NEOShield
A Global Approach to Near-Earth Object Impact Threat Mitigation

<table>
<thead>
<tr>
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<th>FP7-SPACE-2011-282703</th>
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</tr>
</thead>
<tbody>
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<td>Project Coordinator</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Deliverable 9.4</th>
<th>Atmospheric trajectory analysis and ground-damage limitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP Leader</td>
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</tr>
<tr>
<td>Verified by</td>
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</tr>
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</tbody>
</table>

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<table>
<thead>
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<th>DLR, Project Coordinator</th>
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</tr>
</thead>
<tbody>
<tr>
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<td>OBSPARIS</td>
<td>France</td>
</tr>
<tr>
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<td>CNRS</td>
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</tr>
<tr>
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<td>OU</td>
<td>UK</td>
</tr>
<tr>
<td>Fraunhofer Ernst-Mach-Institut</td>
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<td>Germany</td>
</tr>
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<td>Queen's University Belfast</td>
<td>QUB</td>
<td>UK</td>
</tr>
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<td>Astrium GmbH</td>
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<td>Spain</td>
</tr>
<tr>
<td>SETI Institute Corporation Carl Sagan Center</td>
<td>CSC</td>
<td>CIIIA</td>
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<td>TsNIIImash</td>
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<td>Russia</td>
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<td>University of Surrey</td>
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</tr>
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### Version Control / History of Changes

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<th>Version</th>
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<td>D-r R. M. Kovalev</td>
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<td>D-r S.A. Meshcheryakov</td>
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### Title: D9.4 Atmospheric trajectory analysis and ground damage limitation

<table>
<thead>
<tr>
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<th>282703</th>
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<tr>
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Objectives

Provide an analysis of the final phase of the trajectory of 1. an impacting NEO, and 2. fragments arising from a mitigation attempt, taking account of the angle and speed of entry into the atmospheric, and the size, structure, composition, etc. of the NEO/fragments. Provide a means of determining the minimum level of resources required for a mitigation strategy to prevent serious damage on the ground (in case available mitigation resources are stretched to the limit, e.g. short time or unexpectedly large NEO).

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### Change Record

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<tr>
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<td>All</td>
<td>First issue of complete document</td>
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Table of contents

<table>
<thead>
<tr>
<th>Change record</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Figures</td>
<td>5</td>
</tr>
<tr>
<td>List of tables</td>
<td>8</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>8</td>
</tr>
<tr>
<td>2 Motion of an asteroid object or its large fragment in Earth's atmosphere before destruction</td>
<td>11</td>
</tr>
<tr>
<td>3 Calculation of fragmentation and deceleration altitudes for asteroids of different sizes impacting the Earth's atmosphere</td>
<td>12</td>
</tr>
<tr>
<td>4 Determination of breakup and deceleration altitudes of comet-like bodies of various sizes</td>
<td>21</td>
</tr>
<tr>
<td>5 Catastrophic consequences of cosmic bodies impacts (50-500 m in size)</td>
<td>33</td>
</tr>
<tr>
<td>6 Determination of the optimal level of the resources of protection in case of short warning time or unexpectedly large NEO. Possibility of fragmentation and the strategy of protection</td>
<td>41</td>
</tr>
<tr>
<td>7 Implementation</td>
<td>59</td>
</tr>
<tr>
<td>8 Conclusion</td>
<td>62</td>
</tr>
<tr>
<td>9 References</td>
<td>63</td>
</tr>
</tbody>
</table>

