Session 7b: Deflection & Disruption Testing

Chairs: Patrick Michel | Angela Stickle | Megan Syal

Presenters: M. Burkey | A. Stickle | C. Raskin | M. DeCoste | M. Owen
Progress on Developing a Simplified Model of X-Ray Energy Deposition for Nuclear Mitigation Missions

Planetary Defense Conference, April 28th 2021

Mary Burkey
Rob Managan, Kirsten Howley, Nick Gentile, Megan Bruck Syal, Mike Owen
An Option for Planetary Defense: Nuclear Deflection/Disruption

- A nuclear mitigation mission is dependent on many asteroid properties that may be poorly constrained before launch.

- **Successful Deflection Mission:** asteroid remains intact and misses Earth

- **Failed Mission:** asteroid breaks into slow-moving fragments that could hit Earth

- **Successful Disruption Mission:** asteroid is blasted into many small, fast-moving fragments
A problem with two parts

**X-Ray Energy Deposition**

- X rays penetrate 1 μm – 1 cm into the material, causing heating and ionization. Some energy re-radiates away.
- Only a full radiation-hydrodynamics code can cover all the physics that is happening in this process.

**Hydrodynamics**

- Everything that happens after the energy deposition.
- The deposited energy causes material to begin moving and expanding.
- At this point, only a standard hydrocode is needed to follow the material's movement and energy.
Nuclear Deflection/Disruption Modeling: X-ray Energy Deposition

**Old Way: Mercury**

Mercury is a Monte Carlo particle transport code, which works well for neutron energy deposition

- Easy-to-fit energy depositions
- Profiles can be easily scaled by yield and angle of incidence
- Cold opacities assumed
- No re-radiation
- No radiation-hydrodynamics coupling

\[
f(x, \chi) = \frac{1}{\cos(\chi)} \sum A_i \exp \left( \frac{-x}{\lambda_i \cos(\chi)} \right)
\]

**New Way: Kull**

Kull is a mesh-based radiation-hydrodynamics code that was developed for High Energy Density Physics

- Includes re-radiation and rad-hydro effects!
- Uses best-available opacities
- No more easy fits

Mercury Energy Depositions for X rays and Neutrons

*The x ray energy depositions are a simplified with constant opacity. The opacity of the material changes as it is radiated.*

**X-ray normalized energy depositions**

<table>
<thead>
<tr>
<th>Material</th>
<th>Time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>1 ns</td>
</tr>
<tr>
<td>FeNi</td>
<td>10 ns</td>
</tr>
<tr>
<td>S-type</td>
<td>50 ns</td>
</tr>
<tr>
<td>C-type</td>
<td>100 ns</td>
</tr>
<tr>
<td></td>
<td>500 ns</td>
</tr>
</tbody>
</table>

**Neutron Energy Deposition Placeholder**

- Cold opacities assumed
- No re-radiation
- No radiation-hydrodynamics coupling
1D Kull Energy Deposition Tests:

Can we initialize Kull with a Kull-generated energy profile at a specific time and get roughly the same answer as a normal Kull simulation?

We can in most cases reproduce the pure Kull blowoff momentum to within ±50%.

Scope of Study:

Materials
- Silicon Dioxide (SiO₂)
- Forsterite (Mg₂SiO₄)
- Ice (H₂O)
- Iron (Fe)

Source
- 1 keV Black Body at 4
Fluences:
- Low – 1e-4 kt/m²
- Mid – 2.5e-3 kt/m²
- Mid-High – 0.12 kt/m²
- High – 1 kt/m²

Test Asteroid/Case:
- R=150m, Standoff=50m

*Source duration estimates taken from Glasstone, 1977
Level Up: 2D Kull Energy Deposition Tests

