





# Achievement of the Planetary Defense Investigations of the Double Asteroid Redirection Test (DART) Mission

Nancy L. Chabot<sup>1,68</sup> , Andrew S. Rivkin<sup>1</sup> , Andrew F. Cheng<sup>1</sup> , Olivier S. Barnouin<sup>1</sup> , Eugene G. Fahnestock<sup>2</sup> ,  
 Derek C. Richardson<sup>3</sup> , Angela M. Stickle<sup>1</sup> , Cristina A. Thomas<sup>4</sup> , Carolyn M. Ernst<sup>1</sup> , R. Terik Daly<sup>1</sup> ,  
 Elisabetta Dotto<sup>5</sup> , Angelo Zinzi<sup>6,7</sup> , Steven R. Chesley<sup>2</sup> , Nicholas A. Moskovitz<sup>8</sup> , Brent W. Barbee<sup>9</sup> , Paul Abell<sup>10</sup> ,  
 Harrison F. Agrusa<sup>3,11</sup> , Michele T. Bannister<sup>12</sup> , Joel Beccarelli<sup>13</sup> , Dmitriy L. Bekker<sup>1</sup> , Megan Bruck Syal<sup>14</sup> ,  
 Bonnie J. Buratti<sup>2</sup> , Michael W. Busch<sup>15</sup> , Adriano Campo Bagatin<sup>16</sup> , Joseph P. Chatelain<sup>17</sup> , Sidney Chocron<sup>18</sup> ,  
 Gareth S. Collins<sup>19</sup> , Luca Conversi<sup>20,21</sup> , Thomas M. Davison<sup>19</sup> , Mallory E. DeCoster<sup>1</sup> , J. D. Prasanna Deshapriya<sup>5</sup> ,  
 Siegfried Eggl<sup>22</sup> , Raymond C. Espiritu<sup>1</sup> , Tony L. Farnham<sup>3</sup> , Marin Ferrais<sup>23</sup> , Fabio Ferrari<sup>24</sup> , Dora Föhring<sup>21</sup> ,  
 Oscar Fuentes-Muñoz<sup>25</sup> , Igor Gai<sup>26</sup> , Carmine Giordano<sup>24</sup> , David A. Glenar<sup>9,27</sup> , Edward Gomez<sup>17,28</sup> ,  
 Dawn M. Graninger<sup>1</sup> , Simon F. Green<sup>29</sup> , Sarah Greenstreet<sup>30,31</sup> , Pedro H. Hasselmann<sup>5</sup> , Isabel Herreros<sup>32</sup> ,  
 Masatoshi Hirabayashi<sup>33,34</sup> , Marek Husárik<sup>35</sup> , Simone Ieva<sup>5</sup> , Stavro L. Ivanovski<sup>36</sup> , Samuel L. Jackson<sup>29,37</sup> ,  
 Emmanuel Jehin<sup>38</sup> , Martin Jutzi<sup>39</sup> , Ozgur Karatekin<sup>40</sup> , Matthew M. Knight<sup>41</sup> , Ludmilla Kolokolova<sup>3</sup> ,  
 Kathryn M. Kumamoto<sup>14</sup> , Michael Küppers<sup>42</sup> , Fiorangela La Forgia<sup>43</sup> , Monica Lazzarin<sup>43</sup> , Jian-Yang Li<sup>44</sup> ,  
 Tim A. Lister<sup>17</sup> , Ramin Lolachi<sup>9,27</sup> , Michael P. Lucas<sup>45</sup> , Alice Lucchetti<sup>13</sup> , Robert Luther<sup>46</sup> , Rahil Makadia<sup>22</sup> ,  
 Elena Mazzotta Epifani<sup>5</sup> , Jay McMahon<sup>25</sup> , Gianmario Merisio<sup>24</sup> , Colby C. Merrill<sup>47</sup> , Alex J. Meyer<sup>25</sup> ,  
 Patrick Michel<sup>11,48</sup> , Marco Micheli<sup>21</sup> , Alessandra Migliorini<sup>49</sup> , Kate Minker<sup>11</sup> , Dario Modenini<sup>26</sup> ,  
 Fernando Moreno<sup>50</sup> , Naomi Murdoch<sup>51</sup> , Brian Murphy<sup>37</sup> , Shantanu P. Naidu<sup>2</sup> , Hari Nair<sup>1</sup> , Ryota Nakano<sup>33,34</sup> ,  
 Cyrielle Opitom<sup>37</sup> , Jens Ormö<sup>32</sup> , J. Michael Owen<sup>14</sup> , Maurizio Pajola<sup>13</sup> , Eric E. Palmer<sup>44</sup> , Pasquale Palumbo<sup>49</sup> ,  
 Paolo Panicucci<sup>24</sup> , Laura M. Parro<sup>52,53</sup> , Jason M. Pearl<sup>14</sup> , Antti Penttilä<sup>54</sup> , Davide Perna<sup>5</sup> , Elisabeta Petrescu<sup>21,38,40</sup> ,  
 Petr Pravec<sup>55</sup> , Sabina D. Raducan<sup>39</sup> , K. T. Ramesh<sup>56</sup> , Ryan Ridden-Harper<sup>12</sup> , Juan L. Rizos<sup>50</sup> , Alessandro Rossi<sup>57</sup> ,  
 Nathan X. Roth<sup>9,58</sup> , Agata Rožek<sup>37</sup> , Benjamin Rozitis<sup>29</sup> , Eileen V. Ryan<sup>59</sup> , William H. Ryan<sup>59</sup> , Paul Sánchez<sup>60</sup> ,  
 Toni Santana-Ros<sup>52,61</sup> , Daniel J. Scheeres<sup>25</sup> , Peter Scheirich<sup>55</sup> , Cem Berk Senel<sup>40,62</sup> , Colin Snodgrass<sup>37</sup> ,  
 Stefania Soldini<sup>63</sup> , Damya Souami<sup>64</sup> , Thomas S. Statler<sup>65</sup> , Rachel Street<sup>17</sup> , Timothy J. Stubbs<sup>9</sup> , Jessica M. Sunshine<sup>3</sup> ,  
 Nicole J. Tan<sup>12</sup> , Gonzalo Tancredi<sup>66</sup> , Calley L. Tinsman<sup>1</sup> , Paolo Tortora<sup>26</sup> , Filippo Tusberti<sup>13</sup> , James D. Walker<sup>18</sup> ,

C. Dany Waller<sup>1</sup> , Kai Wünnemann<sup>46</sup> , Marco Zannoni<sup>26</sup> , and Yun Zhang<sup>67</sup>   
<sup>1</sup> Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA; [Nancy.Chabot@jhuapl.edu](mailto:Nancy.Chabot@jhuapl.edu)

<sup>2</sup> Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

<sup>3</sup> Department of Astronomy, University of Maryland, College Park, MD 20742, USA

<sup>4</sup> Department of Astronomy and Planetary Science, Northern Arizona University, Flagstaff, AZ, USA

<sup>5</sup> INAF-Osservatorio Astronomico di Roma, Via Frascati 33, I-00078 Monte Porzio Catone, Roma, Italy

<sup>6</sup> Agenzia Spaziale Italiana, Via del Politecnico, snc, I-00133, Rome, Italy

<sup>7</sup> ASI—Space Science Data Center, Via del Politecnico, snc, I-00133, Rome, Italy

<sup>8</sup> Lowell Observatory, Flagstaff, AZ 86004, USA

<sup>9</sup> NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>10</sup> NASA Johnson Space Center, Houston, TX 77058, USA

<sup>11</sup> Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Laboratoire Lagrange, Nice, France

<sup>12</sup> School of Physical and Chemical Sciences | Te Kura Matū, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand

<sup>13</sup> INAF-Astronomical Observatory of Padova, Vicolo Osservatorio 5, I-35122 Padova, Italy

<sup>14</sup> Lawrence Livermore National Laboratory, Livermore, CA, USA

<sup>15</sup> SETI Institute, Mountain View, CA, USA

<sup>16</sup> Instituto de Física Aplicada a las Ciencias y las Tecnologías (IUFACyT), Universidad de Alicante, Alicante, Spain

<sup>17</sup> Las Cumbres Observatory, Goleta, CA 93117, USA

<sup>18</sup> Southwest Research Institute, San Antonio, TX 78238, USA

<sup>19</sup> Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, UK

<sup>20</sup> European Space Agency—ESRIN, Via Galileo Galilei, I-00044 Frascati (RM), Italy

<sup>21</sup> ESA PDO NEO Coordination Centre, Via Galileo Galilei, 1, I-00044 Frascati (RM), Italy

<sup>22</sup> Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

<sup>23</sup> Florida Space Institute, University of Central Florida, 12354 Research Parkway, Orlando, FL 32826-0650, USA

<sup>24</sup> Department of Aerospace Science and Technology, Politecnico di Milano, Italy

<sup>25</sup> Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO, USA

<sup>26</sup> Department of Industrial Engineering, Alma Mater Studiorum—University of Bologna, Forlì, Italy

<sup>27</sup> Center for Space Sciences and Technology, University of Maryland, Baltimore County, Baltimore, MD 21250, USA

<sup>28</sup> School of Physics and Astronomy, Cardiff University, Queens Buildings, The Parade, Cardiff CF24 3AA, UK

<sup>29</sup> The Open University, Milton Keynes MK7 6AA UK

<sup>30</sup> Rubin Observatory/NSF's NOIRLab, Tucson, AZ 85719, USA

<sup>31</sup> Department of Astronomy and the DIRAC Institute, University of Washington, Seattle, WA 98195, USA

<sup>32</sup> Centro de Astrobiología (CAB), CSIC-INTA, Carretera de Ajalvir km 4, E-28850 Torrejón de Ardoz, Spain

<sup>33</sup> Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

<sup>34</sup> Auburn University, Aerospace Engineering/Geosciences, Auburn, AL 36849, USA

<sup>35</sup> Astronomical Institute of the Slovak Academy of Sciences, SK-05960 Tatranská Lomnica, Slovakia

<sup>36</sup> INAF-Osservatorio Astronomico di Trieste, Trieste, Italy

<sup>37</sup> University of Edinburgh, Institute for Astronomy, Royal Observatory, Edinburgh, EH9 3HJ, UK

<sup>38</sup> Space sciences, Technologies & Astrophysics Research (STAR) Institute, University of Liège, B-4000 Liège, Belgium

- <sup>39</sup> Space Research and Planetary Sciences, Physikalisches Institut, University of Bern, Switzerland  
<sup>40</sup> Royal Observatory of Belgium, Brussels, Belgium  
<sup>41</sup> Physics Department, United States Naval Academy, Annapolis, MD, USA  
<sup>42</sup> European Space Agency (ESA), European Space Astronomy Centre (ESAC), Villanueva de la Cañada, Madrid, Spain  
<sup>43</sup> University of Padova, Department of Physics and Astronomy, Vicolo dell' Osservatorio, 3, I-35121 Padova, Italy  
<sup>44</sup> Planetary Science Institute, Tucson, AZ, USA  
<sup>45</sup> Department of Civil & Environmental Engineering & Earth Sciences, University of Notre Dame, Indiana, USA  
<sup>46</sup> Museum für Naturkunde Berlin, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany  
<sup>47</sup> Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY 14853, USA  
<sup>48</sup> University of Tokyo, Department of Systems Innovation, School of Engineering, Tokyo, Japan  
<sup>49</sup> INAF-Istituto di Astrofisica e Planetologia Spaziale, Roma, Italy  
<sup>50</sup> Instituto de Astrofísica de Andalucía, CSIC, E-18008 Granada, Spain  
<sup>51</sup> Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-SUPAERO), Université de Toulouse, Toulouse, France  
<sup>52</sup> University Institute of Physics Applied to Sciences and Technologies, Universidad de Alicante, 03690 San Vicente del Raspeig, Alicante, Spain  
<sup>53</sup> Universidad Complutense de Madrid, E-28040 Madrid, Spain  
<sup>54</sup> Department of Physics, P.O. Box 64, FI-00014 University of Helsinki, Finland  
<sup>55</sup> Astronomical Institute of the Czech Academy of Sciences, Fričova 1, CZ-25165 Ondřejov, Czech Republic  
<sup>56</sup> Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD, USA  
<sup>57</sup> IFAC-CNR, Sesto Fiorentino, I-50019, Italy  
<sup>58</sup> Department of Physics, The Catholic University of America, Washington, DC 20064, USA  
<sup>59</sup> Magdalena Ridge Observatory, New Mexico Institute of Mining and Technology, Socorro, NM, USA  
<sup>60</sup> Colorado Center for Astrodynamics Research, University of Colorado Boulder, Boulder, CO 80303, USA  
<sup>61</sup> Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (IEEC-UB), Carrer de Martí i Franqués, 1, E-08028 Barcelona, Spain  
<sup>62</sup> Archaeology, Environmental Changes & Geo-chemistry (AMGC), Vrije Universiteit Brussel, Brussels, Belgium  
<sup>63</sup> Department of Mechanical and Aerospace Engineering, University of Liverpool, Brownlow street, Liverpool L69 3GL, UK  
<sup>64</sup> LESIA, Observatoire de Paris—Section Meudon, F-92195 Meudon Cedex, France  
<sup>65</sup> NASA Headquarters, 300 E St., SW, Washington DC 20546, USA  
<sup>66</sup> Departamento de Astronomía, Facultad de Ciencias, Udelar, Uruguay  
<sup>67</sup> Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI 48109, USA
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## Abstract

NASA's Double Asteroid Redirection Test (DART) mission was the first to demonstrate asteroid deflection, and the mission's Level 1 requirements guided its planetary defense investigations. Here, we summarize DART's achievement of those requirements. On 2022 September 26, the DART spacecraft impacted Dimorphos, the secondary member of the Didymos near-Earth asteroid binary system, demonstrating an autonomously navigated kinetic impact into an asteroid with limited prior knowledge for planetary defense. Months of subsequent Earth-based observations showed that the binary orbital period was changed by  $-33.24$  minutes, with two independent analysis methods each reporting a  $1\sigma$  uncertainty of 1.4 s. Dynamical models determined that the momentum enhancement factor,  $\beta$ , resulting from DART's kinetic impact test is between 2.4 and 4.9, depending on the mass of Dimorphos, which remains the largest source of uncertainty. Over five dozen telescopes across the globe and in space, along with the Light Italian CubeSat for Imaging of Asteroids, have contributed to DART's investigations. These combined investigations have addressed topics related to the ejecta, dynamics, impact event, and properties of both asteroids in the binary system. A year following DART's successful impact into Dimorphos, the mission has achieved its planetary defense requirements, although work to further understand DART's kinetic impact test and the Didymos system will continue. In particular, ESA's Hera mission is planned to perform extensive measurements in 2027 during its rendezvous with the Didymos–Dimorphos system, building on DART to advance our knowledge and continue the ongoing international collaboration for planetary defense.

*Unified Astronomy Thesaurus concepts:* Asteroids (72); Small Solar System bodies (1469); Near-Earth objects (1092); Asteroid satellites (2207); Planetary science (1255); Solar system astronomy (1529); Asteroid dynamics (2210); Asteroid surfaces (2209); Impact phenomena (779)

## 1. Introduction

The topic of planetary defense encompasses understanding the impact hazards posed by natural objects and the efforts undertaken to mitigate or manage these threats. While planetary defense activities have been undertaken for decades (National Research Council 2010, 2022), in particular searching for and tracking near-Earth asteroids, the Double Asteroid Redirection

Test (DART) was the first spacecraft mission dedicated to demonstrating a potential mitigation approach. DART was designed to demonstrate asteroid deflection through a kinetic impactor technique, which had been previously recommended as the first priority for a space mission in the mitigation area (National Research Council 2010). Although past missions such as Deep Impact (A'Hearn et al. 2005) and Hayabusa2 (Arakawa et al. 2020) utilized impactors to investigate the properties of small bodies, those earlier missions were not intended to deflect their targets and did not achieve measurable deflections.

In 2015, NASA began supporting the Johns Hopkins Applied Physics Laboratory to lead the DART project. The selected target for the DART mission was always the secondary

<sup>68</sup> Corresponding author.



member of the binary (65803) Didymos system, due to the well-characterized properties of the eclipsing binary system and its favorable Earth–Didymos distance in 2022 (Cheng et al. 2015). Didymos was discovered in 1996, and photometric observations led to its identification as an eclipsing binary system (Pravec et al. 2003) and to a precise determination of the orbital period of its secondary member (Pravec et al. 2006; Scheirich & Pravec 2009). Arecibo radar observations of the Didymos system were also obtained in 2003, confirming it to be a binary system and characterizing its shape and properties (Naidu et al. 2020). The radar observations constrained the diameter of Didymos to be roughly 780 m and the secondary member to have a diameter of roughly 150 m. The secondary’s diameter of  $\sim 150$  m made it a suitable candidate for the application of the kinetic impactor planetary defense technique (National Research Council 2010, 2022). The name Didymos was given in 2004 in recognition of its binary nature as it means *twin* in Greek. In 2020, the secondary member (previously referred to as *Didymos B* or informally as *Didymoon*) was named Dimorphos, meaning *two forms* in Greek; the name was chosen to reflect that Dimorphos would be slightly altered by DART’s planned kinetic impact and hence would have pre-impact and post-impact forms.

