Impact Simulations of the Double Asteroid Redirection Test (DART) – Results from the HERA Impact Simulation Group

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HERA mission

▶ ESA’s contribution to AIDA
▶ Launch planned for 2023/2024, arrival after the DART impact
▶ **Goal:** characterisation of the binary system, the moon and the DART crater
HERA Impact Simulation Group

› Chairs: K. Wünneemann (MfN Berlin)
   M. Jutzi (Universität Bern)

› Members of planetary science / astronomy community
  (cratering, collisions, small bodies, ...)

› Hypervelocity impact & engineering community:
  › Fraunhofer EMI
  › SimChoc
  › CEA

› Modelling (ALE, SPH,...)

› Experiments
HERA Impact Simulation Group

› Laboratory Experiments

› Numerical Modelling

› measured ejection parameters

› ground truth to validate models

› Combine advantages of both methods

› systematic parameter study possible

› scale to natural sizes
Goals of Impact Simulation Group

› Predict impact outcome:
  - Complimentary to DART studies -
    › Efficiency of momentum transfer $\beta$

› Range of expected crater morphologies and properties of the surrounding surfaces

Efficiency $\beta = \frac{\text{Didymoon mass} \times \Delta V}{\text{momentum}}$

Morphology: example for 40% porosity and large coefficient of friction (1.0) (Luther et al. 2017)
Benchmarking of Shock Physics Codes: Case I

- DART Benchmark study (Stickle et al., submitted) - additional results:
  - impact of Al on Al
    (strengthless vs constant strength)
- 3 grid Codes (ALE):
  - iSALE (Tillotson EoS)
  - CEA-HESIONE (Tillotson EoS)
  - SimChoc-RADIOSS (Mie-Grüneisen EoS)
Benchmarking of Shock Physics Codes: Case I

Additional results to the DART benchmark study (Stickle et al.):

$D_{\text{hydro}} = 4.4 \pm 1\%$

$D_Y = 2.3 \pm 4\%$

$\text{in agreement with DART benchmark;}$

Next step: compare $\beta$

$\text{d}_{\text{hydro}} = 2.6 \pm 2\%$

$\text{d}_{\gamma} = 1.2 \pm 4\%$
Benchmarking of Shock Physics Codes: Case II

- Simulation of DART impact
  - Target: asteroid Didymos B:
    - Diameter ≈ 160 m
  - Impactor: DART spacecraft
    - Impact angle: head-on
- **Goal:** illustrate differences in results due to:
  - different approaches (code, modeller)
  - assumptions regarding target properties

\[ m = 500 \text{ kg} \]
\[ v = 6 \text{ km/s} \]
Benchmarking of Shock Physics Codes: Case II

› Simulation of DART impact

› Grid based ALE code (iSALE: Raducan et al., Luther et al.)

› Particle based SPH codes (Maindl & Schäfer, Jutzi et al.)

\[ Y_0 = 1 - 100 \text{ kPa} \]
\[ f = 0.6 - 1.0 \]
\[ \Phi = 20 - 50\% \]

\[ Y_0 = 1-10 \text{ kPa}, \Phi = 0.4 - 0.8 \]

\[ Y_0 = 10 \text{ kPa}, f=0.6, \Phi=30\% \]
Crater Diameter

- Derived from scaling laws (e.g. Holsapple & Housen, 2007) and iSALE shock physics code

- $Y_0$, $f$, (and $\Phi$) reduce crater diameter

Effect on $\theta$?
Ejecta Analysis with iSALE

continuum approach in models:
- Good description of crater formation
- ejecta curtain underresolved
→ Tracer enable to quantify ejection
  - velocity \( v \)
  - angle \( \alpha \)
  - launch position \( x \)
Validation of Ejecta Data

› Validation of ejection data for impact experiments into coarse sand

(as basis for determination of $\beta$)

(i) $\frac{v}{\sqrt{gR}}$ vs. $\frac{x}{R}$

(ii) Launch angle $\theta$ vs. $\frac{x}{R}$

$R =$ crater radius, $x =$ launch position

Luther et al. (2018)
Validation of Ejecta Data

Validation of ejection data for impact experiments into coarse sand
(as basis for determination of $\beta$)

(i) $v/(gR)$ vs. $x/R$
(ii) $\theta$ vs. $x/R$

$R$ = crater radius, $x$ = launch position

Luther et al. (2018)
Momentum Multiplication factor

- $\beta$ derived with iSALE shock physics code
- $Y_0, f$ reduce $\beta$

$v = 6 \text{ km/s}$

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Momentum Multiplication factor

- $\beta$ derived with
  iSALE shock physics code
- $Y_0$, $f$, and $\Phi$
  reduce $\beta$

$v = 6$ km/s

- iSALE

$Y_0 = 1$ kPa
- $\Phi = 20\%$
- $\Phi = 30\%$

$Y_0 = 10$ kPa
- $\Phi = 20\%$
- $\Phi = 30\%$

$Y_0 = 100$ kPa
- $\Phi = 20\%$

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Momentum Multiplication factor

