Session 9a: Impact Effects
Chairs: Olga Popova | Michael Aftosmis | Mark Boslough | Jessie Dotson | David Morrison

Presenters: A. Losiak | S. Haihao | S. Liu | D. Glazachev | O. Popova
ENVIRONMENTAL EFFECTS OF VERY SMALL CRATER FORMATION


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Chixulub
10 km asteroid
180 km crater
What about very small craters?

- 17 known craters <200 m

Schmieder and Kring 2020
What about very small craters?

- 17 known craters <200 m
- Should be >20 Holocene ~100m craters
  - There are 5 (80-120m)
Environmental effects: Kaali

- Strewn field
  - Up to 100 m

Veski et al. 2007
Environmental effects: Morasko

- Strewn field
- Up to 100 m
Environmental effects: Morasko

- Strewn field
- Up to 100 m

Pleskot et al. 2018

5500 BP
Charcoal in proximal ejecta of small impact craters
Charcoal in proximal ejecta of small impact craters
Small impacts charcoal: distribution

- Horizontal distribution:
  - Ring <rim to <
  - ~0.1 R
- Vertical distribution:
  - Depth > 50 cm
  - Most close to ejecta base
- Double charcoal layer at overlapping craters
Small impacts charcoal: ages

- ± same age
- Oldest sediments inside craters and proximal ejecta charcoals
- Proximal ejecta charcoals from different craters of the same strewn field
Small impacts charcoal:
REFLECTANCE

Belcher and Hudspith 2016

Impact charcoal

Wildfire charcoal

Charcoal reflectance

Belcher and Hudspith 2016
Heated sand experiments

Max temperature of sand vs Ro of spruce

- Ex_sand
- DrySpruce
- FreshSpruce
- Ex_sand_LONG
- DrySpruce_LONG
- FreshSpruce_LONG
- Ex_sand_ROUND
- DrySpruce_ROUND
- FreshSpruce_ROUND
- Ex_sand_SMALL
- DrySpruce_SMALL

Temperature levels:
- 450°C
- 500°C
- 600°C
- 660°C
ENVIRONMENTAL EFFECTS OF VERY SMALL CRATER FORMATION

A. Losiak\textsuperscript{1,2}, C. Belcher\textsuperscript{1}, J. Plado\textsuperscript{3}, A. Jõeleht\textsuperscript{3}, C. D. K. Herd\textsuperscript{4}, R. S. Kofman\textsuperscript{4}, M. Szokaluk\textsuperscript{5}, W. Szczuciński\textsuperscript{5}, A. Muszyński\textsuperscript{5}, M. Szyszko, E. M. Wild\textsuperscript{6}

\textsuperscript{1}wildFIRE Lab, Hatherly Laboratories, University of Exeter, UK; \textsuperscript{2}Institute of Geological Sciences, PAS, Poland; \textsuperscript{3}Department of Geology, University of Tartu, Estonia; \textsuperscript{4}Institute of Geology, Adam Mickiewicz University in Poznan; \textsuperscript{5}VERA Laboratory, Faculty of Physics, University of Vienna;
Figure 2. Stratigraphy of sediments at the Whitecourt meteorite impact crater. A: Stratigraphy beneath crater floor at its approximate center. B: Stratigraphy of interpreted ejecta and buried paleosol from adjacent terrace ~11.5 m east of crater rim. Radiocarbon ages in $^{14}$C yr B.P. are shown for the buried paleosol.

Campo del Cielo, Argentina, Cassidy et al. 1965

Herd et al. 2008

Whitecourt, Canada
Ries
1 km asteroid
24 km crater

Figure 2. Results of the interpolated morphology of the Bunte Breccia thickness. White areas represent outcropping weathered autochthonous units (e.g., Malmian limestone) or post-impact sediments (e.g., loess) (C—crater center).

Sturm et al. 2013
50-100 m in diameter

J. Bailey & D.A. Kring.
~50 m diameter

Tunguska
Russia
30.06.1908
No crater; Forest damaged
X injured
Chelyabinsk meteor
15 February 2013
> 1000 injured people
~ 20 m in diameter

Popova et al. 2013
Methods: Charcoal reflectance

- Temperature of formation
- Time of heating
- Ignition
- Fuel moisture
  - Fuel type
The Melting Ablation Analysis of Meteorites in High Temperature Flow

Sun Haihao, Luo Yue, Dang Leining, Su Siyao, Shi Weibo, Shi Yilei, Liu Sen

Hypervelocity Aerodynamics Institute of China Aerodynamics Research and Development Center
1. Background

2. Introduction to the Experiments at CARDC

3. Description of Melting Ablation Model

4. Results and Discussions
1. Background

Tunguska event, Russia, 1908, ~70m, ~15km/s

Chelyabinsk event, Russia, 2013, ~20m, ~19km/s

K/T event, Chicxulub, Mexico, 65 millions years ago, extinction of dinosaurs, ~10km, ~14km/s
1. Background

- Ablation of meteoroid caused by aerodynamic heating leads to massive mass loss, affects trajectory and radiation characteristics during Earth entry with hypervelocity speed.
- Ablation coefficient of meteoroid is under large uncertainty, and gives rise to unfavorable effects in risk assessment.
  
  range: $3.5 \times 10^{-10} - 7 \times 10^{-8}$ kg/J

- Aiming to reveal mechanism and predict ablation of meteoroid, ground experiments, modeling and computation had been carried out by NASA, VKI, University of Stuttgart, et al.
- The preliminary work in this field by CARDC will be presented in this paper.
1. Background

2. Introduction to the Experiments at CARDC

3. Description of Melting Ablation Model

4. Results and Discussions
2. Introduction to the Experiments at CARDC

- **Meteorite material**
  - NWA 13132, 2007, Niger, Northwest Africa
  - Ordinary chondrite (L5/6)
  - The meteorite is mainly consisting of olivine, pyroxene, plagioclase, Fe-Ni metal, with minor chromite and phosphates.

<table>
<thead>
<tr>
<th>State</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enthalpy (MJ/kg)</td>
<td>7.7</td>
</tr>
<tr>
<td>Stagnation heat flux (MW/m²)</td>
<td>13.1</td>
</tr>
<tr>
<td>Stagnation Pressure (MPa)</td>
<td>0.51</td>
</tr>
</tbody>
</table>
2. Introduction to the Experiments at CARDC

- Experiment facility: 20 MW arcjet wind tunnel at CARDC
■ Sample #4 of Stony meteorite

- Melt flow over stony meteorite model during arc-jet exposure
- The posttest shape (Sample #4)
2. Introduction to the Experiments at CARDC

- Sample #4 of Stony meteorite

The ablation shape change during the experiment

The surface recession with time at the stagnation
1. Background

2. Introduction to the Experiments at CARDC

3. Description of Melting Ablation Model

4. Results and Conclusions
3. Description of Melting Ablation Model

- **The main phenomena**
  1. The heat conduction in the solid region
  2. The energy taken off by the motion of the melt layer;
  3. The latent heat absorbed during the evaporation process;
  4. The thermal blocking effect induced by the $\text{SiO}_2$ injected into the boundary layer.

