Exploring Effects of Spacecraft Geometry and Target Structure on the DART Impact

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Planetary-scale Impact Experiments

- The DART impact will join Deep Impact and LCROSS as planetary-scale impact experiments
  - Initial impactor parameters are well known
  - Physical properties of the target are not well constrained
Planetary-scale Impact Experiments

- The DART impact will join Deep Impact and LCROSS as planetary-scale impact experiments
  - Initial impactor parameters are well known
  - Physical properties of the target are not well constrained
- Understanding the conditions of the DART impact is essential for interpreting the ability of the kinetic impactor to deflect the asteroid
- *A priori* estimates of the scale of the event are essential for planning Earth-based observations of the impact event
- The DART impact is the first direct test of an asteroid deflection technique and provides critical information to understand what we can do to protect our planet.

Credit: NASA/JPL-Caltech/UMD
Deflecting Asteroids: Adding Momentum via Kinetic Impactors

Pre-impact

\[ m_s \quad v_s \quad m_t \]
Deflecting Asteroids: Adding Momentum via Kinetic Impactors

- Momentum transfer from kinetic impact
- $\beta$ is defined as momentum transferred divided by momentum input

$$\beta \propto \frac{\Delta p_{\text{target}}}{p_{\text{spacecraft}}}$$

- If no ejecta, then $\beta = 1$

Low speed impact, inelastic collision
No ejecta
Deflecting Asteroids: Adding Momentum via Kinetic Impactors

Momentum transfer from kinetic impact enhanced by impact ejecta

- $\beta$ is defined as momentum transferred divided by momentum input

$$\beta \propto \frac{\Delta p_{\text{target}}}{p_{\text{spacecraft}}}$$

- Ejecta release enhances momentum transfer, $\beta > 1$

Estimation of $\beta$ is critical for deflection performance

Hypervelocity Impact
Crater Forms, ejecta adds to “thrust”

$\beta > 1$
Deflecting Asteroids: Adding Momentum via Kinetic Impactors

- Momentum transfer from kinetic impact enhanced by impact ejecta
- $\beta$ is defined as momentum transferred divided by momentum input
  $$\beta \propto \frac{\Delta p_{\text{target}}}{p_{\text{spacecraft}}}$$
  - Ejecta release enhances momentum transfer, $\beta > 1$
  - Spallation reduces momentum transfer, $\beta > 1$

Estimation of $\beta$ is critical for deflection performance
Exploring the unknown with impact models

“Known” Quantities

- Diameter of Didymos-B
- S-type asteroid
- Separation distance from Didymos-A
- Impactor parameters
  - Size
  - Velocity
  - Structure
  - Nominal impact angle

Unbeknown

- Target properties
  - Composition
  - Porosity
  - Shape/topography
  - Internal Structure
  - Mechanical Properties
    - Strength
    - Density
    - Granular properties (e.g., cohesion, friction angle)
- Impact location with respect to COF
- Actual impact angle

Ongoing work

See Emma Rainey’s talk in 20 minutes!
Canvassing large parameter spaces

- Traditional methods involve picking a “nominal” case and moving parameters one at a time
  - Requires MANY runs for a multi-dimensional space
  - Might miss curvature in response (combinations of effects)

- Design of Experiments
  - Statistical method to determine the important parameters causing variance within data
  - Allows optimization of runs to cover large parameter space
    - 2N-1 runs to generate response surface
Because the physical properties of Didymos-B are poorly known, modeling the DART impact outcome will require running simulations over a wide range of potential material properties and internal structures.

A material property sensitivity study was conducted over a subset of the DART material model parameter space using 2D axisymmetric CTH simulations.

