High-Fidelity Blast Modeling of Impact from Hypothetical Asteroid 2023 PDC

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2023 PDC Asteroid Impact “Epoch 1” Scenario

Entry modeling and probabilistic risk assessment

- Diameter: 150–2000 m, most likely 220–660 m, median size 470 m
- Entry speed: 12.67–12.68 km/s
- Energy range from 54-160,000 megatons (Mt)
- Wheeler et. al (PDC2023) showed the highest risk region is Nigeria & Cameroon with average affected population of ~10M

See Wheeler et al. PDC2023 for details of Epoch 1 analysis
### Asteroid Properties

Statistical analysis and Bayesian inference to determine likely asteroid properties

- Epoch 2, PDC2023 remains faint, but have g,r and i band colors which inform inference for taxonomic class, density and strength
- High-fidelity simulations will focus on upper end of “most likely” (68%) range

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>25%</th>
<th>Median 50%</th>
<th>75%</th>
<th>68% (most likely)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H magnitude</td>
<td>19.3</td>
<td>19.1</td>
<td>19.3</td>
<td>19.5</td>
<td>19 - 19.6</td>
</tr>
<tr>
<td>Albedo</td>
<td>0.13</td>
<td>0.04</td>
<td>0.09</td>
<td>0.17</td>
<td>0.01 - 0.15</td>
</tr>
<tr>
<td>Diameter Ø [m]</td>
<td>721</td>
<td>434</td>
<td>617</td>
<td>901</td>
<td>294 - 880</td>
</tr>
<tr>
<td>Density [g/cc]</td>
<td>2.2</td>
<td>1.6</td>
<td>2.0</td>
<td>2.5</td>
<td>1.3 - 2.6</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>$8.5 \times 10^{11}$</td>
<td>$9.6 \times 10^{10}$</td>
<td>$2.5 \times 10^{11}$</td>
<td>$7.5 \times 10^{11}$</td>
<td>$4 \times 10^9 - 5.4 \times 10^{11}$</td>
</tr>
<tr>
<td>Energy [Mt]</td>
<td>16000</td>
<td>1800</td>
<td>4900</td>
<td>14000</td>
<td>76 - 10000</td>
</tr>
</tbody>
</table>

#### Property Distributions (Wheeler: PDC2023 & Dotson: PDC2023)

![Property Distributions](image)
Entry and Energy Deposition

Detailed selection of entry parameters for nominal impact case

- Chose nominal impactor to be near large end of the 68% “most likely case” from risk assessment
  - H-mag 19 & albedo 0.069
  - Nominal impact case is 800m diameter @ 12.67km/s
  - Oblique entry at $\alpha = 54^\circ$ from horizon
- Modeled entry in FCM to get details along trajectory
- Kinetic energy at entry, $E_{\text{Tot}} = 10.3$ Gt
  - $\sim 1.68$ Gt deposited into atmosphere (16.36%)
  - $\sim 8.61$ Gt of ground-impacting energy (83.64%)
- FCM entry modeling parameters shown at right
- Impact in Nigeria has total affected population $\sim 10$ M

Asteroid Threat Assessment Project (ATAP), PDC 2023
Solver Overview: Cart3D

Production solver based on cut-cell Cartesian mesh method

• Originally developed for aerospace applications
• Fully-automated mesh generation for complex geometry
• Inviscid solver using Cartesian cells
  – Fully-conservative finite-volume method
  – Multigrid accelerated 2nd-order upwind scheme
  – Dual-time approach for unsteady simulations
  – Domain-decomposition for good parallel scalability
• All runs are full 3D
  • 220-330 M cells with 20-30k time steps
• Excellent scalability
  – Typical airburst simulations take 8-16 hrs on ~4000 cores
• One of NASA’s most heavily used production solvers, large validation database, 900+ users
• Good comparisons w/ CTH, xRAGE & ALE3D at the 2016 Tsunami Workshop

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Comparison with xRAGE (DoE) at 2016 Tsunami Workshop

