DETERMINATION OF MOMENTUM TRANSFER TO DIMORPHOS FROM THE DART KINETIC IMPACT.
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Abstract: The Double Asteroid Redirection Test (DART) mission performed a kinetic impact on asteroid Dimorphos [1] on Sept. 26, 2022. DART was a planetary defense test to validate kinetic impact for asteroid deflection in order to prevent a potential future asteroid impact upon Earth. DART made the first determination of momentum transferred to an asteroid by a kinetic impact at scales relevant to planetary defense. The DART impact on Dimorphos shortened the orbit period of Dimorphos around Didymos by 33 ± 1 min [2]. The period change implied an instantaneous reduction Δv_T of along-track orbital speed by 2.70 ± 0.10 mm s^{-1}.

This Δv_T produced by the DART kinetic impact indicated an enhanced momentum transfer due to recoil from ejecta streams [4]. DART found that the momentum transfer was enhanced by a factor between 2.2 and 4.9 depending on the mass of Dimorphos [4].

Introduction: The Double Asteroid Redirection Test (DART) mission impacted Dimorphos, the secondary member of the (65803) Didymos binary asteroid, on September 26, 2022 in order to perform the first test of asteroid deflection by kinetic impact. As a planetary defense test mission, a key objective of DART is to determine the amount of momentum transferred to the target body relative to the incident momentum of the spacecraft, quantified by the momentum enhancement factor β (e.g., [4]), defined by the momentum balance of the kinetic impact,

$$M\boldsymbol{\Delta}\vec{\boldsymbol{v}} = m\vec{\boldsymbol{U}} + m(\beta - 1)\big(\widehat{\boldsymbol{E}} \cdot \vec{\boldsymbol{U}}\big)\widehat{\boldsymbol{E}} \,. \qquad (1)$$

Here, M is the mass of Dimorphos, $\boldsymbol{\Delta}\vec{\boldsymbol{v}}$ is the impact-induced change in Dimorphos's orbital velocity, m is DART's mass at impact, $\vec{\boldsymbol{U}}$ is DART's velocity relative to Dimorphos at impact, and $\hat{E}$ is the net ejecta momentum direction. $M\boldsymbol{\Delta}\vec{\boldsymbol{v}}$ is the momentum transferred to Dimorphos, $m\vec{\boldsymbol{U}}$ is DART's incident momentum, and the final term in the equation is the ejecta's net momentum written in terms of the spacecraft incident momentum. In this formulation, β is the ratio of actual imparted momentum to the impactor's momentum in the direction of the net ejecta momentum. A β near 1 would suggest that ejecta recoil had made only a negligible contribution to the momentum transfer. A $\beta > 2$ would mean that the ejecta momentum contribution exceeded the incident momentum from DART. The momentum enhancement factor β is expressed in terms of the along-track component of $\boldsymbol{\Delta}\vec{\boldsymbol{v}}$ by taking the scalar product of (1) with the unit vector $\hat{\boldsymbol{e}}_{\boldsymbol{T}}$ in the along-track direction, yielding

$$\beta = 1 + \frac{\frac{M}{m}(\boldsymbol{\Delta}\vec{\boldsymbol{v}}\cdot\hat{\boldsymbol{e}}_{\boldsymbol{T}}) - (\vec{\boldsymbol{U}}\cdot\hat{\boldsymbol{e}}_{\boldsymbol{T}})}{(\widehat{\boldsymbol{E}}\cdot\vec{\boldsymbol{U}})(\widehat{\boldsymbol{E}}\cdot\hat{\boldsymbol{e}}_{\boldsymbol{T}})} \,. \qquad (2)$$

The along-track component of Dimorphos's velocity change, $\boldsymbol{\Delta}\vec{\boldsymbol{v}} \cdot \hat{\boldsymbol{e}}_{\boldsymbol{T}}$, is written as Δv_T.

Observations from the DART spacecraft on approach found Dimorphos to be an oblate spheroid with a boulder-strewn surface, and the spacecraft impacted within 25 m of the center-of-figure (the Dimorphos volume-equivalent diameter is 151 m) [1]. Ejecta from the DART impact were observed *in situ* by the Light Italian Cubesat for Imaging of Asteroids (LICIACube) spacecraft, which performed a flyby of Dimorphos with closest approach about 168 s after the DART impact [3]. The impact ejecta were further observed by Earth- and space-based telescopes, revealing ejecta streams and dust tails similar to those seen in active asteroids thought to be triggered by natural impacts [5].

The DART impact changed Dimorphos's orbital velocity, and the associated binary mutual orbit period change was determined from ground-based telescopic observations [2]. The size and shape of Dimorphos was determined from DART terminal-approach imaging [1] and from flyby imaging by LICIACube [3].