<table>
<thead>
<tr>
<th>Fluence Level</th>
<th>Low</th>
<th>Mid</th>
<th>Mid-High</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D blowoff momentum (g cm/μs)</td>
<td>4.66e6</td>
<td>3.81e7</td>
<td>4.65e8</td>
<td>1.98e9</td>
</tr>
<tr>
<td>1D integrated blowoff momentum (g cm/μs)</td>
<td>4.74e6</td>
<td>3.92e7</td>
<td>4.55e8</td>
<td>1.91e9</td>
</tr>
<tr>
<td>Time after “detonation” (μs)</td>
<td>1.36</td>
<td>5.0</td>
<td>3.48</td>
<td>2.19</td>
</tr>
</tbody>
</table>

- The 1D and 2D blowoff momentum results from pure Kull simulations match closely
- The energy deposition profiles also match reasonably well...
  - ...And will improve when a time-dependent source is implemented into the 1D simulation.
- We will use the “cleaner” 1D data for fitting an angle-dependent function.
Fitting to 1D Depositions (Preliminary):

Sample 1D Energy Deposition Fit

Energy Deposition Data

Energy Deposition Fit

(Fit – Data)/Avg(Data)

**Energy Deposition Data**

- "High" Fluence
- "Low" Fluence

\[ 1 = \frac{x^2}{a^2} + \frac{y^2}{b^2} \]

\[ y \propto e^{-x} \]

\[ y = Ax + B \]
Preliminary Results and Still To Do

- Preliminary results are promising but should improve with better 1D data.
- Exercise: Asteroid diameter is 120m, material is SiO$_2$, and a “High” Fluence is applied (Yield = 1Mt, Standoff = 9m)

### Preliminary Results and Still To Do

<table>
<thead>
<tr>
<th>Fluence Level</th>
<th>Low</th>
<th>Mid</th>
<th>Mid-High</th>
<th>High</th>
<th>Exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D Pure Kull momentum (g cm/μs)</td>
<td>4.66e6</td>
<td>3.81e7</td>
<td>4.65e8</td>
<td>1.98e9</td>
<td>1.17e8</td>
</tr>
<tr>
<td>2D Deposition Function momentum (g cm/μs)</td>
<td>4.98e6</td>
<td>4.92e7</td>
<td>4.77e8</td>
<td>1.81e9</td>
<td>1.73e8</td>
</tr>
<tr>
<td>Time after “detonation” (μs)</td>
<td>1.36</td>
<td>5.0</td>
<td>3.48</td>
<td>2.19</td>
<td>1.34</td>
</tr>
</tbody>
</table>

- Still lots to do:
  - Global fit over all fluences/source durations
  - Scaling based on density/porosity
  - Same analysis for remaining materials (Forsterite, Ice, and Iron)
  - Thorough study of model weaknesses/errors
Conclusions and Exercise Test with Spheral

- Modeling the x-ray energy deposition is complicated and requires a full rad-hydro simulation to get right.
- Our analytic deposition model is progressing quickly and shows promise.
- The PD community can use our model to more efficiently explore the vast space of potential scenarios and uncertainties.

Getting $\Delta V$ right requires rad-hydro simulations of the x-ray energy deposition.
The Double Asteroid Redirection Test (DART) Impact Modeling Working Group Inverse Test

Angela M. Stickle, Megan Bruck Syal, Wendy K. Caldwell, Mallory DeCoste, Dawn Graninger, Martin Jutzi, Robert Luther, Mike Owen, Jason Pearl, Catherine S. Plesko, Sabina Raducan, Emma Rainey, Cody Raskin, Tane Remington, Andy Rivkin, and the AIDA/DART Impact Modeling Working Group

Planetary Defense Conference 2021
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It allows a deflection demonstration on an asteroid of the relevant size by changing its orbital period by ~1% about the larger asteroid.
Planetary-scale Impacts Provide Partially Well-controlled Experiments

• The DART impact will join Deep Impact and LCROSS as planetary-scale impact experiments
  - Initial impactor parameters are well known
  - Physical properties of Dimorphos are not well constrained
We know little about the object we are going to hit

Dimorphos

ID1: kw4a  ID2: kw4b  ID6: Rashalom  ID7: sphere 1  ID4: Eros  ID5: Kleo  ID3: Mithra
Planetary-scale Impacts Provide Partially Well-controlled Experiments

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

- Understanding the conditions of the DART impact is essential for interpreting the ability of the kinetic impactor to deflect an asteroid (estimating $\beta$)

Credit: NASA/JPL-Caltech/UMD
What Is Beta?