- **The assumption of Model**
  1. Steady state;
  2. Incompressible flow;
  3. Inertia term is ignored in the momentum equation;
  4. The transverse temperature gradient is ignored in the energy equation.
3. Description of Melting Ablation Model

Melting Ablation Mode

- Evaporation rate

\[
\text{SiO}_2(\text{l}) \rightarrow \text{SiO}_2(\text{g})
\]

\[
\text{SiO}_2(\text{g}) \rightarrow \text{SiO}_2 + \frac{1}{2} \text{O}_2
\]

\[
p_s = p_0 \exp \left(18.48 - \frac{57780}{T_w}\right)
\]

\[
C_w = \left[1 + M_{av} \left(\frac{P_s}{P_s} - 1\right)\right]^{-1}
\]

\[
\dot{m}_v = \left(\frac{C_w}{1 - C_w}\right) \left(\varphi q_{av}\right)
\]

- Equations of steady state liquid layer

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

\[
\frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y}\right) = \frac{dp}{dx}
\]

\[
\frac{\partial T}{\partial y} = \frac{k_I}{\rho c_p} \frac{\partial^2 T}{\partial y^2}
\]

\[
\mu = \exp \left(\frac{a}{T} - b\right)
\]

stagnation:

\[
v_w - v_{-\infty} = -\frac{2\delta^2}{\mu_w} \left(\tau_w - 2\tau p_{\delta}\right)
\]

other zone:

\[
\int_0^x (v_{-\infty} - v_w) dx = r \frac{\delta^2}{\mu_w} \left(\tau_w - 2\tau p_{\delta}\right)
\]

3. Description of Melting Ablation Model

- Flowchart of solution:

  1. Determine the pressure gradient, friction and heat transfer coefficient at the wall by CFD method.
  2. Assume an initial temperature.
  3. According to the analogy relation between mass diffusion and energy diffusion in the boundary layer, determine the vaporization rate.
  4. Determine mass loss rate of the liquid layer due to the pressure gradient and friction.
  5. Determine the total ablation rate.
  6. Judge whether the surface energy balance equation is satisfied.
  7. Update temperature.

Iteration end
3. Description of Melting Ablation Model

**Validation: Fused Silica at NASA Ames**

- Fused Quartz test article
  - 45 deg sphere cones
  - 1.524 cm depth
  - 0.635 cm nose radius
  - 3.07 cm base diameter

- State
  - Stagnation pressure 126kPa
  - Stagnation heat flux 3350W/cm2
  - Enthalpy 20.6MJ/kg
  - Exposure time 2.66s

3. Description of Melting Ablation Model

- Validation: CFD Result

The pressure field

The pressure and wall friction distribution along the x-axis
3. Description of Melting Ablation Model

■ Validation: Ablation Results

The ablation recession rate: 0.662mm/s

The surface temperature distribution

The posttest ablation shape at 2.66s
1. Background

2. Introduction to the Experiments at CARDC

3. Description of Melting Ablation Model

4. Results and Conclusions
4. Results and Conclusions

■ The CFD Results

The temperature distribution

The wall friction distribution
4. Results and Conclusions

The Ablation Results

The ablation recession with time

The surface temperature distribution
The Thermal stress analysis

The posttest shape (Model #1)

The von mises stress distribution at 4th second (without ablation)
The brief conclusion:

1. The ablation recession rate and the final ablation shape is consistent with the experiment results.

2. Higher viscosity leads to the lower mass loss rate by the motion of melt layer, more energy are balanced by the evaporation. The surface temperature increases and the total mass loss rate decreases.

3. The thermal stress caused by the temperature gradient exceeds the material’s strength, which cause it to fragment.
The future work:

1. Employing the Numerical method to simulate the motion of melt layer is necessary to handle the asymmetric factors.

2. The theory model is helpful for us to comprehend what happened during the ablation and fragment process, while it is limited for the meteorite with some random structures.

3. The mass loss of the melt layer is sensitive to the viscosity and thermal conductivity of the molten compound, which should be measured precisely.
Thanks for your attention

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Numerical Analysis of Aerodynamic Heating on Asteroid During Entry to Earth’s Atmosphere

Su Siyao, Liu Sen, Dang Leiling, Zhang Zhigang

Hypervelocity Aerodynamics Institute
China Aerodynamics Research and Development Center
Outline

1、Background
2、Numerical method and physical-chemical model
3、Results and discussion
4、Summary
Outline

1. Background
2. Numerical method and physical-chemical model
3. Results and discussion
4. Summary
1. Background

- **Chelyabinsk event, Russia, 2013,** 
  - $\sim 20m$, $\sim 19km/s$

- **K/T event, Chicxulub, Mexico,** 
  - 65 millions years ago, 
  - $\sim 10km$, $\sim 14km/s$
1. Background

- **Meteorites in China**
  - **Jilin meteorites: 1976.3.8**, 3000 meteorites of total 2 ton mass have been recovered, one of the meteorites weighed as much as 1770kg.
  - **Shangri-La, Yunnan: 2017.10.4**, many videos recorded.
  - **Xishuangbanna, Yunnan: 2018.6.1**, many videos recorded.
  - **Song Yuan, JiLin: 2019.10.11**, many videos recorded.

![NO.1 meteor in Jilin meteorite event, 1976.3.8](image)

![Shangri-La Yunnan, 2017.10.4](image)
1. Background

- Earth impact by asteroids
  - Velocity: ~20 km/s (11.7-73 km/s)
  - Size: 0.1 m-10 km

- Luminous and visible at altitude of 100-80 km
- Strong shock wave around meteoroid
- Fragmentation and airburst at altitude of 40-15 km
- Global hazard: climate, living things
  - Local hazard: overpressure, heat radiation, meteor crater, earthquake, tsunami

- Aerodynamic forces and trajectory during ultra-high velocity entry
- Aerodynamic heating during ultra-high velocity entry
- Ablation and thermal response of asteroid structure
- Physical characteristics of asteroid entry process

Earth entry issues in planetary defense
Outline

1、Background
2、Numerical method and physical-chemical model
3、Results and discussion
4、Summary
Could the numerical methods and physical-chemical models purposed for reentry vehicles be used in asteroid entry problems?

