DART AND LICIACUBE: PLANETARY DEFENSE SCIENCE.

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Introduction: The NASA Double Asteroid Redirection Test (DART) mission [1,2] will be the first space experiment to demonstrate asteroid deflection by a kinetic impactor. DART will impact the secondary member of the (65803) Didymos binary asteroid system (informally Didymos B) in late September – early October, 2022 in order to change the orbit of the moon around the primary. DART will carry to Didymos a 6U cubesat called LICIACube, contributed by the Italian Space Agency, to document the DART impact and to observe the impact ejecta. The Hera mission [3,4] has been approved for development and launch in the ESA Space Safety Program by the ESA Council at Ministerial Level Space19+ in November, 2019, to rendezvous with the Didymos system in 2027. Members of the DART, LICIACube, and Hera teams contribute to the Asteroid Impact and Deflection Assessment (AIDA) collaboration. AIDA planetary defense objectives are to support international collaboration in planetary defense, to support the demonstration and validation of technologies needed to deflect a hazardous asteroid by means of a kinetic impactor, and to improve our understanding of the impact process and the momentum transfer to the target asteroid. DART is the first hypervelocity impact experiment on an asteroid at a realistic scale relevant to planetary defense, where the impact conditions and the projectile properties are fully known. The DART impact will change the orbital period of Didymos B. As Didymos is an eclipsing binary [5], this period change is observable through light curve measurements of mutual events and radar positional measurements in the Didymos system to quantify the asteroid deflection. Roughly four years after the impact, ESA's Hera spacecraft will rendezvous with Didymos and will more fully characterize the target asteroid, image the crater made by DART, and refine the momentum transfer efficiency determination.

The AIDA collaboration will use data from DART, LICIACube, and Hera to validate the effectiveness of the kinetic impactor technique and to improve models of momentum transfer to reduce risks and uncertainties of possible future applications to asteroid deflection.

Planetary defense science: The impact of the 610 kg DART spacecraft at 6.58 km/s on the 163 m Didymos B will change the binary orbital period [1,2] by ~10 minutes (more than a 1% change) assuming momentum transfer efficiency $\beta = 1$. Values of $\beta > 1$ are expected for the impact because ejecta carries momentum, primarily in the direction opposite the DART approach direction. As noted, this change will be measured by supporting Earth-based optical and radar observations, since Didymos in October, 2022 will be only 0.072 AU from Earth. These measurements determine the orbital velocity change from the DART impact.

The momentum transfer efficiency β depends on impact conditions such as local slope, on target physical properties such as strength and porosity, and on internal structures such as boulders. To understand the effectiveness of the kinetic impact deflection, DART will determine or constrain these impact conditions and target characteristics in order to compare experimental results with hypervelocity impact simulations [6,7,8] of impact effects and momentum transfer efficiency. DART will determine the DART impact location and the local surface slope and topography by returning high-resolution images (ground sampling distance of 50 cm per pixel or better) from the terminal approach.

LICIACube will execute a flyby of Didymos with closest approach about 3 minutes after the DART impact. LICIACube will observe the structure and evolution of the DART impact ejecta plume and will obtain images of the surfaces of both bodies at peak ground sampling better than 2 m per pixel. LICIACube imaging importantly includes the non-impact hemisphere of the target asteroid, the side not imaged by DART.

The planetary defense science objectives and DART and LICIACube measurements are shown in Table 1. The DART spacecraft observations consist of approach imaging to measure Didymos light curves to determine rotation and orbital characteristics, further approach imaging to measure the sizes and shapes of Didymos A and B, and terminal approach imaging to determine impact site location and local surface geology.

The contributions of LICIACube observations to the DART investigations are important for determinations of the momentum transfer efficiency β of the DART impact. The determination of β from DART measurements and modeling is a critically important planetary defense science objective.

The primary measurements of asteroid deflection made by the DART mission are the ground-based telescopic measurements of the orbital period change from the DART impact. The period change measurement determines the transverse velocity change, which is the component along the circular orbit motion. The other two components of velocity change are not measured by DART. The transverse component of the momentum transfer is then determined from the transverse velocity change, using a mass M for the target body Didymos B determined from approach imaging. DART will determine M from approach imaging by finding the size and the shape and hence the volume and assuming that the Didymos primary bulk density 2170 kg m^{-3} [4] applies also to the secondary.

Table 1. DART Objectives and Measurements

<table>
<tr><th>Objectives</th><th>Measurements</th></tr>
<tr><td>Demonstrate asteroid deflection by kinetic impact</td><td rowspan="3">Earth-based observations to determine orbital period change of the Didymos binary system induced by DART impact</td></tr>
<tr><td>Impact moon of Didymos system in Sept.–Oct. 2022</td></tr>
<tr><td>Determine the amount of deflection</td></tr>
<tr><td rowspan="4">Determine momentum transfer efficiency of kinetic impact on an asteroid

Improve modelling and simulation capabilities</td><td>DART approach imaging for impact site location and local surface geology</td></tr>
<tr><td>DART approach imaging to measure sizes and shapes of Didymos A and B</td></tr>
<tr><td>LICIACube imaging of impact ejecta for plume density structure and evolution</td></tr>
<tr><td>LICIACube imaging of non-impact hemispheres</td></tr>
</table>

LICIACube makes an important contribution to this mass determination because it will provide images of the non-impact hemisphere of Didymos B obtained after closest approach, viewing the side of Didymos not seen by DART. LICIACube images will significantly improve the volume determination for Didymos B. An initial estimate for β is then obtained from the mass M and the transverse velocity change, with a correction for the angle between the incident velocity and the orbital velocity, which is 15.5° for the first day of the DART launch window.

However, this estimate for β includes several idealizing assumptions. In order to make an estimate for β that is generalizable to other conditions, numerical simulations will be performed. Furthermore, the estimate for β will be improved by additional observations. These additional observations include LICIACube imaging of the ejecta plume structure and evolution to constrain and infer the ejecta momentum both in direction and magnitude, in addition to DART terminal approach imaging to locate the impact site and characterize its topography and local structures.

LICIACube ejecta plume observations of plume structure and evolution can discriminate between different target physical properties (mainly strength and porosity), thereby allowing inferences of the magnitude of the ejecta momentum. This is because the ejecta plume structure, as it evolves over time, is determined by the amount of ejecta that has reached a given altitude at a given time. The LICIACube plume images enable characterization of the ejecta mass versus velocity distribution, which is strongly dependent on target properties like strength and porosity, and which is therefore a powerful diagnostic of the DART impact in much the same way as measurements of the DART impact crater will be (crater measurements will be obtained later by the ESA Hera mission). LICIACube ejecta plume images further provide direct information on the direction of the ejecta momentum, also important for accurate determination of the vector momentum transfer from the DART impact.

Models of the ejecta plume evolution as imaged by LICIACube show how LICIACube images determine the plume geometry in order to constrain the direction of the ejecta momentum by finding the direction of the plume axis and determining the asymmetry if any around this axis. In addition, the ejecta plume optical depth profiles and the changes with time after the DART impact enable characterization of ejecta mass versus velocity distributions, leading to inferences of target physical properties. The LICIACube plume optical depth profiles can distinguish between gravity-controlled and strength-controlled impact cases with target properties ranging from very strong and nonporous to very weak and porous, using specific observables from the plume images, which include for example the time at which clearing of ejecta becomes evident over the impact site.

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