Determination of Momentum Transfer fromDART Kinetic Impact: initial results

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Cheng AF et al. 2023, Nature, doi: 10.1038/s41586-023-05878-z

- **The Double Asteroid Redirection Test (DART) mission performed a kinetic impact on asteroid Dimorphos 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**
  - ✓ **First asteroid impact experiment at scales relevant to planetary defense**
- **DART made the first determination of momentum transferred to an asteroid by a kinetic impact**
  - ✓ **The DART impact on Dimorphos changed the orbit period of Dimorphos around Didymos**
  - ✓ **Observed reduction of orbit period by 33 ± 1 min implied an instantaneous reduction Δv_T of along-track orbital speed by 2.70 ± 0.10 mm s^{-1}**
  - ✓ **The momentum transferred to Dimorphos from the DART impact depends on mass of Dimorphos which is not measured by DART**

Daly T et al. 2023, Nature, doi: 10.1038/s41586-023-05810-5 Thomas C. et al.2023, Nature, doi: 10.1038/s41586-023-05805-2

- **This Δv_T indicated an enhanced momentum transfer due to recoil from ejecta streams produced by the DART kinetic impact**
- **DART found that the momentum transfer was enhanced by a factor between 2.2 and 4.9 depending on the mass of Dimorphos**
  - ✓ **If Dimorphos and Didymos have equal densities 2400 kg m^{-3}, enhancement is $\beta = 3.61^{+0.19}_{-0.25}(1\sigma)$**

Li J-Y et al., Nature, doi: 10.1038/s41586-023-05811-4

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Momentum transfer enhancement factor β defined by momentum balance of kinetic impact

DART momentum

Ejecta momentum

Momentum transfer to Dimorphos

$$M\boldsymbol{\Delta}\vec{\boldsymbol{v}} = m\vec{\boldsymbol{U}} + m(\beta - 1)\left(\hat{\boldsymbol{E}} \cdot \vec{\boldsymbol{U}}\right)\hat{\boldsymbol{E}}$$

β expressed in terms of the along-track component of $\boldsymbol{\Delta}\vec{\boldsymbol{v}}$ is

$$\beta = 1 + \frac{\frac{M}{m}(\boldsymbol{\Delta}\vec{\boldsymbol{v}} \cdot \hat{\boldsymbol{e}}_T) - \left(\vec{\boldsymbol{U}} \cdot \hat{\boldsymbol{e}}_T\right)}{\left(\hat{\boldsymbol{E}} \cdot \vec{\boldsymbol{U}}\right)(\hat{\boldsymbol{E}} \cdot \hat{\boldsymbol{e}}_T)}$$

where $\Delta v_T = \boldsymbol{\Delta}\vec{\boldsymbol{v}} \cdot \hat{\boldsymbol{e}}_T$ is along-track component of $\boldsymbol{\Delta}\vec{\boldsymbol{v}}$