Spectral observations of the Didymos system showed that Didymos is an S-class asteroid (de León et al. 2006), linked to ordinary chondrites (Dunn et al. 2013), the most common type of meteorites found on Earth. While there were no direct spectral measurements of Dimorphos, binary asteroid formation models predicted that it was likely that the secondary would have the same composition as the primary (Walsh & Jacobson 2015). Overall, these combined observations made the Didymos system one of the best-characterized binary asteroid systems, and also one with size and composition characteristics highly relevant for planetary defense.

The Didymos system was shown to be accessible by a range of spacecraft trajectory designs (Atchison et al. 2016). Additionally, the distance between Didymos and Earth would be  $<0.1$  au in September and October of 2022 (Atchison et al. 2016) with the Didymos system reaching a maximum brightness of  $V$  magnitude 14.4 (Rivkin et al. 2021). This minimum Earth–Didymos distance does not occur again for another 40 yr (Rivkin et al. 2021). Consequently, the DART mission concept always planned to impact Dimorphos during the 2022 September–October timeframe, to allow Earth-based telescopes to play a critical role in assessing the effectiveness of the kinetic impact deflection technique. Table A1 summarizes key parameters for the Didymos system.

In contrast, the specific details of the DART mission and spacecraft design underwent a number of iterations during its concept development phases, from 2015–2019. In its earliest development phase, DART’s baseline mission included a chemical propulsion trajectory that utilized a small launch vehicle (Atchison et al. 2016; Cheng et al. 2016). However, by 2017, the mission design had changed to utilize an ion-propulsion system, NASA’s Evolutionary Xenon Thruster-Commercial (NEXT-C) system, as its primary propulsion system with a launch as a secondary payload (Cheng et al. 2018). By 2019, when the mission held its Critical Design Review, the DART spacecraft had returned to utilizing a chemical propulsion trajectory with a dedicated launch vehicle, while also carrying and demonstrating the NEXT-C ion-propulsion system in flight (Adams et al. 2019). The

accommodation of NEXT-C heavily influenced the design and development of the spacecraft, its subsystems, and operations (Adams et al. 2019; Badger et al. 2022). In particular, to generate the necessary power for NEXT-C, the DART spacecraft included two large Roll-Out Solar Arrays (ROSA), each 8.5 m in length, becoming the first spacecraft to carry this technology (Shapiro & Rodovskiy 2023).

The DART spacecraft included a single instrument payload, the Didymos Reconnaissance and Asteroid Camera for Optical navigation (DRACO). DRACO was a narrow-angle telescope with a 208 mm aperture, a field of view  $0.29^\circ$  wide, a 2560 by 2160 raw pixel complementary metal-oxide semiconductor (CMOS) detector, and a design derived from the high-resolution imager on the New Horizons mission (Fletcher et al. 2018, 2022). DRACO images (Ernst et al. 2024) were utilized by the onboard autonomous algorithms named Small-body Maneuvering Autonomous Real Time Navigation (SMART Nav; Chen et al. 2018; Ericksen et al. 2023; Jensenius et al. 2023; Sawyer et al. 2023). As part of the guidance, navigation, and control (GNC) system (O’Shaughnessy & Hefter 2023), SMART Nav was designed to autonomously identify and distinguish between Didymos and Dimorphos and then, working in concert with the other GNC elements (Miller et al. 2023; Superfin et al. 2023) and navigation efforts (Bellerose et al. 2023), direct the spacecraft toward the smaller body, Dimorphos, all within roughly an hour of impact. The SMART Nav operations were required to work in parallel with the spacecraft system while also streaming images to the ground in real-time prior to impact (Smith et al. 2020), where an optimized data processing pipeline allowed the processed images to be shared quickly with the public and the team (Bekker et al. 2023; Waller et al. 2024). These requirements also influenced the design and development of other aspects of DART, including the flight software (Heistand et al. 2019), autonomy system (Tropf et al. 2023), the Single Board Computer Field Programmable Gate Array (Zhan et al. 2021), and its associated image processing pipeline (Bekker et al. 2021).

In 2019, DART was chosen to launch on a SpaceX Falcon 9 from Vandenberg Air Force Base (renamed Vandenberg Space Force Base in 2021). In 2021 February, the decision was made to move from the mission’s primary launch window, which opened in 2021 July, to the secondary window, which opened in late 2021 November. The change in launch periods did not affect DART’s planned impact date with Dimorphos, and the decision noted two technical challenges with mission critical components in particular: the need to reinforce DRACO to ensure it would withstand the stress of a launch, and delays in ROSA development due to supply chain impacts, in part due to the COVID pandemic. The DART spacecraft, shown in Figure 1, launched on 2021 November 24, 06:21 UT, the first day of the launch window (Atchison et al. 2023b). The ROSAs were fully deployed successfully within hours after launch. A brief demonstration of NEXT-C was performed during DART’s initial check-out period, but there was no further use due to an anomaly observed in the spacecraft’s power system electronics (John et al. 2023). The DART spacecraft followed a single-phase ballistic trajectory with a series of trajectory correction maneuvers prior to reaching the Didymos system roughly 10 months after launch (Atchison et al. 2023b). The DART project was funded by NASA from 2015–2023 with a



**Figure 1.** The DART spacecraft in 2021 September, during the pre-ship inspection at the Johns Hopkins Applied Physics Laboratory. In this image, the NEXT-C ion-propulsion engine is at the top of the spacecraft, one of the rolled-up ROSAs is on the right side, and LICIAcube is contained on the gold-colored blanketed spacecraft side. In this position, DRACO is not visible as it is pointing at the floor. The main structure of the spacecraft is roughly a cube with dimensions of about 1.3 m, from which other structures extend to result in measurements of roughly 1.8 m in width, 1.9 m in length, and 2.6 m in height.

total mission cost of roughly \$260 M for spacecraft development and operations and \$67 M for launch services.

The DART mission was driven by Level 1 requirements, which were approved by NASA in 2017, and these shaped the planetary defense investigations planned by the team (Rivkin et al. 2021). The DART Level 1 requirements were as follows:

1. *DART-1.* DART shall intercept the secondary member of the binary asteroid (65803) Didymos as a kinetic impactor spacecraft during its 2022 September–October close approach to Earth.
2. *DART-2.* The DART impact on the secondary member of the Didymos system shall cause at least a 73 s change in the binary orbital period.
3. *DART-3.* The DART project shall characterize the binary orbit with sufficient accuracy by obtaining ground-based observations of the Didymos system before and after spacecraft impact to measure the change in the binary orbital period to within 7.3 s ( $1\sigma$  confidence).
4. *DART-4A.* The DART project shall use the velocity change imparted to the target to obtain a measure of the momentum transfer enhancement parameter referred to as *beta* ( $\beta$ ) using the best available estimate of the mass of Didymos B.
5. *DART-4B.* The DART project shall obtain data, in collaboration with ground-based observations and data from another spacecraft (if available), to constrain the location and surface characteristics of the spacecraft impact site and to allow the estimation of the dynamical changes in the Didymos system resulting from the DART impact and the coupling between the body rotation and the orbit.

The Level 1 requirement DART-4B mentions the possibility of data from another spacecraft, “if available.” In 2018, the



**Figure 2.** LICIAcube in 2021 August, prior to its integration on the DART spacecraft. LICIAcube is a 6U CubeSat contributed by the Italian Space Agency, with dimensions of  $10 \times 20 \times 30$  cm.

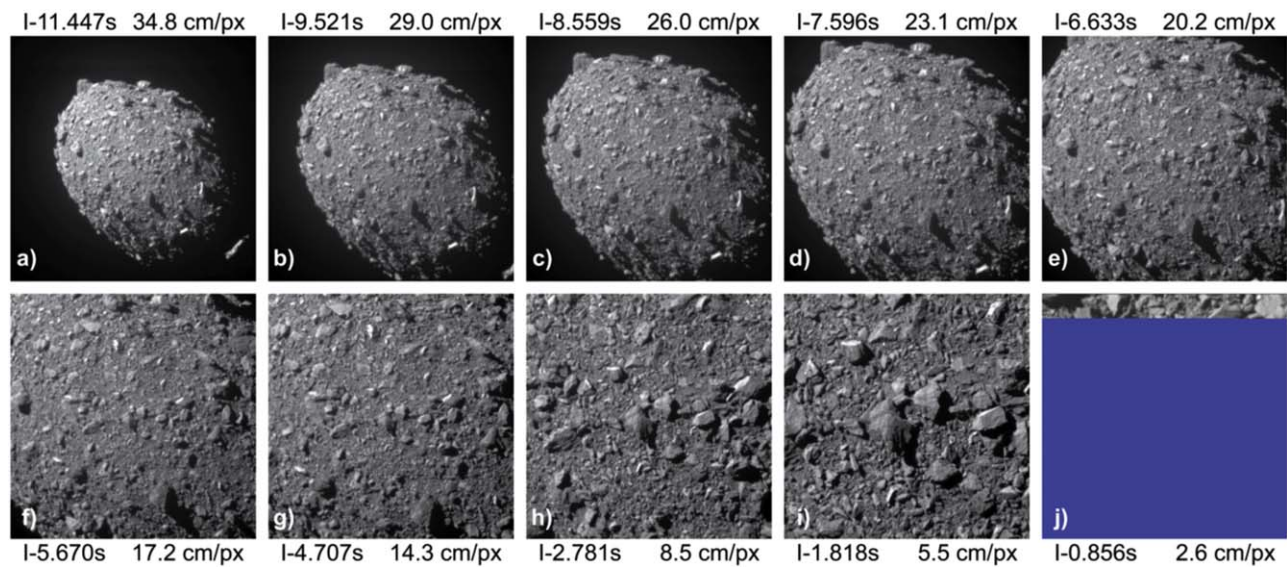
Light Italian CubeSat for Imaging of Asteroids (LICIAcube) was added to the DART mission as a secondary spacecraft. Contributed by the Italian Space Agency (Agenzia Spaziale Italiana, ASI), LICIAcube, shown in Figure 2, was a 6U CubeSat developed by Argotec under the scientific coordination of the Italian Istituto Nazionale di Astrofisica (INAF; Dotto et al. 2021). LICIAcube was equipped with two cameras: the LICIAcube Explorer Imaging for Asteroid (LEIA), a narrow field panchromatic camera, and the LICIAcube Unit Key Explorer (LUKE), a wide field red, green, and blue (RGB) camera (Poggiali et al. 2022). LICIAcube was released from the DART spacecraft on 2022 September 11, 15 days prior to DART’s impact, to capture the aftermath of DART’s collision and provide key information to inform the resulting planetary defense investigations.

Following impact, the DART project was funded for 1 yr, to carry out the mission’s planetary defense investigations and complete the Level 1 requirements. In the next sections, we summarize the achievement of each of DART’s Level 1 requirements through its combined planetary defense investigations. In the final section, we discuss the international collaboration on DART and look forward to ESA’s Hera mission.

## 2. DART-1: Impact Dimorphos

DART successfully impacted asteroid Dimorphos on 2022 September 26, becoming the first mission to demonstrate asteroid deflection (Daly, Ernst, Barnouin et al. 2023). Shared live via a NASA broadcast, over a million concurrent viewers around the world watched as the DART spacecraft streamed images to Earth up to the final subsecond before its impact with Dimorphos, as shown in Figure 3.

Having precise information about the Didymos–Dimorphos system before DART’s impact provided key inputs to plan DART’s specific impact time. With this motivation, the DART team led a focused effort to obtain lightcurve measurements in 2021 and to combine the results with observations from earlier



**Figure 3.** Final 10 images returned by DRACO, spanning from 11.5 s prior to impact to a partial image acquired less than a second prior to impact. The timing and pixel scale of each image (a)–(j) are labeled for each panel. In (a), Dimorphos is roughly 177 m in length. In (i), the final complete image has a pixel scale of 5.5 cm pixel<sup>-1</sup> and shows an area approximately 28 m in length (Ernst et al. 2024).

years to determine the pre-impact properties of the Didymos system (Pravec et al. 2022). These combined observations yielded greatly improved knowledge of the Didymos system (Scheirich & Pravec et al. 2022) and importantly constrained the knowledge of the orbital phase of Dimorphos relative to Didymos at the time of impact to within 5.4°, 3 $\sigma$  uncertainty (Naidu et al. 2022). DART’s impact time was chosen with consideration to having direct Earth communication coverage, to having Dimorphos at maximum elongation from Didymos as viewed by the DART spacecraft, to having the solar phase angle  $\leq 60^\circ$ , and to impacting as nearly head-on as possible, with the motion of the spacecraft in the opposite direction of the motion of Dimorphos about Didymos (Atchison et al. 2023b). The resulting impact angle between DART and Dimorphos was 166.2°, with DART’s approach velocity being 9.7° out of the binary orbital plane (Atchison et al. 2023b). In-flight DRACO calibrations during the cruise to the Didymos system (Ernst et al. 2024) included imaging of stars and using Jupiter and transits of its moon Europa as targets to test SMART Nav functionality (Ericksen et al. 2023; Sawyer et al. 2023).

DRACO (Fletcher et al. 2022) first detected the Didymos system 61 days prior to impact. Optical navigation was used heavily during the final month to ensure the spacecraft was positioned to impact Dimorphos and to inform the associated trajectory correction maneuvers (Bellerose et al. 2023; Rush et al. 2023). The final trajectory correction maneuver was executed 24 hr prior to the planned impact and placed DART on a trajectory to impact Didymos (Atchison et al. 2023b). At 4 hr and 5 minutes prior to impact, SMART Nav took control of the spacecraft navigation (Daly, Ernst, Barnouin, et al. 2023; Ericksen et al. 2023; Jensenius et al. 2023). The SMART Nav system first detected Dimorphos 73 minutes prior to impact, and 50 minutes prior to impact, SMART Nav began maneuvering toward Dimorphos. The DART spacecraft impacted Dimorphos on 2022 September 26, at 23:14:24 UTC, with a speed of 6.1 km s<sup>-1</sup> and a mass of 579 kg (Daly, Ernst, Barnouin, et al. 2023). Evaluation of DART’s impact shows that the spacecraft impacted within 2 m of the center of

the illuminated figure (Jensenius et al. 2023) and within 25 m of the center of figure of Dimorphos, with an impact angle of roughly 17° from the surface normal (Daly, Ernst, Barnouin, et al. 2023). Autonomously targeting a small asteroid with limited prior knowledge at high speed was a key accomplishment for the DART mission and marked the achievement of the DART-1 Level 1 requirement. DART’s successful kinetic impactor performance also provided mission design and navigation lessons learned for future planetary defense missions (Atchison et al. 2023a).

### 3. DART-2: Change the Binary Orbital Period

The DART-2 Level 1 requirement to cause at least a 73 s change in the binary orbital period was derived from requiring that, after 1 month, the orbit phase would have been changed by at least one-tenth of an orbit, to ensure that the ground-based telescopes would be able to confidently measure the new period (Rivkin et al. 2021). This requirement factored into the design of the DART spacecraft (Adams et al. 2019) and the mission’s trajectory and impact geometry (Atchison et al. 2016; Rivkin et al. 2021). An analysis conducted during DART’s 10 months cruise period indicated that, given the spacecraft’s mass, speed, and planned intercept design, any impact of the DART spacecraft with Dimorphos would result in reducing the orbital period by more than 73 s, including grazing impacts that occurred well off-center from the body.

If DART impacted near the center of Dimorphos and the incident momentum from the DART spacecraft was simply transferred to Dimorphos in a completely inelastic collision with no further momentum enhancement, a binary orbital period reduction of roughly 7 minutes was expected (Cheng et al. 2018). However, the impact simulations conducted in preparation for DART’s kinetic impact test indicated that there could be considerable enhancement to the momentum transferred to Dimorphos due to the ejecta produced, depending on the material strength, impact conditions, and other properties of Dimorphos and DART’s impact (Raducan & Jutzi 2022; Stickle et al. 2022). Dynamical models and analysis showed that the resulting binary orbital period could be reduced by

more than 40 minutes for the momentum enhancement factors indicated by some of the impact simulations (Meyer et al. 2021).

Following DART’s kinetic impact, both photometric observations and planetary radar observations began, with the goal to determine the post-impact binary orbit period through two independent approaches. Although the ejecta produced by DART’s impact event resulted in an immediate brightening of the system that lasted for  $\sim 24$  days (Graykowski et al. 2023; Kareta et al. 2023), the first photometric observations that could detect a mutual event in the lightcurve were obtained on 2022 September 28, just 29 hr after DART’s impact (Moskovitz et al. 2024; Thomas et al. 2023a). The first radar detection of Dimorphos in the echo power spectra occurred even earlier, on September 27, just 12 hr after DART’s impact (Thomas et al. 2023a). Radar observations continued through October 13, during the time when the distance between Earth and the Didymos system made such observations possible; echo power spectra were obtained during each radar observing window, and range-Doppler images were acquired on 10 different days (Thomas et al. 2023a). The initial set of post-impact photometric observations extended through October 10, until the bright Moon reduced the precision with which photometric observations could be obtained. During the time period from impact through October 10, measurements of 25 mutual events were obtained (Thomas et al. 2023a).

