Optical Characterization Model of the DART Impact Ejecta Plume

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November 22, 2022

Abstract

The Double Asteroid Redirection Test (DART) mission is the world's first planetary defense mission. Reaching the binary (65803) Didymos-Dimorphos asteroid system in late September or early October 2022, it aims to change the orbit of the secondary member, Dimorphos, through kinetic impact deflection. The spacecraft will hit the 160 m diameter Dimorphos at a speed of approximately 6 km/s with the objective of changing its orbital period about Didymos by at least 73 s and creating an impact ejecta plume in the process. These events will be observed both from Earth and by its ride-along companion SmallSat, LICIACube. These observations will be used to determine and understand the momentum transfer efficiency of the impact [1]. The resulting plume properties, including ejecta momentum and consequently momentum transfer efficiency are controlled by several global factors related to the asteroid material: strength, porosit, cohesiveness, and internal structure (e.g., is it a "rubble pile"? is there a regolith layer present?) [2,3]. However, factors local to the impact site can also play a major role. For instance, the value for transfer efficiency can change dramatically depending on whether DART impacts into a boulder or regolith [4]. One method of characterizing the impact ejecta is via optical observations of the evolving impact plume brightness coupled with radiative transfer reconstructions of sunlight scattering by ejecta particles. This approach can give information about composition, and the developing spatial and mass distributions of ejecta material. Using radiative transfer models to analyze and reconstruct an impact plume has a precedent. Previously, simulations were conducted using results from the Deep Impact mission in order reconstruct the plume 1 s after impact in order to analyze its composition [5]. For DART, an initial radiative transfer prediction study of the LICIACube flyby observations was carried out by the mission team [1]. Estimates for geometric optical depth of the impact plume, as well as order-of-magnitude approximations for plume surface brightness were made, consistent with the measured Didymos geometric albedo of 0.15 [6]. These estimates were made assuming large, isolated plume particles, i.e., extinction coefficient of 2, an assumed isotropic phase function and single scattering. Unfortunately, if the same methodology is applied to reconstructions of the actual plume observations it is likely to result in large radiance differences and misinterpretation of ejecta properties. This is because it is vital to any such modelling effort to have a realistic treatment of the plume particle scattering properties, as well as the effects of large optical depth. Using the flyby geometry of the study [1] we have performed our own reconstructions of the DART impact ejecta plume observations combining a 3D plume geometry, realistic phase function and the multiple-scattering radiative transfer software DISORT [7].

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PRESENTED AT:

I INTRODUCTION

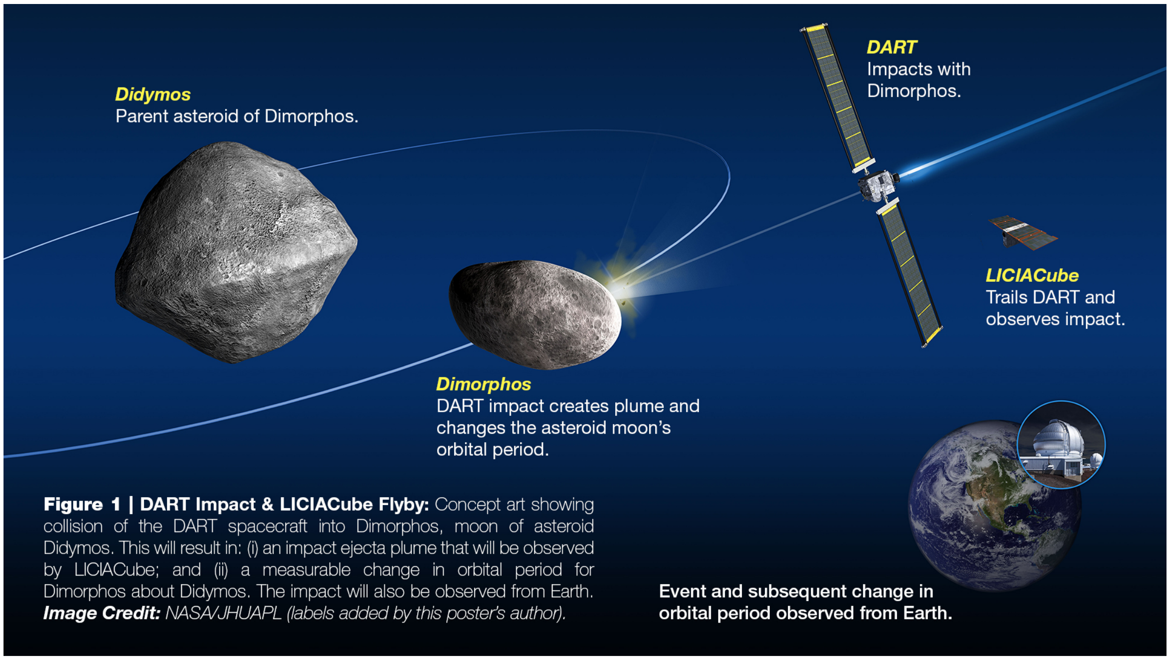

Figure 1 | DART Impact & LICIACube Flyby: Concept art showing collision of the DART spacecraft into Dimorphos, moon of asteroid Didymos. This will result in: (i) an impact ejecta plume that will be observed by LICIACube; and (ii) a measurable change in orbital period for Dimorphos about Didymos. The impact will also be observed from Earth. ***Image Credit:*** *NASA/JHUAPL (labels added by this poster's author).*

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- The Double Asteroid Redirection Test (DART) mission is the world's first planetary defense mission.
- Reaching the binary (65803) Didymos-Dimorphos asteroid system in September/October 2022, it aims to change the orbit of the secondary member, Dimorphos, through kinetic impact deflection and creating an impact ejecta plume in the process (Fig. 1).
- These events will be observed both from Earth and by its ride-along companion SmallSat, LICIACube [1].
- Optical observations coupled with radiative transfer modeling of solar light scattered by the impact plume can be used as part of the impact momentum transfer efficiency analysis, but realistic treatment of scattering parmeters is needed.
- We present an example approach and its benefits.