List of Figures

<table>
<thead>
<tr>
<th>Numbers</th>
<th>Captions</th>
<th>pp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Meteorite mass normalized to its initial mass and stagnation point pressure at different drag coefficients for meteorite atmospheric motion without accounting for fragmentation.</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>Meteorite mass normalized to its initial mass and stagnation point pressure at different heat transfer coefficients for meteorite atmospheric motion without accounting for fragmentation.</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>Temperature, streamlines and contact boundary for stony meteorite flow for altitudes of 50 (a), 40 (b) and 31 (c) km.</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>Heat fluxes and ablation mass flow rate along the meteorite surface for altitudes of 50 (a), 40 (b) and 31 (c) km.</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>Distributions of temperature and pressure across the shock layer in stagnation region $(\theta=0^\circ)$ (a) and at the side surface $(\theta=90^\circ)$ (b) for flight altitude of 31 km.</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Distributions of molar mass fractions across the shock layer in stagnation region $(\theta=0^\circ)$ (a) and at the side surface $(\theta=90^\circ)$ (b) for flight altitude of 31 km.</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>The destruction of a stony meteoroid with a diameter of 60 m falling at a velocity of 20 km/s at an angle of 45° (variant 13). The distributions of density (decimal logarithm of density in g/cm$^3$) are shown at different altitudes. The distances along the trajectory are given on the vertical axis, while the distances in the distance perpendicular to the trajectory are on the horizontal axis. The black line indicates the boundary between the meteoroid vapors and the air.</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>The dimensionless meteoroid mass (related to its initial mass) and the dimensionless bolide velocity (related to the initial velocity of the meteoroid) as functions of height. The bolide velocity is found as the velocity of the motion of the lower boundary of the glowing region (to be more exact, of the region with a temperature of 0.5 eV). The meteoroid has the same parameters as in Fig. 7.</td>
<td>26</td>
</tr>
<tr>
<td>9</td>
<td>The height distribution of the meteoroid material (vapors) $f_m$ and released energy $f_e$ at the moment of total deceleration. Both distributions are dimensionless, normalized to the total initial mass and energy of the meteoroid, respectively. The meteoroid has the same parameters as in Fig. 7.</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>Destruction of a rocky meteoroid of 40 m in diameter falling at a speed of 20 km/s at an angle of 45° (variant 13).</td>
<td>29</td>
</tr>
<tr>
<td>Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>11</td>
<td>Destruction of a rocky meteoroid 40 m in diameter falling at a speed of 20 km/s at an angle of 45° calculated with an internal friction coefficient of K = 0.7. The density distributions (the darker color corresponds to a larger density) are shown at different altitudes H. The vertical axis indicates the distance along the trajectory.</td>
<td>29</td>
</tr>
<tr>
<td>12</td>
<td>The destruction of a rocky meteoroid 40 m in diameter falling at a speed of 20 km/s at an angle of 45° calculated with the internal friction coefficient K = 0.1. The density distributions (the darker color corresponds to a larger density) are shown at different altitudes H. The vertical axis indicates the distance along the trajectory.</td>
<td>31</td>
</tr>
<tr>
<td>13</td>
<td>Scenarios resulting from cometary (a) and asteroidal (b) impacts. Light region corresponds to crater-forming impacts, dark region marks aerial bursts, intermediate region corresponds to surface GBs. White ellipse shows possible parameters of the Tunguska projectile.</td>
<td>33</td>
</tr>
<tr>
<td>14</td>
<td>Destruction of a comet-like meteoroid falling in the atmosphere. The temperature distribution (left) and density (decimal logarithm density expressed in g/cm³) at several altitudes H are shown. The vertical axis shows the distance along the trajectory. The black line is the boundary between vapor and air.</td>
<td>36</td>
</tr>
<tr>
<td>15</td>
<td>Dependence of the velocity on the height during the fall of comet-like bodies with a diameter of 100 m at an angle of 45° to the Earth’s surface at speeds of 50 km/s (solid lines) and 20 km/s (dashed). Body velocity was calculated as the velocity of motion of the lower boundary of the luminous region (more precisely, an area with a temperature of 0.5 eV).</td>
<td>38</td>
</tr>
<tr>
<td>16</td>
<td>The dependence of maximal altitude of explosion, at which the damage on the surface occurs, on the impactor diameter (assuming comet entry velocity of 50 km/s and asteroid entry velocity of 20 km/s).</td>
<td>42</td>
</tr>
<tr>
<td>17</td>
<td>Spectra of the pressure at the Earth’s surface for a series of atmospheric explosions. The numbers at the curves correspond to the explosion numbers in Table 4.</td>
<td>44</td>
</tr>
<tr>
<td>18</td>
<td>The surface wave amplitude versus the earthquake magnitude for a series of atmospheric nuclear explosions. The circles are values of $A_R$ calculated by formula (12) and the triangles are results of calculations in which the surface pressure below the threshold value 0.05$P_0$ was set to be equal to zero. The solid and dotted lines show approximations (11) and (14), respectively.</td>
<td>45</td>
</tr>
<tr>
<td>19</td>
<td>The dependence of maximal altitude, at which the fires on the Earth surface can occur, on energy of the explosion given in impactor diameters (cometary impactor has velocity 50 km/s; asteroidal - 20 km/s).</td>
<td>46</td>
</tr>
<tr>
<td>20</td>
<td>Isolines of radiation energy absorbed by a unit area in J/cm². It is assumed that the irradiated surface is at the sea level and is best oriented to accept the maximum radiation. Results of computations are shown for atmospheric visibility 40 km (a) and 20 km (b). The coordinates start at the epicenter—the Z-axis meets the trajectory at an altitude of 7 km. The Y-axis is a projection of the meteoroid trajectory to the Earth’s surface.</td>
<td>48</td>
</tr>
<tr>
<td>21</td>
<td>The relative pressure $P/P_0$ distribution ($P_0$ is the pressure at the surface) for case III, case of 300 kt TNT continuous energy release with three flares (see text).</td>
<td>51</td>
</tr>
<tr>
<td>22</td>
<td>The surface area corresponding to overpressures of $\Delta p &gt; 500$ Pa (relative overpressure $&gt;0.005$, colored grey) and $\Delta p &gt; 1000$ Pa (relative overpressure $&gt;0.01$, colored black) for three considered cases.</td>
<td>52</td>
</tr>
<tr>
<td>24</td>
<td>Initial stage of asteroid 300-m in diameter impact (velocity 18 km/s). Black- condensed matter of target and impactor, light-grey - vapor (bounded by thin black curve), grey - air (the darker - the larger its density). Black points correspond to ejecta fragments with size 0.03 mm- 3 cm, light-grey points - fragments smaller 0.03 mm.</td>
<td>54</td>
</tr>
<tr>
<td>25</td>
<td>Final stage of asteroid 300-m in diameter impact (velocity 18 km/s). Black- condensed matter of target and impactor, light-grey - vapor (bounded by thin black curve), grey - air</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>26</td>
<td>The flow pattern in the vertical impact of the asteroid with a diameter of 300 m. The distribution of the relative density ( \rho/\rho_0(z) ) where ( \rho_0(z) ) the equilibrium density of air at height ( z ). Distances along the horizontal and vertical axes are in kilometers.</td>
<td>56</td>
</tr>
<tr>
<td>27</td>
<td>Dependence of the maximum relative pressure ( p/p_0 ) on the surface at different distances from the impact point for the impact of an 300m asteroid.</td>
<td>57</td>
</tr>
<tr>
<td>28</td>
<td>Dependence of the maximum wind speed on the surface at different distances from the impact point for the impact of an asteroid of 300 m in diameter.</td>
<td>57</td>
</tr>
<tr>
<td>29</td>
<td>The formation of water crater due to impact of asteroid (300 m diameter) in the ocean with depth of 5 km.</td>
<td>58</td>
</tr>
<tr>
<td>30</td>
<td>Formation of tsunami waves due to the impact of 1 km in diameter asteroid into the ocean with depth of 5 km at an angle of 15 degrees (to the horizon).</td>
<td>59</td>
</tr>
</tbody>
</table>
List of tables