- Approach allows for large number of fast-running simulations at high resolution
- Effect of impact geometry cannot be tested in 2D axisymmetry

Goals of the 2D study:

- Inform current estimates of range of outcomes for DART impact
- Determine relative importance of material properties for predicting $\beta$ and crater size
- Reduce parameter space for future 3D simulations
DOE Impact Simulation Setup

- 17 inputs were varied for this study
  - Include: strength parameters, EOS, porosity, density
- 28 simulations were conducted with different combinations of parameters varied
- JMP software Custom Design tool for Design of Experiments was used to create run set
  - Power analysis gave probability of detection > 0.85 for all effects tested
- Run set was designed to cover entire parameter space
  - Some input combinations describe improbable material behavior for asteroid (e.g., highly porous material that is also strong)

Spacecraft mass and impact speed taken from baseline DART trajectory as of December 2018. Baseline trajectory as of April 2019 has impact speed of 6.6 km/s and arrival mass ~500 kg.
Momentum enhancement factor $\beta$ was calculated by summing total post-impact vertical momentum of target material below the impact crater.

As a check, values were compared with $\beta$ calculated by summing total vertical momentum of ejecta.

Predicted change in target velocity was calculated from $\beta$ and total target mass.

Crater width and depth were measured at end of simulation.

- Crater depth is distance from impact plane at $y=0$ to base of crater.
- Crater width is rim-to-rim distance at $y=0$. 

Crater size, $\beta$, $\Delta v$ were calculated from CTH simulations.
The Material Property Sensitivity Study Identified A Wide Range of Impact Outcomes

- Calculated values of $\beta$ range from ~1-16
- Includes implausible combinations of material properties
- Range of crater widths from 2.5-17.6 m, crater depths from 1.3-6.8 m
Inputs with highest statistical significance for predicting $\beta$ are (1) porosity, (2) yield strength at low pressure, (3) tensile strength, and (4) average crack spacing.

- Fit model for $\beta$ constructed from these four variables alone has $R^2 = 0.88$.

Inputs with highest significance for crater width and width/depth ratio are porosity, yield strength at low pressure, tensile strength, average crack spacing, Poisson ratio, and impactor shape.

- Fit models for crater width and width/depth ratio have $R^2 > 0.90$.  

Initial studies suggest yield strength and porosity are most important for crater morphology and beta.
Uncertainty in Asteroid Mass May Lead to Impact Outcome Ambiguity

- Post-impact measurements will give change in Didymos-B velocity, not $\beta$
- Measured deflection velocity will be used along with images of impact site and best estimate of asteroid mass to calculate $\beta$ and model impact outcome
- Uncertainty in mass of Didymos-B may mean significant uncertainty in initial estimates of $\beta$

Impact Outcomes vs. Microporosity and Material Strength

- High Porosity, Low Strength:
  - Model $\beta \sim 1.7$
  - Deflection Speed = 2.0 cm/s
  - Crater Width/Depth = 2.0

- Low Porosity, Low Strength:
  - Model $\beta \sim 13.3$
  - Deflection Speed = 9.3 cm/s
  - Crater Width/Depth = 3.5

- High Porosity, High Strength:
  - Model $\beta \sim 1.0$
  - Deflection Speed = 1.2 cm/s
  - Crater Width/Depth = 1.8

- Low Porosity, High Strength:
  - Model $\beta \sim 1.9$
  - Deflection Speed = 1.3 cm/s
  - Crater Width/Depth = 4.0
Traditionally, models use simplified shapes to represent spacecraft

- The spacecraft “equivalent mass” can be represented by a solid sphere or cylinder

This is DART!

So how representative is this, really?
Goals and setup of this study test simplifying assumptions in impact models

- Study how $\beta$ changes with the shape of a 2D projectile
  - Solid Sphere
  - Solid Box
  - Thin Shelled Box
  - Thin Shelled Box with Solid Sphere

- Study how beta changes with grid resolution
  - 2-30 Cells per projected radius (cppr)
Hollow and underdense projectiles cause unusual ejecta curtains