Beta = 1
No ejecta and small momentum increase

Beta = 2
Moderate ejecta and momentum increase

Beta = 4
Heavy ejecta and large momentum increase
The DART Impact Modeling Inverse Test

- Inverse problems tell us about parameters that we cannot directly observe
- Goal: determine the model parameters that best fit a given deflection observation
  - Trial and Error Method
  - Optimization algorithms (see Cody Raskin’s talk, next)

Questions we want answered:

- What is the expected uncertainty on β estimates following the DART impact from simulations? How do target property choices affect the predicted values?
- How well can the impact scenario be recreated from limited information?
- Are current data analysis procedure and handoffs adequate or do new tools need to be developed?
- How long do these simulations take to provide answers and how many different simulations need to be run?
DART “Inverse Test” provides a different controlled experiment

Step 1: Set up “observations” → “The Game Masters”/Truth team

Test shape model and impact scene generated by ProxOps team
Pass to impact team
Impact models generate a $\Delta v$ from a DART impact
Work with other working groups
Turn $\Delta v$ into an “observed” $\Delta p$ and period change

Step 2: Simulate post-impact modeling activities → “The Adventurers”

Receive shape model, mass estimate, period change, impact angle, simulated impact site image
Use prediction simulations to identify range of possible material parameters
Turn $\Delta v$ into a $\beta$ with assumed material properties
Impactor properties, limited target properties, impact geometry, and deflection velocity were provided to team.
DART Truth Model #1 – simple case

CTH Simulations run by Emma Rainey

\[ \Delta v = 0.096 \pm 0.0029 \text{ cm/s} \]

\[ \Delta v = 0.115 \pm 0.017 \text{ cm/s} \]
Analytic model illustrates that a range of strength/porosity values can give you the same momentum enhancement

Model by Sabina Raducan

2D: $\beta = 1.167 \pm 0.035$
SL WCB diameter ~ 7.5 m

Models by Andy Cheng, Mallory DeCoster, Dawn Graninger, Robert Luther, Mike Owen, Jason Pearl Cody Raskin, Tane Remington
The second exercise provides a more stressing case

Beta will be estimated using procedure determined by DART team

Impact Location from DRACO (simulated)

Impact Location Plotted on STL

Truth models still in construction. Stay tuned!
Implications for DART

• Values provided to the team and specific hand-off procedures are vital to test before impact

• We know that $\beta$ is not uniquely tied to one set of material parameters
  - Other information (e.g., crater size) is vital to limit range of possible values
  - Modeling work group simulation library provides important limits and starting points for parameters

• Given a deflection velocity, the adventurers were able to reproduce $\beta$ values within $\sim$10-15% of the “truth” value
  - This is comparable or better than variability due to different codes and/or users [Stickle et al. 2020]
  - Crater size has a larger range, depending on values chosen for strength

• In simple case, all adventurers were able to determine parameters similar to truth

• “Trial and error” methods can reproduce $\beta$ in this simple case
  - More complex optimization methods could provide more robust answers if more complicated simulations are required? → See Cody Raskin’s talk for descriptions of these types of simulations from LLNL

• Inverse test #2 will require more complicated models and provide better constraints on expected uncertainty in post-impact $\beta$ calculations
Accelerated Root Finding for the DART Inverse Test Using Machine Learning Decision Trees

April 23, 2021

Cody Raskin, Tane Remington, Jason Pearl
The DART Inverse Test

- Triaxial, rocky body
  - Uniform, constant density
  - No porosity

- Spherical impactor mass = 570 kg
  - Impactor momentum = 3.42E11 g cm/s
  - No impact angle (head on)

- Vary the yield strength and density parameters to drive to $\Delta v = 0.115$ cm/s
3D Calculations

