The boulder size-frequency distribution derived from DART/DRACO images of Dimorphos: First results

M. Pajola[1], F. Tusberti[1], A. Lucchetti[1], O. Barnouin[2], C.M. Ernst[2], E. Dotto[3], R.T. Daly[2], G. Poggiali[4,5], M. Hirabayashi[6], E. Mazzotta Epifani[3], N. L. Chabot[2], V. Della Corte[7], H. Agrusa[8,22], R.-L. Ballouz[2], N. Murdoch[9], C. Robin[9], A. Rossi[10], S.R. Schwartz[11], S. Ieva[3], S. Ivanovski[12], A. Campo-Bagatin[13], L. Parro[13,18], P. Benavidez[13], J.B. Vincent[14], F. Ferrari[15], G. Tancredi[16], J.M. Trigo-Rodriguez[17], S. Raducan[18], J. Sunshine[8], T. Farnham[8], E. Asphaug[19], A. Rivkin[2], J.D.P. Deshapriya[3], P.H.A. Hasselmann[3], J.R. Brucato[3], A. Zinzi[20,21], M. Amoroso[20], S. Pirrotta[20], G. Impresario[20], S. Cambioni[22], P. Michel[23], A. Cheng[2], I. Bertini[24], A. Capannolo[9], S. Caporali[3], M. Ceresoli[15], B. Cotugno[25], G. Cremonese[1], M. Dall'Ora[26], V. Di Tana[25], I. Gai[27], M. Lavagna[15], F. Miglioretti[25], D. Modenini[27], P. Palumbo[24], D. Perna[3], S. Simonetti[25], P. Tortora[27], M. Zannoni[27], G. Zanotti[15].

[1]INAF-Astronomical Observatory of Padova, Vic. Osservatorio 5, 35122 Padova, Italy (maurizio.pajola@inaf.it); [2]Johns Hopkins University Applied Physics Laboratory, Laurel, MD-USA; [3]INAF-Osservatorio Astronomico di Roma, Monte Porzio Catone, Roma, Italy; [4]INAF-Osservatorio Astrofisico di Arcetri, Firenze, Italy; [5]LESIA-Observatorie de Paris PSL, Paris, France; [6]Auburn University, AL-USA; [7]INAF-Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy; [8]University of Maryland, Department of Astronomy, MD-USA; [9]Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), Université de Toulouse, France; [10]IFAC-CNR, Sesto Fiorentino, Firenze, Italy; [11]Planetary Science Institute; University of Arizona, AZ-USA; [12]INAF-Osservatorio Astronomico di Trieste, Trieste, Italy; [13]Universidad de Alicante, Spain; [14]DLR Berlin, Germany; [15]Politecnico di Milano - Bovisa Campus, Dipartimento di Scienze e Tecnologie Aerospaziali, Milano, Italy; [16]Dpto. Astronomia, Facultad Ciencias Igua 4225, Montevideo, Uruguay; [17]Institute of Space Sciences (ICE, CSIC) and Institut d'Estudis Espacials de Catalunya (IEEC), Catalonia, Spain; [18]University of Bern, Switzerland;v[19]University of Arizona, AZ-USA; [20]Agenzia Spaziale Italiana, Roma, Italy; [21]Space Science Data Center – ASI, Roma Italy; [22]Dept. of Earth, Atmospheric and Planetary Sciences, Massachussets Institute of Technology, Cambridge, MA-USA; [23]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France; [24]Università degli Studi di Napoli "Parthenope", Dipartimento di Scienze & Tecnologie, Centro Direzionale, Napoli, Italy; [25]Argotec, Torino, Italy; [26]INAF-Osservatorio Astronomico di Capodimonte, Napoli, Italy; [27]Alma Mater Studiorum - Università di Bologna, Dipartimento di Ingegneria Industriale, Forlì, Italy; Alma Mater Studiorum - Università di Bologna, Centro Interdipartimentale di Ricerca Industriale Aerospaziale, Forlì, Italy.