<table>
<thead>
<tr>
<th>Reentry vehicle</th>
<th>Asteroids</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
<td>&lt;6m</td>
</tr>
<tr>
<td><strong>Shape</strong></td>
<td>regular, smooth</td>
</tr>
<tr>
<td><strong>Surface Materials</strong></td>
<td>TPS Materials C/H/O/N/Si</td>
</tr>
<tr>
<td><strong>Interior structure</strong></td>
<td>few defect</td>
</tr>
<tr>
<td><strong>Entry speed (km/s)</strong></td>
<td>7.5–13</td>
</tr>
<tr>
<td><strong>Peak temperature</strong></td>
<td>≤20000K</td>
</tr>
</tbody>
</table>

Comparison between the reentry vehicle and asteroid
As the primary flow regime of asteroid’s entry is continuum-near continuum, the CFD methods might be applicable for asteroid entry calculation;

However, the physical-chemical models relevant to high temperature gas effects of traditional CFD should be confirmed and improved.

Ref 1: D.Prabhu.et.al. AIAA SCiTech 2016. Thermophysics Issues Relevant to High-Speed Earth Entry of Large Asteroids
Thermodynamic properties of ultra-high-temperature gas

- Thermodynamics properties of ultra-high-temperature gas are sensitive to the number of electronic states, high-lying level energies and cut-off criteria.

- Thermodynamics properties database valid up to 50,000 K should be constructed for both air species and ablation products.

Ref 2: Capitelli.et.al. ESA STR246. Tables of internal partition functions and thermodynamic properties of high-temperature Mars-atmosphere species from 50K to 50000K

Ref 3: Z. Qin .et.al. JQSRT 210 (2018) 1–18 . High-temperature partition functions, specific heats and spectral radiative properties of diatomic molecules with an improved calculation of energy levels
Transport properties of ultra-high-temperature gas

- Based on the Chapman-Enskog method, the collision cross section are needed for transport properties computation.
- High accuracy database of collision cross section up to 50,000 K are needed for both air species and ablation products.

Chemical kinetics of ultra-high-temperature gas

- Chemical kinetics models for vehicle entry should not be used directly for asteroid entry.
- New chemical kinetics such as multiple stage ionization, photochemical kinetics and chemical kinetics for asteroid ablation products should be developed.

- Chemical kinetics for multiple stage ionization

\[ N^+ + e \leftrightarrow N^{++} + e + e \]

\[ O^+ + e \leftrightarrow O^{++} + e + e \]

- Photochemical kinetics

- Chemical kinetics for ablation products

Ref 5: Johnston et al. AIAA 2017-4533. Impact of Coupled Radiation and Ablation on the Aerothermodynamics of Meteor Entries
Internal degree relaxation model of ultra-high-temperature gas

- Park’s two-temperature model (Ttr-Tve), Multi-temperature model (Tt-Tr-Tvi-Tel), State-To-State model.

- model parameter such as vibrational relaxation time need to be validated at ultra-high-temperature.

Radiation model of ultra-high-temperature gas

- Radiation computation: line-by-line method, e.g. NEQAIR.
- Radiation database: TOPbase, HITEMP. Radiation band of asteroid ablation products should be developed.

### Table 3: Summary of molecular band modeling for meteor ablation products[5]

<table>
<thead>
<tr>
<th>Specie</th>
<th>Transition</th>
<th>Spectral Range (eV)</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO</td>
<td>A-X</td>
<td>4.54-5.79</td>
<td>Franck-Condon factors and energy levels from Geier et al., and band oscillator strength from Park and Arnold.</td>
</tr>
<tr>
<td>SiO</td>
<td>E-X</td>
<td>5.74-7.55</td>
<td>Franck-Condon factors and band oscillator strength taken from Naidu et al., and Driera, and energy levels from Lagerqvist.</td>
</tr>
<tr>
<td>FeO</td>
<td>Orange</td>
<td>1.68-2.38</td>
<td>Oscillator strengths and energy levels taken from Michels.</td>
</tr>
<tr>
<td>MgO</td>
<td>B-A</td>
<td>1.72-2.45</td>
<td>Oscillator strengths and energy levels taken from Daily and Bell.</td>
</tr>
<tr>
<td>MgO</td>
<td>D-A</td>
<td>1.72-2.45</td>
<td>Oscillator strengths and energy levels taken from Naulin et al. and Bell et al.</td>
</tr>
<tr>
<td>MgO</td>
<td>B-X</td>
<td>2.38-2.69</td>
<td>Oscillator strengths and energy levels taken from Daily and Bell.</td>
</tr>
<tr>
<td>CaO</td>
<td>A-X</td>
<td>1.1-2.0</td>
<td>Oscillator strengths and energy levels taken from Doherty and Liszt.</td>
</tr>
<tr>
<td>CaO</td>
<td>B-X</td>
<td>2.6-3.7</td>
<td>Oscillator strengths and energy levels taken from Pasternack and Liszt.</td>
</tr>
<tr>
<td>CaO</td>
<td>Orange</td>
<td>1.7-2.2</td>
<td>Oscillator strengths and energy levels taken from Pasternack and Liszt.</td>
</tr>
<tr>
<td>CaO</td>
<td>Green</td>
<td>1.7-2.2</td>
<td>Oscillator strengths and energy levels taken from Pasternack, Liszt, and Baldwin.</td>
</tr>
<tr>
<td>SO</td>
<td>A-X</td>
<td>3.8-5.0</td>
<td>Franck-Condon factors and band oscillator strength taken from Borin and energy levels from Rosen.</td>
</tr>
<tr>
<td>AlO</td>
<td>B-X</td>
<td>2.2-3.0</td>
<td>Oscillator strengths and energy levels taken from Borovicka.</td>
</tr>
</tbody>
</table>

Ref 5: Johnston et al. AIAA 2017-4533. Impact of Coupled Radiation and Ablation on the Aerothermodynamics of Meteor Entries
AHENS

- The CFD code AHENS, developed at our institute for aerothermal environment simulation, solves the NS equations on structured grids.

Numerical Method

- The finite-volume method is used to discretize the governing equations.

  - Hybrid Steger-Warming and Godunov flux scheme with second-order spatial accuracy.

  - LU-SGS implicit algorithm for time step iteration.