- SPH with Tillotson EOS
  - No damage model
    - Damage in all cases pushed beta much too high for this exercise
- Monolithic material (no boulder-like inclusions)
- 10cm resolution at impact site
- Assuming no information about total mass (or density) of Dimorphos – fixing only the triaxial dimensions (volume)
The Simulation Outputs Group Into Families

- Varying density and yield strength together results in families of $\Delta \nu$ or $\beta$, grouped by the choice of maximum yield stress. $Y_i = Y_0 + \frac{\mu_i P}{1 + \mu_i P/(Y_m - Y_0)}$

![Graph showing beta cycle with density and yield strength values]

- $\rho = 2.65-2.85 \text{ g/cc}$
- $Y_m = 1.5 \text{ GPa}$
- $Y_m = 2.0$
- $Y_m = 2.5$
- $Y_m = 3.0$
Inverse Problems are Typically Time-Consuming

- Repeated guessing and checking or running thousands of simulations and hoping for a “hit”
**Decision Tree Regressor**

- Most popular fast, supervised machine learning algorithm
- Non-parametric
  - Makes no assumptions about the parametric form of the output functor (good)
  - Generally requires large datasets to be accurate (bad)
- Steerable (good)
- Naïve (bad)
Is this Overkill?

- Future trials may involve many more input and output parameters
  - Difficult for humans to find trends
  - Easy for computers

- Computer cycles are cheap – Human cycles are not

- “Going too far is half the fun of getting nowhere.”
  - Bill Griffith
An Initial Scan of the Parameter Space Already Found Two Successes

$\Delta v = 0.115 \text{ cm/s}$
ML Algorithm Chooses the Next Parameter Set From the Prediction Space
ML Algorithm Refines the Prediction Space and Chooses More Samples
Enhance...
Enhance!!!
Several Candidate Parameter Sets Found in Short Order
Key judgments from the Exercise

- The synthetic observations are most consistent with a uniform, non-porous, single-density body with $\rho \approx 2.79 - 2.83$ g/cc and $Y_m \approx 2.3 - 2.0$ GPa.

- Including any damage model would require tuning the damage parameters to something akin to no damage, or tuning the density and yield strength to something very unlike rock.

- We did not assess the effects of porosity as this would not drive the $\Delta v$ results in a helpful direction. Additionally, guidance from the Red Team briefing suggested bulk densities that are inconsistent with porous granite. It is still possible for a highly porous, metallic body to result in a similar $\Delta v$. 
Major Caveats / Things to Try Next

- $\rho$ and $Y_m$ alone are probably not a sufficient input parameter set
  - A curve of possible input choices yield the same output
  - $Y_0$ and porosity could also drive the decision tree
  - Lack of damage model is simplifying, but unrealistic

- $\Delta\nu$ need not be the only output parameter
  - Crater size
  - Velocity dispersion of the debris
  - Flavor profile of the caramelized debris…

- I made no mention of the error analysis
  - And I’m not going to
Projectile Geometry Effects on Momentum Enhancement of Hypervelocity Impact Simulations

Mallory E. DeCoster,¹ Dawn Graninger,¹ Emma Rainey,¹ Michael Owen,² Angela Stickle,¹

¹Johns Hopkins University/Applied Physics Laboratory
²Lawrence Livermore National Laboratory
Is momentum enhancement ($\beta$) tied to the efficiency of the projectile to generate ejecta during crater formation? If so, is a simplified point source solution accurate for efficiently modeling the DART intercept?

$V_{impact} = 6500 \text{ m/s}$

Ikeda et al., Procedia Engineering 204 (2017) 138-145
The simulation parameters defined for the 3D CTH tests were adapted from the benchmarking study and standardized across the different codes. This time we used a more realistic target material of 30% porous basalt.