Context: On 26 September 2022, the Double Asteroid Redirection Test (DART) spacecraft impacted the surface of Dimorphos, the ~150 m size satellite of the near-Earth binary asteroid (NEA) (65803) Didymos (~760 m-size, [1]). Numerical models of asteroid disruption, the analyses of asteroids' shapes, and in-situ observations, support the interpretation that small asteroids (0.2-10 km size range) are reaccumulated remnants from disrupted parent bodies, also called rubble-piles (e.g. [2, 3]). Surface boulders on rubble piles, therefore, represent directly the fragments of those parent-body disruptions followed by some evolutionary process such as cratering and thermal breakdown, followed by the size-sorting and migration of granular materials when an asteroid's regolith is mobilized. Hence, the observed size-frequency distribution (SFD) of boulders on the surface of a NEA and the corresponding fitting indices is a powerful tool for understanding the initial formation of boulders and their subsequent evolution. The boulder SFD is also important in understanding the conditions of the surface for any kinetic deflection experiment such as DART.

Dataset: During the last minutes of the DART mission, the DRACO scientific camera [4] imaged the surface of Dimorphos at increasingly fine spatial scales, ranging from few meters to a best resolution of 5.5 cm. In order to identify and manually count all boulders located in the illuminated surface of the asteroid, we decided to use two DRACO images with a phase angle of 59.4°, taken from target distances of 52.56 km and 40.73 km. The resulting illuminated surface in these images was imaged at a spatial scale of 0.26 m and 0.20 m, hence all features larger than 0.6-0.8 m in size can be identified (Fig.1).

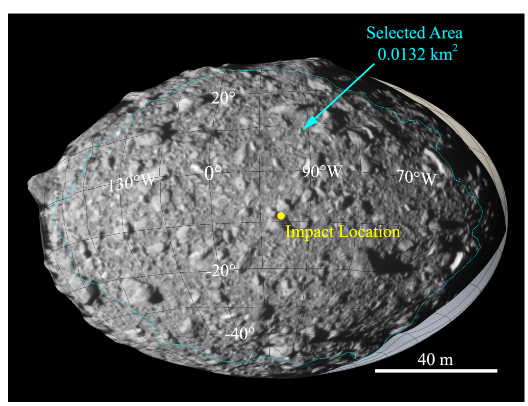

Figure 1. The DRACO images projected onto the Dimorphos shape model. The study area is within the light-blue polygon. The DART impact location is indicated with a yellow dot.

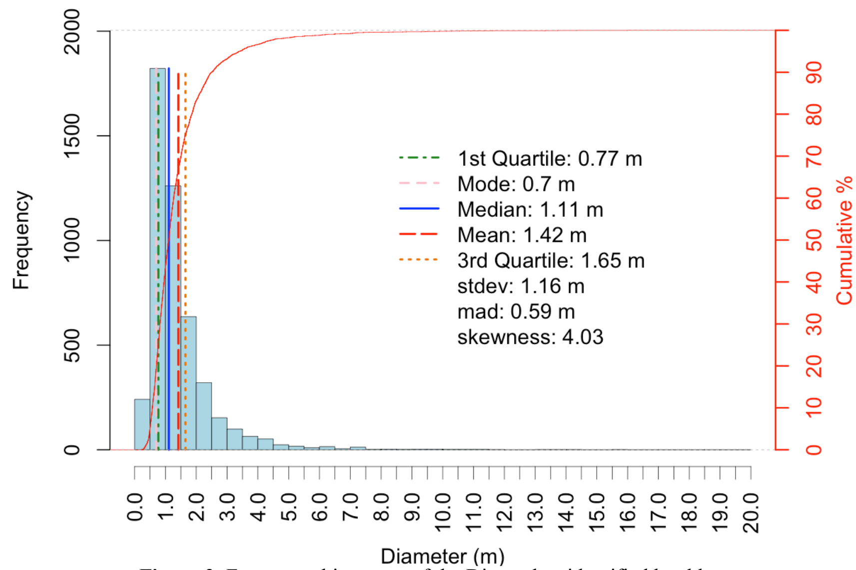

Figure 2. Frequency histogram of the Dimorphos identified boulders.