<table>
<thead>
<tr>
<th>Numbers</th>
<th>Captions</th>
<th>pp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calculated integral parameters for stony meteorite entry</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Stony meteor bodies. The first column gives the variant number; $D$ is the diameter of the meteoroid; $V$ is the initial velocity of the meteoroid; $\alpha$ is the inclination of the trajectory (with respect to the horizon) in degrees; $H_{\text{min}}$ is the minimal height of the lower boundary of the glowing region (when the vapor jet does not reach the Earth's surface); $U$ is the velocity at which the vapor jet hits the Earth's surface (if it reaches the surface); and $H_{\text{evap}}$ is the height at which the meteoroid material is completely evaporated.</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>Variants of simulations of the impacts of comet-like bodies. $N$ is the variant number, $D$ is the diameter of the meteoroid, $V$ is the initial velocity of the meteoroid, $\theta$ is the angle of a trajectory inclination (to the horizon) in degrees, $H_{\text{min}}$ is the minimum height of the lower boundary of the luminous volume (when the vapor jet does not reach the Earth's surface), $U$ is the speed of a vapor jet when it hits the Earth's surface (if it reaches the ground), $H_{\text{evap}}$ is the height where the meteoroid material is completely vaporized.</td>
<td>39</td>
</tr>
<tr>
<td>4</td>
<td>Parameters of the most powerful air explosions</td>
<td>44</td>
</tr>
<tr>
<td>5</td>
<td>The minimal level of resources needed to prevent serious damage and injuries of the population on the ground depending on a warning time and the size of space body.</td>
<td>62</td>
</tr>
</tbody>
</table>