**Dimorphos (Target) Shape**
- Sphere
  - Radius (r) = 80 m
  - Mass = 1.3x10⁹ kg
- Material: 30% porous basalt

**2D/3D Impactor Shapes**

**Asteroid Equation of State: Sesame**
- Bulk density = 2.65 g/cc
- Porous density = 1.8536 g/cc (30% porosity)
- Pore compaction pressure = 280 MPa
- P-alpha describes pore crushing process

**Base Asteroid Strength**
- Model: Brittle Damage with Localized Thermal Softening (BDL-Basalt)
  - Cohesion of intact material: 90 MPa
  - Limiting strength: 3.5 GPa
  - Tensile/spall strength: -10 MPa

**Impactor Properties**
- Mass = 550 kg
- Velocity = 6.65 km/s
- Simple shapes: Fully dense Aluminum
- Spacecraft: 10 different materials (Al, Al alloys, steel, oxides, water, xenon)
The temporal evolution of $\beta$ for the 2D and 3D spheres are very similar. The momentum enhancement for the 3D sphere over predicts the spacecraft $\beta$ by $\sim$10%.
The temporal crater evolution of the 3D spacecraft is much different than the 3D sphere. In contrast to a singular transient crater that is wider than it is deep, the spacecraft produces a very complex-looking crater shape with side lobes.
All impactors produce craters that are wider than they are deep. The sphere’s crater is symmetrical while the spacecraft results in a more complex crater that is not as deep or wide as the sphere.
The 3D DART spacecraft produces \(~3\times\) less ejecta mass than the sphere, which is responsible for the smaller $\beta$. Our results suggest a fully dense Al sphere projectile excessively over predicts $\beta$ for the DART intercept event.

\[ \beta = 1 + \frac{\sum m_{\text{ejecta}} v_{\text{ejecta}}}{m_{\text{projectile}} v_{\text{projectile}}} \]
The sphere projectile creates a very different ejecta cloud compared to the spacecraft. While the range of ejecta velocities are similar, the ejecta formed from the sphere has a higher population of fast moving material.
Conclusion: The results show that a simplified model of the projectile overpredicts $\beta$ by $\sim$ 10%. The sphere is a more efficient projectile resulting in more total ejecta mass and a larger population of fast moving material.

This study investigates the effects of projectile geometry on the momentum enhancement factor ($\beta$) for efficiently simulating the DART hypervelocity impact.
Backups
The processes which form large impact craters resulting from hypervelocity impacts are not fully known. We’d like to understand if the projectile can be represented as a simplified point source to make modeling more efficient.

DART benchmarking studies show the propagation of error associated with variables in the phase space. The strength model and material parameters produce the largest uncertainty (~20%) in the prediction of crater size and momentum enhancement.

Stickle et al., Icarus 338 (2020) 113446
While it has been shown that $\beta$ is directly linked to the target material properties, the effects of the projectile geometry on momentum enhancement are relatively unknown. Due to the extra boost provided to $\beta$ by escaping crater ejecta, it has been suggested that projectile configurations that promote large amounts of ejecta excavation will be more efficient impactors.

$\beta = \frac{\Delta P_{\text{Dimorphos}}}{m_{\text{projectile}}v_{\text{projectile}}}$

$\beta = 1 + \frac{\text{Total Ejecta Momentum}}{m_{\text{projectile}}v_{\text{projectile}}}$

$\beta > 1$, maybe $>> 1$

Ikeda et al., Procedia Engineering 204 (2017) 138-145

Ejecta = any material with mass above 80 cm of impact plane (1% target radius) with positive velocity normal to the impact plane, and a volume fraction < 1.
The simulation parameters defined for the initial 2D CTH tests were adapted from the benchmarking study and performed with no porosity in the basalt target.