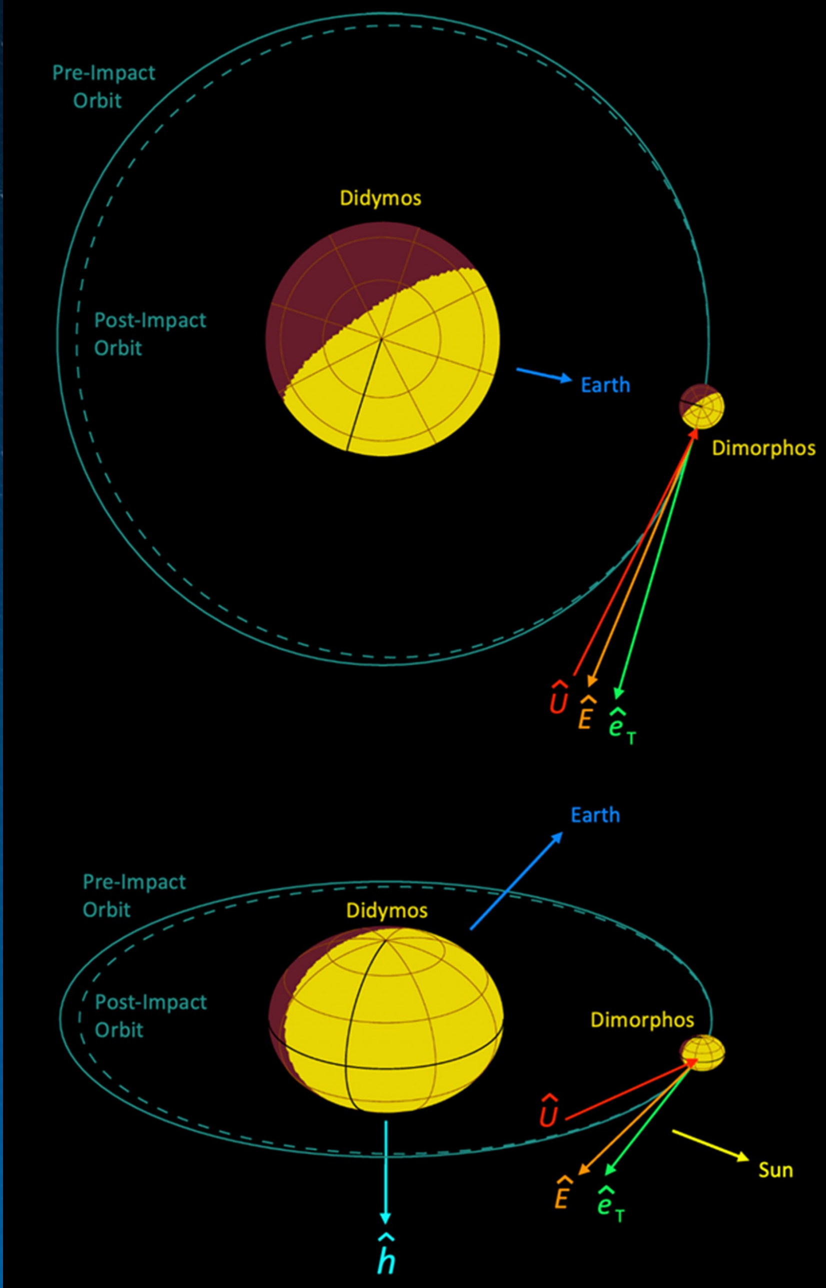
$\hat{\boldsymbol{E}}$ is the direction of net ejecta momentum

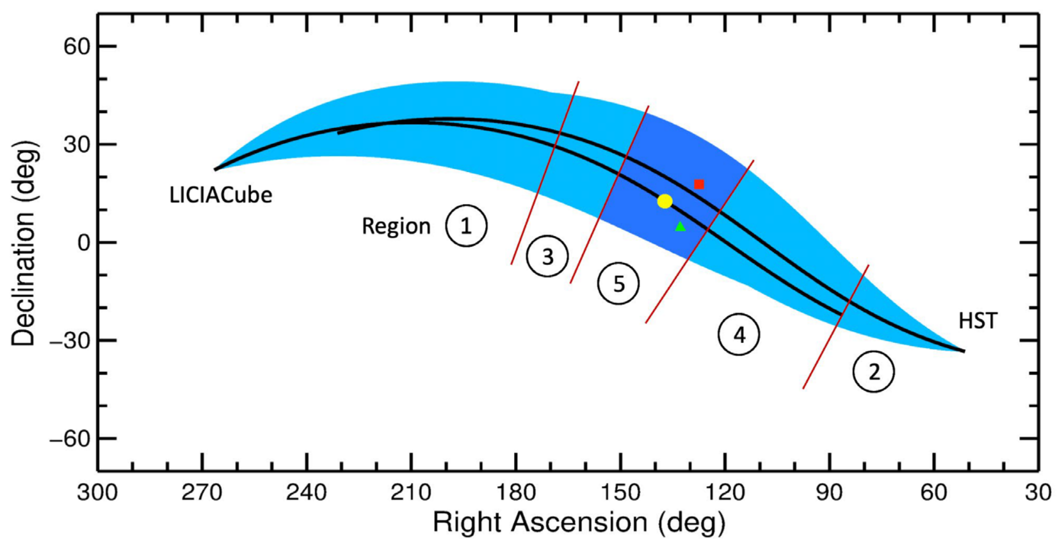
Geometry of DART impact on Dimorphos. Pre-impact and post-impact orbits around Didymos.

The positive pole direction of Didymos is $\hat{h}$ (bottom panel). DART's incident direction is $\hat{U}$, the net ejecta momentum direction is $\hat{E}$ (from HST and LICIACube images, pointing to RA= 138° and Declination = +13°). The direction of Dimorphos's orbital motion, or along-track direction, is $\hat{e}_T$.