Glossary
Designations

Section 2

$M$ running mass of a meteor body
$\theta$ running angle of incidence (between a trajectory and a horizontal plane)
$V$ speed of the body
$C_D$ drag coefficient
$\rho_\infty$ local density of air
$S$ cross-section area
$g$ gravity acceleration
$Q$ effective heat of sublimation (or heat of melting if the ablation is caused by melting), including also the energy of temperature heating
$C_H$ averaged coefficient of heat transfer
$V_{cr}$ speed corresponding to ablation ($\approx 3$ km/sec)
$h$ and $x$ vertical and azimuthal coordinate of the body
$R_E$ radius of Earth
$C_L$ aero dynamical coefficient of lift force
$\sigma = C_H/(Q\cdot C_D)$ ablation coefficient

Section 3

$q$ flux of radiation
$\Delta t$ step on time
$Q$ vaporization temperature

Section 4

$D$ diameter of comet
$V$ initial speed

$\theta$ entry angle (measured from a horizontal plane)

Section 5

Designations in 5

$p_0$ standard atmosphere pressure

$P(r,t)$ distribution of pressure on the surface of Earth

$E_R$ energy of generated surface waves

$c_R$ phase speed of Rayleigh wave

$C$ dimensional coefficient depending on properties of the media in the epicenter of burst (phase speed of seismic waves and Lame parameters)

$p(\omega,k)$ spectrum of pressure

$J_0$ Bessel function

$P_0$ atmosphere pressure at the surface of Earth

$k=\omega/c_R$ wave number

$E_{RI}$ energy of the main mode of Rayleigh wave

$M_S$ magnitude of earthquake determined by vertical displacement

$e_{cr}$ critical burning energy density

$h_2$ altitude limit for burning of inflammable materials

$Q$ radiation energy coming onto the surface of object

$E$ energy of burst (kinetic energy of body)

$r$ distance between a burst and a surface

$L$ visibility in atmosphere

$\alpha$ angle between the normal to an illuminated area and the vector oriented from the object to the radiation source

$f$ coefficient of burst energy transformation in heat radiation that passes through atmosphere

Section 6

$T_{00}$ time between the first observation of dangerous body and its collision with Earth

$T_{01}$ time between the exact determination of orbital parameters of dangerous body and its collision with Earth

$T_{02}$ time between the attempt to deflect a dangerous body and its collision with Earth
Indices

<table>
<thead>
<tr>
<th>0, 00, 01, 02</th>
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</tr>
</thead>
<tbody>
<tr>
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<tr>
<td><strong>iscn</strong></td>
<td>испарение</td>
</tr>
<tr>
<td><strong>Rl, R</strong></td>
<td>Рэлей</td>
</tr>
<tr>
<td><strong>S</strong></td>
<td>удар</td>
</tr>
<tr>
<td><strong>E</strong></td>
<td>Земля</td>
</tr>
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<td><strong>H</strong></td>
<td>теплообмен</td>
</tr>
</tbody>
</table>