**Dimorphos (Target) Shape**
- **Sphere**
  - Radius \( r \) = 80 m
  - Mass = \( 1.3 \times 10^9 \) Kg

**Material**
- Fully dense basalt
- Cohesion = 90 MPa (strong target)

**Asteroid Equation of State:**
- **Sesame**
  - \( F(V, T) = \phi_0(V) + F_{ion}(V, T) + F_{el}(V, T) \)
  - Bulk density = 2.648 g/cc

**Base Asteroid Strength**
- Model: Brittle
- Damage with Localized Thermal Softening (BDL)
  - Damage is evolved in Asteroid

**2D Impactor Shapes**
- **10 cm wall**
- **15 cm wall**
- **1462 Kg**
- **650 Kg**

**Impactor Properties**
- Composition: Fully dense Aluminum
  - Mass = 650 - 1462 Kg
  - Velocity = 6.65 km/s
The 2D results show that there is not a strong dependence between $\beta$ and projectile shape when the projectile mass is evenly distributed during impact. A natural question to ask is how does this translate to a more complex projectile shape, like the full spacecraft model with deployed solar panel wings?
The temporal crater evolution of the 3D spacecraft is much different than the 3D sphere. In contrast to a singular transient crater that is wider than it is deep, the spacecraft produces a very complex-looking crater shape.
A much more complex crater is created by the spacecraft, as the solar panels contribute to the coupling of the spacecraft to the target.
Spacecraft Geometry Effects on Cratering and Deflection in the DART Mission

Presented at the 2021 Planetary Defense Conference

J. Michael Owen\textsuperscript{1}, Mallory DeCoste\textsuperscript{2}, and Dawn Graninger\textsuperscript{2}

\textsuperscript{1}Lawrence Livermore National Laboratory, mikeowen@llnl.gov
\textsuperscript{2}Johns Hopkins University/Applied Physics Laboratory

April 28, 2021
At the 2019 PDC we presented early work looking at spacecraft geometry effects.

- We compared models using spheres, cubes, and a spacecraft model based on DAWN.
  - We found the impactor geometry could affect $\beta$ by 10%-15% (lowest for the spacecraft model, highest for symmetric impactors like the sphere).
  - The crater morphology was also affected:
    - Diameters and depths varied by roughly a meter (10%), again with the larger/deeper craters for simple symmetric impactors like the sphere and smaller craters due to the most realistic spacecraft model.

- This year we would like to finalize this study with several improvements over our prior study:
  - Improved material modeling, with damaged rock behaving more like granular material rather than a strengthless fluid (in Spheral – CTH already had this model).
  - Higher fidelity models of the spacecraft scenario:
    - Realistic materials (previously just used Si and Al).
    - Real CAD based geometry with true geometry, components, panels, and voids.
      - Prior simulations relied on full density solid impactor models, implying we shrunk the spacecraft volume in order to match the true mass.

- Multiple codes used to model the problem: Spheral (ASPH) and CTH (AMR Eulerian).
The spacecraft model is based on a simplified DART CAD model.

- We use STL models for each part in a simplified model
  - Roughly 50 individual components (panels, camera, struts, etc.)
  - We use one of 4 material models for each component in the model: Al, Ti-6Al, Stainless Steel, and Si.

- Spheral fills each STL part model with ASPH (Adaptive SPH) points, while CTH paints in each component on an AMR mesh.

- The total spacecraft mass is 535kg, which is distributed between the materials as:

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>377kg</td>
</tr>
<tr>
<td>Si</td>
<td>57.3kg</td>
</tr>
<tr>
<td>Ti-6Al</td>
<td>41.35kg</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>59.35kg</td>
</tr>
</tbody>
</table>
We consider a variety of idealized impactor geometries for comparison with the high fidelity DART model.

- The game here is to maintain the same impactor mass (535 kg) and impact velocity (6.65 km/sec), while varying the geometry.

- In both Spheral and CTH we compare two impactor geometries: DART and a sphere.

- In Spheral we have also modeled a few more cases:
  - A hollow cuboid with the same moment of inertia as DART.
  - A series of solid cylinders (or disks), with diameters in the range $D=\{0.5, 1, 1.25, 1.5\}$ meters.

- All cases model Dimorphos as a uniform SiO$_2$ sphere of 160 m diameter and bulk porosity $\phi=30\%$.
The full DART model impactor results in a fairly complex crater, with evident side craters due to the solar arrays and booms.

