eq. (1):

$$\begin{cases} \ddot{x} = -\frac{\mu}{r^3}x + \sum_{j=1}^{N_{Pj}} a_{Pj_x} + a_{SRP_x} + a_{poly_x} \\ \ddot{y} = -\frac{\mu}{r^3}y + \sum_{j=1}^{N_{Pj}} a_{Pj_y} + a_{SRP_y} + a_{poly_y} \\ \ddot{z} = -\frac{\mu}{r^3}z + \sum_{j=1}^{N_{Pj}} a_{Pj_z} + a_{SRP_z} + a_{poly_z} \end{cases} \tag{1}$$

where μ is the gravitational constant of Dimorphos ($3.2451 \cdot 10^{-10}\ km^3 s^{-2}$). The first term of the right-hand side of Eq. (1) represents the gravity of Dimorphos as a point mass, while the term $\vec{a}_{poly}$ is the difference between the acceleration computed using Dimorphos's polyhedron model and its point mass representation. In particular, the polyhedron model acceleration is expressed with respect to the asteroid Body Fixed (BF) rotating frame and a rotation is required to express the polyhedron acceleration from the asteroid body fixed to the J2000 reference frame as in Eq. (2):

$$\vec{a}_{poly} = \boldsymbol{M}_{BFtoJ2000}\, \vec{a}_{poly,BF} \tag{2}$$

where $\boldsymbol{M}_{BFtoJ2000}$ is the transformation matrix from coordinates in body fix frame to J2000 frame. The multiple-body acceleration for the Sun, the other planets, and Didymos as a point mass is given by Eq. (3):

$$\vec{a}_{Pj} = \vec{\nabla} U_j\left(-\vec{\Delta}_j\right) + \vec{\nabla} U_j(\vec{d}_j) \tag{3}$$

with $-\vec{\Delta}_j = \vec{r} - \vec{d}_j$ where r is the spacecraft's position vector from Dimorphos, and d is the position vector of the perturbing body (Pj) from Dimorphos. When interfacing with NASA's SPICE Toolkit, the ephemeris is often provided in a reference frame centered in the Solar System Barycenter (SSB). In this case, vector $\vec{d}_j$ is given by the position vector of the planet in SSB coordinates minus the position vector of Dimorphos in SSB coordinates. The effect of the binary is thus included in the multiple-body acceleration term. The goNEAR tool can also handle a third-body acceleration of Didymos with a polyhedron model. goNEAR implements the SRP acceleration model of either a nondiffusive Earth-tracking flat surface (e.g., spacecraft's solar panels) or a simpler cannonball model. In this work, the cannonball model to reproduce the dynamics of spherical ejecta fragments is of the form

$$\vec{a}_{SRP} = -\frac{P_0}{c}\frac{A}{m}\left(\frac{AU}{r_{ls}}\right)^2\cos\theta\left((1-\epsilon)\frac{\vec{r}_{ls}}{r_{ls}} + 2\epsilon\cos\theta\,\hat{n}\right) \qquad (4)$$

where $\vec{\boldsymbol{r}}_{ls}$ is the Sun-particle direction, A is the cross-section area, m is the particle mass, P_0 is the solar flux (1366 W m^{-2}), c is the speed of light ($2.99792458 \cdot 10^8$ m s^{-1}), and ϵ is the reflectivity of the particle. $\hat{n}$ is the unitary vector normal to a flat surface and θ is the angle between $\hat{n}$ and the Sun.

Preliminary Results: Figure 1 shows the ejecta evolution for five independent simulations where the particle sizes vary between radii of 0.18-57 mm. The morphology of the tails analyzed is affected by SRP where particles of 0.18 mm size escape the system shortly after impact. Conversely, the dynamics of particles greater than 14 mm is influenced also by the gravity of Didymos and Dimorphos slowing down their escape. Since the impact occurred at 9.7° south of the plane (Didymos south) of Dimorphos, the tail displays a spiral geometry. Bifurcation of the tails occurs because of SRP, which implies that a particle in a specific size range experience a distinctly perturbed trajectory evolution due to SRP. Figure 2 provides a comparison between the classic Hill problem and the photo-gravitational Hill problem, which includes the effect of SRP for a fragment 1.53 m in diameter.