Chelyabinsk Ground Footprints
Chelyabinsk airburst: AIAA Paper 2016-0998, Jan 2016

Image credit AIAA 2016-0998, used with permission.
2023 PDC Impactor – Simulation setup

54° entry of Ø 800 m, asteroid at 12.673 km/s, $\rho = 2000 \text{ kg/m}^3$

- Entry profile from FCM with deposition of mass, momentum & energy
- $E_{\text{Tot}} = 10.3 \text{ Gt}$, ~200 times more energy than median 2021 PDC case
  - 16.36% (1.68 Gt) of $E_{\text{Tot}}$ released in atmosphere
  - 83.64% (8.61 Gt) of $E_{\text{Tot}}$ remains at impact
- Impact Modeling
  - Model impact as entry + detonation
  - 2018 studies with ALE3D (Robertson) indicate 3-5% of impact energy couples to airblast

Entry Profile from FCM with deposition of mass, momentum & energy.

- Entry profile from FCM with deposition of mass, momentum & energy.

Energy deposition graph showing:
- Mass/entryMass
- V/entryVelocity
- Edep/Edep Impact

Computational domain (not to scale):

- 1.68 Gt released in atmosphere.
- 8.61 Gt remains at impact.
- 54° Entry.

FCM Entry Profile: 2023 PDC

- 2023 PDC Nominal Impactor
- Peak Edep: 0 km, 16.36% Energy
- 10% Energy Alt: 3.14 km

Asteroid Threat Assessment Project (ATAP), PDC 2023
Blast Propagation for 2023 PDC

54° entry of Ø 800 m, asteroid at 12.67 km/s

• 1.68 Gt energy deposited during entry
  – Very strong atmospheric blast
  – Ground impact at elapsed time $t = 6.62$ s

• Impact energy is 8.61 Gt
  – 95% goes into ground
  – ~5% (430.5 Mt) couples to atmosphere
  – Impact modeled as detonation (430.5 Mt) near ground

• Simulation spans more than 20 min of real time to observe atmospheric response
  – Blast first reaches downrange domain boundary (320 km from impact) about 12 min after entry
**Temperature**  
54° entry of Ø 800 m asteroid at 12.67 km/s

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Temperature [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Local Mach Number  54° entry of Ø 800 m asteroid at 12.67km/s
Blast Propagation for 2023 PDC

54° entry of Ø 800 m, asteroid at 12.67 km/s

- Iso-Mach contours
- Blast from entry corridor and impact disrupts entire atmosphere
- Supersonic spreading at altitude creates oblique shocks which lead the main blast on the ground
- 10 psi overpressures extend 75-80 km from impact
- 4 psi overpressure extends to ~150 km
- 1 psi overpressure extends to domain boundary
- At later times, energy release fills entire domain, and atmosphere oscillates like an elastic membrane
Blast Propagation for 2023 PDC

54° entry of Ø 800 m, asteroid at 12.67 km/s

- Ground overpressure footprint evolves for over 12 mins to cover 640 km² of terrain
- 10 psi contours nearly circular, mean radius of 74 km
- Lower overpressure contours slightly elliptical due to oblique entry
- 1 psi contour driven by oscillation of the atm & extends > 320 km to domain boundary

<table>
<thead>
<tr>
<th>Footprint of Peak Ground Overpressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean blast radius (km)</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Unsurvivable 10 psi</td>
</tr>
<tr>
<td>Critical 4 psi</td>
</tr>
<tr>
<td>Severe 2 psi</td>
</tr>
<tr>
<td>Serious 1 psi</td>
</tr>
</tbody>
</table>
Blast Propagation for 2023 PDC
54° entry of Ø 800 m, asteroid at 12.67 km/s

- Wind is supersonic for over 15 km from impact
- Category 5 winds extend 80-100 km from impact
- Category 1-2 winds extend 180 km from impact and sustain for several minutes
- Speeds near edge likely contaminated by domain boundary conditions

