Scattering Properties of the DART Impact Plume: Phase Angle and Color Dependence.

R. Lolachi[1,2,3], D. A. Glenar[1,2,3], T. J. Stubbs[2], L. Kolokolova[4], P. H. Hasselmann[5], G. Poggiali[6,7], J-Y. Li[8], E. Dotto[5], A. Rossi[9], V. Della Corte[10], and A. Zinzi[11,12]. [1]University of Maryland, Baltimore Co., Baltimore, MD (rlolachi@umbc.edu); [2]NASA Goddard Space Flight Center, Greenbelt, MD; [3]Center for Research and Exploration in Space Science and Technology, NASA/GSFC, Greenbelt, MD; [4]University of Maryland, College Park, MD; [5]INAF-Osservatorio Astronomico di Roma, Monte Porzio Catone, Roma, Italy; [6]INAF-Astrophysical Observatory of Arcetri, Firenze, Italy; [7]LESIA-Observatorie de Paris PSL, Paris, France [8]Planetary Science Institute, Tucson, AZ, USA; [9]IFAC-CNR, Sesto Fiorentino, Firenze, Italy [10]INAF-Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy; [11]Agenzia Spaziale Italiana, Roma, Italy; [12]Space Science Data Center (ASI), Roma Italy.

Introduction: The Double Asteroid Redirection Test (DART) mission was the world's first planetary defense mission. After reaching the binary (65803) Didymos-Dimorphos asteroid system it hit the 160 m diameter secondary, Dimorphos, on September 26. Impacting at a speed of approximately 6 km s^{-1} it successfully demonstrated the kinetic impact deflection technique changing Dimorphos' orbital period about Didymos by about 30 min and creating a complex impact ejecta plume with filamentary structures in the process [1]. These events were observed both from Earth and by DART's ride-along companion CubeSat, LICIACube. These observations will be used to determine and understand the momentum transfer efficiency of the impact [2].

Calculating ejecta mass is critical to understanding momentum transfer. This requires an accurate knowledge of scattering properties [3] including the ejecta particle size distribution. Analysis of LUKE brightness measurements at widely separated phase angles and in multiple colors comprise nearly independent measures for constraining the effective size of scattering particles.

We have used LUKE RGB data to examine the spatial and temporal variation of effective particle size within the ejecta plume structure and filaments, as outlined below.

Viewing Geometry: A summary of the LICIACube flyby geometry is given in Fig. 1, which is conceptually the impact and coordinate geometry as used in the DART team analysis [1]. The expanding impact plume is modeled as a hollow cone at the origin. The DART velocity vector forms the y-axis, with relative velocity $\boldsymbol{v}_\mathbf{F}$, where y bisects the evolving ejecta cone. LICIACube flies parallel and behind DART, forming the x-y coordinate plane, with the approach vector defining the x-axis. During most of the approach, LICIACube views scattered sunlight from the interior surface of the outward expanding plume. This geometry holds until the spacecraft crosses the extension of the plume surface, at which point an abrupt change in plume transmittance and scattering behavior seen by the observer is expected. Between plume plane crossings, the line of sight passes through both plume layers in tandem, before again viewing separate surfaces.

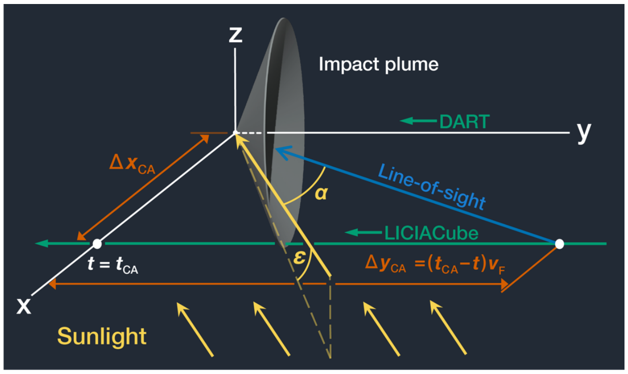

Figure 1: *LICIACube Viewing Geometry:* LICIACube encounter with evolving optical scattering geometry based on Cheng et al. [2] (**CA** = Closest Approach, $\boldsymbol{v}_\mathbf{F}$ = LICIACube velocity, $\boldsymbol{\alpha}$ = phase angle, and $\boldsymbol{\varepsilon}$ = Sun elevation angle).

Phase Function Modeling: A selection of realistic analogs have been constructed (Fig. 2):

- *Ultra-fine grains* from *Discrete Dipole Approximation (DDA)* computations [4].
- *Sand* and *mm-grain* shapes from the Granada-Amsterdam light scattering database [5] and Muñoz et al. [6].
- *Bennu:* Average for naturally ejected particles (Hergenrother et al. [7, 8])
- *"Rocks & Boulders"* constructed using the *H-G* magnitude system at small phase angles (G=0.20), and $A(\alpha=0)$=0.15, and Lommel-Seeliger form at high phase angles.