Abbreviations and terms

<table>
<thead>
<tr>
<th>NEO</th>
<th>Near-Earth Object</th>
</tr>
</thead>
<tbody>
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<td><strong>kt</strong></td>
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</tr>
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<td><strong>Mt</strong></td>
<td>Megatons of TNT</td>
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<tr>
<td>n.e.</td>
<td>nuclear explosion</td>
</tr>
<tr>
<td><strong>TNT</strong></td>
<td>trinitrotoluol</td>
</tr>
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<td>Institute of Dynamics of Geospheres</td>
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<td>Institute of astronomy of RAS</td>
</tr>
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<td><strong>SOVA, CTH</strong></td>
<td>Multidimensional hydrocodes</td>
</tr>
<tr>
<td><strong>GB</strong></td>
<td>Giant bolide</td>
</tr>
</tbody>
</table>
1. Introduction

Object kinetic energy \( E_k = \frac{1}{2}MV^2 \), where \( M \) – body mass and \( V \) – its velocity relative to the Earth surface have to be considered as a main characteristics of the object responsible for possible impact damage under entering of high-velocity NEO to the Earth's atmosphere. Though the object velocity can be varied within a sufficiently wide range \( (11 \text{ km/s} \leq V \leq 72 \text{ km/s} \) for meteoroids of asteroid origin\) the most expected entry velocity is \( V \sim 20-30 \text{ km/s} \). Therefore, the main parameter responsible for consequences of the entering is the object mass \( M \) or its characteristic size \( D \), that can be altered from microns to tens of kilometers. In this case, the value of the total energy coming to the atmosphere will be varied from \(~100 \) to \(~10^{24} \text{ J} \) \((~10^{7} - 10^{14} \text{ tons in TNT equivalent})\). In the latter case this energy exceeds considerably the total world nuclear weapon potential. In most cases (excluding ricochet entering through atmosphere or bringing crater ejecta beyond the Earth's atmosphere with escape velocities) all this energy will be released either in atmosphere or near the surface of Earth. Hence, consequences of entering of such large object into the atmosphere can be comparable (or even more disastrous) with the consequences of global nuclear catastrophe. But, compared to nuclear explosion with aimed energy release, which should provide maximum damage, the consequences of meteoroid entering are of unintended nature and can have very different character depending on what physical processes will be pumped with the energy of the meteoroid. This energy redistribution principally depends on the body characteristics – its mass, velocity, shape, entry angle, object constitution, porosity, strength and thermophysical properties. Under random entry of such body these characteristics are unknown and may be very different. In case of controlled entry, knowledge of these body characteristics is extremely important as it provide more reliable predictions of the consequences of that fall.

This consequences maybe either short-term (with time-scale of order of body atmospheric flight duration) or long-term (days, months or even years) ones as well as may differ by their spatial scale – local, regional or global.

In general case, the physical situation that can occur in case of entering of a sufficiently large (and threatening) meteoroid into the atmosphere can be subdivided into several phases: transatmospheric flight, disruption, surface impact, forming of the impact crater and ejection from it, as well as consequent long-term effects \((1-5)\).

At high flight altitudes the body moves almost straightforward with constant velocity. As the body dips into dense atmosphere the surface heat flux (radiative and convective) grows up together with the surface ablation and recession. Small bodies burn out in the upper atmosphere but larger bodies intrude into all the more dense atmosphere layers. Surface ablated materials come into the wake region behind the body, this wake is cooled and expands to the ambient pressure and slowly floats to the higher atmospheric layers. With increasing ambient density the body drag force grows too and frontal pressure reaches virtually the strength of the meteoroid body and it starts fragmenting. Not very large meteoroids have enough time for their disruption onto several (or swarm) fragments. In this case aerodynamic drag of forming debris increases abruptly and the object decelerates or even almost stops. Velocity reduction brings about drop in the body kinetic energy that will be consumed by air heating in the shock wave and radiation. It looks like an intensive flush – airburst – sharp increase in the bolide luminosity. This energy release leads to forming unsteady shock wave leaving the body. There can be several these flashes corresponding to successive stage of body fragmentation, the last of those – "end flash" corresponds to almost total stopping of the body, after that body glowing breaks down and body fragments not burned during this last flash hit the Earth surface with relative low velocity. Chelyabinsk meteorite fall of 15.02.2013 followed this scenario.