  - MPI based parallelism.
High-temperature Gas Model

- 1T / 2T /3T Multi-species gas mixture model.
- Finite-rate chemistry model.
- Polynomial fitting method for thermodynamic properties.
- Gupta’s model with collision cross section data for transport coefficients.
- Modified Fick’s model for mass diffusion.

\[
J_{s\neq e} = -\rho D_s \nabla Y_s - Y_s \sum_{r \neq e} -\rho D_r \nabla Y_r \\
J_e = -\frac{1}{q_e} \sum_{s \neq e} q_s J_s
\]

It ensures that the sum of mass fluxes is zero.
Boundary condition

- Freestream inflow, extrapolation outflow, symmetry.
- RCS jet boundary condition, stagnation boundary condition.
- Unslip or slip boundary condition.
- Isothermal wall or radiative equilibrium wall condition.
- Quasi steady ablation with finite-rate surface chemistry.
- Catalytic wall condition: non-catalytic, super-catalytic, specified catalytic coefficients.
Radiation model

- Non-Boltzmann models for diatomic molecules and atomic species electronic state populations
- Line information and cross-sections following the work of Johnston.\(^{[7]}\)

<table>
<thead>
<tr>
<th>Molec.</th>
<th>Transition</th>
<th>Name</th>
<th>Spectral Range (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_2)</td>
<td>B(^3)(\Pi_g) - A(^3)(\Sigma_u^+)</td>
<td>1(^+) (1(^{st})-positive)</td>
<td>0.2 - 2.5</td>
</tr>
<tr>
<td>(N_2)</td>
<td>C(^3)(\Pi_u) - B(^3)(\Pi_g)</td>
<td>2(^+) (2(^{nd})-positive)</td>
<td>2.7 - 4.7</td>
</tr>
<tr>
<td>(N_2)</td>
<td>C(^4)(\Sigma^+_u) - X(^1)(\Sigma_g^+)</td>
<td>Carroll-Yoshino</td>
<td>11.5 - 14.0</td>
</tr>
<tr>
<td>(N_2)</td>
<td>C(^3)(\Pi_u) - X(^1)(\Sigma_g^+)</td>
<td>Worley-Jenkins</td>
<td>11.5 - 14.0</td>
</tr>
<tr>
<td>(N_2)</td>
<td>b(^1)(\Pi_u) - X(^1)(\Sigma_g^+)</td>
<td>Birge-Hopfield I</td>
<td>7.0 - 13.1</td>
</tr>
<tr>
<td>(N_2)</td>
<td>b(^1)(\Sigma_u^-) - X(^1)(\Sigma_g^+)</td>
<td>Birge-Hopfield II</td>
<td>7.6 - 14.0</td>
</tr>
<tr>
<td>(N_2)</td>
<td>O(^3)(\Pi_u) - X(^1)(\Sigma_g^+)</td>
<td>Worley</td>
<td>10.4 - 14.0</td>
</tr>
<tr>
<td>(N_2^+)</td>
<td>B(^3)(\Sigma_u^+) - X(^1)(\Sigma_g^+)</td>
<td>1(^+) (1(^{st})-negative)</td>
<td>1.2 - 4.6</td>
</tr>
<tr>
<td>NO</td>
<td>B(^\Pi) - X(^\Pi)</td>
<td>(\beta) (beta)</td>
<td>2.1 - 6.9</td>
</tr>
<tr>
<td>NO</td>
<td>A(^3)(\Sigma^+) - X(^2)(\Pi)</td>
<td>(\gamma) (gamma)</td>
<td>3.2 - 7.5</td>
</tr>
<tr>
<td>NO</td>
<td>C(^\Pi) - X(^\Pi)</td>
<td>(\delta) (delta)</td>
<td>3.7 - 7.6</td>
</tr>
<tr>
<td>NO</td>
<td>D(^3)(\Sigma^+) - X(^2)(\Pi)</td>
<td>(\epsilon) (epsilon)</td>
<td>3.4 - 8.0</td>
</tr>
<tr>
<td>NO</td>
<td>B(^2)(\Delta) - X(^2)(\Pi)</td>
<td>(\beta') (beta-prime)</td>
<td>3.9 - 8.4</td>
</tr>
<tr>
<td>NO</td>
<td>E(^3)(\Sigma^+) - X(^2)(\Pi)</td>
<td>(\gamma') (gamma-prime)</td>
<td>4.6 - 8.9</td>
</tr>
<tr>
<td>O(_2)</td>
<td>B(^3)(\Sigma_u^-) - X(^3)(\Sigma_g^-)</td>
<td>Schumann-Runge</td>
<td>2.6 - 7.0</td>
</tr>
</tbody>
</table>

molecular band systems

Radiation Transfer

- Radiative Transfer Equation:

\[ \frac{dI_v(s, \Omega)}{ds} = j_v(s) - \kappa_v^t(s)I_v(s, \Omega) \]

- Tangent Slab approximation:
Loosely coupled approach

Coupled simulation of flow and radiation
Outline

1、Background
2、Numerical method and physical-chemical model
3、Results and discussion
4、Summary
Stardust vehicle reentry

The radiation-flow coupling effect is relatively small to the flowfield of the reentry vehicle.

<table>
<thead>
<tr>
<th>case</th>
<th>H(km)</th>
<th>Voo(m/s)</th>
<th>AoA(°)</th>
<th>Wall condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>59.77</td>
<td>11136.7</td>
<td>0</td>
<td>super-catalytic</td>
</tr>
</tbody>
</table>

Comparison of the predicted flow properties
Stardust Capsule reentry

- The convective is the dominated mechanism of aerodynamic heating for reentry vehicles, un-coupled radiation simulation can be adopted.

Comparison of the predicted heat flux
Asteroid entry

- Coupled and uncoupled radiation simulations are carried out for typical asteroid entry condition to investigate the influence mechanism radiation-flow coupling on aerodynamic heating.

- A 13 species (N2, O2, N, O, NO, NO+, N2+, N+, N++, O2+, O+, O++, e-) ionized air model is incorporated. [8]

<table>
<thead>
<tr>
<th>case</th>
<th>H(km)</th>
<th>Voo(km/s)</th>
<th>Wall condition</th>
<th>D(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>15、20</td>
<td>super-catalytic</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>15、20</td>
<td>super-catalytic</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
<td>15、20</td>
<td>super-catalytic</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>15、20</td>
<td>super-catalytic</td>
<td>140</td>
</tr>
</tbody>
</table>

Asteroid entry

- Radiation-flow coupling effect plays a significant role in flow structure of asteroid entry.
- Compared with uncoupled case, the temperature and thickness of shock layer are much smaller.
Asteroid entry

- With the increase of entry velocity, the coupling effects on flowfield is enhanced, and the variations of shock standoff distance and peak temperature are enlarged.

![Flow temperature along stagnation line (D=50m)](image-url)
Asteroid entry

The radiative cooling and thin shock layer are the physical mechanism that radiation-flow coupling will ease aero-heating.

Heat flux along surface

- Heat flux for D=20m, V=20km/s
- Heat flux for D=50m, V=20km/s
Asteroid entry

- There are obvious differences of heating character between asteroid entry and hypersonic vehicle reentry:
  - The radiative heating is dominant for asteroid entry and the convective heating is negligible.
  - Total heat flux at stagnation point increases with diameter.

![Heat flux graph](image-url)
Outline

1. Background
2. Numerical method and physical-chemical model
3. Results and discussion
4. Summary
(1) Hypervelocity aerothermodynamics plays an important role in the analysis of asteroid impacting the Earth.