Viewed from negative pole

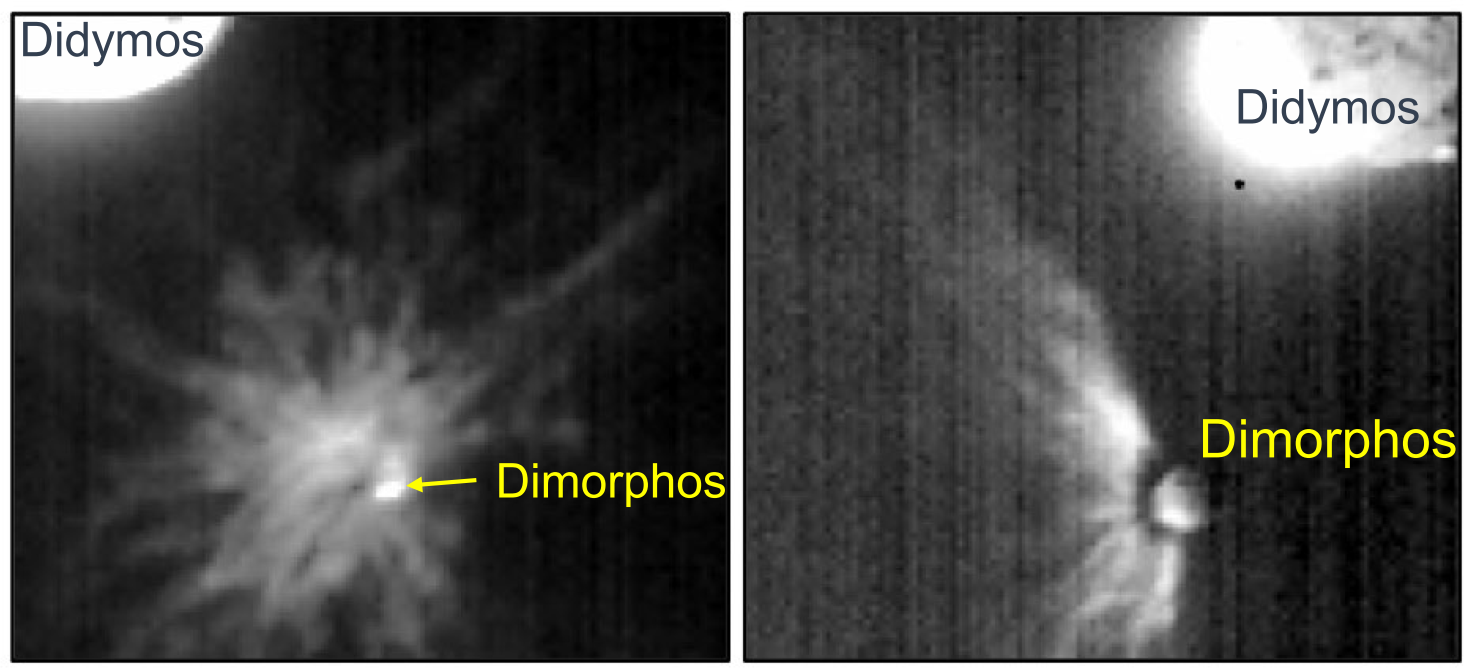
Perspective view





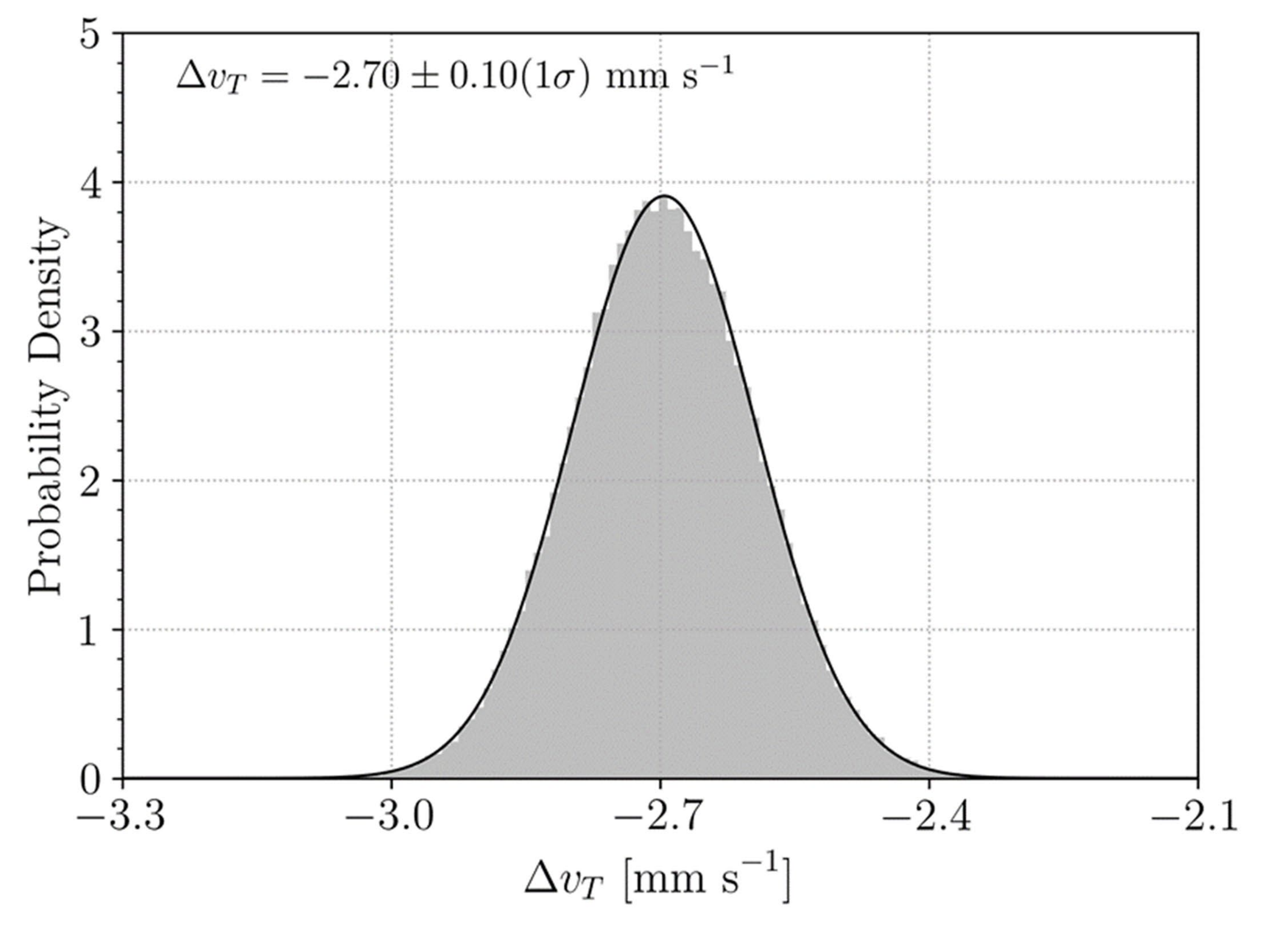
Ejecta cone orientation in the swaths of sky (black lines) defined by HST and LICIACube observations. The light-blue envelope outlines the axis position uncertainty in the sky plane. Red lines divide sky plane swaths into excluded regions: 1,2 excluded because ejecta cone would point in opposite direction to observed; 3 has axis too close to sky plane; 4 has axis too close to line of sight.

Cone axis in region 5 shown by yellow dot (RA,Dec) = [138° ,+13°] .
Red square incoming DART trajectory.
Green triangle is along-track direction of Dimorphos.