- In these models we impact with solar arrays parallel to Dimorphos’ surface.
- This animation shows the materials in Spheral’s polyhedral reconstruction.
- This is a slice through the simulation, run to 50 milliseconds final time.
- The crater is not a simple bowl: the solar panel structures (primarily the stainless steel booms and rollers) result in shallow craters on both sides of the primary crater.
The effect of the CAD geometry on the crater is evident compared with the spherical impactor.

- In these mass density images we can clearly see the imprint of full DART geometry at 50 ms.
  - Compared with the spherical impactor the central crater is shallower and not as wide.
  - The side craters are evident from the solar arrays (at least for this simple monolithic target at early time).
The crater tends to be smaller for more complex impactor shapes that do not penetrate as well.

- This is particularly clear for the cylinder/disk impactors: the wider/thinner the disk, the shallower and narrower the crater.

- CTH tends to find smaller crater volumes than Spheral.
  — Note, the CTH DART model is shown at 13 ms (not 50 ms), and so may grow with time still.
The ejecta momentum enhancement ($\beta$) shows trends with impactor geometry, though Spheral finds the sphere fortuitously matches DART reasonably in this quantity.

- Spheral and CTH agree reasonably on $\beta$ for the sphere, with Spheral somewhat higher.
  - This despite CTH finding less ejecta mass and a smaller crater volume compared with Spheral (note, both CTH models at earlier time).
  - Both find the DART model $\beta$ to be reduced (CTH more so).

- The disk/cylinder models show a clear pattern in $\beta$ -- penetrating rods produce higher $\beta$.

- The idealized impactors follow a tight correlation of ejecta mass vs. $\beta$.
  - The DART model is an outlier in this plot, producing more $\beta$ per ejecta mass.

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**$\beta$ history (Spheral models)**

**$\beta$ vs. ejecta mass**

- $t=13\text{ms}$
- $t=20\text{ms}$
The ejecta velocity distribution is also affected by impactor geometry, though again the sphere and DART agree reasonably.

- The shapes of the ejecta distributions are similar for the sphere vs. DART.
  - Spheral finds the magnitudes of the two case are close, though the mass of slow ejecta is reduced for DART.
  - CTH shows the DART distributions are similar in shape but reduced in magnitude vs. the sphere.
  - Recall though the CTH calculations are at earlier times (20ms for the sphere, 13ms for DART).

- The disk/cylinder models show consistent effects:
  - Ejecta from flat disks is systematically lower at all velocities.
  - The rod shows the most ejecta/highest $\beta$ of all cases.
Overall we find the impactor geometry can affect the measurable quantities in kinetic impactors.

- In terms of crater geometry, we see a roughly 15% effect in the main crater dimensions:
  - 7m wide for DART vs. 8m for the sphere; 4.5m deep for DART vs. 5.5m deep for the sphere

- The ejecta shows some large differences, with the sphere producing significantly more ejecta mass: 2x @ 50ms, with the sphere ejecta mass still climbing (consistent with the different crater volumes).
  - CTH finds a 3x ejecta mass discrepancy.

- This effect is somewhat mitigated in $\beta$, as the DART model produces slightly more ejecta at moderate velocities vs. the sphere.
  - The sphere still produces a larger $\beta$ in the end, but not by quite as much as the difference in ejecta mass would suggest. CTH finds this discrepancy between the sphere and DART to be even larger (10% in $\beta$).

- We find that varying the impactor geometry in a systematic way (varying cylinders for instance) produces measurable and predictable changes in $\beta$ and crater dimensions.
  - The sphere, cylinders, and cuboid produce distinct ejecta cloud properties, but fall on a single linear relation when we plot $\beta$ vs. total ejecta mass.
  - The DART model does not fall on this trend however.

- Gratifyingly, the broad conclusions comparing the spherical impactor vs. DART are consistent between CTH and Spheral, the two codes discussed in this study.
Q&A
Session 7b: Deflection & Disruption Testing
Break

Up next: Session 8b - Mission & Campaign Design