1) Earth impact by asteroids
   - Velocity: ~20 km/s (11.7-73 km/s)
   - Size: 0.1 m-10 km

2) Luminous and visible at altitude of 100-80 km
3) Strong shock wave around meteoroid
4) Fragmentation and airburst at altitude of 40-15 km
5) Global hazard: climate, living things
6) Local hazard: overpressure, heat radiation, meteor crater, earthquake, tsunami

- aerodynamic forces and trajectory during ultra-high velocity entry
- aerodynamic heating during ultra-high velocity entry
- ablation and thermal response of asteroid structure
- physical characteristics of asteroid entry process
(2) In order to investigate the aerothermodynamic problems in asteroid entry to Earth, the high temperature gas models, such as thermo-chemical models and radiation data, need to be extend to greater than 20000K.

(3) Since there are strong coupling effects among flow-field, radiation and ablation in Earth entry problem of asteroid, both the coupling mechanism and numerical methods are needed to be further explored.

Ref 9: Eric Stern et al. Entry Modeling for Asteroid Threat Assessment
Thanks for your attention

Hypervelocity Aerodynamics Institute of China Aerodynamics Research and Development Center
IMPACT EFFECTS CALCULATOR
http://AsteroidHazard.pro
SHOCK WAVE EFFECTS FROM IMPACTS OF COSMIC OBJECTS WITH DIAMETER FROM A FEW METERS TO 3KM

IAA PLANETARY DEFENSE CONFERENCE 2021
26-30 APRIL 2021

IDG RAS
D.O. Glazachev, O.P. Popova, V.V. Svetsov, V.V. Shuvalov, N.A. Artemieva, and E.D. Podobnaya
The main motivation is to create a quick and accurate tool for assessing the consequences of the impact of a cosmic body.
Relative density distribution along trajectory at different altitudes $h$:

- D=40 m, V=18 km/s; chondritic material (2650 kg/m$^3$), $\alpha=90^0$.

Black – solid meteoroid material.

Quasi-liquid meteoroid model

**Basis:**

- Large meteoroid deformation begins at $h$, where aerodynamical loading $>>$ strength.

**Main assumptions**

- Zero strength
- Ablation as evaporation
- Radiation transfer in thermal conductivity approximation

**Formal range**

- D>30-50 m; h<40 km (Svettsov et al. 1993)

**Restrictions:**

- Quasi-liquid assumption

Quasi-liquid model = QL model
D-30-45-20  
density: 3320 kg/m³  
diameter: 30 m  
entry angle: 45°  
velocity: 20 km/s

Overpressure distribution obtained for one variant
Modeled variants

- Square figures – asteroids (3320 kg/m³)
- Triangle figures – granite (2630 kg/m³)
- Circle figures – comets (1000 kg/m³)

Total 81 variants of different diameter, fall angle, velocity and density
Effective airburst altitude

For quick rough evaluation of the impact consequences (levels of damage, area of the damage, etc) at large distances from the ground zero spherical source - reasonable SW evaluation if the altitude $H_{\text{eff}}$ of E-equivalent point explosion is correctly determined

QL model was used to determine $H_{\text{eff}} = f(D, \text{density}, \alpha)$ (Shuvalov et al. 2016)

This approach:
- Precision of estimates - 2-3 km (random character of disruption)
- Is applicable for $D > 10-30$ m
- For $D \sim 10-30$ m the uncertainty in effective altitude may reach 10-15 km (Chelyabinsk, TC32008 and other cases)
- (strength, fragmentation features etc)

Effective altitude dependence on meteoroid size

$$H_{\text{eff}} = \left( -1.3 \times H \times \ln(D \times (\sin(\alpha)/H) \times (\rho/\rho_0)^{2/3}) + H \right)/1000$$

Determination of the height of the “meteoric explosion”
Shuvalov et al. Solar System Research 2016, V.50, I.1, pp 1-12
Effective airburst altitude – uncertainty area

\[ H_{\text{eff}} = (-1.3 \times H \times \ln(D \times \sin(\alpha)/H) \times (\rho/\rho_0)^{2/3}) + H)/1000 \]
Scaling relation for overpressure

\[ \Delta p = el \times m \times \left( \frac{E_k^{1/3}}{H_{eff}^2 + x^2 + y^2} \right)^{pow} \]

\( x, y \) – spatial coordinates
\( el \) – ellipticity parameter,
\( E_k \) – kinetic energy of the impactor in kt TNT,
\( H_{eff} \) – effective height of point source,
\( \phi \) – \( \arctan(y/x) \).

**Airburst**

\( pow = 1.5 \)
\( m = \text{const} \)
\( H_{eff} = function(\rho, D, \alpha) \)
\( el = el(\phi, n_{ab}, b_{ab}, f_{ab}) \)
\( n_{ab} = function(\rho, D, \alpha, V) \)
\( b_{ab} = function(\rho, D, \alpha, V) \)
\( f_{ab} = function(\rho, D, \alpha, V) \)

**Crater-forming**

\( pow = 1.4 \)
\( m = function(E_k) \)
\( H_{eff} = 0 \)
\( el = el(\phi, n_{cf}, b_{cf}, f_{cf}) \)
\( n_{cf} = function(\rho, D, \alpha, V) \)
\( b_{cf} = function(\rho, D, \alpha, V) \)
\( f_{cf} = function(\rho, D, \alpha, V) \)

Wind speed:

\[ V_{max} = \frac{330}{\gamma} \times (p/p_0 - 1) \times \left( 1 + \frac{\gamma + 1}{2 \times \gamma} \times (p/p_0 - 1) \right)^{-1/2} \]

\( \gamma \) - adiabatic index

\[ v_{max} = \begin{cases} 
67.1 \times \frac{E_k^{0.38}}{H_{eff}^{1.53}}, \rho = 1000 \text{ kg/m}^3 \\
40.51 \times \frac{E_k^{0.39}}{H_{eff}^{1.45}}, \rho = 3320 \text{ kg/m}^3 
\end{cases} \]
Overpressure field with model and errors

Plot №17, D: 50 m, α: 30°, V: 15 km/s, ρ: 3320 kg/m³, E: 5.8 Mt TNT
Results comparison

Our scaling relations
http://AsteroidHazard.pro

D-50-30-15
density: 3320 kg/m³
diameter: 50 m
fall angle: 30°
velocity: 15 km/s

Collins et al. 2017

\[ p(r) = 3.14 \times 10^{11}(r^2 + z_b^2)^{-2.6/2} \]
\[ + 1.8 \times 10^7(r^2 + z_b^2)^{-1.13/2} \]  \hspace{1cm} (7)
\[ z_{b,50\%} = 25.7 - 7.83 \log_{10}E_{M_t} - 0.31(\log_{10}E_{M_t})^2 \]  \hspace{1cm} (6b)
Modeled variants in 2021 PDC excercise

«As mentioned previously, the size of 2021 PDC is highly uncertain, ranging from as small as 35 meters to as large as 700 meters. This estimate is based on the asteroid’s brightness, its estimated distance, and the wide range of possible albedos (reflectivities).