II METHODS: PLUME PARTICLES & MODEL

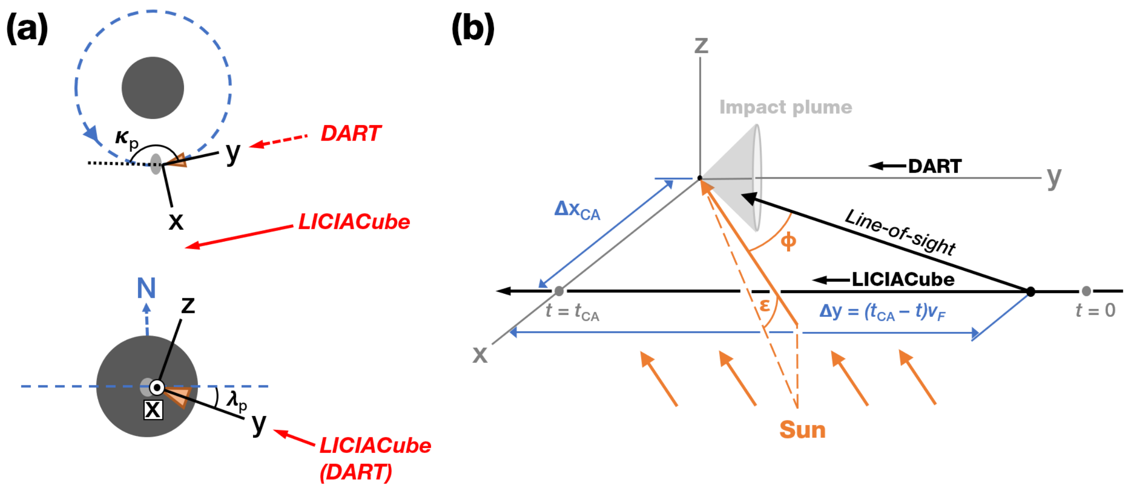

Figure 2 | LICIACube encounter with evolving optical scattering geometry: ***(a) LICIACube Flyby Concept:*** Top-down/side views of Dimorphos (light grey) orbital plane around Didymos (dark grey); ejecta plume (orange triangle); trajectory of LICIACube (red solid line); direction taken by DART, along y-axis (red dotted line); κ_p and λ_p are the Dimorphos orbital in- and out-of-plane angles for the DART/LICIACube paths (exaggerated for clarity). ***(b) LICIACube Flyby Geometry (based on [1]):*** Origin at impact and ejecta plume centered on y-axis. Diagram shows position of LICIACube as a function of time following impact. v_F is relative velocity, Δx_{CA} is distance from origin at closest approach, ϕ is the phase angle observed at LICIACube (where $\phi = \pi - \theta_{sc}$ and θ_{sc} is the scattering angle), and ε is Sun elevation angle.

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- *Simplified plume geometry:* Hollow cone with interior angle of 90°.
- Evolving LICIACube viewing geometry (Fig. 2) based on geometry used by DART team [1].
- *Plume surface:* Layer of plume particles modeled with geometric albedo set to that of Didymos, A_G = 0.15 [6].
- *Plume Particles:* Small, opaque spheres with scattering surfaces, characterized by a Lommel-Seeliger phase function, typical of low-reflectance solar system objects [8]. Real impact fragments will probably be irregular and possibly porous. Approximate corrections for these effects can be made by geometric codes for computing the reflectance from irregular shapes, followed by orientation averaging.
- Using the plume particles and 3D geometry outlined above we conducted line of sight radiative transfer simulations using DISORT [7] for normal geometric optical depths ranging from 0.01 to 10, for two cases: a) using our realistic multiple-scattering plume particles and b) using the simplifying scattering assumptions (extinction coefficient of ~2, an assumed isotropic phase function and single scattering) of the DART team [1].

III RESULTS

Simple scattering assumptions (e.g., single scattering, isotropic phase functions) can lead to **errors exceeding one order of magnitude**.

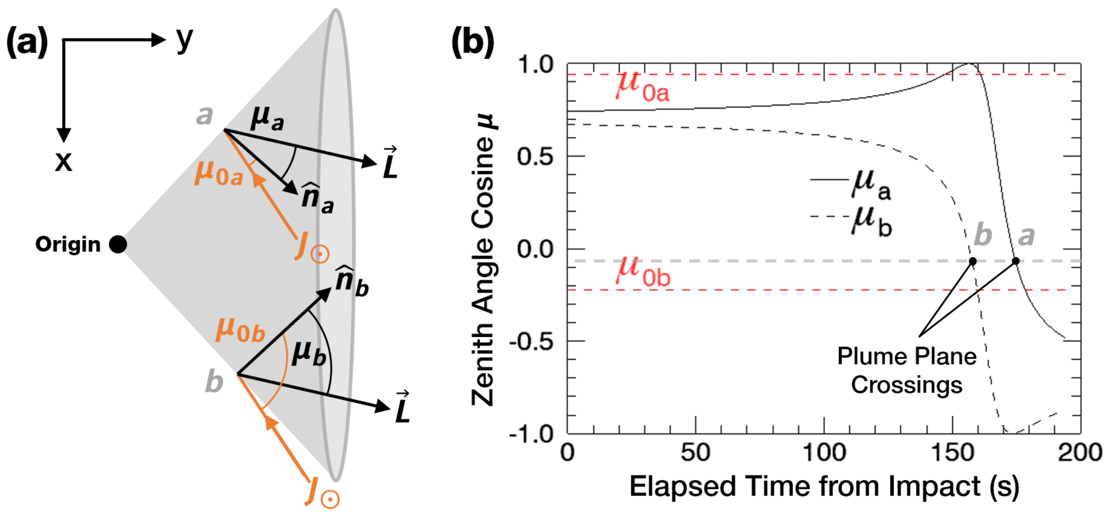

Figure 3 | Evolution of LICIACube plume viewing geometry, a critical component in accurate plume reconstruction: ***(a) Illumination geometry at plume faces a and b.*** Quantities μ_0 (orange) and μ (black) are the zenith angle cosines to the Sun and observer, as required for radiative transfer calculations. Plume normal is $\hat{n}$ (black) and solar radiation vector is $J_\odot$ (orange). ***(b) Plot of μ_0 and μ in the x-y plane as a function of elapsed time.***