Independent analysis of both the photometric observations and radar observations yielded the same determination of the binary orbital period change. During a NASA press conference on 2022 October 11, just 15 days following DART’s impact, the NASA Administrator announced the initial result from the DART team that the binary orbital period of Dimorphos had been reduced by 32 minutes with an uncertainty of  $\pm 2$  minutes. Continued analysis of these initial data over the next months refined the period change determination to  $-33.0 \pm 1.0$  ( $3\sigma$ ) minutes (Thomas et al. 2023a). This result definitively verified the DART-2 Level 1 requirement, that the DART kinetic impact into Dimorphos had produced at least a 73 s binary orbital period change.

#### 4. DART-3: Precisely Measure the Period Change

Photometric observations from 2015 to 2021 obtained by 11 different telescopes were combined with data from observations obtained in 2003 to determine the pre-impact binary orbital period of Dimorphos about Didymos (Pravec et al. 2022). The pre-impact binary orbital period was determined with two separate analysis models, resulting in values of  $11.921473 \pm 0.000138$  hr ( $3\sigma$ ) (Scheirich & Pravec 2022) and  $11.921487 \pm 0.000028$  hr ( $1\sigma$ ) (Naidu et al. 2022). Using additional pre-impact observations from 2022 (Moskovitz et al. 2023), the pre-impact binary orbital period was further refined to  $11.921493 \pm 0.000091$  hr ( $3\sigma$ ) (Scheirich et al. 2024). These pre-impact best-estimates are consistent with each other within their uncertainties, fulfilling a portion of the DART-3 Level 1 requirement to determine the binary orbital period precisely before impact.

Additionally, this pre-impact knowledge put the post-impact observations in a good position to be able to achieve the remainder of the DART-3 Level 1 requirement of determining the change in the binary orbital period to within 7.3 s ( $1\sigma$ ) without being limited by the pre-impact knowledge of the system. The required value of 7.3 s was derived from ensuring

the post-impact orbital period was determined with an accuracy of at least 10%, even if only the minimum 73 s period change resulted from DART’s impact (Rivkin et al. 2021).

Post-impact photometric observations that were carried out for roughly 5 months, extending through 2023 February, contributed to the combined data set used to determine the period change (Moskovitz et al. 2024). From 2022 July through 2023 February, a total of 28 different telescopes distributed across the globe contributed to acquiring  $>38,000$  individual exposures and 224 lightcurves, representing over 1000 hr spent targeting the Didymos system (Moskovitz et al. 2024). This unprecedented observational data set of a binary asteroid system enabled the post-impact period change to be determined with high precision. Applying similar independent analysis models used pre-impact, the final binary orbital period following all these observations was determined to be  $11.3675 \pm 0.0012$  hr ( $3\sigma$ ) (Scheirich et al. 2024) and  $11.3674 \pm 0.0004$  hr ( $1\sigma$ ) (Naidu et al. 2024), indicating a period change of  $-33.24$  or  $-32.25$  minutes, respectively. The two independent analysis values provide the same result within their uncertainties, with each reporting a  $1\sigma$  error of 1.4 s, which is well below 7.3 s and thus achieving the DART-3 Level 1 requirement.

The high quality of the post-impact observational data set additionally allowed an examination of whether the period change remained at a constant value during the timeframe of the observations, from 2022 September through 2023 February. The two analysis models indicate that the binary orbital period immediately after impact was  $\sim 20$ – $30$  s longer than the final period observed, depending on the approach used to account for the changing period (Naidu et al. 2024; Scheirich et al. 2024). The changing period following DART’s impact is consistent with the presence of an exponentially decaying drag-like force acting on Dimorphos, with an estimated time constant of  $\sim 12$  days (Naidu et al. 2024). Analysis of the dynamics of the system supports that the changing period may be caused by interactions with the massive cloud of ejecta, with the outward scattering of ejecta decreasing the orbital period (Richardson et al. 2024). By a few months after DART’s impact, the data do not indicate any further measurable change in the orbital period (Naidu et al. 2024; Scheirich et al. 2024).

The extensive post-impact observational data sets also contributed key insights into understanding DART’s impact event and the dynamics of the binary Didymos system. These aspects are covered under the requirement DART-4B and discussed in Section 6. It is worth noting here, though, that the rotation of Didymos is a necessary component to account for in the lightcurve analysis to determine the binary orbital period. The analysis shows that the rotation period of Didymos post-impact is indistinguishable from its pre-impact value of  $2.260 \pm 0.001$  hr ( $3\sigma$ ) (Thomas et al. 2023a), with ongoing work to further reduce that uncertainty.

#### 5. DART-4A: Determine the Momentum Enhancement Factor

The momentum enhancement factor,  $\beta$ , is the ratio of the momentum transferred to the target body relative to the incident momentum of the spacecraft and quantifies how the ejecta produced during a deflection attempt contributes to the momentum imparted to the target (Holsapple & Housen 2012). In a perfectly inelastic collision, with zero ejecta momentum,  $\beta = 1$  by definition. However, the ejecta produced during a

deflection attempt carries off momentum, effectively giving an extra push to the target and making  $\beta > 1$ . While  $\beta$  is conceptually simple as just the ratio of the imparted momentum to the incident momentum, the mathematical details become more complicated when the geometry of the Didymos binary asteroid system, DART's impact event, local impact site topography, and resulting ejecta properties are fully considered. Consequently, prior to DART's impact event, Appendix B of Rivkin et al. (2021) provides a detailed three-page mathematical description of the formulation of  $\beta$  and its planned application in the context of the DART mission. The determination of  $\beta$  from DART's results is given in Cheng et al. (2023), which details the specific mathematical approach ultimately used and shows the details of DART's impact geometry.

The mass, impact velocity, and incoming trajectory of the DART spacecraft are well-determined quantities (Daly, Ernst, Barnouin, et al. 2023), leaving the major unknown components required to determine  $\beta$  to be the change in the orbital velocity of Dimorphos, the mass of Dimorphos, and the net ejecta direction. A Monte Carlo approach was used to produce a distribution of velocity changes that were consistent with the period change determined by the ground-based observations (Thomas et al. 2023a) and that accounted for uncertainties in the Didymos-system parameters (Cheng et al. 2023). The net ejecta direction was constrained using observations from Hubble Space Telescope (Li et al. 2023) and LICIAcube images (Dotto et al. 2024), which showed the net ejecta direction to be opposite of DART's incoming trajectory to within roughly  $20^\circ$  (Cheng et al. 2023; Deshapriya et al. 2023; Hirabayashi et al. 2024). The net ejecta direction and Dimorphos' orbital velocity direction were thus roughly the same, and hence,  $\beta$  was calculated in the along-track direction (Cheng et al. 2023).

The sizes of Didymos and Dimorphos and their separation distance were constrained by DRACO approach images, and DRACO images were also used to determine the shape, and hence volume, of Dimorphos (Daly, Ernst, Barnouin, et al. 2023; Thomas et al. 2023a). The total mass of the binary system is constrained by the pre-impact orbit period; though, given that Didymos is significantly larger than Dimorphos, this does not provide a direct constraint on the mass of Dimorphos. Telescopic observations of the Didymos system taken after DART's impact, during the following days when the signal from the Didymos system was dominated by ejecta from Dimorphos, indicate that Dimorphos, like Didymos, is an S-type asteroid (Bagnulo et al. 2023; Lin et al. 2023; Polishook et al. 2023; Gray et al. 2024; Ieva et al. 2024; Lazzarin et al. 2024). While these telescopic observations provide evidence that the composition of Dimorphos is the same as Didymos, the density of the objects could still be different depending on the macroporosity of the bodies. Thus, the analysis considered a range for the density of Dimorphos from 1500–3300 kg m<sup>-3</sup>, with a preferred estimate of the density of Dimorphos of 2400 kg m<sup>-3</sup>, given the knowledge of the Didymos system at the time (Cheng et al. 2023).

From the Monte Carlo approach, an instantaneous reduction in Dimorphos' along-track orbital velocity component of  $2.70 \pm 0.10$  mm s<sup>-1</sup> ( $1\sigma$ ) was calculated (Cheng et al. 2023). Considerations of mass loss, reshaping, and additional observational data suggest minor refinements in the estimate of the along-track velocity change (Meyer et al. 2023a;

Naidu et al. 2024; Richardson et al. 2024), but the density of Dimorphos is the largest source of uncertainty currently. Considering the full range of plausible Dimorphos densities, the calculation of  $\beta$  yielded a range of values from 2.4 to 4.9 (Cheng et al. 2023). If Dimorphos is assumed to have a density of 2400 kg m<sup>-3</sup>, then the resulting  $\beta$  value is 3.6 (Cheng et al. 2023). The largest uncertainty in the  $\beta$  value resulting from DART's kinetic impact test is due to the uncertainty in the mass of Dimorphos. Thus, minor refinements in the shape of Dimorphos (Daly et al. 2024) or the period change caused by DART's impact (Naidu et al. 2024; Scheirich et al. 2024) that have occurred since this initial calculation of  $\beta$  (Cheng et al. 2023) do not have a significant impact on this overall result (Richardson et al. 2024). The determination of the  $\beta$  value produced from DART's kinetic impact test achieved the mission's DART-4A Level 1 requirement.

The range of  $\beta$  values determined from the DART mission are within the range of pre-impact predictions from simulations, which spanned  $\beta$  values from 1 to 6 (Raducan & Jutzi 2022; Stickle et al. 2022). Experiments have also determined a comparable range of  $\beta$  values, including an experiment with a target that was a collection of stones to mimic a rubble pile and resulted in a  $\beta$  value of 3.4 (Walker et al. 2022). Section 6.3 provides a more complete reference listing of pre-impact models and experiments. While there is uncertainty in the  $\beta$  value due to the unknown mass of Dimorphos, the full range of  $\beta$  values determined for the DART experiment are all  $>2$ , indicating that more momentum was transferred to Dimorphos from the escaping impact ejecta than was incident with the DART spacecraft. The  $\beta$  value is key to informing the strategy of a kinetic impactor approach to mitigate a future asteroid impact threat to Earth. Should a  $\beta$  value  $>2$  be valid across a wide range of asteroids, it would mean important performance improvements for kinetic impactor asteroid deflection missions.

## 6. DART-4B: Investigate the Didymos–Dimorphos System and the Results of DART's Impact

In contrast to the other DART Level 1 requirements, DART-4B was written to be less prescriptive, to encompass the wide range of possible effects resulting from DART's first-of-its-kind kinetic impact test, and to enable activities within DART's investigation to understand them. The overall intent of DART-4B captures the requirement to not simply report what DART's kinetic impact test did to Dimorphos but rather also to understand DART's kinetic impact, so it could be applied to other asteroids in the future, if the need arises. In addition to DRACO and LICIAcube images, over 5 dozen telescopes on all seven continents and in space participated in the 2022–2023 observation campaign of the DART Investigation Team, as shown in Figure 4. Additionally, telescopic observations were conducted by groups unaffiliated with the DART Investigation Team and are also discussed in the subsections that follow, all working to maximize the data obtained from DART's unique first demonstration of asteroid deflection. Given the wide-ranging results that relate to the DART-4B Level 1 requirement, this section is broken into four subsections below.

### 6.1. Ejecta Observations and Evolution

The ejecta produced by DART's collision was observed by LICIAcube, space-based imaging systems, and ground-based



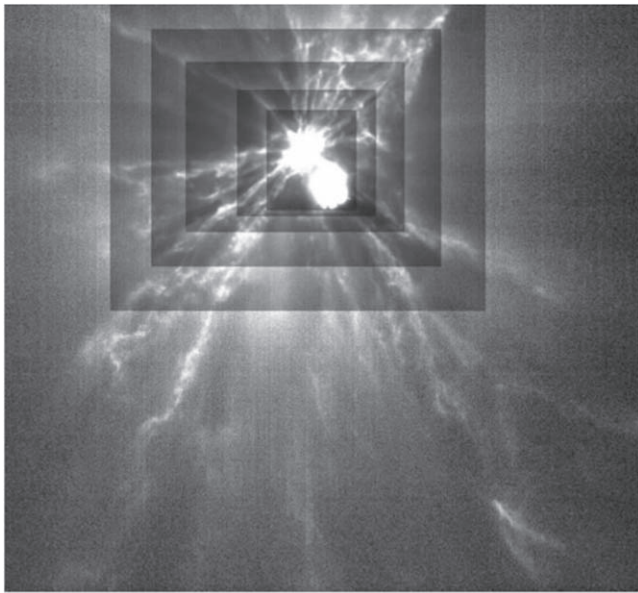
**Figure 4.** Map depicting the telescopic facilities on Earth and in space that contributed observations to the efforts of the DART Investigation Team. Numerical figures in parentheses next to telescope names indicate the telescope size. Telescopes, alphabetically by state/country, followed by space telescopes—Antarctica, Antarctic Search for Transiting ExoPlanets (ASTEP); Arizona, Lowell Discovery Telescope (LDT), Lowell Observatory 42 inch Hall telescope; Spacewatch, University of Arizona; Vatican Advanced Technology Telescope (VATT); Argentina, Bosque Alegre Astrophysics Station (EABA), Jorge Sahade Telescope at the El Leoncito Astronomical Complex; Australia, Las Cumbres Observatory Global Telescope Network (LCOGT); Bulgaria, Rozhen; California, Table Mountain Observatory (TMO) and the Goldstone Observatory; Palomar Observatory; Canary Islands, Telescopio Nazionale Galileo (TNG), Nordic Optical Telescope (NOT), Las Cumbres Observatory Global Telescope Network (LCOGT), Telescopio Carlos Sánchez (TCS), Jacobus Kapteyn Telescope (JKT), Instituto de Astrofísica de Canarias (IAC), Telescopio Abierto Remoto (TAR); Czechia, Ondřejov; Chile, Atacama Large Millimeter Array (ALMA) Radio Telescope, Very Large Telescope (VLT), Magellan Clay Telescope, Southern Astrophysical Research Telescope (SOAR), La Silla Observatory, Las Cumbres Observatory Global Telescope Network (LCOGT), Swope Telescope; Asteroid Terrestrial-impact Last Alert System (ATLAS), Small and Moderate Aperture Research Telescope System (SMARTS), TRAnsiting Planets and Planetesimals Small Telescope (TRAPPIST)-South; Georgia, Abastumani; Hawaii, NASA Infrared Telescope Facility (IRTF); Asteroid Terrestrial-impact Last Alert System (ATLAS); Faulkes North; Israel, Wise Observatory; Italy, Asiago Astrophysical Observatory; Kazakhstan, Tien Shan; Kenya, DART-OPTIK team; Massachusetts, Sugarloaf Mt.; Michigan, Michigan State University (MSU); Morocco, TRAnsiting Planets and Planetesimals Small Telescope (TRAPPIST)-North; Namibia, Drebach-South Observatory, Springbok Observatory; New Mexico, Magdalena Ridge Observatory (MRO); New Zealand, University of Canterbury Ōteihai Mount John Observatory, Microlensing Observations in Astrophysics (MOA); Qatar, Qatar University; Réunion Island, Les Makes Observatory; Slovakia, Stará Lesná; South Africa, South African Astronomical Observatory (SAAO), Las Cumbres Observatory Global Telescope Network (LCOGT), Small Aperture Robotic Telescope Network (SMARTnet), Watcher Telescope; Asteroid Terrestrial-impact Last Alert System (ATLAS); South Korea, Bohyunsan Optical Astronomy Observatory (BOAO); Texas, Las Cumbres Observatory Global Telescope Network (LCOGT); Turkey, TÜBİTAK National Observatory (TUG); Uzbekistan, Maidanak; West Virginia, Green Bank Observatory. Space telescopes: Hubble Space Telescope (HST), James Webb Space Telescope (JWST), NASA’s Lucy mission spacecraft’s L’LORRI imager.

telescopic facilities. These observations, ranging from a spacecraft flying by the Didymos system moments after DART’s impact to telescopic facilities observing Didymos for 9 months post-impact, provide a rich data set and insight into the ejecta and its evolution.