Little is known about other properties of the object, such as composition and density. As a result, the potential impact damage and population risk is also highly uncertain. Based on these estimates, the possible energy released on impact could range from 1.2 Mt to 13 Gt (TNT equivalent).

Velocity from 15.12 to 15.87 km/s
Entry angle from 0° to 90°
Scaling relation for different diameters

density: 3320 kg/m³
diameter: various
fall angle: 60°
velocity: 15 km/s
Scaling relation for different diameters

density: 3320 kg/m³
diameter: various
fall angle: 60°
velocity: 15 km/s
Scaling relation for different entry angles

density: 3320 kg/m³
diameter: 300 m
fall angle: various
velocity: 15 km/s

a: 30°

a: 60°

a: 75°
Location map of eyewitness reports.

Glass damage (filled red circle); glass rattled, not broken (o); chum destruction (Λ); heat and unconsciousness (orange X); people falling (person symbol).

Gray areas - $\Delta P$ based on scaling relations (12 Mt, 2000 kg/m$^3$, 25°, 27 km/s).

Contours (from dark to light): $\Delta P \sim$1500, 1000, 700 and 500 Pa

$\Delta P$ obtained in the frame of QL model (Shuvalov et al. 2017),

black circles - reported damage, open circles – no damage.

Main characteristics of $\Delta P$ zones (>1 kPa) - satisfactory agreement

Scaling relations (not given) are also in agreement.
Impact Effects

<table>
<thead>
<tr>
<th>Projectile Parameters</th>
<th>Entry Parameters</th>
<th>Observation Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter: 78 km</td>
<td>Velocity: 18 km/s</td>
<td>Zero Point: The point of intersection of the trajectory with the Earth's surface</td>
</tr>
<tr>
<td>Density: 3,300 kg/m³</td>
<td>Entry Angle: 18°</td>
<td>Angle to Trajectory Projection, p: 92°</td>
</tr>
<tr>
<td>Energy: 3.6 x 10³ J</td>
<td>Latitude: 44.44°</td>
<td>Distance to the Zero Point, L: 167 km</td>
</tr>
<tr>
<td>Energy (at TNT): 8.23 x 10³ J/tn</td>
<td>Longitude: 64.65°</td>
<td>Distance Across the Trajectory Projection, L: 167 km</td>
</tr>
<tr>
<td></td>
<td>Altitude: 155°</td>
<td>Distance Along the Trajectory Projection, L: 53 km</td>
</tr>
</tbody>
</table>

### RESULTS

<table>
<thead>
<tr>
<th>Effect</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airblast Wave</td>
<td>Overpressure: 0.0016 atm (0.16 kPa)</td>
</tr>
<tr>
<td>Irradiation</td>
<td>Thermal exposure: 0.14 J/cm²</td>
</tr>
<tr>
<td>Crater</td>
<td>No crater</td>
</tr>
<tr>
<td>Ejecta</td>
<td>No ejecta</td>
</tr>
<tr>
<td>Seismic effect</td>
<td>Magnitude: 3.4</td>
</tr>
<tr>
<td>Atmospheric disturbances</td>
<td>Peak amplitude of relative density oscillations at an altitude of 300 km: 0.32</td>
</tr>
</tbody>
</table>

Impact Effects

Comprehensive assessment of hazardous effects caused by impacts of cosmic bodies

Navigation

About
Calculator
Artists

Language

Russian
English
Impact Effects

Projectile Parameters

- Diameter: 30 m
- Density: 3320 kg/m³
- Energy: 5.24 x 10^14 J
- Energy (41 TNT): 7.25 x 10^9 kT TNT

Entry Parameters

- Velocity: 15,000 km/s
- Entry Angle: 60°
- Latitude: 54.45°
- Longitude: 64.55°
- Azimuth: 120°

Observation Point

- Zero Point: The point of intersection of the trajectory with the Earth's surface
- Angle to Trajectory Projection, θ: 180°
- Distance to the Zero Point, Lz: 50 km
- Distance Across the Trajectory Projection, Lx: 9 km
- Distance Along the Trajectory Projection, Ly: 50 km
- Latitude, θ: 54.46°
- Longitude, λ: 64.45°

RESULTS

Airblast Wave

Overpressure: 0.013 atm (1.3 kPa)

Effective Altitude: 12 km
Maximal overpressure: 0.12 atm (12 kPa)
Distance to the center of a overpressure field from the point of intersection of the trajectory with the Earth's surface: 3.6 km
Areas, at which chosen levels of overpressure exceed:
- at 0.02 atm: 0.42 km²
- at 0.05 atm: 0.67 km²
- at 0.1 atm: 0.84 km²
- at 0.2 atm: 0.92 km²

The value of the overpressure in the point of observation: 0.013 atm (1.3 kPa)
Maximan wind speed behind the shock front in the point of observation: 3 m/s

Irradiation

Thermal exposure: 1.0 J/cm²

Numerical simulations of a shock wave from the cosmic object impact provide possibility to suggest scaling relations for a value of maximal overpressure and its distribution on the surface, for maximal wind velocity behind the front and for a squares, where overpressure is larger than a fixed level. All values are determined based only on the properties of the impactor.

http://www.AsteroidHazard.pro
API (application programming interface)

HTTP post request

```
    <| "effects" -> {"shockwave"},
    "impactor" -> <|"diameter" -> d, "density" -> 3320|>,
    "entry" -> <|"angle" -> 18.3, "velocity" -> 19|>,
    "point_of_effect" -> <|
    "distance_across_trajectory" -> 20,
    "distance_along_trajectory" -> 5|>
    |>,
    "RawJSON", "Compact" -> True] |>,
    "RawJSON"]]["shockwave"]]["overpressure"]["value"]];
```

http://AsteroidHazard.pro
Summary

• The scaling relations for shock wave effects for 20 – 3000 m objects impact are presented. Scaling relations for overpressure, wind and some other characteristics are constructed.

• For the first time this scaling relations take into account spatial asymmetry induced by impact angle.

• Suggested scaling relations were compared with modelling results and existing observational data and demonstrated reasonable agreement

• Described scaling relations are implemented into web-based calculator

• PDC probable impactor parameters are very uncertain and its impact may result in consequences of different scale.
Thank you for attention

follow the updates on the site
AsteroidHazard.pro
IMPACT EFFECTS CALCULATOR

RADIATION AND SOME OTHER EFFECTS

www.AsteroidHazard.pro

Olga Popova
Vladimir Svetsov
Valery Shuvalov
Dmitry Glazachev
Elena Podobnaya
Valery Khazins
Natalia Artemieva

IAA PLANETARY DEFENSE CONFERENCE 2021
26-30 APRIL 2021
Asteroids and cometary objects from 20 m to 3 km in diameter were considered.