Larger bodies (with sizes more than hundred meters for stony meteorites) do not have time for fragmentation and reach the surface without changing their sizes and velocities. When colliding into
the ocean these falls lead to tsunami formation and falling into the land lead to the formation of impact crater (or strewn crater field). Intensive shock waves in the body and target will be formed under surface crater formation those will compress the media of meteorite and Earth's crust. Surface seismic waves will be emitted out of the collision region inferring earthquakes with amplitudes determined by the fall energy. At releasing the material of colliding object and part of target material will be fragmented, fused or sublimed forming initially dense cloud of gases and fragments rising up in the atmosphere. At releasing the material of colliding object and a part of target material are fragmented, fused and sublimed debris that floats from the crater to atmosphere. Moving up the ejecta is gradually cooled due to expansion, its optical thickness decreases and it starts radiating intensively that can lead to mass fires in direct sight areas. A part of ejecta with higher speeds can escape Earth's atmosphere, another part with lower speeds will fall down as secondary fragments. Gas phase will be condensed forming fine-dyspersated dust in upper atmosphere that can constitute a dense curtain shielding Sun radiation. For sufficiently large sizes of the meteorite (≥ 1km) it can give rise to global climate change, total cooling, sharp drop of photosynthesis, destruction of ecosystems, extinction of agriculture and mass starvation. Besides, increase of nitrogen oxide and sulfur oxide fractions in the atmosphere will lead to acid rain fallings and additional deaths of terrestrial flora. Another consequence of this fall will be destruction of ozone layer and sharp drop in UV radiation absorption by the atmosphere. All these processes possess complex, insufficiently studied nature and require for diversity of additional scientific researches on mechanical, thermophysical, chemical and optical properties of meteoritic bodies, properties of Earth's atmosphere and lithosphere, response of ecosystems on catastrophic impacts, etc.

2 Motion of an asteroid object or its large fragment in Earth's atmosphere before destruction

The simplest (and widely-used) model for description of large meteorite body in the atmosphere is so-called "physical" model (e.g. (6-7)). The momentum equation (projected to the flight trajectory) can be written as:

\[ M \frac{dV}{dt} = -\frac{1}{2} C_D \rho_\infty V^2 S + Mg \sin \theta \]

where \( M \) – instant mass of the meteor body, \( \theta \) – instant angle of trajectory inclination to horizon, \( V \) – absolute value of body velocity, \( C_D \) – drag coefficient, \( \rho_\infty \) – inflow air density, \( S \) – midsection area, \( g \) – gravity force acceleration. This equation is the second Newton law projected to the object flight trajectory, that demonstrates that acceleration/deceleration of the body is proportional to the aerodynamic drag force and projection of gravity force vector to the flight path (reactive forces due to the mass loss is negligible for large bodies and not considered here). In most cases the gravitational term of (1) can also be neglected compared to aerodynamic deceleration. Value of the drag coefficient – \( C_D \) is usually assumed to be constant and close to unity for a meteoroid body of compact shape. The body mass is changed along the trajectory due to ablation of its surface layers according to equation:

\[ Q \frac{dM}{dt} = -\frac{1}{2} C_H \rho_\infty V^3 S \cdot \max \left( 0, \frac{V^2 - V^2_{\text{cr}}}{V^2} \right) \]

where \( Q \) – effective sublimation heat (or melting heat, if ablation goes through the fusion mechanism), which also includes energy of material heating to the sublimation (or melting)
temperature. \(C_H\) – average heat transfer coefficient and \(V_{cr}\) – magnitude of body velocity below which ablation can be neglected (≈3 km/s).