Dimorphos's computed volume was combined with a range of assumed density values to calculate a range of possible mass values and the associated momentum change caused by DART's impact [4]. A Monte Carlo analysis was used to produce a distribution for Δv_T consistent with the measured period change that incorporates the various uncertainties involved. The Monte Carlo analysis sampled many possible combinations of Didymos system parameters, including the ellipsoid shape extents of the asteroids, pre-impact orbit separation distance between the two asteroids' centers of mass (i.e., Dimorphos's pre-impact orbit radius), pre- and post-impact orbit periods, and net ejecta momentum direction $\widehat{\boldsymbol{E}}$.

The General Use Binary Asteroid Simulator (GUBAS), a full two-body problem code [6] which implements coupled rotational and orbital dynamics, was used to calculate Δv_T for each sampled combination of input parameters. A range of values for M was generated by combining the volumes of Dimorphos's sampled ellipsoid shape parameters with values for the density. Since Dimorphos's density has not been directly measured and has a large uncertainty, it is treated as an independent variable that is sampled uniformly over a range of possible values between 1,500 and 3,300 kg m^{-3}, a range that encompasses the 3σ uncertainty given by [1].

Observations of the impact ejecta by LICIACube [3] and by the Hubble Space Telescope [5] are used to obtain a preliminary measurement of the axis of the ejecta cone geometry. Using the cone axis direction for $\hat{\boldsymbol{E}}$ assumes that the ejecta plume is axisymmetric and holds the momentum uniformly. It is found that $\hat{\boldsymbol{E}}$ points toward a right ascension (RA) and declination (Dec) of 138° and +13°, respectively, in the J2000 Ecliptic coordinate frame [4]. A conservative uncertainty of 15° is assigned around this direction. The impact ejecta momentum vector is not exactly collinear with the incident spacecraft momentum. Finally, β also depends on DART's mass and impact velocity, as well as Didymos's pole orientation [1,2]. Those quantities have negligibly small uncertainties relative to those of the other parameters discussed previously and are therefore treated as fixed values (not sampled).

The Monte Carlo results are shown in Fig. 1 [4]. The momentum enhancement factor β from the DART impact is $3.61^{+0.19}_{-0.25}$ (1σ) if Dimorphos and Didymos are assumed to have equal densities of 2,400 kg m^{-3}, and it ranges from 2.2 to 4.9 over the likely range of Dimorphos density values, 1,500 to 3,300 kg m^{-3} [4]. Extensive numerical studies of the DART impact have revealed an important non-uniqueness in the interpretation of β, in that many distinct sets of target material properties yield almost identical β for the DART impact conditions. LICIACube images, which resolve the ejecta plume spatial structures and study the temporal evolution, have the potential to discriminate between differences in plume structure and evolution resulting from different target physical properties, mainly strength, porosity, and internal friction, thereby allowing inference of target properties. Data provided by the Hera spacecraft mission, planned to arrive at the Didymos system in 2026 [7], is anticipated to further reduce uncertainties in both β and Dimorphos's physical properties. We will present initial results for the determination of β, discuss implications for the physical properties of Dimorphos, and describe how these results inform future planetary defense efforts.

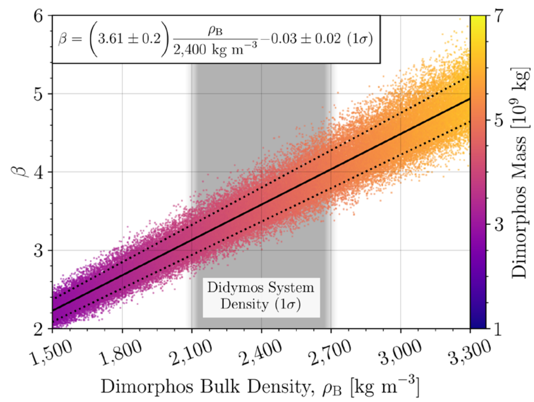

Figure 1. β as a function of Dimorphos's bulk density ρ_B, from the dynamical Monte Carlo analysis. Individual samples are plotted as points, while the linear fit for the mean β is plotted as the solid line and the dotted lines show the 1σ confidence interval. The color bar indicates the mass of Dimorphos corresponding to each Monte Carlo sample, which is determined by bulk density and the volume.

References: [1] T. Daly et al., 2022 submitted. [2] C. Thomas et al., 2022 submitted. [3] E. Dotto et al., 2021 *Planet. Space Sci.* **199**, 105185; Dotto et al. 2022 in preparation. [4] A. Cheng et al., 2022 submitted. [5] J-Y Li et al. 2022 submitted. [6] A. B. Davis, & D. J. Scheeres 2020, *Icarus* **341**, 113439. [7] P. Michel et al., 2022 *Planet. Sci. J.* **3** 160