Entry angles - from 15° to 90°;
Entry velocity - from 15 to 70 km/s

Total 122 cases:
56 airbursts, 66 crater-forming (including transitional)

Uncertainty in Heff is assumed to be ~5 km

The smaller $\alpha$ the larger D is needed to create a crater

Transition sizes for asteroids:
~60 – 250 m based on Heff ~ f($\alpha$)

Kinetic energy range
~3 $10^4$ – 5 $10^5$ kt TNT based on serial simulations

2021 PDC probable impactor: asteroid, V~15 km/s D~35 - 700 m, $\alpha$~3-90°

Can be both an airburst and crater-forming
RADIATION FLUXES AND THERMAL EXPOSURE ON THE GROUND

The equation of radiative transfer

$$\frac{dI_\varepsilon}{ds} + k_\varepsilon I_\varepsilon = k_\varepsilon B_\varepsilon$$

is solved along rays crossing the heated volume of air and vapor.

The total radiation intensity on the surface for a given angle of a ray is obtained by summing the intensities of radiation over photon energies.

Radiative flux density in a given point on the Earth's surface is calculated by integrating the radiation intensity, multiplied by the cosine of the angle between the ray and the normal to the irradiated surface, over all angles.

The integration of the flux over time allows us to determine radiant exposure (radiation energy received by a surface per unit area).

Thermal radiation – one of the main dangerous consequences of cosmic object impacts.

Direct thermal radiation from fireballs and impact plumes poses a great danger to people, animals, plants, and economic objects.
THERMAL EXPOSURE ON THE GROUND

**Airburst** - bolide radiation
50 m, asteroid, 20 km/s, 45°, Svetsov&Shuvalov 2018

**Crater-forming** - plume radiation
1 km, asteroid, 20 km/s, 45°
Svetsov&Shuvalov 2018

In dependence on impact scenario the thermal radiation is produced by fireball or/and impact plumes.
Analyzes of serial simulations permit to suggest \textit{scaling relations (SC)},
- allow us to estimate radiation field on the surface based only on impactor properties \((D, V, \alpha, \rho)\)

To describe the thermal exposure \(Q \ [\text{J/cm}^2] \) the point source approximation, corrected on spatial heterogeneity is suggested:

\[
Q = 4.184 \cdot 10^{12} \cdot \frac{1}{4\pi} \cdot \frac{\eta}{100} \cdot \frac{E_{kt}}{10^{10} \left(H_{rad}^2 + x^2 + \varepsilon l \cdot y^2 \right)}
\]

\(x, y\) – spatial coordinates (km) (point of origin is under point of maximal thermal effect),
\(H_{rad}\) – radiative altitude (km), \(\varepsilon l\) – ellipticity parameter, \(E_{kt}\) – kinetic energy of impactor in kt TNT
\(\eta\) – integral luminous efficiency in %

The thermal exposure value of 10 J/cm\(^2\) roughly corresponds to the first degree burn.
The value of about 500 J/cm\(^2\) essentially exceeds the amount needed to ignite most materials (Glasstone&Dolan 1977)

Scaling relation (SC) for \(Q\) was aimed to be applicable in the range 10-500 J/cm\(^2\)
INTEGRAL LUMINOUS EFFICIENCY

\( \eta \) – the fraction of the impactor kinetic energy, which is converted into the radiation

\[ \eta \]

\( \text{Small meter-scale impactors} \)
\( \text{Airbursts, tens of meters} \)
\( \text{Crater-formings} \)

\( \eta \) for asteroids of different sizes entering at \( \alpha \approx 25-65^\circ \) with \( V \approx 15-25 \text{ km/s} \) obtained based on SC
(a) is compared with \( \eta \) for meter-scale meteoroids (b); is extended to larger energies

(a) \( \eta \) is increasing with size up to \( \approx 20\% \) at \( E \approx 500 -1000 \text{ kt} \) and is decreasing for large objects. This decrease is probably connected with an increase of the optical thickness of the emitting region, which leads to radiation losses mainly from its surface.

(b) Minimal efficiency is obtained for transition between airbursts-crater-formings, probably connected with change of the main input from bolide to the rarefied plume. Need to be clarified further.
SCALING RELATION FOR INTEGRAL LUMINOUS EFFICIENCY

\( \eta \) – the fraction of the impactor kinetic energy, which is converted into the radiation

Integral luminous efficiency for asteroids \( V \sim 20-30 \text{ km/s} \)
\( \alpha \sim 15-90^\circ \) based on SC

Crater-formings:

\[
\eta_{crater} = \frac{0.021 \cdot D^{1.3} \cdot v^{1.5}}{E_{kt}^{0.45}}
\]

Airbusts:

\[
\eta_{airbust} = \begin{cases} 
100 \cdot \frac{10939 \cdot v^{0.56}}{E_{kt} \cdot \sin \alpha}, & \rho = 3320 \text{ kg/m}^3 \\
100 \cdot \frac{1225 \cdot v^{0.39}}{E_{kt}^{0.3} \cdot \sin \alpha}, & \rho = 1000 \text{ kg/m}^3
\end{cases}
\]

for any other density of the impactor - line interpolation by density is working well

Transition: conventional division by impactor diameter, if \( D \leq 100-150 \text{ m} \) AB values are used, if \( D \geq 300 \text{ m} \) CF values are applied, inbetween the linear interpolation by \( E_{kt} \) is used

Real dependence of \( \eta \) on \( V, \alpha \) etc is quite complicated, but nevertheless suggested SC provides satisfactory agreement with modeling results with precision about 2 times.
RADIATIVE ALTITUDE AND TIME

(a) $H_{\text{rad}}$ in dependence on $E_{\text{kt}}$ based on SC (b) The characteristic time of radiation (80% of total thermal exposure is irradiated)

Airbursts radiation can be represented as radiation of the source at $H_{\text{rad}}$ (from 20–30 to several km) with spatial heterogeneity and duration $\sim$1-4 s.

$H_{\text{rad}} > H_{\text{eff}}$ and maximal thermal effect is shifted relatively the overpressure maximum.

$H_{\text{rad}}$ for crater-formings is an adjustable parameter, is not the effective source height, affects $Q$ only in the central zone, where $Q$ has a complex structure (due to the complex nature of the flow, propagation, interaction and mixing of emissions from the crater with the atmosphere).

$H_{\text{rad}}$ is fixed as 100 km for large impacts.
Ellipticity \( e_l \) allows to take into account the spatial inhomogeneity of the radiation field; \( e_l = f(E_{kt}, \alpha, H_{eff}) \).

Ingomogenity is more evident forward along the trajectory (after the epicenter)

Q (values are shown on contours, J/cm\(^2\)) obtained in the numerical simulations – solid lines.
Dashed – Q based on SC, Q\(_{sc}\)
Gray - the ratio of Q\(_{sc}\)/Q
Bottom panel - central part on a larger scale.