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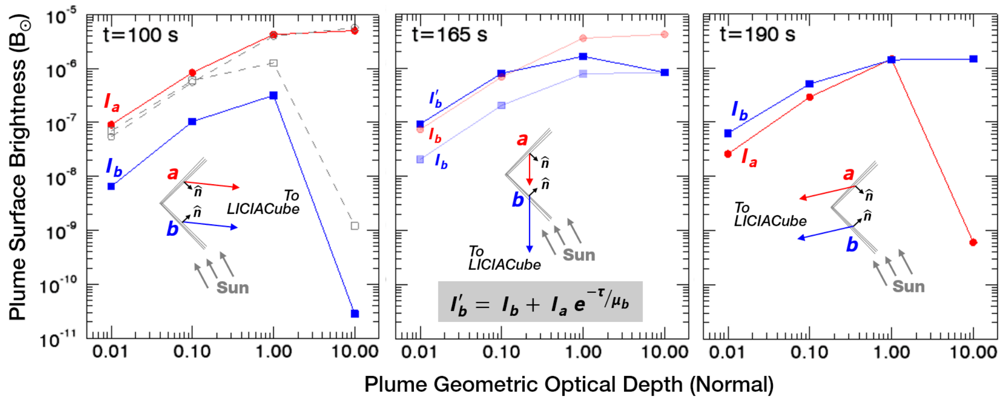

Figure 4 | Plume surface brightness as a function of optical depth, as viewed by LICIACube along its flyby trajectory. Brightness is in units of mean solar disk intensity, $B_\odot$. Sketches in inset depict the observing geometry at each time. Scatterers which make up the plume are assumed to be large and opaque, but well-separated impact fragments having a Lommel-Seeliger (LS) phase function and geometric albedo A_G = 0.15. They are therefore strongly backscattering (i.e., reflecting). Because of the solar incidence direction, plume surface ***a (red)*** will appear brighter than ***b (blue)*** during early approach. The opposite will be true at times after close approach. At t = 165 s (close approach), the CubeSat views the superposition (I'_b) of ***a*** and ***b***, as illustrated. For comparison, we also include the brightness computed for the simplistic assumption of isotropic scatterers, as used by Cheng et al., (2020) [1], shown as gray dashed lines in the left panel. This can lead to errors exceeding one order of magnitude, as shown by the large differences seen between the isotropic and LS (ours) scattering cases.

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IV SUMMARY

- Using geometry outlined we conducted line of sight simulations for normal geometric optical depths ranging from 0.01 to 10, for two cases:
  - a) using our realistic scattering plume particles
  - b) using the simplifying scattering assumptions of the DART team [1].
- It was found that this yielded differences in plume surface brightness exceeding an order of magnitude in the worst cases.
- This result highlights the importance of a realistic scattering parametrization and modeling regime.

ACKNOWLEDGEMENTS

This work was funded by the NASA/GSFC Internal Scientist Funding Model (ISFM) Exospheres, Ionospheres, Magnetospheres Modeling (EIMM) team through NASA award number 80GSFC17M0002.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

ABSTRACT

Introduction: The Double Asteroid Redirection Test (DART) mission is the world's first planetary defense mission. Reaching the binary (65803) Didymos-Dimorphos asteroid system in late September or early October 2022, it aims to change the orbit of the secondary member, Dimorphos, through kinetic impact deflection. The spacecraft will hit the 160 m diameter Dimorphos at a speed of approximately 6 km s^{-1} with the objective of changing its orbital period about Didymos by at least 73 s and creating an impact ejecta plume in the process (Fig. 1). These events will be observed both from Earth and by its ride-along companion SmallSat, LICIACube. These observations will be used to determine and understand the momentum transfer efficiency of the impact [1].