- $\beta$ derived with iSALE shock physics code
- $Y_0$, $f$, and $\Phi$ reduce $\beta$

\[ v = 6 \text{ km/s} \]
Momentum Multiplication factor

\( \beta \) derived with iSALE shock physics code

\( Y_0, f, \) and \( \Phi \) reduce \( \beta \)
Momentum Multiplication factor

- Differences for same code and material due to:
  - projectile set-up
  - EoS
  - model parameters

\[ v = 6 \text{ km/s} \]
differences for same code and material due to:
  > projectile set-up
  > EoS
  > model parameters

\[ \Delta \beta \approx 2\% \]
\[ \Delta \beta \approx 4\% \]

\( v = 6 \text{ km/s} \)
Momentum Multiplication factor

- differences for same code and material due to:
  - projectile set-up
  - EoS
  - model parameters
  - layering

\[ v = 6 \text{ km/s} \]

\[ \beta \]

\[ Y_0 = \text{1 kPa, iSALE} \]

- two layers: top \( \Phi = 50\% \)
- bottom \( \Phi = 30\% \)

\[ \text{iSALE, } f=0.6 \]

\[ Y_0 = \text{1 kPa} \]

\[ Y_0 = \text{10 kPa} \]

\[ Y_0 = \text{100 kPa} \]
Momentum Multiplication factor

- differences for same code and material due to:
  - projectile set-up
  - EoS
  - model parameters
  - layering

\[ \Delta \beta \approx 5\% \]

\( v = 6 \text{ km/s} \)

\( Y_0 = 1 \text{ kPa, iSALE} \)

- top \( \Phi = 50\% \)
- bottom \( \Phi = 30\% \)

\( Y_0 = 1 \text{ kPa} \)
\( Y_0 = 10 \text{ kPa} \)
\( Y_0 = 100 \text{ kPa} \)

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Momentum Multiplication factor

- differences for same code and material due to:
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  - layering
Momentum Multiplication factor

differences for same code and material due to:
  › projectile set-up
  › EoS
  › model parameters
  › layering

\[ \Delta \beta \approx 5\% \]
\[ \Delta \beta \approx 4\% \]
Momentum Multiplication factor

- differences for same code and material due to:
  - projectile set-up
  - EoS
  - model parameters
  - layering
  - Codes used

\[ \Delta \beta \approx 11\% \]
\[ \Delta \beta \approx 5\% \]
in agreement with results from DART benchmark

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Momentum Multiplication factor

- Differences for same code and material due to:
  - Projectile set-up
  - EoS
  - Model parameters
  - Layering
  - Codes used

- Target properties are most crucial
- More constraints than $\beta$ required to assess target properties (crater size)

$\Delta \beta \approx 45\%$
Conclusion

› Modelling aims at reliable predictions

› Preliminary results indicate an overall good agreement between:
  › different users (few % deviations)
  › iSALE and SPH calculations (~10% deviations)

› Results ($\beta$, crater size, etc.) strongly depend on material properties
  (50% deviations in $\beta$):
  › cohesion is most important parameter
  › porosity and coefficient of friction also affect $\beta$
  › layering plays a role for $\beta$

› projectile set-up might have some influence on results
Next Steps

› more detailed comparisons of crater morphologies and $\beta$
  between different codes and for different target properties

› study of more complex effects:
  › shape, local topography, ...

› further comparisons to experiments

› connect in-situ observations with properties of subsurface
Thank you for your attention.
Benchmarking of Shock Physics Codes

- effect of impact angle (SPH), $45^\circ$:
  - $\Phi = 0$: decrease of $\theta$ by $\sim 7\%$
  - $\Phi > 0$: increase of $\theta$ by $\leq 17\%$

$\Phi = 0$: decrease of $\beta$ by $\sim 7\%$

$\Phi > 0$: increase of $\beta$ by $\leq 17\%$

Single Al particle

$m = 500$ kg

basalt

$Y = 100$ kPa
Examples of ongoing modelling & experiments: SimChoc

› Impact Simulation Code: RADIOSS

Simulation Capabilities:

- Crash and Safety
- Drop & Impact
- Blast & Hydrodynamic Impact
- Fluid-Structure Interaction
- Terminal Ballistic
- Forming & Composites Mapping

Multiphysics Analysis and Optimization
Examples of ongoing modelling & experiments: Fraunhofer Ernst-Mach-Institut

› Diagnostics for experimental reproduction of DART Impact

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Laboratory experiments important for code validation!
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› Predict impact outcome:
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    › Range of expected crater morphologies and properties of the surrounding surfaces
  › Efficiency of momentum transfer $\beta$

Morphology: example for 40% porosity and large coefficient of friction (1.0) (Luther et al. 2017)

Efficiency $\beta = \frac{\text{Didymos mass} \times \Delta V}{\text{momentum}}$