It follows from kinematic consideration that coordinates of moving body can be specified from

\[
\frac{dh}{dt} = -V \sin \theta
\]

(3)

\[
\frac{dx}{dt} = \frac{V \cos \theta}{1 + h/R_E}
\]

Then, the trajectory slope angle can be determined from expression

\[
\frac{d\theta}{dt} = \frac{Mg \cos \theta - \frac{1}{2} C_L \rho_\infty V^2 S}{MV} - \frac{V \cos \theta}{R_E + h}
\]

(4)

where \(h\) and \(x\) – vertical and azimuthal coordinates of the body, \(R_E\) – Earth radius and \(C_L\) – aerodynamic lift coefficient. Because of randomness of initial shape of the object it often supposed to be axisymmetric and mowing at zero angle of attack, then lift force can be omitted. Also, terms connected to the curvature of the planet surface contribute to eq. (3-4) only for very slant trajectories, when we have considerable (comparable to the Earth radius) displacement in the horizon direction.

Distribution of air density vs. altitude \((\rho_\infty = \rho_\infty(h))\) is taken from the standard atmosphere tables, but in the simplest case (assuming isothermal atmosphere) can be specified by barometric relationship

\[
\rho_\infty = \rho_0 \exp \left( -\frac{h}{H} \right)
\]

(5)

where \(\rho_0\) – sealevel air density, \(H\) – characteristic length scale of the atmosphere, \(h \approx 7.4-8.1\) km.

At constant values of \(C_D, C_H, Q, S\) eqs. (1-4) can be readily integrated starting from initial conditions for the entry point

\[
t = 0, \ h = h_0, \ V = V_0, M = M_0, \theta = \theta_0, \chi = 0
\]

(6)

With these assumptions the system of equations turns to be closed and it allows obtaining trajectory parameters for the "intact" meteorite, moving through the atmosphere without mechanical disintegration (fragmentation) but with account for ablative mass reduction while hitting the Earth's surface. For the exponential atmosphere (5) these equations can be integrated to quadratures (6), and for an arbitrary atmosphere – numerically with any required accuracy.

In this case the principal problem is conditions of permanency of the model constants, first of all – drag and heat transfer coefficients.

For bluff body shapes, like that of meteoroids, the drag coefficient \(C_D\) is close to unity for continuum flow regime. Hypersonic Newtonian approximation provides \(C_D = 1\) for spherical body
and $C_D=2$ for flat face body. Modified Newtonian theory (8) gives magnitudes of 0.92, 0.96 and 0.975 for a sphere in hypersonic flow for $\gamma = 1.4, 1.2$ and 1.1 respectively ($\gamma$ – specific heat ratio). Numerical simulations for parallelepiped-shaped bodies with sharp or rounded edges (9) provide the drag coefficients from 1.6 (sharp edged body) to 0.86 (spherical bluntness). CFD modeling of spherical body entry with account for surface recession due to ablation (10) demonstrates variation of drag coefficient from 0.86 to 1.2 as material blown down from the frontal surface of the meteorite.

For small-size meteor bodies the blow of ablation products to the shock layer can considerably affect the drag coefficient magnitude, because it displaces inflow gases out of the wall and changes the bow shock shape. Nevertheless, in case of large meteoroids, that only considered here, the thickness of layer of the surface vapor gases is much lower than the body sizes and this correction is small.

Effect of drag coefficient variation to the trajectory parameters of a meteorite (with body diameter of $D = 19.8$ m, density of $\rho_m = 3.3$ g/cm$^3$, entry velocity of $V_0 = 19.16$ km/s, entry angle of $\theta_0 = 18.3^\circ$ – the data corresponding to Chelyabinsk meteorite entry (11), at constant values of $C_n=0.1$ and $Q = 6.25$ MJ/kg that is assumed to be suitable for ordinary chondrites) obtained by eqs. (1-4) are presented in Fig.1a,b for the case of nonfragmented meteorite.