LICIACube captured images both immediately before and after DART’s impact and detected a brightness increase of roughly a factor of 5 in the LEIA pixel values due to DART’s impact (Dotto et al. 2024). LICIACube made its closest approach to Dimorphos 168 s after DART’s impact at a distance of approximately 58 km; LICIACube continued to image the Didymos system until 320 s after impact (Dotto & Zinzi 2023). In total, 426 scientific images were returned, and LICIACube continued to communicate with Earth for roughly 1 month following its Didymos flyby, after which time communication was lost. The LICIACube images reveal a complex and heterogeneous ejecta pattern, as shown in

Figure 5. By tracking ejecta features and clumps in the rays through the LICIACube images, early evolution ejecta speeds were found to range from a few tens of meters per second up to roughly  $500 \text{ m s}^{-1}$  (Dotto et al. 2024). Analysis of the LICIACube images shows a wide cone of ejecta, with an opening angle of  $\sim 140^\circ$  (Dotto et al. 2024). Further analysis of LICIACube images have shown that the geometry of the ejecta plume is an elliptical cone that can be described by two angles, a wide opening angle of about  $138^\circ$  and a narrow opening angle of about  $102^\circ$  (Deshapriya et al. 2023). Additionally, the intersection of the derived ejecta cone with the surface of Dimorphos corresponds to a region roughly 65 m in radius, which is a substantial portion of the impact hemisphere of Dimorphos (Deshapriya et al. 2023). Examination of the RGB images returned by LUKE suggests that the ejecta plume became spectrally redder with increased distance from Dimorphos, which is attributed to either the smaller size of





**Figure 5.** LICIACube image acquired 143 s following DART’s kinetic impact, showing a complex system of ejecta rays. Each rectangle represents a different level of contrast in order to better see the fine structure in the ejecta. The innermost rectangle is roughly 1.3 km wide. (LICIACube LUKE image triplet acquired at 23:16:47 UTC; credit: ASI/NASA/APL.)

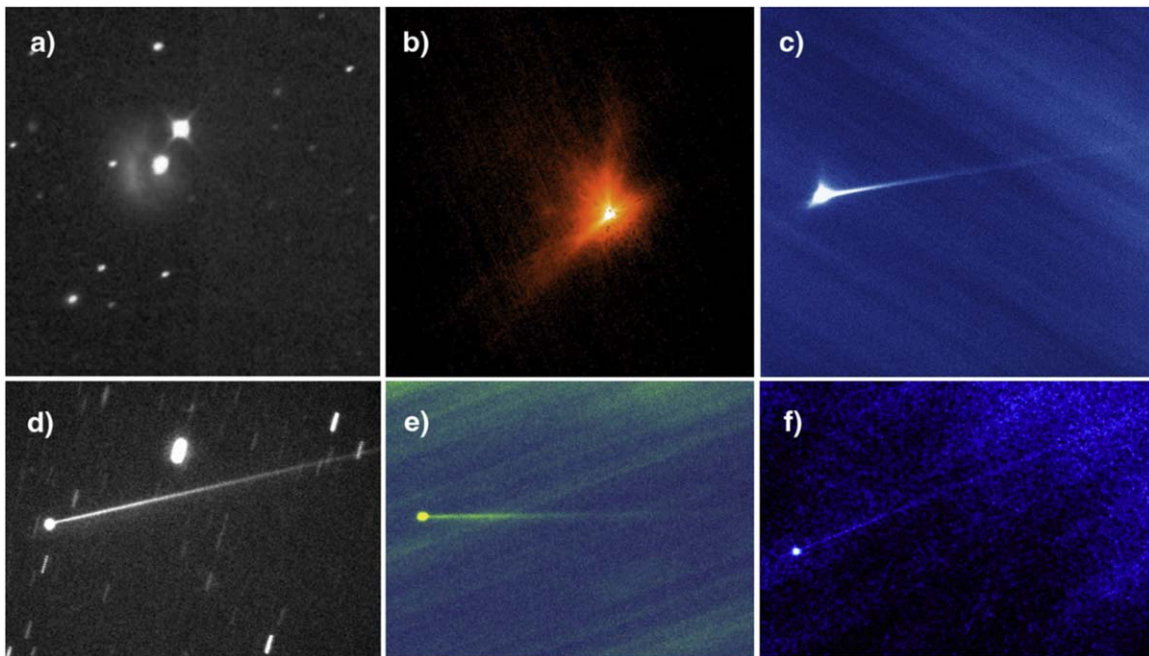
the dust grains in the outer ejecta or less altered material excavated from Dimorphos’ subsurface (Dotto et al. 2024). In addition to clumps and diffuse features viewed in the LICIACube images, the images also show numerous individual boulders ejected from Dimorphos. As determined by mapping  $>90$  ~meter-sized boulders, the distribution of the boulders that can be tracked in the LICIACube images shows clustering in an ejection direction nearly perpendicular to DART’s incoming trajectory, in the direction of Dimorphos’ south pole, with a speed of tens of meters per second (Farnham et al. 2023). Efforts to provide additional constraints on the ejecta properties from modeling LICIACube images are ongoing (Kolokolova et al. 2022; Lolachi et al. 2023; Ivanovski et al. 2024).

The moment of DART’s impact was also captured by a number of Earth-based telescopes (Fitzsimmons et al. 2023; Graykowski et al. 2023; Shestakova et al. 2023) as well as the Lucy mission in space (Weaver et al. 2024). An immediate fast plume of material was observed, as shown in Figure 6(a), composed of material with speeds reported as ranging from roughly  $1 \text{ km s}^{-1}$  up to  $3.6 \text{ km s}^{-1}$  (Fitzsimmons et al. 2023; Graykowski et al. 2023; Shestakova et al. 2023; Weaver et al. 2024). In particular, alkali metal neutral emission lines were observed associated with DART’s impact event that suggested relative amounts close to solar system abundances, evidence that is consistent with the fast plume being composed of material that originated from Dimorphos (Shestakova et al. 2023). The brightness of the fast plume was seen to correlate with the filter bandpass, such that Earth-based observations taken through filters that encompassed Na or K emissions observed a brighter fast plume (Fitzsimmons et al. 2023). A lower brightness observed by Lucy in comparison to ground-based observations has also been attributed to the wider bandpass of that instrument though, different phase angle viewing conditions may have contributed as well (Weaver et al. 2024). While the fast ejecta plume contributed substantially to the overall initial brightening of the Didymos system, the upper

limit estimates of the mass associated with the fast ejecta plume are just a few hundreds to a few thousands of kilograms of material (Fitzsimmons et al. 2023; Graykowski et al. 2023; Weaver et al. 2024), a small fraction of the total ejecta mass estimated, as discussed in the next paragraphs.

In the hours that followed DART’s impact, both Hubble Space Telescope (HST; Li et al. 2023) and James Webb Space Telescope (JWST; Thomas et al. 2023b; Figure 6(b)) captured views of the Didymos system and the resulting ejecta. The wide opening angle of the ejecta cone viewed by LICIACube in the minutes following impact was confirmed in these telescopic observations. An analysis that combined the LICIACube and HST observations and accounted for the different viewing conditions of each also showed an elliptical ejecta plume (Hirabayashi et al. 2024), with cone geometry results similar to those obtained by analyzing only LICIACube images (Deshapriya et al. 2023). Ground-based telescopes and HST also obtained views of the evolution of the ejecta over its first few hours, evolving from a cone to the initial indications of a tail of material leaving the Didymos system within a few hours of DART’s impact (Li et al. 2023; Murphy et al. 2023; Opatom et al. 2023; Rožek et al. 2023; Lister et al. 2024). The complex evolution of the ejecta is consistent with being influenced by the gravitational interaction between Didymos and Dimorphos as a binary system and with the ejected dust being driven out into a tail by solar radiation pressure (Li et al. 2023). Observations of the ejecta tail continued for many months following DART’s impact (Kareta et al. 2023; Lin et al. 2023; Moreno et al. 2023; Murphy et al. 2023; Opatom et al. 2023; Rožek et al. 2023; Gray et al. 2024; Lister et al. 2024) as shown by the examples in Figures 6(c)–(f). The ejecta tail ultimately extended over 70,000 km in length. Deep HST images acquired in 2022 December revealed a population of meter-sized and larger boulders, comoving with the Didymos system with speeds consistent with being among the slowest moving material to escape the system (Jewitt et al. 2023).

As the tail driven by solar radiation pressure continued to lengthen, the Didymos system remained clearly elevated in brightness due to ejecta in the system for  $\sim 24$  days following DART’s impact (Graykowski et al. 2023; Kareta et al. 2023; Lister et al. 2024). At roughly 8 days post-impact, a pause in the dimming of the brightness was noted by multiple telescopes (Kareta et al. 2023; Rožek et al. 2023; Lister et al. 2024), which also coincided with the observation of a secondary tail in the ejecta (Li et al. 2023; Murphy et al. 2023). It has been suggested that these features at 8 days post-impact may be due to a secondary release of material, such as fallback of larger ejecta from the initial impact event (Kareta et al. 2023; Lin et al. 2023), which models suggest would occur for the first few weeks following DART’s impact (Moreno et al. 2023; Ferrari et al. 2024). However, it has also been suggested that the gravitational interactions between slower ejecta and the Didymos binary system naturally can produce a secondary tail without the need for additional impact or disruption events (Ferrari et al. 2024) or that the appearance of a secondary tail may be due to the projection of the ejecta cone and the viewing geometry of the observations (Kim & Jewitt 2023). Spectral and color observations (Lin et al. 2023; Polishook et al. 2023; Ieva et al. 2024) as well as polarimetry observations (Bagnulo et al. 2023; Gray et al. 2024) provide evidence that the ejecta excavated from Dimorphos share similar properties to Didymos as an S-type asteroid. Extended polarimetry observations show



**Figure 6.** A small sampling of the observations of the ejecta resulting from DART’s kinetic impact event. (a) Las Cumbres Observatory Global Telescope Network, South Africa—2022 September 26, 15 minutes post-impact. The frame is roughly 19,000 km across. (b) JWST NIRCam—2022 September 27, 1.5 hr post-impact, acquired in the F090W filter (pivot wavelength 0.90  $\mu\text{m}$ ). The frame is roughly 300 km across. (c) Ōtehiwai Mt. John Observatory, New Zealand—2022 October 6. The frame is roughly 24,000 km across. (d) Magdalena Ridge Observatory, USA—2022 November 30. The frame is roughly 24,000 km across. (e) Lowell Discovery Telescope, USA—2023 March 14. The tail is measured in this deep stack of frames totaling 20,000 s to be roughly 70,000 km in length. (f) Hubble Space Telescope—combined products from images acquired 2023 June 30–July 6, with 2.4 hr total exposure time, with filter F350LP (pivot wavelength 587 nm). The frame is roughly 70,000 km across.

that an immediate drop in polarization was associated with DART’s impact event and that lower polarization persisted through all the subsequent months of observations; this suggests that smaller or brighter particles than the pre-impact surface were ejected by DART and that these particles continue to exist in the system, either in orbit or deposited on the surface (Gray et al. 2024; Penttilä et al. 2024). Spectral variations observed about 25 days after DART’s impact suggest the presence of a cloud of dust around the system, partially and unevenly obscuring the surface, and similar spectral observations in late 2022 December do not show such spectral variations (Lazzarin et al. 2024), consistent with the majority of the ejecta having dissipated within a month following DART’s impact event and the system brightness returning to its pre-impact level (Graykowski et al. 2023; Kareta et al. 2023; Lister et al. 2024).

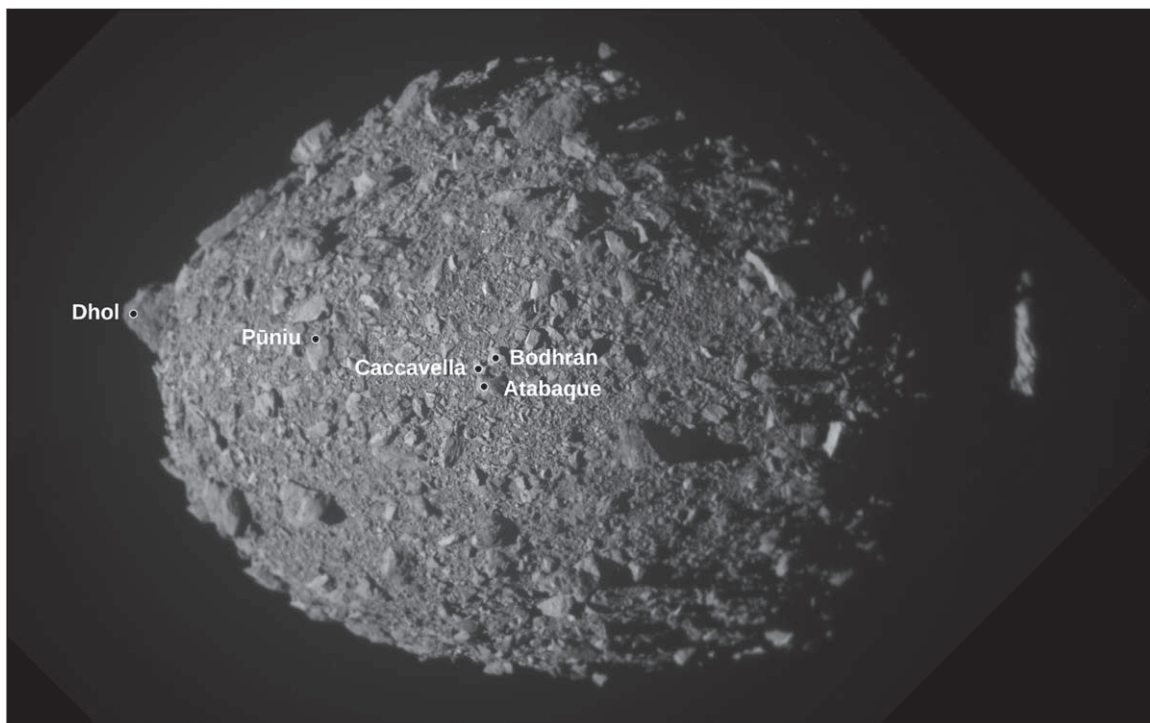
Analysis and models of the ejecta observations, informed by pre-impact studies (Fahnestock et al. 2022; Ferrari et al. 2022; Moreno et al. 2022; Rossi et al. 2022; Tancredi et al. 2022), were used to characterize the ejecta dust properties, including the particle size distribution and mass. The particle sizes in the ejecta tail are estimated to range from micrometers to a few centimeters, with radiation pressure sorting the particle size distribution along the tail (Li et al. 2023; Lin et al. 2023; Moreno et al. 2023; Ferrari et al. 2024). Observations of the reflectance slope of the evolving ejecta showed that the initial ejecta was bluer than the pre-impact system, while the tail that formed became redder over the weeks following impact, consistent with being composed of progressively larger particles (Opitom et al. 2023). Observations made with the Atacama Large Millimeter/Submillimeter Array (ALMA) and the Atacama Compact Array determined the thermal emission from the Didymos system and the resulting ejecta, providing an

estimate for the mass of the ejecta of  $1\text{--}6 \times 10^7$  kg (Roth et al. 2023). A total ejecta mass estimate of  $>10^7$  kg is consistent with the mass of ejecta estimated from modeling the fading rate of Didymos over the first few weeks from optical observations (Graykowski et al. 2023) and consistent with the results and lower limits derived from modeling the ejecta evolution (Kim & Jewitt 2023; Moreno et al. 2023; Ferrari et al. 2024), as tabulated in Richardson et al. (2024). Investigating the longer-term evolution of the dust produced by DART’s impact event suggests that very small amounts of dust may become meteors on Mars in the next century or the Earth–Moon system over the next millennium (Peña-Asensio et al. 2024).

The final observations of the ejecta tail obtained in 2023 were made by HST in 2023 July, as shown in Figure 6(f), and they show a well-resolved ejecta tail without a clear sign of detachment even 9 months following DART’s impact event. Observations of the Didymos system will be possible again in 2024, which opens the possibility to continue studying the evolution of the ejecta created by DART’s kinetic impact, to understand DART’s planetary defense test as well as to gain insight into active asteroids and natural impact events on small bodies (Li et al. 2023).

## 6.2. *Dimorphos and the Impact Site*

Reconstruction of the DART spacecraft’s trajectory into the local topography of Dimorphos shows that the DART spacecraft bus impacted between two large, roughly 6 m boulders, with the solar arrays impacting these boulders tens of microseconds prior to the main mass of the DART spacecraft (Daly, Ernst, Barnouin, et al. 2023). Following the IAU-approved nomenclature theme of percussion musical instruments for features on Didymos and Dimorphos, in 2023



**Figure 7.** Mosaic of Dimorphos, with named features. This high-resolution view of Dimorphos was created by combining the final 10 full-frame images obtained by DRACO and layering the higher-resolution images on top of the lower-resolution ones. Dimorphos is oriented so that its north pole is toward the top of the image. The extent of Dimorphos in the Z-direction is 115 m.

January, these two boulders were named Atabaque and Bodhran, and are shown in Figure 7. Caccavella is a 2 m boulder also near the impact site. Other features named in 2023 January include Pūniu, which is a small boulder well-resolved in the DRACO images but located farther from the impact site that is used to define the Dimorphos coordinate system, and Dhol, the distinctive boulder seen on the limb of Dimorphos.