Data Reduction: Absolute pixel responsivity (i.e., single pixel response in *DN*/ms per unit scene brightness) in the LUKE RGB channels is necessary for relating the measured response to line-of-sight optical depth and therefore plume mass. We examined a set of 48 raw images chosen from the LUKE data set, with observing phase angles spanning ≈43–116°. Absolute response was estimated for all three camera channels following a succession of Bayer filter masking, subframe creation and background subtraction steps. Pixel response in the Green channel is approximated by comparing the encircled *DN* from Didymos (in unsaturated images) with a Didymos irradiance model based on its known *V*-band reduced magnitude [9], expected phase function shape (see the *"Rocks and*

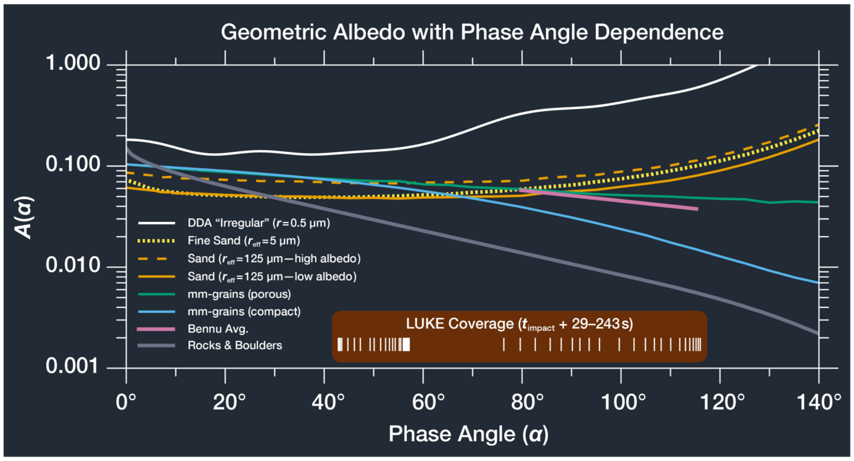

Figure 2: *Phase Functions:* As grain size gets smaller phase functions tend to get brighter. Comparing *I/F* at multiple phase angles helps constrain the right phase function and hence effective grain size.

Boulders" curve in Fig. 2) and the known LICIACube observing geometry at each time step. Pixel response in the remaining (Red and Blue) channels was inferred from the Green values using measurements of Didymos' color [10]. Separating the responses in all three bands required a spectral weighting step using the color filter profiles [11] as well as solar spectral irradiance.

Discussion: A first-look comparison of images at widely separated phase angles (Fig. 3) appears to show a steep drop in reflectance with increasing phase angle in the outer plume regions, suggesting that large (mm or larger) grains dominate the scattered light there.

- Using the latest estimates for actual plume geometry, we are analyzing a few specific plume filaments that have been identified. Knowing the axis and the opening angle means that we can estimate incidence angle and make path length corrections.
- Brightness at small phase angle (minimum divergence between candidate phase curves) should then allow optical depth (hence LOS mass) estimates.
- Although plume color is being closely studied by other DART team members, we will examine these filaments in order to quantify possible gradients in color (hence effective particle size) as a function of radial distance from the impact point.

Acknowledgments: This research was supported by the NASA/GSFC Internal Scientist Funding Model (ISFM) Exospheres, Ionospheres, Magnetospheres Modeling (EIMM) team, and the NASA Solar System Exploration Research Virtual Institute (SSERVI). The work done through the Center for Research and Exploration in Space Science and Technology (CRESST-II) is supported by NASA award number 80GSFC21M0002. LK acknowledges support from NASA DART PSP grant 80NSSC21K1131. PHH, GP, ED, AR, VDC, and AZ are supported by the Italian Space Agency (ASI) within the LICIACube project (ASI-INAF agreement AC n.2019-31-HH.0).

References: [1] Dotto et al. (2023) *Nature*, Submitted. [2] Cheng A. F. et al. (2020) *Icarus, 352,* 113989. [3] Lolachi et al. (2022), *PSJ*, In Press. [4] Richard, D. et al. (2011) *PSS*, 59, 1804–1814. [5] Muñoz et al. (2012) *JQSRT*, 113, 565, 822. [6] Muñoz et al. (2007) *JGR (Atmos.)*, 112, D13215. [7] Hergenrother et al. (2020) *JGR (Plan.)*, 125, e06381. [8] Fahnestock, E. G. et al. (2022) *PSJ*, 3, 206. [9] Pravec, P. (2022) *PSJ*, 3, 7. [10] Kitazato, K. (2004), *LPSC XXXV*, Abstract #1623. [11] AMS (2020) CMV2000 Datasheet v2.14.

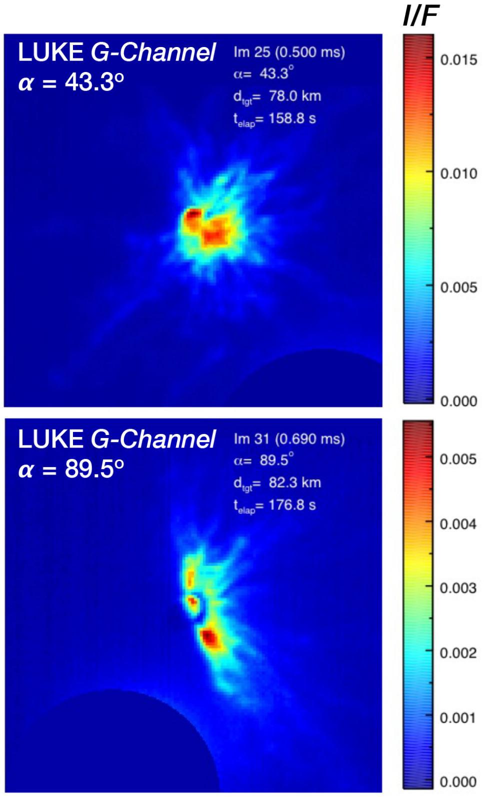

Figure 3: *Green Channel Images:* Plume images at widely separated phase angles (43.3° and 89.5°) indicate a factor of ≈3 reduction in outer-region reflectance as phase angle increases from 43.3° to 89.5° (intensity scale bars). No corrections have been made for changes in plume orientation or geometry. Blue circles are masks.