By using the Small Body Mapping Tool (SBMT, [5]) we directly projected the DRACO images onto the Dimorphos shape model [6] and then counted boulders as ellipses from an area that is 0.0132 km^2 wide (this area is the largest one identifiable where distorted features are not present, Fig. 1). The value of an ellipse's major axis is then used as the maximum size of the boulder. The total number of boulders identified is 4757, with a maximum size of 16 m. The frequency histogram of the counts is in Fig.2.

SFD fitting curves: To evaluate whether or not the resulting SFD is fitted by a power-law or not we made use of the Clauset et al. [7] method to validate the existence of the power-law fitting model [8]. This method allows the identification of the completeness limit, x_{min}, which is the threshold value above which the power-law exists. The estimation of x_{min} is done through the Kolmogorov-Smirnoff (KS) statistic and allows to find the value minimizing it. Afterwards, the power-law index (α) of the fitting curve is determined through the maximum likelihood estimator (MLE). The uncertainty for both α and x_{min} is then derived through a non-parametric bootstrap procedure that generates a large number of synthetic datasets from a power-law random generator and performs a number of KS tests to verify if the generated and observed data come from the same distribution. This technique returns a p-value that can be used to quantify the plausibility of the hypothesis.

The above methodology applied on our data return an α value of -2.45 $\pm$ 0.2 and an x_{min} of 2.0 $\pm$ 0.5 m. Nevertheless, considering the significance level of 0.10, our preliminary p-value of 0.06 (computed from 2500 KS statistic tests) suggests that the Dimorphos boulder SFD is not well fit by a single power law distribution, but instead, from a different one.

Due to the 0.20-m spatial scale of the images used, all boulders larger than 0.60 m, i.e., 3 pixels, can be positively identified. To be conservative, we then decided to use a lower limit of 1.0 m to compute the exponential-law and Weibull parameters.

Through this preliminary work, we have identified that the Weibull fitting curve better represents the boulder SFD on Dimorphos in the 1.0-16.0 m size range. While a single power-law SFD would indicate a single-event fragmentation (for example during impact cratering) that leads to a branching tree of cracks that have a fractal character [9, 10], the Weibull distribution is thought to result from sequential fragmentation [11] and is often used to describe the particle distribution resulting from grinding experiments [12]. This suggests that the boulders SFD on Dimorphos might have originated from impacts, but it was later modified by other processes (repeated impacts, thermal fragmentation, reaccumulation related processes, burial) that are still being debated and that will be presented at the time of the conference.

Acknowledgments: This research was supported by the Italian Space Agency (ASI) within the LICIACube project (ASI-INAF agreement AC n. 2019-31-HH.0) and the DART mission, NASA Contract No. NNN06AA01C to JHU/APL. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 870377 (project NEO-MAPP) and CNES.

References: [1] Rivkin, A.S., et al. 2021. PSJ, 2, 173. [2] Watanabe, S., et al. 2019. Science, 364, 268. [3] Lauretta, D.S., et al. 2019. Nature, 568, 55. [4] Fletcher, Z. J., et al. 2018. SPIE 10698. [5] Ernst, C.M. et al. (2018), *LPSC #49, 2018, ab. 2083.* [6] Daly, R.T., et al. (2023), LPSC. [7] Clauset, A., et al., (2009) SIAM Rev. 2009, 51, 661–703. [8] DeSouza et al., (2015), Icarus, 247, 77-80.[9] Turcotte, D.L., 1997. Cambridge University Press. [10] Pajola, M., et al. (2022), Icarus, 375, 114850. [11] Brown, W.K., Wohletz, K.H. (1995). J. Appl. Phys. 78, 2758. [12] Rosin, P., Rammler, E. (1933). J. Inst. Fuel 7, 29.