The shape of Dimorphos was derived from stereophotoclinometry using calibrated DRACO images (Ernst et al. 2024), following the methods established pre-impact (Daly et al. 2022). The approach greatly benefitted from the distinctive curvature of the terminator as captured in the images and from reflected light from Didymos faintly illuminating the nonsunlit surface of Dimorphos in the DRACO images (Daly et al. 2024). The final shape model of Dimorphos (Daly et al. 2024) provides minor improvements over the preliminary version (Daly, Ernst, Barnouin, et al. 2023), particularly for boulders along the sunlit limb, fine-scale lit terrain along the terminator, and the shape of the dark limb lit by Didymos; however, the volume differs by  $<3\%$  between the preliminary and final models (Daly et al. 2024) and hence does not affect the determination of  $\beta$  discussed in Section 5, given the remaining large uncertainty in the mass of Dimorphos. Dimorphos' extents in the X, Y, Z dimensions are 179, 169, and 115 m (Daly et al. 2024). This result is in contrast to the elongated shape that was assumed for Dimorphos prior to impact based on comparisons to other binary asteroid systems, where the X and Y extents differ more substantially (Rivkin et al. 2021; Richardson et al. 2022). The analysis of LICIAcube images of Dimorphos, obtained from a different viewing geometry than DRACO and illuminated by scattered light within the ejecta cloud, is also consistent with this derived final shape model (Zinzi et al. 2023).

Calibrated DRACO images (Ernst et al. 2024) that have been projected onto the Dimorphos shape model (Daly et al. 2024) have enabled detailed geologic investigations of Dimorphos and the DART impact site, in many cases by taking advantage of the analysis capabilities of the Small Body Mapping Tool (Ernst et al. 2018). The size–frequency distribution of boulders on Dimorphos is fit by a Weibull distribution, which suggests that the boulders might have originated from impacts but were also later modified by other processes, such as repeated impacts, thermal fragmentation, or reaccumulation processes (Pajola et al. 2024). Mapping of individual cracks seen on boulders also suggests that thermal-driven stresses are affecting the boulders on Dimorphos (Lucchetti et al. 2024). The boulders on Dimorphos are elongated, with a width-to-length ratio of  $\sim 0.6$ , which is similar to that measured for the small rubble-pile asteroids of Itokawa, Ryugu, and Bennu (Robin et al. 2024). These axial ratios imply that the boulders were formed through impact processing and support the hypothesis that Dimorphos' formation involved a catastrophic disruption event (Robin et al. 2024). Additionally, the measurements of the angularity of the boulders provide insight into the bulk internal friction angle of Dimorphos' surface materials, with an estimate of  $\sim 35^\circ$ , which is also similar to that determined for these other small asteroids (Robin et al. 2024).

Although the surface of Dimorphos is dominated by boulders, 12 topographic depressions have been identified as plausible impact craters, ranging in size from 3 to 11 m, and a few long lineaments have been mapped on its surface (Barnouin et al. 2024). Applying a photometric correction to the DRACO images to account for the lighting geometry shows evidence for a set of long albedo striations running across Dimorphos, which have been suggested to be due to variations in surface roughness (Buratti et al. 2024). The surface geology of Dimorphos is suggestive of a loosely consolidated rubble

pile, although the possibility of some larger, stronger aggregates in its interior cannot be ruled out currently, and the presence of lineaments has implications for the body's strength and subsurface structure (Barnouin et al. 2024). These geologic studies provide insight into understanding Dimorphos as it relates to DART's kinetic impact test but also to understanding the asteroid population in general, as Dimorphos is the smallest asteroid ever investigated by a spacecraft.

### 6.3. DART's Kinetic Impact Event

All of the previously discussed results, from the details of DART's impact, to the period change, to the determination of  $\beta$ , to observations of the ejecta and the nature of Dimorphos, factor into understanding DART's kinetic impact event. As such, it is a complicated problem with many factors and parameters to consider. Pre-impact models (Jutzi & Michel 2014; Stickle et al. 2015; Bruck Syal et al. 2016; Stickle et al. 2017; Raducan et al. 2019, 2020; Rainey et al. 2020; Stickle et al. 2020; Raducan et al. 2021, 2022a, 2022b; Kumamoto et al. 2022; Luther et al. 2022; Owen et al. 2022; Raducan & Jutzi 2022; Stickle et al. 2022; Graninger et al. 2023; DeCoster et al. 2024b) and experiments (Walker et al. 2013; Flynn et al. 2015; Hoerth et al. 2015; Durda et al. 2019; Chourey et al. 2020; Flynn et al. 2020; Ormö et al. 2022; Walker et al. 2022) showed a range of possible  $\beta$  values and have been crucial for informing the post-impact models and interpretations. Also, despite the wealth of data associated with DART's kinetic impact test, there still remain some key unknown quantities, in particular the mass and material properties of Dimorphos, ranging from the small-scale properties to the global-scale interior structure. Nonunique combinations of these asteroidal mechanical properties can produce similar values of  $\beta$  in impact simulations (Stickle et al. 2022).

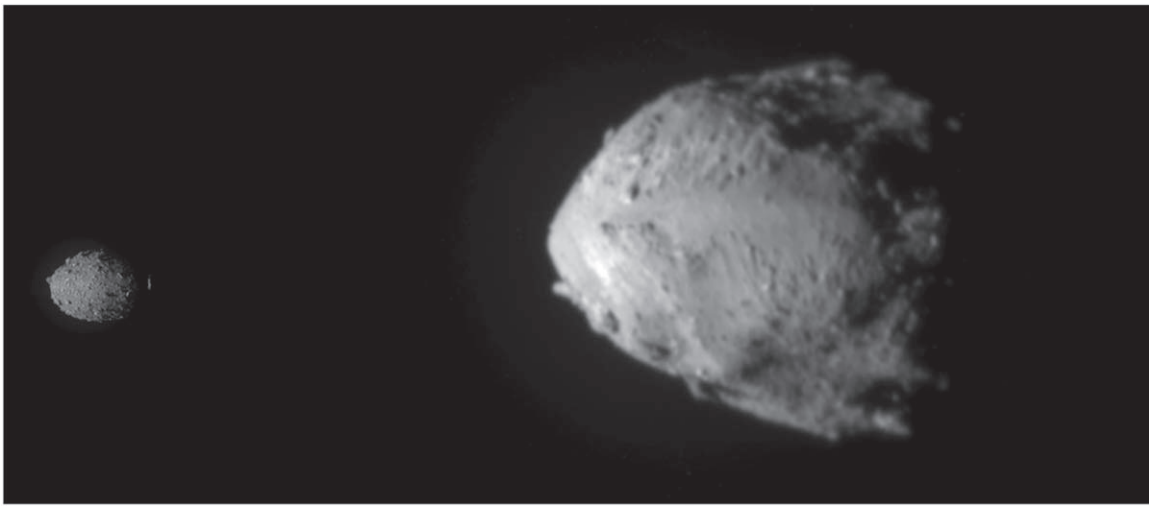
Numerical models conducted post-impact were informed by the shape of Dimorphos and its boulder-strewn surface and the trajectory and impact conditions of the DART spacecraft and incorporated those details into the starting conditions (DeCoster et al. 2024a; Raducan et al. 2024a; Stickle et al. 2024). The models show that the generally complex heterogeneous nature of the ejecta rays viewed by LICIACube, as seen in Figure 5, are consistent with DART's impact into a nonuniform surface, with the location and size of the boulders influencing the resulting ejecta pattern (Raducan et al. 2024a; Stickle et al. 2024). This is in line with laboratory observations of ray formation after impact into heterogeneous materials (Kadono et al. 2019; Ormö et al. 2022). Impact simulations have been successful at modeling the wide opening angle of the ejecta cone discussed in Section 6.1 (Raducan et al. 2024a; Stickle et al. 2024); though, some models have suggested that, for cohesive strengths  $>500$  Pa, the wide ejecta cone is poorly reproduced (Raducan et al. 2024a). Impact simulations have also produced results consistent with the  $\beta$  values determined for DART's impact, as discussed in Section 5, but the models have differed in the conclusions they have drawn for the implied strength of Dimorphos. Some models where the near-surface strength can range from near-zero ( $\sim 10$  Pa) to "moderately weak" (tens of kPa) have been shown to produce  $\beta$  values consistent with DART's results (Stickle et al. 2024), while other models have concluded that cohesive strengths  $<$  a few Pa are required to provide the best-fit outcome in terms of  $\beta$  and the excavation timescale (Raducan et al. 2024a).

Analyses using LICIACube images of the plume have also been used to provide constraints on Dimorphos' material properties, using the approach established in pre-impact models (Cheng et al. 2020, 2022). LICIACube imaging of the ejecta plume shows no evidence for plume clearing at low altitude, and at roughly 3 minutes after DART's impact, the images show that the ejecta plume remains optically thick (Cheng et al. 2024). Modeling efforts concluded that these LICIACube imaging results, in combination with considering the momentum enhancement that resulted from DART's impact, are consistent with models where Dimorphos' strength is  $<500$  Pa and that the best fit results are obtained for the 5–50 Pa strength cases, which were the lowest considered in the study (Cheng et al. 2024).

The cohesive strength also factors into predicting the outcome of DART's impact on Dimorphos' surface. For a set of simulations that suggest  $>10$  Pa to tens of kPa, a crater with a diameter of  $\sim 30$ – $60$  m is predicted (Stickle et al. 2024), which is a sizable crater on Dimorphos, whose volume-equivalent diameter is only 150 m (Daly et al. 2024). For models that suggest a strength  $<$  a few Pa, the simulations suggest that DART's impact caused global deformation and reshaping of Dimorphos rather than a well-defined crater (Raducan et al. 2024a). Global reshaping from DART's impact event has also been suggested to potentially result in some deformation in the antipodal hemisphere based on numerical simulations of a gravitational aggregate target (Liu et al. 2024).

Given the high-quality and extensive post-impact photometric observations (Moskovitz et al. 2024), the observations have been able to provide constraints on the post-impact axial dimensions of Dimorphos, through both dynamical modeling of the orbit (Naidu et al. 2024) and by directly measuring the rotational lightcurve of Dimorphos in a subset of the observations (Pravec et al. 2023). The estimated post-impact equatorial axis ratio of Dimorphos from modeling the orbit is 1.3 (Naidu et al. 2024), differing significantly from the pre-impact oblate shape with an equatorial axis ratio of 1.02 (Daly et al. 2024). The Dimorphos rotational lightcurve is also suggestive of Dimorphos having different post-impact axial ratios (Pravec et al. 2023), outside of the uncertainties associated with the axial ratios that were determined using the pre-impact DRACO images (Daly et al. 2024). That the intersection of the derived ejecta cone with the surface of Dimorphos corresponds to a region roughly 65 m in radius also suggests large-scale modification of Dimorphos' surface (Deshapriya et al. 2023). Different post-impact axial ratios for Dimorphos are evidence of the creation of a large crater or reshaping of the body due to DART's impact. Perturbations on the gravitational fields between the two bodies that could stem from a DART-induced reshaping of Dimorphos are strong enough to influence the orbit period of Dimorphos and provide a minor contribution to the resulting period change (Nakano et al. 2022). An estimate of approximately  $-100$  s of the observed  $-33.24$  minutes period change may be attributed to this effect, although, the precise amount is sensitive to the extent of the reshaping (Nakano et al. 2024), and this has implications for fully interpreting the  $\beta$  value due to DART's impact (Meyer et al. 2023a; Nakano et al. 2024; Richardson et al. 2024).

DART's kinetic impact test demonstrated that the ejecta carried considerable momentum, and work is ongoing to more fully understand and evaluate how each ejecta component



**Figure 8.** A mosaic of DRACO images showing Dimorphos (left, extent in Z-direction, 115 m) and Didymos (right, extent in Z-direction, 607 m) oriented with their north poles toward the top of the image and with each asteroid and their distance to each other to scale. Dimorphos is a scaled down version of Figure 7. The image of Didymos is a composition of 58 DRACO images assembled by layering the higher-resolution images on top of the lower-resolution ones.

contributed to the  $\beta$  value determined. Analysis of the ejecta plume geometry suggests that Dimorphos’ curvature resulted in an elliptical ejecta cone and a reduction of the momentum transferred relative to an impact on a flat target (Hirabayashi et al. 2024). Thus, a kinetic deflection strategy that gives consideration to the size of the object relative to the cone of the ejecta plume to be produced could result in higher  $\beta$  values by potentially utilizing multiple smaller impactors rather than a single one, and this may become even more relevant for smaller asteroid targets (Hirabayashi et al. 2024). For smaller asteroid targets, understanding when disruption rather than deflection will occur is also important, as modeling suggests that DART’s impact event may have been capable of disrupting an approximately 80 m diameter or smaller rubble-pile object (Raducan et al. 2024b). Prior knowledge of the target asteroid can provide valuable information to inform a kinetic impactor strategy (Statler et al. 2022), building on the knowledge gained from DART’s first kinetic impact test to inform future planetary defense missions (Chabot et al. 2023; Rivkin & Cheng 2023).

#### 6.4. The Binary Didymos System

The binary nature of the Didymos system was critical to the design of DART’s asteroid deflection mission, enabling Earth-based telescopes to measure and evaluate the deflection efficiency, as discussed in previous sections. In addition, investigations of Didymos and Dimorphos provide new insights into the formation and evolution of binary asteroids, which compose roughly 15% of the near-Earth asteroid population (Pravec et al. 2006). Figure 8 shows the Didymos–Dimorphos binary system to scale as imaged by DRACO. DRACO imaging of Didymos was more limited than for Dimorphos, as Didymos was not visible in the DRACO images sent to Earth as the spacecraft got closer to impacting Dimorphos (Ernst et al. 2024). The last image to contain all of Didymos’ sunlit surface was acquired 2.7 minutes prior to DART’s impact, providing a pixel scale of  $4.9 \text{ m pixel}^{-1}$  on Didymos. The final DRACO image that showed any of Didymos’ surface was obtained 1.2 minutes prior to impact, showing a very small portion of the surface near Didymos’ sunlit limb at  $2.2 \text{ m pixel}^{-1}$ . Thus, the spatial resolution of

DRACO images for Didymos is much lower than that of the submeter pixel-scale images obtained of Dimorphos, as shown in Figure 3.

One of the immediate results upon seeing the DRACO images was the realization that the shape of Didymos differed from that developed based on radar observations (Naidu et al. 2020). The Didymos radar shape model contained the distinctive bulge of Didymos seen at the equator in Figure 8, resulting in a “top-shape” as seen on other asteroids such as Ryugu (Watanabe et al. 2019) and Bennu (Barnouin et al. 2019). However, the  $X$ ,  $Y$ ,  $Z$  dimensions determined for Didymos from the radar shape model were 832, 838, and 786 m (Naidu et al. 2020). In contrast, the Didymos shape model derived by stereophotoclinometry using DRACO and LICIA-Cube images yields  $X$ ,  $Y$ ,  $Z$  extents of 819, 801 m, and only 607 m (Barnouin et al. 2024). This substantial difference in the  $z$ -axis, which was the dimension least constrained by the radar measurements, was apparent even in the approach images of DRACO, as seen in Figure 8. Dynamical modeling of Dimorphos’ orbit yields best-fit parameters for the dimensions of Didymos that are smaller than either those obtained by using the spacecraft images or the radar observations, giving  $X$ ,  $Y$ ,  $Z$  dimensions for Didymos of 788, 788, and 580 m (Naidu et al. 2024).

The smaller size of Didymos derived from spacecraft imaging and dynamical orbital modeling versus the previous radar observations affects the calculated density of Didymos, as the mass of the binary system is derived by fitting the binary orbit. DRACO imaging also provided a new data set to use to determine the separation distance of Didymos and Dimorphos prior to DART’s impact (Thomas et al. 2023a; Naidu et al. 2024). The best-fit orbit semimajor axis of  $1190 \pm 30 \text{ m}$  had been previously determined from radar observations (Naidu et al. 2020), and an analysis of DART data sets constrained the value to  $1189 \pm 17 \text{ m}$  (Naidu et al. 2024). Both of these factors contribute to determining the density of the Didymos system. Prior to DART’s impact, the density of the Didymos system was estimated as  $2170 \pm 350 \text{ kg m}^{-3}$  (Naidu et al. 2020), but using the results derived from dynamical modeling of Dimorphos’ orbit, the current best-estimate of the Didymos-system density is considerably higher, now estimated as 2790

$\pm 140 \text{ kg m}^{-3}$  (Naidu et al. 2024). Thermophysical modeling of the Yarkovsky effect yields a bulk density of  $2750 \pm 350 \text{ kg m}^{-3}$  for the Didymos system (Rozitis et al. 2024), also supporting a higher density for Didymos than previous work. The mass of Didymos comprises  $>99\%$  of the system's mass, and hence, the density of Dimorphos remains largely unconstrained by these calculations. However, a density of  $2790 \text{ kg m}^{-3}$  for Didymos has important implications for the stability, formation, and evolution of the Didymos binary system (Richardson et al. 2024). In particular, material cohesive strength is no longer a crucial requirement for maintaining Didymos' structural stability at the spin period of 2.26 hr, in contrast to pre-impact models that utilized a lower density for Didymos (Agrusa et al. 2024). Didymos' surface boulders and flattened shape with an equatorial ridge provide evidence that the body is a rubble pile, although, the noncircular, angular equatorial perimeter of Didymos also indicates that its interior probably contains some larger distinct aggregates as well (Barnouin et al. 2024).