Hollow vs. solid projectile experiments. High speed images (recorded at 500,000 frames per second; selected frames are temporally matched in this figure) derived from closer to the impact point), it attains a greater ballistic height and thermally self luminous for both. The ejection angles progress upward toward forming. High-angle reverse plumes have been observed experimentally separating from the canonical "inverted lampshade" low-angle ejecta. The first high-speed ejecta to emerge is extremely low angle ejecta evolution, ejected at high speeds and angles of >75°. The high-angle plume is more difficult than main-stage ejecta. This component persists into the "high-angle plume" (Schultz et al., 2010). This element of the low-angle material excavates material from a maximum of 10 m under the pre-curtain and persists in ballistic flight after low-angle main-stage ejecta has returned to the surface. Frames are taken at 809, 6128, 18870, and 188,865 s after impact.

Hermalyn et al. (2012), Icarus

Images of ejecta from impacts into sand targets illustrate that the impact point crushed and compacted the material prior to excavation depths failed to eject tracers from a projectile diameter underneath the surface. The fine-grained and optically-thin curtain and persists in ballistic flight after low-angle main-stage ejecta has returned to the surface. Frames are taken at 809, 6128, 18870, and 188,865 s after impact.
(Low resolution 2D) studies predict larger craters for under-dense projectiles compared to solid box assumptions.

* Note, mass is maintained when internal structure is altered. Analysis to remove size effects is underway.
Beta depends strongly on resolution & Structure of impactor affects predicted values in 2D models

Mallory DeCoster and Tom Rosch

2D Projectile (Sphere)

Increased resolution

2D Projectile (Solid Box, Thin Shelled Box, Thin Shelled Box with Sphere)
Studies underway to test effects of real spacecraft geometry

The solar panels are there, I swear! They’re not plotted due to resolution effects
Studies underway to test effects of real spacecraft geometry
Asymmetrical interior spacecraft structure affects crater evolution and coupling of spacecraft to target during impact

Mallory DeCoster and Tom Rosch

Asymmetric crater formation will depend on spacecraft orientation (roll) on impact

Early time evolution strongly depends on s/c geometry, but this may even out in final crater evolution/size

Asymmetric shock wave at early times

Pressure

-10^5
-10^4
-10^3
-10^2
-10^1
10^1
10^2
10^3
10^4
10^5
Discussion

- DART is the first direct planetary-scale test of a kinetic impactor and provides critical information about how to deflect an asteroid for planetary defense.
- Choice of strength model, and values chosen in that model, affect predicted impact outcomes
  - Porosity, cohesion, and low-pressure strength are most important
- Models including realistic spacecraft shapes result in different predicted craters and beta than simplified projectiles
- Crater formation and ejecta curtain structure depend on spacecraft structure and how spacecraft hits
  - Especially important for early-time effects
The Double Asteroid Redirection Test (DART)

- Intercept of the moon of a binary asteroid in 2022, launch 2021
- Goal: to impact Didymos-B and change the period of the moon
- Measure period change from Earth-based assets
- First direct test of a kinetic impactor for deflection

LAUNCH
22 July, 2021

Flyby
9 July, 2022
1994 AW1
Binary asteroid
Primary: 715 meters, S-type,
2.5-hour rotation rate
Secondary: 379 meters,
22.45-hour orbital period

DART Spacecraft
650 kg Arrival Mass
12.5 m x 2.4 m x 2.0 m
6.65 km/s closing speed

LICIA Cube
(Light Italian Cubesat
for Imaging of Asteroids)
ASI contribution

Earth Based
Observations
0.07 AU range at impact
Predicted ~10 minute
change in binary orbit period

IMPACT
27 Sept, 2022

Didymos-A
780 m
S-type
2.26 hr rotation period

1180 m separation
between centers
of A and B

Didymos-B
163 m
11.92 hr orbital period

1194 AW1
Binary asteroid
Primary: 715 meters, S-type,
2.5-hour rotation rate
Secondary: 379 meters,
22.45-hour orbital period
Assumed aluminum “spacecraft” impactor with varying shape and average density

CTH Brittle Damage with Localized Thermal Softening (BDL) model was used for asteroid strength