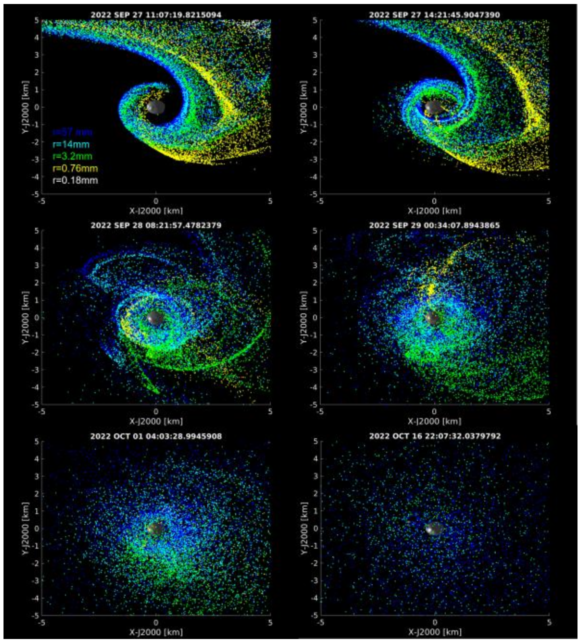

Figure 1: Fate of ejecta 0-3 weeks after DART impact; view extents are 5 km from Didymos barycenter.

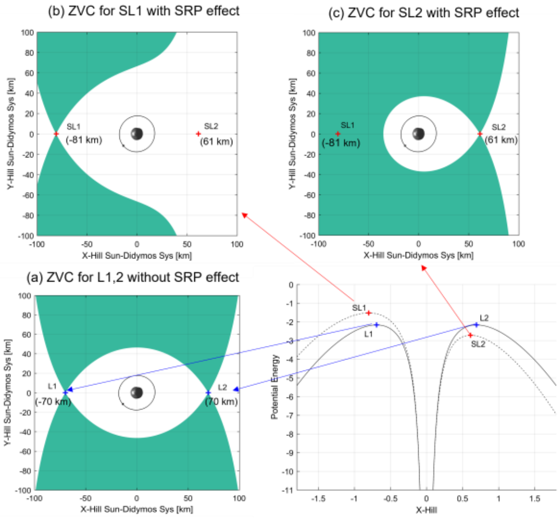

Figure 2: The Zero Velocity Curves (ZVCs), contour of the green areas, and position of the Lagrangian points with (SL1,2) and without (L1,2) the effect of SRP for a particle size of 1.53 m in diameter, shown in the Hill coordinate frame of the Sun–Didymos system. The center figure is in nondimensional coordinates. Didymos, Dimorphos, and the orbit of Dimorphos are not to scale. The position of Dimorphos is at the epoch of impact [5].

It is interesting to note that, while the potential energy of SL1 increases with respect to L1, SL2's potential energy decreases with respect to L2. This case differs from the Sun–Earth system, where the potential energy of SL2 of the Sun–Earth system increases with respect to L2. However, in both the Sun–Earth and Sun–Didymos systems, the x-coordinates of L1,2 shift toward the Sun. This happens as the SRP acceleration has an opposite sign with respect to the Sun's gravity, resulting in a "lower" pseudo-gravitational pull from the Sun. Further analysis should be carried out to match the observations. The fact that SL2 has a potential energy lower than L2 has an important implication for the potential energy of the ejecta and the chances to stay in a stable orbit. Indeed, particles confined in a bunded motion around the Didymos system (white area surrounded by the green forbidden region in Fig. 2b) are not able to escape the system and can potentially stay in orbit for the time of Hera spacecraft arrival.

References: [1] Daly et al, (2022) *Nature* (under review) [2] Michel et al., *PSJ,* 3, 160 (2022) *Meteoritics & Planet. Sci., 50,* 834–849. [3] Dotto et al, (2022) *Nature* (under review) [4] Li et al., (2022) *Nature* (under review) [5] Ferrari et al, (2019) *PSJ*, (2022) 3, 177 [6] Soldini et al., (2020) *PSS, 180* [7] Soldini et al., (2020) *AsDyn*, 4, 265.