The geologic features on the surface of Didymos appear more varied than the boulder-strewn surface of Dimorphos and include some of the features a pre-impact synthesis paper proposed might be seen in the images (Pajola et al. 2022). Three geological regions on Didymos have been mapped: one region located at low latitudes that possesses fewer large boulders and has a slightly lower albedo, another region at higher latitudes with multiple large boulders and degraded craters, and a transition region between the two other regions (Barnouin et al. 2024). The Didymos geology correlates with its surface elevation, with the rougher terrain corresponding to highlands and the smoother terrain to lowlands (Barnouin et al. 2024). Multiple plausible craters have been identified in the higher latitude region, with the largest being roughly 270 m in diameter (Barnouin et al. 2024). The crater size–frequency analysis suggests that the surface age of Didymos is  $\sim 12.5$  Myr, and Dimorphos is  $<0.3$  Myr (Barnouin et al. 2024). There is evidence for boulder tracks in the higher latitude region, which provide constraints on the surface cohesion of Didymos (Barnouin et al. 2024) and Didymos' bearing capacity, which corresponds to the maximum pressure that a surface can withstand without experiencing shear failure (Bigot, Lombardo, et al. 2024). In particular, the bearing capacity of Didymos is estimated to be substantially less than comparable materials on the Earth or the Moon, implying that it requires only a low amount of force for surface failure to occur for Didymos' low gravity environment (Bigot, Lombardo, et al. 2024). An examination of the surface roughness properties of both asteroids also suggests that some localized areas on Didymos may have experienced more recent resurfacing events, and that Dimorphos' comparatively rougher surface may be due to being younger than Didymos (Vincent et al. 2024).

The boulder size–frequency distribution for Didymos appears consistent with a continuation of that measured on Dimorphos, although, such effort is limited to boulders 10 m and larger in size, due to the DRACO pixel scales (Pajola et al. 2024). A comparison to the boulder size–frequency distributions observed on other asteroids indicates that Didymos and Dimorphos may be the most boulder-dense asteroids visited by spacecraft to date (Pajola et al. 2024). The boulder size–frequency distributions are consistent with both bodies having experienced catastrophic disruption in their past and being

rubble piles today, and are also suggestive that Dimorphos has inherited its material by mass-shedding from Didymos (Pajola et al. 2024). Investigations regarding the albedo, colors, and photometric properties of Didymos are ongoing, and can be used to inform pre-impact observations that suggested a subtle spectral variability in Didymos as a function of its rotational phase (Ieva et al. 2022), although spectral observations for a complete rotational period of Didymos in 2022 December did not find evidence for any significant variations (Lazzarin et al. 2024). The pre-impact thermal inertia value derived for Didymos is consistent with other S-type near-Earth asteroids (Rozitis et al. 2024). Observations using JWST 2 months following DART's impact showed that DART's impact did not change the thermal inertia of the Didymos system and also provided new insight into the thermal properties of Didymos' surface, showing spectral properties consistent with S-complex asteroids and suggesting emission from surface particles smaller than  $25 \mu\text{m}$  in size (Rivkin et al. 2023). Photometric properties of the Didymos system, derived by combining DRACO's approach imaging with ground-based observations over a range of solar phase angles, are also typical for S-type asteroids (Buratti et al. 2024). A Didymos brightness phase curve, constructed by combining both LICIAcube LUKE and ground-based observations, shows some differences from a typical S-type asteroid, leading to the suggestion that Didymos' surface may contain shock-darkened or impact melt minerals (Hasselmann et al. 2024).

Pre-impact studies were important in establishing the methodologies to be applied to investigate the post-impact dynamics of the Didymos system and in considering a wide range of possible outcomes (Agrusa et al. 2020, 2021; Meyer et al. 2021, 2023b; Agrusa et al. 2022; Makadia et al. 2022; Richardson et al. 2022). Overall, the DART kinetic impact test resulted in a small change to the dynamical state of the Didymos system that is generally consistent with pre-impact expectations, with the biggest surprises attributed to the flattened shape of Didymos compared to the radar-based model and the oblate pre-impact shape of Dimorphos (Richardson et al. 2024). Modeling the dynamics of the binary system following DART's impact indicates that the semimajor axis of Dimorphos' orbit was decreased by roughly 37 m (Meyer et al. 2023a) and now has a value of  $1152 \pm 18 \text{ m}$  ( $1\sigma$ ) (Richardson et al. 2024).

Models of the evolution of the ejecta suggest that roughly  $10^6 \text{ kg}$  of material are expected to have reimpacted Didymos or Dimorphos within the first 15 days following DART's impact (Moreno et al. 2023; Ferrari et al. 2024), with potential implications for the dynamics of the system (Richardson et al. 2024). Pre-impact studies suggested that ejecta impacting Didymos could result in reshaping of the body, which would be accompanied by a change in the rotational period of Didymos (Hirabayashi et al. 2019, 2022; Nakano et al. 2022); no change in the rotational period of Didymos has been detected over the months of telescopic observations that followed DART's impact event (Thomas et al. 2023a; Naidu et al. 2024; Scheirich et al. 2024), suggesting that measurable reshaping of Didymos did not occur.

No rotation period of Dimorphos has been obtained from pre-impact observations. However, the post-impact observations that have resolved the lightcurve of Dimorphos (Pravec et al. 2023) are consistent with Dimorphos being tidally locked, while also suggesting the possibilities of tumbling of

Dimorphos (Agrusa et al. 2021; Meyer et al. 2023a) and/or reshaping. If DART’s impact produced considerable reshaping of Dimorphos as discussed in Section 6.3, this reshaping may place the body outside of a currently stable shape and dynamical configuration, possibly providing a reservoir of material to maintain the tail (Richardson et al. 2024). Additionally, dynamical models show that reshaping also increases the chances for Dimorphos to enter a tumbling state (Meyer et al. 2023a; Nakano et al. 2024), and analyses of the Didymos-system lightcurve data show some deviations starting roughly 70 days after DART’s impact that may indicate the onset of tumbling (Scheirich et al. 2024). The investigation of the timescale of how a reshaped Dimorphos would reequilibrate into a new shape and dynamical configuration is ongoing.

As it relates to the formation of the Didymos binary system, the oblate shape of Dimorphos (Daly et al. 2024) was unexpected and is in contrast to the prolate shapes associated with other secondary members of binary asteroid systems (Ostro et al. 2006; Becker et al. 2015; Naidu et al. 2015; Pravec et al. 2016, 2019). The observation that pre-impact Dimorphos did not have an irregular shape and had a boulder-covered surface is consistent with modeling its formation as quickly accreting from material shed by a fast-spinning Didymos (Madeira et al. 2023), although, such a model also produces a prolate rather than oblate shape for Dimorphos. A suite of  $N$ -body simulations that followed the gravitational accumulation of a satellite after a mass-shedding event by a rapidly rotating primary showed that prolate shapes for the resulting satellite were preferred but that oblate shapes, like Dimorphos, were also occasionally formed (Agrusa et al. 2024). The  $N$ -body simulations showed that the satellite formed quickly, within a matter of days, and that the accretion process was highly chaotic, resulting in a wide range of outcomes (Agrusa et al. 2024). Whether Dimorphos formed with an oblate shape or evolved into an oblate shape is an ongoing area of study to gain understanding into the formation of binary asteroid systems (Agrusa et al. 2024).

The long-term dynamical evolution of a rubble-pile binary asteroid system is driven by binary Yarkovsky–O’Keefe–Radzievskii–Paddack (BYORP) effect and tides (Richardson et al. 2022). DART data have informed predictions for the effects of DART’s impact event on the long-term dynamical evolution of the Didymos–Dimorphos system, although, such predictions are sensitive to the exact shape of Dimorphos and the nature of any cratering or reshaping experienced (Cueva et al. 2024). In the case of a binary system, there are two  $\beta$  values to be considered: a  $\beta$  value for Dimorphos, which has been the focus of DART’s investigation (Cheng et al. 2023), and a heliocentric  $\beta$  value for the Didymos system, the momentum enhancement factor caused by the ejecta that escapes the binary system. A pre-impact analysis examined the range of possible heliocentric  $\beta$  values that could result from DART’s impact and demonstrated that the Didymos system would not be shifted onto a collision course with the Earth (Makadia et al. 2022), although, a measure of the Didymos system’s deflection about the Sun potentially could be made in the future (Richardson et al. 2022). A measurement of heliocentric  $\beta$  for the Didymos system has not yet been made; though, multiple high-quality stellar occultation observations obtained in 2022–2023, including detections of Dimorphos as the smallest object ever observed during an occultation

campaign, may make such a measurement possible in the next few years (Makadia et al. 2024).

During the DART mission, the team used a tabulated summary of the current best knowledge of the Didymos system, referred to as the design reference asteroid (DRA; Rivkin et al. 2021). The DRA was updated throughout the mission as new information yielded refined results for both pre-impact and post-impact parameters of the Didymos system, and it served to provide common input for the many modeling and analysis efforts being led in parallel across the team, such as the determination of  $\beta$ . Values summarized in the last version of the DRA produced by the DART team are provided in Table A1.

## 7. International Collaboration and the Hera Mission

International collaboration has been at the core of the DART mission since its origin. In 2003, ESA produced the first study report, led by Andrea Milani (1948–2018), for the Don Quijote mission concept, which would involve two spacecraft, one serving as a kinetic impactor and the other serving as an orbiter to measure the impact outcomes (Milani et al. 2003). ESA continued to study multiple variations on the Don Quijote concept through 2007 (Wolters et al. 2011; Michel et al. 2022). This led to the Asteroid Impact and Deflection Assessment (AIDA) collaboration a few years later (Cheng et al. 2015), with the NASA-led DART kinetic impactor spacecraft (Cheng et al. 2016) and the ESA-led Asteroid Impact Mission (AIM) rendezvous spacecraft (Michel et al. 2016). The AIM spacecraft, which would have rendezvoused with the Didymos system prior to DART’s impact and hence characterized the system both before and after DART’s kinetic impact test, was not selected for flight in 2016. The Hera mission was subsequently developed as an optimized version of AIM, with reduced risks and cost (Michel et al. 2018), and in 2018, Hera was approved for flight by ESA. Hera is on track to launch in 2024 and rendezvous with the Didymos system in late 2026 December, conducting a robust remote sensing campaign in 2027 to investigate the aftermath of DART’s kinetic impact event (Michel et al. 2022).

Given the development history of AIDA, DART, LICIA-Cube, and Hera, the DART Investigation Team benefited extensively from continued close international collaboration throughout the mission. The DART Investigation Team included roughly 300 scientists from over 100 different institutions that represented 29 different countries, as listed in Table B1. Thirty-two U.S. members were supported by NASA through the DART project as coinvestigators or in team leadership roles to ensure that the mission achieved its Level 1 requirements. In 2021, NASA selected four additional U.S. scientists to join the DART Investigation Team through a Participating Scientist Program. However, by having the DART Investigation Team open to individuals beyond those directly supported by NASA for the DART mission, both U.S. as well as international scientists were able to join and contribute to the DART Investigation Team through a wide range of funding sources, as detailed in the Acknowledgements section of this paper. This organization of the DART Investigation Team enabled the mission to include international cooperation for the international issue of planetary defense and to maximize what was learned from humanity’s first demonstration of asteroid deflection. While NASA’s DART project ended in 2023, the DART mission data archive

(Waller et al. 2024) is available within NASA's Planetary Data System, supporting further investigations and informing future international planetary defense investigations, such as Hera.

Hera is a highly capable orbiter spacecraft, equipped with a set of optical cameras, a spectral imager, a LIDAR, a thermal infrared imager, and a radio science system (Michel et al. 2022). In addition, Hera carries two CubeSats, which will be deployed in the Didymos system and communicate with the main spacecraft. The CubeSat Juventas carries a low-frequency monostatic radar as well as a gravimeter and an accelerometer (Michel et al. 2022). The Milani CubeSat, named in honor of Andrea Milani for the Don Quijote concept, has a near-infrared spectral imager and a microthermogravimeter (Michel et al. 2022). Hera's rendezvous observations will provide key measurements to further investigate the results of DART's kinetic impact test, in particular by measuring the mass of Dimorphos, by observing the surface of Dimorphos to reveal the nature of cratering or reshaping that resulted from DART's impact, by investigating the interior structure of the asteroids, and by making fundamental measurements of properties of the post-impact binary system. Additionally, Hera's extensive remote sensing capabilities are positioned to enable the mission to go beyond DART-related investigations and to advance our understanding of the properties of asteroids with implications for the formation and evolution of our solar system.

As DART's pioneering planetary defense mission is followed by the Hera mission, and as more planetary defense missions begin to move from concepts to reality, it is also important to emphasize that these two missions are just one part of a much larger planetary defense strategy. The combined efforts of the DART and Hera missions are providing fundamental insight into understanding the kinetic impactor technique as a potential method of asteroid deflection, taking the first steps to develop a capability to potentially prevent an asteroid impact with the Earth in the future, if such a need should arise. However, for a kinetic impactor to have any chance at successfully deflecting an asteroid on a collision course with Earth, warning time is key. To be most effective, the kinetic impactor should be used many years or decades in advance of the predicted Earth impact date (National Research Council 2010, 2022). Thus, finding, tracking, and characterizing near-Earth objects is vital to the overall planetary defense strategy, as are international collaboration and coordinated communication efforts. DART and Hera represent some of the first spacecraft missions in the ongoing and growing international efforts related to planetary defense.

### Acknowledgments

The DART mission is a result of the dedicated efforts of more than a thousand people working for years to make the mission successful. DART Investigation Team and LICIA Cube Team members beyond those listed as coauthors are thanked for their contributions to the discussions that led to the results summarized in this paper. This work was supported by the DART mission, NASA contract 80MSFC20D0004, and by the Italian Space Agency, Agenzia Spaziale Italiana (ASI) within the LICIA Cube project (ASI-INAF agreement AC n. 2019-31-HH.0).

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Modeling (EIMM) team. The work done through the Center for Research and Exploration in Space Science and Technology (CRESST-II) is supported by NASA award No. 80GSFC21M0002. N.X.R. acknowledges support by the Planetary Science Division Internal Scientist Funding Program through the Fundamental Laboratory Research (FLaRe) work package. P.M. acknowledges funding from ESA, CNES, the CNRS through the MITI interdisciplinary programs. For P.M., R.L., K.W., T.S.-R., C.B.S., and A.C.B.: funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 870377, through Near Earth Object Modelling and Payloads for Protection (NEOMAPP) project (H2020-EU-2-1-6/870377, EC H2020-SPACE-718 2018-2020, H2020-SPACE-2019). R.M. and S. E. acknowledge funding from a NASA Space Technology Graduate Research Opportunities (NSTGRO) award, contract No. 80NSSC22K1173. For P.P. and P.S.: this work was supported by the Grant Agency of the Czech Republic, grant 20-04431S. A.M. acknowledges the Italian Space Agency (ASI) for financial support through agreement No. 2022-8-HH.0 for ESA's Hera mission. I.H. acknowledges the Spanish Research Council (CSIC) support for international cooperation I-LINK project ILINK22061. For J.O.: this work was supported by the Spanish Ministry of Science and Innovation/State Agency of Research MCIN/AEI by grant PID2021-125883NB-C22 and by "ERDF A way of making Europe." For M.H.: this work was supported by the Slovak Grant Agency for Science VEGA (grant No. 2/0059/22) and by the Slovak Research and Development Agency under contract No. APVV-19-0072. G.S.C. and T.M.D. acknowledge funding from the UK Science and Technology Facilities Council, grant ST/S000615/1. For L.M.P.: contribution was supported by the Margarita Salas postdoctoral grant funded by the Spanish Ministry of Universities—NextGenerationEU. F.F. acknowledges funding from the European Research Council (ERC) under the European Union's Horizon Europe research and innovation program (grant agreement No. 101077758). For T. S.-R.: this work was also partially supported by the Spanish MICIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe" by the "European Union" through grant PID2021-122842OB-C21, and the Institute of Cosmos Sciences University of Barcelona (ICCUB, Unidad de Excelencia 'Maria de Maeztu') through grant CEX2019-000918-M. For J.M.: funding support acknowledged from the DART Participating Scientist Program (\#80NSSC21K1048). For A.P.: financial support from Academy of Finland grant No. 1345115. For A.C.B.: funding support from MICINN (Spain) PGC2021, PID2021-125883NB-C21. R.N. acknowledges support from NASA/FINESST (NNH20ZDA001N). J.-Y.L. acknowledges grants HST-GO-16674, HST-GO-17292, and HST-GO-17330 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, under NASA contract NAS 5-26555.

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## Data Availability

The DART mission archive at NASA's Planetary Data System contains data from DRACO, LICIACube, and DART-supported telescopic data sets, as well as associated documentation, SPICE, and advanced products, including the shape models of Didymos and Dimorphos.<sup>69</sup> The Small Body Mapping Tool developed by Johns Hopkins Applied Physics Lab contains the shape models of both asteroids with DRACO images and associated backplanes that resolve the surfaces of the asteroids.<sup>70</sup>

## Appendix A

This appendix provides values summarized in the final DRA produced by the DART Investigation Team in Table A1. The values used in an earlier DRA used by the DART team are

provided in Rivkin et al. (2021). The DRA reflects a summary of the current best knowledge of the Didymos system, covering values for the system both before and after DART's impact event. The different values are determined by different studies, and hence, the specific values are not necessarily consistent with each other. In particular, the axial extents for Didymos determined using spacecraft images (Barnouin et al. 2023) differ from the ellipsoid axes for Didymos determined by the best-fit dynamical model for the orbit of Dimorphos (Naidu et al. 2023). For this table, we have decided to list the values from multiple studies, for easy comparison. This reflects the current best understanding of the Didymos system, and this summary of key values tracked in the DRA is provided here as a resource for future investigations of the Didymos system.