Suggested scaling relations allow us to estimate thermal exposure and radiative flux distributions based on the impactor parameters with uncertainty of about two times.

Trajectory is top – bottom
Axes origin – trajectory intersection with ground (no deceleration)
TUNGUSKA THERMAL RADIATION

Data to fit – area of burn trees, visible charring - at 40 J/cm² (Svetsov 1996)
Impactor parameters uncertain, numerical simulations results: **50 m, 20 km/s, 3300 kg/cm³**

![Diagram](image)

**Model by Johnston&Stern 2019**
Carbonaceous chondrite 3000 kg/m³
D~50-400 m, V~6-18 km/s, H~10-30 km, pancake fragmentation model

Scaling relation distribution Q_sc example

Despite a range of impactor parameters allows to describe burn area, different model results are quite close, our modeling suggested more oblique impact.
THERMAL EXPOSURE BASED ON SC FOR CRATER-FORMINGS

Thermal exposure $Q$ obtained in the numerical simulations - solid contours with black labels and $Q_{sc}$ based on scalings (dashed contours with blue labels $[J/cm^2]$).

Bottom panels - central part on a larger scale. Color - the ratio of $Q_{sc}/Q$.

Trajectory is top-bottom.

Spatial heterogeneity is excluded from $Q_{sc}$ (no ellipticity).

Additional multiplier is included – to limit $Q$ at the outer areas.

In most cases an uncertainty in estimates based on this scaling relation does not exceed 4 times in the range $Q \approx 10-500 \text{ J/cm}^2$. 

---

Thermal exposure $Q$ obtained in the numerical simulations - solid contours with black labels and $Q_{sc}$ based on scalings (dashed contours with blue labels $[J/cm^2]$).

Bottom panels - central part on a larger scale. Color - the ratio of $Q_{sc}/Q$.

Trajectory is top-bottom.
As expected the radiatively damaged area is dependent on entry angle and size.
IONOSPHERIC DISTURBANCES

Impact -> plume formation -> its deceleration/oscillation at H>100 km -> energy is transformed into heat -> heated region expands laterally -> disturbances spread over thousands of km

Initial plume formation

Further evolution

Chelyabinsk impact for comparison

distributions of relative density $\xi = \max(\text{abs}(\rho/\rho^* - 1))$ at different time moments

$\alpha = 45^0$ D=80 m V=30 km/s, comet (Shuvalov&Khazins 2017; Artemieva et al.2018)
IONOSPHERIC DISTURBANCES

Disturbances parameter $\xi$ - relative density

$\xi = \text{max}(\text{abs}(\rho/\rho^* - 1))$ - asymmetric:

Two factors: - asymmetry of the initial disturbances; - maximum H reached by plumes.

Asymmetry is the most prominent in the 45° scenario.

Maximal $\xi$ is largest in the vicinity of the epicenter and decreases at the scale of thousands km.

$\xi$ is oscillating at a point (x,y).

Distribution of maximal $\xi$ at H=300 km in a plane perpendicular to the Earth's surface and passing through the impactor trajectory.

Solid - numerical modeling, dashed - interpolation.

Shuvalov&Khazins 2017; Artemieva et al.2018

Distributions of disturbances parameter $\xi$ : (a)13 Mt spherical explosion at H~ 10 km
(b) 13 Mt impact ($\alpha=45^0$, D=80 m, V=30 km/s, comet)

The explosion produces smaller disturbances than a real impact.
IONOSPHERIC DISTURBANCES

The only instrumental data on ionospheric disturbances – Chelyabinsk event
Well-pronounced TEC disturbances with an average period ~10 min and amplitude of 0.07–0.5 TECU (total electron content unit, 1 TECU = $10^{16}$ el/m$^2$) were detected (Perevalova et al. 2015).

Dependence of disturbances parameter $\xi$ on impactor size

![Graph showing dependence of disturbances parameter $\xi$ on impactor size.

2021 PDC probable impactor:
asteroid, V~15 km/s
D~35 - 700 m
entry angle – 3-90°, more probable 50-80°

Northeastward from the airburst

![Graph showing TEC disturbances.

observed – grey
model at 300 km from epicenter – black
T~8-16 min

It is assumed that
TEC $\sim \rho \sim \xi$,
value of $\xi$ at H~300 km is considered as basis to estimate of TEC

![Graph showing observed and model TEC disturbances.

CH33-PRN26

airburst

maximal $\xi$

$\alpha=80^\circ$, V=15 km/s
$\rho=3000$ kg/m$^3$
SEISMIC EFFECTS

To calculate the seismic magnitude of an impact event – one needs to know “seismic efficiency” $k_s$, the fraction of the kinetic energy of the impact $E_{kt}$ that ends up as seismic wave energy $E_{seism}$.

Modeling: Svetsov et al. (2017), Khazins et al. (2018)

**Airbursts:** causes a seismic effect due to the impact of a shock wave on the surface.

Average seismic efficiency $k_{sa} = 2.5 \times 10^{-5}$

Lower for vertical impacts (upward motion influence)

Isolines of overpressure ($p-p_0$, atm)

**Crater-forming impacts:**

comparative calculations of SW generation by crater-forming impacts and explosions

seismic efficiency $k_{sc} = 10^{-3}$ (vertical impact)

$k_{sc}(\alpha) = k_{sc}(90^\circ) \cdot \sin(\alpha)$

*Collins et al. (2005):* $k_{sc} = 10^{-4}$

**Intermediate cases:**

If impactor energy is dissipated both in the air ($E_a$) and in crater formation ($E_c$) then

$$E_{seism} = k_{sa} E_a + k_{sc} E_c$$
2021 PDC probable impactor: asteroid, V~15 km/s
- as small as 35 meters to as large as 700 meters
- entry angle – 3-90°, more probable 50-80°

catastrophic destruction
PGV>100 cm/s

Chelyabinsk: M~3.7-4
Tunguska: M~4.8-5.2
CONCLUDING REMARKS

Serial numerical calculations of the cosmic objects impacts were conducted in a frame of special gasdynamic model with radiative transfer.

Results of these simulations allowed us to construct scaling relations, which permit one to quickly assess different dangerous consequences of impacts based on impactor parameters.

First time modeling and scalings for airbust radiation are suggested and demonstrated satisfactory agreement with existing observational data and other modeling.

First time modeling and scalings for ionispheric disturbances are suggested.

Scalings for seismic efficiency are improved based on impact modeling, the efficiency essentially differ from seismic efficiency for explosions.

Described scaling relations are implemented into web-based calculator.

Scalings in transition region of sizes/energies should be considered in more detail.

PDC probable impactor parameters are very uncertain and its impact may result in consequences of different scale.
Q&A
Session 9a: Impact Effects
7th IAA Planetary Defense Conference
26-30 April 2021, Online Event
Hosted by UNOOSA in collaboration with ESA

Break
Up next: Session 10a - Disaster Management