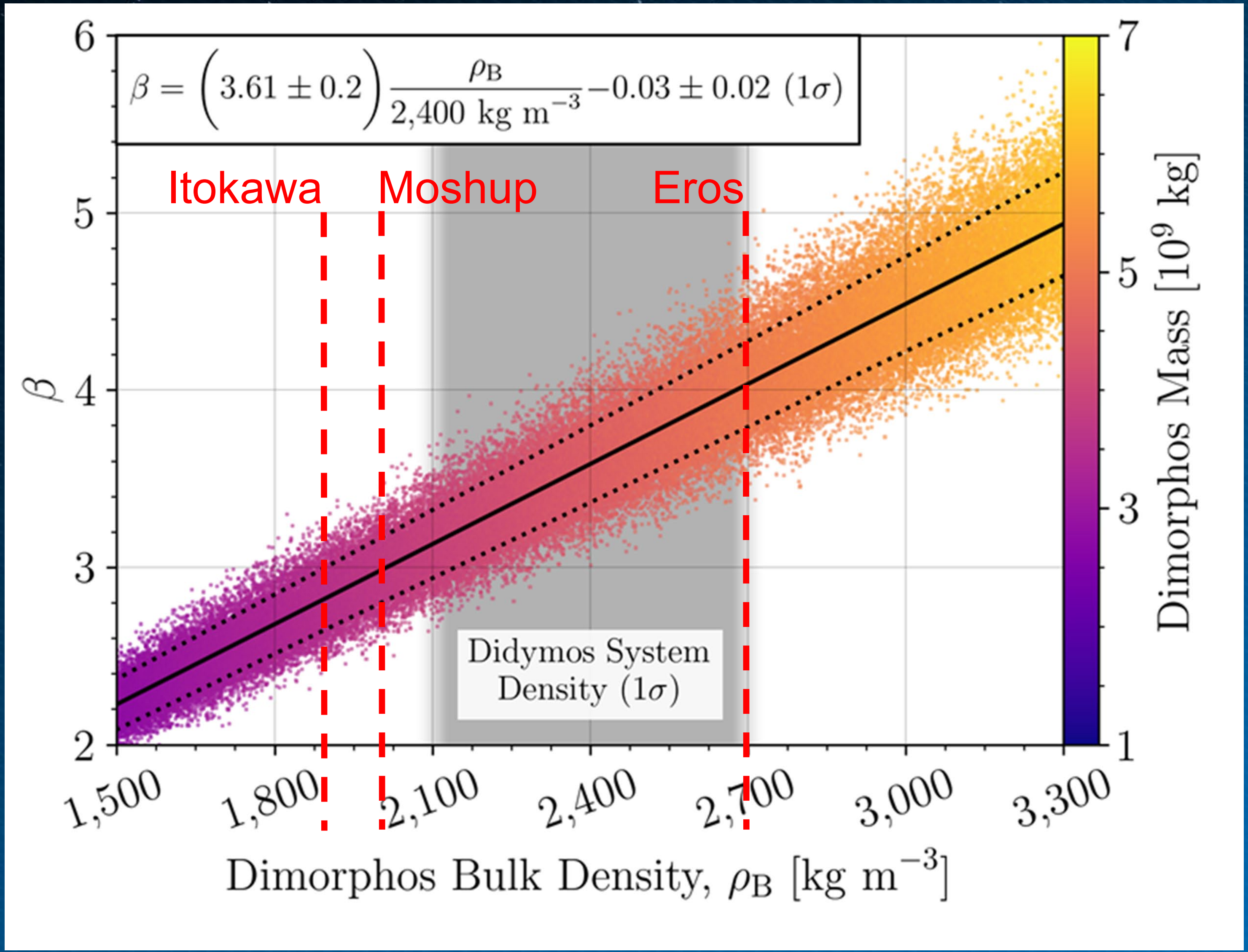


LICIACube images of ejecta cone.
(left) 156 sec after Dart Impact
(right) 175 sec after DART impact

Probability distribution of Δv_T, from Full 2-Body Monte Carlo analysis, sampling input parameter uncertainties. The histogram consists of 100,000 Monte Carlo samples and is normalized to an area of unity. A Gaussian fit to the distribution yields a mean $\Delta v_T = -2.70$ mm s^{-1} with a standard deviation of 0.10 mm s^{-1}.



β as a function of Dimorphos's bulk density, from dynamical Monte Carlo analysis. Individual samples plotted as points, while linear fit for mean β is plotted as solid line. Dotted lines show the 1σ confidence interval. Color bar shows mass of Dimorphos for each Monte Carlo sample, which is determined by bulk density and the volume.



Conclusions

- Momentum transfer to Dimorphos from DART kinetic impact was >2x incident momentum
  - Recoil of escaping impact ejecta transferred more momentum than was incident with DART
- The DART kinetic impact was highly effective for asteroid deflection
- For planetary defense, an increased momentum transfer means that a given kinetic impactor can deflect a larger target wirth same warning time, or require less warning time to deflect a given target
- What are possible implications for material properties of Dimorphos?
  - See presentations by Raducan, Kunamoto, Graninger
- Hera mission will visit Didymos-Dimorphos in late 2026, will measure mass of Dimorphos, and search for or measure impact crater and target deformation

Monte Carlo Study Parameter Values

Parameter	Nominal	1σ
Didymos ellipsoid extents (x,y,z) [m]*	851, 849, 620	±15, ±15, ±15
Dimorphos ellipsoid extents (x,y,z) [m]*	177, 174, 116	±2, ±4, ±2
Didymos density [kg/m^3]*	2400	±300
Dimorphos density [kg/m^3]*	2400	±300
Pre-impact Didymos orbit period [hrs]^	11.92148	±0.000044
Post-impact Didymos orbit period [hrs]^	11.372	±0.0055
Pre-impact body separation distance [m]^	1206	±35
Assumed pre–impact eccentricity	0	--

*Daly, et al. 2022. *Nature*. doi: 10.1038/s41586-023-05810-5 ^Thomas et al. 2022. *Nature*. doi: 10.1038/s41586-023-05805-2

Methodology for Beta Study Using Secant Search