**Table A1**  
Parameters of the Didymos System

Parameter	Value	Comments and References
System Characteristics		
Mean absolute magnitude, $H$	$18.16 \pm 0.04$	Pravec et al. (2012)
Geometric albedo	$0.17 \pm 0.01$	Naidu et al. (2020)
Radar polarization ratio	$0.20 \pm 0.02$	Neese et al. (2020)
Spectral type of Didymos	S-class	de León et al. (2006)
Best meteorite analog	L/LL chondrite	Dunn et al. (2013)
S-band radar albedos	$0.20 \pm 0.05$	Naidu et al. (2020)
X-band radar albedos	$0.30 \pm 0.08$	Naidu et al. (2020)
Heliocentric orbit parameters (pre- and post-impact)	see reference	JPL Solar System Dynamics Horizons System: <sup>a</sup>
Pre-Impact Parameters		
Semimajor axis of system (m)	$1189 \pm 17$	Naidu et al. (2024)
System GM ( $\text{m}^3 \text{s}^{-2}$ )	$35.4 \pm 1.5$	Naidu et al. (2024)
Didymos spin pole, $\lambda, \beta$ ( $^\circ$ )	$310 \pm 3, -80.7 \pm 0.5$	Naidu et al. (2024)
Dimorphos orbital eccentricity	$< 0.03$	Assumed based on Scheirich & Pravec (2009)
Bulk density of Didymos ( $\text{kg m}^{-3}$ )	$2790 \pm 140$	Naidu et al. (2024)
Bulk density of Dimorphos ( $\text{kg m}^{-3}$ )	$2400 \pm 300$	Daly, Ernst, Barnouin, et al. (2023)
Volume equivalent diameter of Didymos (m)	$730 \pm 8$	Barnouin et al. (2024)
Volume equivalent diameter of Dimorphos (m)	$150 \pm 2.5$	Daly et al. (2024)
Didymos extents along $x, y, z$ axes (m)	$819 \pm 14, 801 \pm 14, 607 \pm 14$	Barnouin et al. (2024)
Didymos ellipsoid $a, b, c$ axes (m)	$818 \pm 14, 796 \pm 14, 590 \pm 14$	Barnouin et al. (2024)
Didymos ellipsoid $a, b, c$ axes (m)	$788 \pm 22, 788 \pm 22, 580 \pm 32$	Naidu et al. (2024)
Dimorphos extents along $x, y, z$ axes (m)	$179 \pm 1, 169 \pm 4, 115 \pm 1$	Daly et al. (2024)
Dimorphos ellipsoid $a, b, c$ axes (m)	$173 \pm 1, 170 \pm 4, 113 \pm 1$	Daly et al. (2024)
Dimorphos elongation for ellipsoid, $a/b, a/c, b/c$	$1.02 \pm 0.02, 1.52 \pm 0.02, 1.49 \pm 0.04$	Daly et al. (2024)
Didymos oblateness (J2)	$0.090 \pm 0.008$	Naidu et al. (2024)
Dimorphos orbital period (hr)	$11.921493 \pm 0.00003$	Scheirich et al. (2024)
Rotation period of Didymos (hr)	$2.2600 \pm 0.0001$	Naidu et al. (2020)
Rotation period of Dimorphos	$11.921493 \pm 0.00003$	Assumed to have a synchronous orbit
Post-Impact Parameters		
Semimajor axis of system (m)	$1152 \pm 18$	Meyer et al. (2023a) gives a change of $37 \pm 1$ m
Dimorphos orbital geometric eccentricity	$0.0274 \pm 0.0015$	Naidu et al. (2024)
Dimorphos ellipsoid $a, b, c$ axes (m)	$192 \pm 12, 148 \pm 8, 118 \pm 14$	Naidu et al. (2024)
Dimorphos elongation for ellipsoid, $a/b, a/c, b/c$	$1.30 \pm 0.01, 1.6 \pm 0.3, 1.3 \pm 0.2$	Naidu et al. (2024)
Dimorphos orbital period (hr)	$11.3675 \pm 0.0004$	Scheirich et al. (2024)
Dimorphos orbital period (hr)	$11.3674 \pm 0.0004$	Naidu et al. (2024)
Rotation period of Didymos (hr)	$2.2600 \pm 0.0003$	Thomas et al. (2023a)

**Note.** All uncertainties are  $1\sigma$ .

<sup>a</sup> [https://ssd.jpl.nasa.gov/tools/sbdb\\_lookup.html#/?sstr=didymos](https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=didymos)

<sup>69</sup> [https://pds-smallbodies.astro.umd.edu/data\\_sb/missions/dart/index.shtml](https://pds-smallbodies.astro.umd.edu/data_sb/missions/dart/index.shtml)

and [https://naif.jpl.nasa.gov/pub/naif/pds/pds4/dart/dart\\_spice/](https://naif.jpl.nasa.gov/pub/naif/pds/pds4/dart/dart_spice/)

<sup>70</sup> <https://sbmt.jhuapl.edu/>

## Appendix B

This appendix lists the members of the DART Investigation Team in alphabetical order by last name in Table B1.

**Table B1**  
DART Investigation Team Members

Last Name	First Name	Home Institution
Abe	Lyu	Observatoire de la Côte d'Azur
Abell	Paul	NASA Johnson Space Center
Agrusa	Harrison	University of Maryland
Amoroso	Marilena	Italian Space Agency (ASI)
Arakawa	Masahiko	Kobe University
Arredondo	Anicia	SwRI
Asphaug	Erik	University of Arizona
Bagnulo	Stefano	Armagh Observatory and Planetarium
Baki	Paul	Technical University of Kenya
Ballouz	Ron	JHUAPL
Bannister	Michele	University of Canterbury, New Zealand
Barbee	Brent	NASA/Goddard Space Flight Center
Barnouin	Olivier	JHUAPL
Barucci	Antonella	LESIA -Paris Observatory
Beccarelli	Joel	INAF of Padova
Bekker	Dmitriy	APL
Bellerose	Julie	Jet Propulsion Laboratory
Belskaya	Irina	V.N. Karazin Kharkiv National University
Benavidez	Paula	Universidad de Alicante
Benner	Lance	Jet Propulsion Laboratory
Berthier	Jerome	IMCCE/Observatoire de Paris
Bertini	Ivano	University of Naples "Parthenope," Italy
Bhaskaran	Shyam	Jet Propulsion Laboratory
Bigot	Jeanne	ISAE-SUPAERO
Birlan	Mirel	IMCCE, Paris Observatory, France
Bjornes	Evan	Lawrence Livermore National Laboratory
Bottke	William	Southwest Research Institute
Brucato	John Robert	INAF—Arcetri Astrophysical Observatory
Bruck Syal	Megan	Lawrence Livermore National Laboratory
Brucker	Melissa	University of Arizona
Buratti	Bonnie	JPL
Burger	Christoph	University of Tübingen
Burkey	Mary	Lawrence Livermore National Laboratory
Busch	Michael	SETI Institute
Caballo Perucha	Piluca	Joanneum Research
Caldwell	Wendy	Los Alamos National Laboratory
Cambioni	Saverio	Massachusetts Institute of Technology
Campo Bagatin	Adriano	Universidad de Alicante
Capannolo	Andrea	Politecnico di Milano
Caporali	Simone	Università degli studi di Firenze
Carroll	Kieran	Gedex Systems Inc.
Carry	Benoit	Observatoire de la Cote d'Azur
Castellini	Francesco	ESOC
Cellino	Alberto	INAF—Osservatorio Astrofisico di Torino
Ceresoli	Michele	Politecnico di Milano
Chabot	Nancy	

**Table B1**  
(Continued)

Last Name	First Name	Home Institution
		Johns Hopkins Applied Physics Lab
Charnoz	Sebastien	IPGP/Université Paris Cité
Cheng	Andy	Johns Hopkins Applied Physics Lab
Chesley	Steve	JPL
Chocron	Sidney	Southwest Research Institute
Choi	Young-Jun	Korea Astronomy and Space Science Institute
Ciarletti	Valerie	LATMOS
Cintala	Mark	NASA Johnson Space Center
Cline	Christopher	NASA Johnson Space Center
Colazo	Milagros	IATE (CONICET)
Collins	Gareth	Imperial College London
Contreras	Carlos	Las Campanas Observatory
Cotugno	Biagio	Argotec
Cremonese	Gabriele	INAF-Padova
Cueva	Rachel	University of Colorado Boulder
Cuk	Matija	SETI Institute
Dall'Ora	Massimo	INAF-OACN
Daly	Terik	Johns Hopkins University Applied Physics Laboratory
Daly	Michael	York University
Davis	Alex	University of Colorado
Davison	Thomas	Imperial College London
de Leon	Julia	Instituto de Astrofisica de Canarias
DeCoster	Mallory	Johns Hopkins University Applied Physics Lab
Della Corte	Vincenzo	INAF, Italian National Astrophysics Institute, IAPS
Dello Russo	Neil	JHU/APL
Deshapriya	J. D. Prasanna	INAF—Osservatorio Astronomico di Roma
Dotto	Elisabetta	INAF—Osservatorio Astronomico di Roma
Duffard	René	Instituto de Astrofisica de Andaluca—CSIC
Durda	Dan	Southwest Research Institute
Eggl	Siegfried	University of Illinois at Urbana-Champaign
Erasmus	Nicolas	South African Astronomical Observatory
Ernst	Carolyn	Johns Hopkins University Applied Physics Laboratory
Espiritu	Raymond	JHUAPL
Essert	Jan	ESA
Fahnestock	Gene	JPL / Caltech
Falke	Albert	Airbus Defence and Space GmbH, Germany
Farnham	Tony	University of Maryland
Ferrais	Marin	Arecibo Observatory / University of Central Florida
Ferrari	Fabio	Politecnico di Milano
Filice	Valerio	Royal Observatory of Belgium
Fitzsimmons	Alan	Queen's University Belfast
Föhring	Dora	European Space Agency
Frattin	Elisa	University of Padua
Fu	Xiaoyu	University of Liverpool
Fuentes-Munoz	Oscar	University of Colorado Boulder
Gai	Igor	University of Bologna
Gaitanas	Michalis	Aristotle University of Thessaloniki
Gaskell	Robert	Planetary Science Institute
Gil	Jesus	ESA

**Table B1**  
(Continued)

Last Name	First Name	Home Institution
Giordano	Carmine	Politecnico di Milano
Gkolias	Ioannis	Aristotle University of Thessaloniki
Glenar	Dave	UMBC
Gomez Casajus	Luis	Università di Bologna, Bologna, Italy
Gramigna	Edoardo	University of Bologna (UNIBO)
Graninger	Dawn	Johns Hopkins University Applied Physics Laboratory
Granvik	Mikael	University of Helsinki / Luleå University of Technology
Gray	Zuri	Armagh Observatory and Planetarium
Green	Simon	The Open University
Grieger	Björn	Aurora Technology B.V. for ESA, ESAC, Spain
Guillot	Tristan	Observatoire de la Côte d'Azur, CNRS, France
Güldemeister	Nicole	Museum für Naturkunde Berlin
Hamilton	Douglas	University of Maryland
Hartzell	Christine	University of Maryland
Hasselmann	Pedro Henrique	INAF-Osservatorio di Roma
Henry	Grégoire	Royal Observatory of Belgium
Herfort	Ulrich	European Space Agency—ESOC
Hergenrother	Carl	Ascending Node Technologies, LLC
Herique	Alain	Université Grenoble Alpes—IPAG
Herreros	Isabel	Centro de Astrobiología (CAB), CSIC-INTA
Hestroffer	Daniel	IMCCE/Paris Observatory, Univ. PSL
Hirabayashi	Masatoshi	Auburn University
Holler	Bryan	STScI
Holt	Carrie	University of Maryland
Howell	Ellen	University of Arizona
Howley	Kirsten	Lawrence Livermore National Laboratory (LLNL)
Hsieh	Syau-Yun	Johns Hopkins Applied Physics Lab
Husárik	Marek	Astronomica Institute of the Slovak Academy of Sciences
Ieva	Simone	INAF-Osservatorio astronomico di Roma
Impresario	Gabriele	Agenzia Spaziale Italiana
Ivanovski	Stavro	National Institute for Astrophysics Italy
Jackson	Samuel	University of Edinburgh
Jacobson	Seth	Michigan State University
Jehin	Emmanuel	University of Liège
JeongAhn	Youngmin	Korea Astronomy and Space Science Institute
Jutzi	Martin	University of Bern
Kadono	Toshihiko	University of Occupational and Environmental Health
Karatekin	Ozgur	Royal Observatory of Belgium
Kareta	Theodore	Lowell Observatory
Karthick	Chrisphin	Indian Institute of Astrophysics (IIA)
Kašpárek	Tomáš	Brno University of Technology
Kikwaya Eluo	Jean-Baptiste	Vatican Observatory
Kim	Myung-Jin	Korea Astronomy and Space Science Institute
Knight	Matthew	United States Naval Academy
Kohout	Tomas	University of Helsinki, Finland

**Table B1**  
(Continued)

Last Name	First Name	Home Institution
Kokotanekova	Rosita	Bulgarian Academy of Sciences
Kolokolova	Ludmilla	University of Maryland, College Park
Kramer	Emily	Jet Propulsion Laboratory
Krugly	Yurij	Institute of Astronomy of V.N. Karazin Kharkiv National University
Kumamoto	Kathryn	Lawrence Livermore National Laboratory
Küppers	Michael	ESA/ESAC
La Forgia	Fiorangela	University of Padova
Larson	Jennifer	University of Central Florida
Lasagni Manghi	Riccardo	University of Bologna
Lazzarin	Monica	Padova University
Leakey	Acacia	Turkana Basin Institute
Lee	Hee-Jae	Korea Astronomy and Space Science Institute
Li	Jian-Yang	Planetary Science Institute
Libourel	Guy	Université Côte d'Azur, Observatoire de la Côte d'Azur
Lin	Zhong-Yi	Institute of Astronomy, NCU
Lister	Tim	Las Cumbres Observatory
Lolachi	Ramin	UMBC/NASA GSFC/CRESST II
Lombardo	Marco	University of Bologna
Lombardo	Pauline	ISAE-SUPAERO
Long	Chloe	CU Boulder
Lubey	Daniel	JPL
Lucas	Michael	University of Notre Dame
Lucchetti	Alice	INAF-OAPD Astronomical Observatory of Padova
Luther	Robert	Museum für Naturkunde Berlin
Lyzhof	Josh	NASA Goddard Space Flight Center
Madeira	Gustavo	Institut de Physique du Globe de Paris
Makadia	Rahil	University of Illinois at Urbana-Champaign
Manzoni	Claudia	London Stereoscopic Company
Marchi	Simone	Southwest Research Institute
Marzari	Francesco	Padova University
May	Erin	JHUAPL
May	Brian	London Stereoscopic Company
Mazzotta Epifani	Elena	INAF-Office of Aerospace Research (OAR)
McMahon	Jay	University of Colorado
Meneghin	Andrea	INAF
Merisio	Gianmario	Politecnico di Milano
Merrill	Colby	Cornell University
Meyer	Alex	University of Colorado Boulder
Michel	Patrick	Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange Lab
Migliorini	Alessandra	INAF, Institute for Space Astrophysics and Planetology
Milam	Stefanie	NASA/GSFC
Miller	Paul	Lawrence Livermore National Laboratory
Minker	Kate	Observatoire de la Côte d'Azur
Mitra	Nilanjan	Johns Hopkins University
Modenini	Dario	University of Bologna
Moissl	Richard	ESA/ESTEC
Mondal	Bhaskar	University of Illinois at Urbana-Champaign