The resulting plume properties, including ejecta momentum and consequently momentum transfer efficiency are controlled by several global factors related to the asteroid material: strength, porosity (micro- and macroscopic), cohesiveness (do particles stick together?), and internal structure (e.g., is it a "rubble pile"? is there a regolith layer present?) [2,3]. However, factors local to the impact site can also play a major role. For instance, the value for transfer efficiency can change dramatically depending on whether DART impacts into a boulder or regolith [4].

One method of characterizing the impact ejecta is via optical observations of the evolving impact plume brightness coupled with radiative transfer reconstructions of sunlight scattering by ejecta particles. This approach can give information about composition, and the developing spatial and mass distributions of ejecta material. Using radiative transfer models to analyze and reconstruct an impact plume has a precedent. Previously, simulations were conducted using results from the Deep Impact mission in order reconstruct the plume 1 s after impact in order to analyze its composition [5].

For DART, an initial radiative transfer prediction study of the LICIACube flyby observations was carried out by the mission team [1]. Estimates for geometric optical depth of the impact plume, as well as order-of-magnitude approximations for plume surface brightness were made, consistent with the measured Didymos geometric albedo of 0.15 [6]. These estimates were made assuming large, isolated plume particles, i.e., extinction coefficient of ~2, an assumed isotropic phase function and single scattering. Unfortunately, if the same methodology is applied to reconstructions of the actual plume observations it is likely to result in large radiance differences and misinterpretation of ejecta properties. This is because it is vital to any such modelling effort to have a realistic treatment of the plume particle scattering properties, as well as the effects of large optical depth.

Using the flyby geometry of the study (Fig. 2) [1] we have performed our own reconstructions of the DART impact ejecta plume observations combining a 3D plume geometry, realistic phase function and the multiple-scattering radiative transfer software DISORT [7].

Geometry: A summary of the LICIACube flyby geometry is given in Fig. 2, which is the same impact and coordinate geometry as used in the DART team analysis [1]. The expanding impact plume is modeled as a hollow cone with interior angle of 90°. The DART velocity vector forms the y-axis, with predicted relative velocity $\boldsymbol{v_F}$ of 6.6 km s^{-1}, which impacts Dimorphos normal to its surface so that y bisects the evolving ejecta cone. LICIACube flies parallel and behind DART, forming the **x-y** coordinate plane, with the approach vector defining the **x**-axis. During most of the approach, LICIACube views scattered sunlight from the interior surface of the outward expanding plume. This geometry holds until the spacecraft crosses the extension of the plume surface, at which point there is an abrupt change in plume transmittance and scattering behavior seen by the observer. Between plume plane crossings, the line of sight passes through both plume layers in tandem, before again viewing separate surfaces.

Plume Particles: One plausible model for plume particles is impact fragments with reflectance properties similar to Didymos, which has a known geometric albedo $\boldsymbol{A_G}$ = 0.15 [6]. Implicitly, we assume small, opaque spheres with scattering surfaces, characterized by a Lommel-Seeliger phase function, typical of low-reflectance solar system objects [8]. Real impact fragments will probably be irregular and possibly porous. Approximate corrections for these effects can be made by geometric codes for computing the reflectance from irregular shapes, followed by orientation averaging.

Model & Discussion: Using the geometry outlined above we conducted line of sight simulations for normal geometric optical depths ranging from 0.01 to 10, for two cases: a) using our realistic scattering plume particles and b) using the simplifying scattering assumptions of the DART team [1]. It was found that this yielded differences in plume surface brightness exceeding an order of magnitude in the worst cases. This result highlights the importance of a realistic scattering parametrization and modelling regime.

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