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impactor Properties</td>
<td></td>
</tr>
<tr>
<td>Impactor shape</td>
<td>Sphere, cylinder, cylinder with wide panels</td>
</tr>
<tr>
<td>Average density</td>
<td>0.27–2.7 g/cc</td>
</tr>
<tr>
<td>Target Properties</td>
<td></td>
</tr>
<tr>
<td>EOS</td>
<td>SESAME, Aneos, Mie-Gruneisen</td>
</tr>
<tr>
<td>Yield Strength at Low Pressure</td>
<td>0.1-100 MPa</td>
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<tr>
<td>Tensile Strength</td>
<td>0.1-100 MPa</td>
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<tr>
<td>Yield Strength at Infinite Pressure</td>
<td>300 MPa − 3.5 GPa</td>
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<tr>
<td>Microporosity</td>
<td>0-40%, with and without crush curve</td>
</tr>
<tr>
<td>Coefficient of Friction</td>
<td>1-2 (intact material), 0.1-0.8 (damaged material)</td>
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<tr>
<td>Failure Strain</td>
<td>0.01-0.05 (brittle regime), 0.05-0.1 (ductile regime), 0.1-0.3 (plastic regime)</td>
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<tr>
<td>Poisson Ratio</td>
<td>0.2-0.4</td>
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<tr>
<td>Melting Temperature</td>
<td>1200-1800 K</td>
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<tr>
<td>Average Crack Spacing</td>
<td>0.5-5 m</td>
</tr>
<tr>
<td>Damage at Failure</td>
<td>0.7-0.95</td>
</tr>
</tbody>
</table>
Rubble Piles: Do we care?

- Mounting evidence over the past few decades that many rocky asteroids are non-monolithic rubble piles.

Ryugu from Hayabusa 2

Image credits: JAXA

Minerva Rover 1b – Ryugu Surface

Itokawa as observed by Hayabusa

Close up of surface
Theories for binary formation

- Disruption of parent body/fission after oblique impact (main belt)
- Mutual capture of objects (TNOs)
- YORP spin-up and mass shedding (typical of NEOs)

Origin of binary by Yorp spin-up

Walsh et al. (2008)

DART – Double Asteroid Redirection Test

8 May 2019 | 29
Rubble Piles: Do we care?

- Mounting evidence over the past decades that many rocky asteroids are non-monolithic rubble piles.
  - DART’s target will likely be a YORP spin-up rubble pile
  - Most mitigation modeling has examined monolithic structures

- Big question to ask:

Does this structure have consequences for mitigation (either deflection or disruption)?
Comparing porosity type

The type of porosity in the target affects the momentum transferred and resultant velocity change following impact.

No porosity

$\beta = 1.32$

$\Delta v = 1.75 \text{ cm/s}$

Microporosity

$\beta = 1.14$

$\Delta v = 1.87 \text{ cm/s}$

porosity

$\beta = 1.55$

$\Delta v = 2.53 \text{ cm/s}$

$\beta = \frac{p_{\text{moon}}}{p_{\text{spacecraft}}}$

$\phi \approx 20\%$
Modeling possible outcomes of DART requires creating random rubble pile realizations.

2D Rubble Pile Model

3-D Didymos-B Rubble Pile Model
3D simulation: Impact into Rubble Pile Itokawa

Granular material, ~20% porous
Competent rock
Brittle failure model

Projectile size scaled to Itokawa to match DART into Didymoon
Example: Oblique Impact into a Rubble Pile

Pressure at 3.01e-04 s

(dyn/cm$^2$)

10$^8$

10$^7$

10$^6$

10$^5$

10$^4$

10$^3$

10$^2$

10$^1$

10$^0$

-100 -50 0 50 100

X (m)

-10 0 10

X (m)

-20 -10 0 10

X (m)

100 150

Materia

A.M. Stickle, PDC 2C
Impacts into matrix/regolith may cause local disruption of boulders, adding to ejecta and momentum enhancement.