**Table B1**  
(Continued)

Last Name	First Name	Home Institution
Moon	Hong-kyu	Korea Astronomy and Space Science Institute
Moreno	Fernando	Instituto de Astrofísica de Andalucía, CSIC
Mosher	Joel	JPL
Moskovitz	Nicholas	Lowell Observatory
Mueller	Michael	ESOC
Muinonen	Karri	University of Helsinki
Murdoch	Naomi	ISAE-SUPAERO
Murphy	Brian	University of Edinburgh
Naidu	Shantanu	Jet Propulsion Laboratory
Nair	Hari	JHU/APL
Nakamura	Akiko	Kobe University
Nakano	Ryota	Georgia Institute of Technology
Noiset	Guillaume	Royal Observatory of Belgium
Nolan	Michael	University of Arizona
Nugent	Carrie	Olin College
Ogawa	Kazunori	Japan Aerospace Exploration Agency
Oldroyd	Will	Northern Arizona University
Opitom	Cyrielle	University of Edinburgh
Ormö	Jens	Centro de Astrobiología (CAB), CSIC-INTA
Osip	David	Carnegie Observatories: Las Campanas Observatory (LCO)
Oszkiewicz	Dagmara	Adam Mickiewicz University
Owen	John	Lawrence Livermore National Laboratory
Owen	Chu	Travelling Telescope
Paar	Gerhard	JOANNEUM RESEARCH
Pajola	Maurizio	INAF—Astronomical Observatory of Padova
Pajuelo	Myriam	Pontificia Universidad Católica del Perú
Palamakumbure	Lakshika	University of Helsinki
Palmer	Eric	Planetary Science Institute
Palumbo	Pasquale	Parthenope University of Naples; INAF—Istituto di Astrofisica e Planetologia Spaziale (IAPS) in Roma
Panfichi	Aldo	Pontificia Universidad Católica del Perú
Panicucci	Paolo	Politecnico di Milano
Parro	Laura	Complutense University of Madrid / University of Arizona / University of Alicante
Pearl	Jason	Lawrence Livermore National Laboratory
Penttilä	Antti	University of Helsinki
Perna	Davide	INAF—Osservatorio Astronomico di Roma
Petrescu	Elisabeta	European Space Agency, ESOC
Pirrotta	Simone	Italian Space Agency
Pittichova Chesley	Jana	JPL/Caltech
Plesko	Catherine	Los Alamos National Laboratory
Poggiali	Giovanni	INAF—Arcetri Observatory, University of Florence
Polakis	Tom	Lowell Observatory
Polishook	David	Weizmann Institute of Science
Popescu	Marcel	Astronomical Institute of the Romanian Academy
Pou	Laurent	JPL
Pravec	Petr	

**Table B1**  
(Continued)

Last Name	First Name	Home Institution
		Astronomical Institute of the Academy of Sciences of the Czech Republic
Pugliatti	Mattia	Politecnico di Milano
Raducan	Sabina	University of Bern
Rainey	Emma	Johns Hopkins University Applied Physics Laboratory
Rambaux	Nicolas	IMCCE—Observatory of Paris
Ramesh	KT	Johns Hopkins University
Raskin	Cody	Lawrence Livermore National Laboratory
Regiec	Alysen	JHU/APL
Richardson	Derek	University of Maryland
Ridden	Ryan	University of Canterbury
Rivkin	Andrew	JHU/APL
Rizos	Juan	Instituto de Astrofísica de Andalucía—CSIC
Robin	Colas	ISAE-SUPAERO
Rosch	Thomas	Johns Hopkins University Applied Physics Laboratory
Rossi	Alessandro	IFAC-CNR
Roth	Nathan	NASA Goddard Space Flight Center
Rožek	Agata	University of Edinburgh
Rozitis	Ben	The Open University
Russell	Shannon	Two Sigma
Ryan	Eileen	New Mexico Institute of Mining and Technology/MRO
Ryan	William	New Mexico Institute of Mining and Technology
Sánchez	Paul	University of Colorado Boulder
Santana-Ros	Toni	Universidad de Alicante / Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (IEEC-UB)
Sarid	Gal	SETI Institute
Schaefer	Christoph	University of Tuebingen
Scheeres	Daniel	University of Colorado
Scheirich	Peter	Astronomical Institute ASCR, Ondrejov, Czech Republic
Schultz	Peter	Brown University
Schwartz	Stephen	University of Arizona
Senel	Cem Berk	Royal Observatory of Belgium
Serebryanskiy	Aleksander	Fesenkov Astrophysical Institute
Shestakova	Lyubov	Fesenkov Astrophysical Institute (FAI)
Sickafoose	Amanda	PSI/MIT
Simioni	Emanuele	INAF—OAPD
Simonetti	Simone	Argotec
Smith	Matthew	JPL
Snodgrass	Colin	University of Edinburgh
Soldini	Stefania	University of Liverpool
Souami	Damyá	LESIA, Observatoire de Paris
Statler	Thomas	NASA Headquarters
Steckloff	Jordan	Planetary Science Institute
Stickle	Angela	JHU/APL
Stubbs	Timothy	NASA Goddard Space Flight Center
Sunday	Cecily	Institut Supérieur de l'Aéronautique et de l'Espace
sunshine	Jessica	University of Maryland
Tancredi	Gonzalo	Depto. Astronomia, UdelaR, Uruguay


















































**Table B1**  
(Continued)



















Last Name	First Name	Home Institution
Tanga	Paolo	Observatoire de la Côte d'Azur
Tardivel	Simon	Centre National d'Etudes Spatiales (CNES)
Tasev	Elisa	Royal Observatory of Belgium
Telus	Myriam	University of California Santa Cruz
Thomas	Cristina	Northern Arizona University
Thomas-Osip	Joanna	Gemini Observatory
Tinsman	Calley	APL
Titus	Timothy	USGS Astrogeology Science Center
Tortora	Paolo	University of Bologna
Trigo-Rodríguez	Josep M.	Institute of Space Sciences (CSIC/IEEC)
Troianskyi	Volodymyr	Astronomical Observatory Institute, A. Mickiewicz University
Tsiganis	Kleomenis	Aristotle University of Thessaloniki
Tubiana	Cecilia	IAPS/INAF, Rome, Italy
Tusberti	Filippo	INAF—Astronomical Observatory of Padova
Veillet	Christian	Large Binocular Telescope Observatory
Venditti	Flaviane	Arecibo Observatory
Veras	Dimitri	University of Warwick
Vincent	Jean-Baptiste	DLR Institute for Planetary Research
Voyatzis	George	Aristotle University of Thessaloniki, Greece
Wada	Koji	Chiba Institute of Technology
Walker	James	Southwest Research Institute
Walker	Harry	European Space Agency
Waller	Dany	Johns Hopkins University Applied Physics Laboratory
Walsh	Kevin	Southwest Research Institute
Washington	Antoine	University of Maryland
Weaver	Hal	JHU Applied Physics Laboratory
Whizin	Akbar	Southwest Research Institute
Wimarsson	John	University of Bern
Wolfmayr	Monika	University of Jyväskylä, Finland
Wong	Ian	NASA GSFC
Wuennemann	Kai	Museum fuer Naturkunde Berlin
Xiang	Zhen	University of Bern
Yanamandra-Fisher	Padma	Space Science Institute
Yu	Yang	Beihang University
Zannoni	Marco	University of Bologna
Zanotti	Giovanni	Politecnico di Milano
Zhang	Yun	Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange Lab
Zinzi	Angelo	Agenzia Spaziale Italiana (ASI)—Space Science Data Center
Zou	Xiaoduan	Planetary Science Institute

**ORCID iDs**

Nancy L. Chabot <https://orcid.org/0000-0001-8628-3176>  
 Andrew S. Rivkin <https://orcid.org/0000-0002-9939-9976>  
 Andrew F. Cheng <https://orcid.org/0000-0001-5375-4250>  
 Olivier S. Barnouin <https://orcid.org/0000-0002-3578-7750>  
 Eugene G. Fahnestock <https://orcid.org/0000-0003-1391-5851>

Derek C. Richardson <https://orcid.org/0000-0002-0054-6850>  
 Angela M. Stickle <https://orcid.org/0000-0002-7602-9120>  
 Cristina A. Thomas <https://orcid.org/0000-0003-3091-5757>  
 Carolyn M. Ernst <https://orcid.org/0000-0002-9434-7886>  
 R. Terik Daly <https://orcid.org/0000-0002-1320-2985>  
 Elisabetta Dotto <https://orcid.org/0000-0002-9335-1656>  
 Angelo Zinzi <https://orcid.org/0000-0001-5263-5348>  
 Steven R. Chesley <https://orcid.org/0000-0003-3240-6497>  
 Nicholas A. Moskovitz <https://orcid.org/0000-0001-6765-6336>  
 Brent W. Barbee <https://orcid.org/0000-0003-3739-3242>  
 Paul Abell <https://orcid.org/0000-0002-6233-1820>  
 Harrison F. Agrusa <https://orcid.org/0000-0002-3544-298X>  
 Michele T. Bannister <https://orcid.org/0000-0003-3257-4490>  
 Joel Beccarelli <https://orcid.org/0000-0002-9418-8301>  
 Dmitriy L. Bekker <https://orcid.org/0000-0002-0293-8938>  
 Megan Bruck Syal <https://orcid.org/0000-0003-2776-9955>  
 Bonnie J. Buratti <https://orcid.org/0000-0002-5901-4875>  
 Michael W. Busch <https://orcid.org/0000-0003-2474-7523>  
 Adriano Campo Bagatin <https://orcid.org/0000-0001-9840-2216>  
 Joseph P. Chatelain <https://orcid.org/0000-0002-1278-5998>  
 Sidney Chocron <https://orcid.org/0000-0002-6838-3330>  
 Gareth S. Collins <https://orcid.org/0000-0002-6087-6149>  
 Luca Conversi <https://orcid.org/0000-0002-6710-8476>  
 Thomas M. Davison <https://orcid.org/0000-0001-8790-873X>  
 Mallory E. DeCoster <https://orcid.org/0000-0002-1139-9235>  
 J. D. Prasanna Deshapriya <https://orcid.org/0000-0002-5758-1286>  
 Siegfried Eggl <https://orcid.org/0000-0002-1398-6302>  
 Raymond C. Espiritu <https://orcid.org/0000-0002-5091-827X>  
 Tony L. Farnham <https://orcid.org/0000-0002-4767-9861>  
 Marin Ferrais <https://orcid.org/0000-0002-0535-652X>  
 Fabio Ferrari <https://orcid.org/0000-0001-7537-4996>  
 Dora Föhrling <https://orcid.org/0000-0001-9259-2688>  
 Oscar Fuentes-Muñoz <https://orcid.org/0000-0001-5875-1083>  
 Igor Gai <https://orcid.org/0000-0002-5367-3650>  
 Carmine Giordano <https://orcid.org/0000-0003-0833-4729>  
 David A. Glenar <https://orcid.org/0000-0003-2155-3854>  
 Edward Gomez <https://orcid.org/0000-0001-5749-1507>  
 Dawn M. Graninger <https://orcid.org/0000-0003-1582-0581>  
 Simon F. Green <https://orcid.org/0000-0002-9153-9786>  
 Sarah Greenstreet <https://orcid.org/0000-0002-4439-1539>  
 Pedro H. Hasselmann <https://orcid.org/0000-0003-1193-8945>  
 Isabel Herreros <https://orcid.org/0000-0001-5284-8060>  
 Masatoshi Hirabayashi <https://orcid.org/0000-0002-1821-5689>  
 Marek Husárik <https://orcid.org/0000-0002-5932-7214>  
 Simone Ieva <https://orcid.org/0000-0001-8694-9038>  
 Stavro L. Ivanovski <https://orcid.org/0000-0002-8068-7695>  
 Samuel L. Jackson <https://orcid.org/0000-0001-9242-4254>  
 Emmanuel Jehin <https://orcid.org/0000-0001-8923-488X>  
 Martin Jutzi <https://orcid.org/0000-0002-1800-2974>  
 Ozgur Karatekin <https://orcid.org/0000-0003-0153-7291>

Matthew M. Knight  <https://orcid.org/0000-0003-2781-6897>  
 Ludmilla Kolokolova  <https://orcid.org/0000-0002-9321-3202>  
 Kathryn M. Kumamoto  <https://orcid.org/0000-0002-0400-6333>  
 Michael Küppers  <https://orcid.org/0000-0002-5666-8582>  
 Fiorangela La Forgia  <https://orcid.org/0000-0003-3924-1867>  
 Monica Lazzarin  <https://orcid.org/0000-0001-7976-2339>  
 Jian-Yang Li  <https://orcid.org/0000-0003-3841-9977>  
 Tim A. Lister  <https://orcid.org/0000-0002-3818-7769>  
 Ramin Lolachi  <https://orcid.org/0000-0001-5764-7639>  
 Michael P. Lucas  <https://orcid.org/0000-0001-5377-3128>  
 Alice Lucchetti  <https://orcid.org/0000-0001-7413-3058>  
 Robert Luther  <https://orcid.org/0000-0002-0745-1467>  
 Rahil Makadia  <https://orcid.org/0000-0001-9265-2230>  
 Elena Mazzotta Epifani  <https://orcid.org/0000-0003-1412-0946>  
 Jay McMahon  <https://orcid.org/0000-0002-1847-4795>  
 Gianmario Merisio  <https://orcid.org/0000-0001-8806-7952>  
 Colby C. Merrill  <https://orcid.org/0000-0002-5566-0618>  
 Alex J. Meyer  <https://orcid.org/0000-0001-8437-1076>  
 Patrick Michel  <https://orcid.org/0000-0002-0884-1993>  
 Marco Micheli  <https://orcid.org/0000-0001-7895-8209>  
 Alessandra Migliorini  <https://orcid.org/0000-0001-7386-9215>  
 Kate Minker  <https://orcid.org/0009-0002-6435-9453>  
 Dario Modenini  <https://orcid.org/0000-0002-1517-3938>  
 Fernando Moreno  <https://orcid.org/0000-0003-0670-356X>  
 Naomi Murdoch  <https://orcid.org/0000-0002-9701-4075>  
 Brian Murphy  <https://orcid.org/0000-0002-8137-5132>  
 Shantanu P. Naidu  <https://orcid.org/0000-0003-4439-7014>  
 Hari Nair  <https://orcid.org/0000-0002-9753-7650>  
 Ryota Nakano  <https://orcid.org/0000-0002-9840-2416>  
 Cyrielle Opatom  <https://orcid.org/0000-0002-9298-7484>  
 Jens Ormö  <https://orcid.org/0000-0002-5810-9442>  
 J. Michael Owen  <https://orcid.org/0000-0003-4796-124X>  
 Maurizio Pajola  <https://orcid.org/0000-0002-3144-1277>  
 Eric E. Palmer  <https://orcid.org/0000-0001-6755-8736>  
 Pasquale Palumbo  <https://orcid.org/0000-0003-2323-9228>  
 Paolo Panicucci  <https://orcid.org/0000-0003-3743-6302>  
 Laura M. Parro  <https://orcid.org/0000-0001-6696-461X>  
 Jason M. Pearl  <https://orcid.org/0000-0002-5340-7272>  
 Antti Penttilä  <https://orcid.org/0000-0001-7403-1721>  
 Davide Perna  <https://orcid.org/0000-0002-4545-3850>  
 Elisabeta Petrescu  <https://orcid.org/0000-0003-0874-1703>  
 Petr Pravec  <https://orcid.org/0000-0001-8434-9776>  
 Sabina D. Raducan  <https://orcid.org/0000-0002-7478-0148>  
 K. T. Ramesh  <https://orcid.org/0000-0003-2659-4698>  
 Ryan Ridden-Harper  <https://orcid.org/0000-0003-1724-2885>  
 Juan L. Rizos  <https://orcid.org/0000-0002-9789-1203>  
 Alessandro Rossi  <https://orcid.org/0000-0001-9311-2869>  
 Nathan X. Roth  <https://orcid.org/0000-0002-6006-9574>  
 Agata Rožek  <https://orcid.org/0000-0003-2341-2238>  
 Benjamin Rozitis  <https://orcid.org/0000-0001-9893-241X>  
 Eileen V. Ryan  <https://orcid.org/0000-0001-6921-9877>  
 William H. Ryan  <https://orcid.org/0000-0002-9226-4956>  
 Paul Sánchez  <https://orcid.org/0000-0003-3610-5480>  
 Toni Santana-Ros  <https://orcid.org/0000-0002-0143-9440>  
 Daniel J. Scheeres  <https://orcid.org/0000-0003-0558-3842>  
 Peter Scheirich  <https://orcid.org/0000-0001-8518-9532>

Cem Berk Senel  <https://orcid.org/0000-0002-7677-9597>  
 Colin Snodgrass  <https://orcid.org/0000-0001-9328-2905>  
 Stefania Soldini  <https://orcid.org/0000-0003-3121-3845>  
 Damya Souami  <https://orcid.org/0000-0003-4058-0815>  
 Thomas S. Statler  <https://orcid.org/0000-0003-4909-9542>  
 Rachel Street  <https://orcid.org/0000-0001-6279-0552>  
 Timothy J. Stubbs  <https://orcid.org/0000-0002-5524-645X>  
 Jessica M. Sunshine  <https://orcid.org/0000-0002-9413-8785>  
 Nicole J. Tan  <https://orcid.org/0000-0001-6541-8887>  
 Gonzalo Tancredi  <https://orcid.org/0000-0002-4943-8623>  
 Calley L. Tinsman  <https://orcid.org/0000-0002-8078-7303>  
 Paolo Tortora  <https://orcid.org/0000-0001-9259-7673>  
 Filippo Tusberti  <https://orcid.org/0000-0002-9290-1679>  
 James D. Walker  <https://orcid.org/0000-0002-3093-8978>  
 C. Dany Waller  <https://orcid.org/0000-0002-6310-3766>  
 Kai Wünnemann  <https://orcid.org/0000-0001-5423-1566>  
 Marco Zannoni  <https://orcid.org/0000-0002-4151-9656>  
 Yun Zhang  <https://orcid.org/0000-0003-4045-9046>

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