Saffir-Simpson Hurricane wind scale

<table>
<thead>
<tr>
<th>SSHWS Category</th>
<th>Speed (mph)</th>
<th>Mean radius (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>157</td>
<td>95</td>
</tr>
<tr>
<td>4</td>
<td>130</td>
<td>140</td>
</tr>
<tr>
<td>3</td>
<td>111</td>
<td>155</td>
</tr>
<tr>
<td>2</td>
<td>96</td>
<td>180</td>
</tr>
<tr>
<td>1</td>
<td>74</td>
<td>210</td>
</tr>
</tbody>
</table>
Lamb Wave Formation
54° entry of Ø 800 m, asteroid at 12.67 km/s

- Can compute the expected period of a Lamb wave from detonations in the atmosphere as a function of the energy released (Revelle, 1996)
- Well known, and is basis for
  - CTBT infrasound monitoring
  - Infrasound estimates of bolide energy release
- Observed oscillation period of upper atmosphere in simulation is around 180-240s
- Total energy in simulation is sum of E-dep during entry + energy coupling to airblast at impact
- Observed frequency in simulation matches classical prediction extremely well

Hunga-Tonga eruption in 2022 (VEI 5-6) created Lamb wave with max. overpressure of 780Pa.

2023 PDC impact is at least an order of magnitude more energetic
  - Will resonate around the globe for several days
  - Potential for triggering tsunamis far from impact

Thermal Radiation

1-D radiation analysis

- Wide flat atmospheric slab (640 x 640 km) allows use of 1-D radiation approx. via *Stephan-Boltzmann Law*
- Radiative heating is \( \dot{q} = \varepsilon \sigma (T_h^4 - T_c^4) A_h \), where \( \sigma \) is the Stephan-Boltzmann constant, \( T_h = T_{\text{hot gas}} \), \( T_c = T_{\text{ambient}} \)
- Used emissivity, \( \varepsilon \), of 0.1 for hot air
- Gives heating of approx. \( \dot{q} = 77 \text{ Watts/m}^2 \)
- Below threshold to ignite forest floors and damp leaves (Durda & Kring, 2004)
- Below ignition threshold of fescue grass, pine needles & paper (Pitts, 2007)

Not enough energy to ignite entire domain, but easy to see that with a little more energy, or earlier in the evolution, significant regions of the domain could ignite.
Summary

- **Probabilistic risk assessment** and statistical inference was used to develop a nominal impactor and entry profiles for hypothetical asteroid “2023 PDC” in sufficient detail to enable high-fidelity simulation.
- **Performed high-fidelity 3D entry simulations** for self-consistent Ø800 m asteroid entering at 12.67 km/s and 54° to compute ground overpressure footprints and maps of local maximum wind speed to drive hazard modeling using NASA’s Cart3D simulation package.
- **Ground footprints show very large areas of devastation** from both blast and wind and generally exceed those predicted by the fast-running engineering methods in PAIR.

- **In addition to local blast damage:**
  - Analysis reveals initiation of atmospheric Lamb waves with initial overpressures of ~1 psi which will travel around the globe for days after impact and raise tsunami threat
  - 1-D thermal analysis shows radiation from post-impact energy lingering in upper atmosphere may pose a credible ignition threat to grasslands and forests throughout the simulation domain

<table>
<thead>
<tr>
<th>Blast Severity</th>
<th>Mean blast radius (km)</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsurvivable</td>
<td>10 psi</td>
<td>74</td>
</tr>
<tr>
<td>Critical</td>
<td>4 psi</td>
<td>155</td>
</tr>
<tr>
<td>Severe</td>
<td>2 psi</td>
<td>235</td>
</tr>
<tr>
<td>Serious</td>
<td>1 psi</td>
<td>&gt;320</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hurricane Category</th>
<th>Speed (mph)</th>
<th>Mean radius (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>157</td>
<td>95</td>
</tr>
<tr>
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References