These calculations demonstrate only minor influence of drag coefficient variation on trajectory parameters of the meteoroid. Some difference is just observed for ablation value (Fig.1a) and stagnation point pressure (fig.1b) and merely for altitudes ≤ 10 km. For larger meteorites and higher entry velocities the difference in calculated results by relationships of (1)-(4) appears to be even smaller. In above consideration it should be accounted for that meteorites of not very big sizes ($\geq 100$ m) are totally fragmented in the dense atmosphere, whereas eqs. (1)-(4) (without corrections for fragmenting) are valid only for an intact object. In practice it means that when modeling meteorite motion the assumption of constant drag coefficient can be valid until starting of intensive object fragmentation. For large meteorites, that reaches the Earth’s surface practically without fragmentation, the variation of the drag coefficient can influence only at altitudes lower than 10 km.

Variation of meteorite mass along the trajectory (Fig.1a) is described well with an algebraic relation, obtained in assumption of isothermal atmosphere and neglecting gravitational force (6).
\[ \frac{M}{M_0} = \exp \left[ \frac{\sigma}{2} (V^2 - V_0^2) \right] \]  

(7)

where \( \sigma = C_H/(Q \cdot C_D) \) – ablation coefficient. Results of using this equations is practically coincident with the results presented in Fig.1a along all the trajectory and is not shown in the figure. However, because of exponential character of expression (7) remarkable difference in final mass can be observed for bodies that loses substantial part of its mass due to ablation but, at the same time, reaches the surface without disintegration.

Value of specific destruction energy \( (Q) \) is determined by the constitution of meteoritic body (strictly speaking, flow pressure and enthalpy have to be considered as well) and, according to accepted now estimations, is about 8 MJ/kg for iron meteorites, 5-8 MJ/kg for ordinary chondrites, 5 MJ/kg for carbonaceous chondrites and 1-2.5 MJ/kg for short- and long-periodic comets (12-15).

Value of integral heat transfer coefficient \( (C_H) \) has much wider spread. Theoretical analysis of (16) predicted magnitudes of \( C_H \sim 10^{-3} \). Bronshten (6) pointed out that the best agreement with observations of bolide luminosities can be obtained using values of \( C_H \sim 10^{-1} \). In (7) magnitudes of this coefficient cover the region of 0.6-0.01 though authors used magnitude of \( C_H =0.02 \) in their numerical calculations. Stulov (17) provided values of \( C_H =0.01-0.02 \) for iron meteorites (Sikhote-Alin meteorite), \( C_H =0.012-0.018 \) for stony one (Benešhov) and \( C_H =0.1-0.09 \) for Tunguska object. In (12) as well as in many others the recommendation of Bronsten were used and it was supposed that \( C_H =0.1 \). Magnitudes of \( C_H = 10^{-2}-10^{-3} \) and even lower were reported in (18) for meteoroids with \( D = 1 \) and 10 m, moving with velocities of 10,20,30 km/s for altitudes of 0,10,20,30,40 and 50 km on the basis of numerical simulations of radiative heat fluxes to a sphere in air flow with velocity \( \leq 15 \) km/s (19). Processing of experimental data on luminosity of a number of bolides (13, 14) provided magnitudes of \( C_H=0.06-0.07, 0.07-0.08, 0.15-0.2 \) for three observed events (Innisfree, Lost City, Pribram, correspondingly). Trajectory numerical modeling with equilibrium air model (10) for Sikhote-Alin meteorite gave variation of \( C_H = 0.06-0.03 \) under body descent from 40 to 12 km. Theoretical calculations with account for radiation absorption by the ablation products with a four-group absorption model gave values of \( C_H = 0.05-0.04 \) for one meter cylindrical body (ordinary chondrite) with velocity of 20 km/s [20]. Finally, constant value of \( C_H = 0.1 \) was used under treatment of trajectory observation data of Chelyabinsk meteorite (11).

This figures indicate that (1) there is considerable scatter in possible values of the heat transfer coefficient for meteoroid bodies and (2) there is essential difference in theoretical predictions of the heat transfer coefficient and those values extracted from the observations of atmospheric entries of bright bolides. In Fig.2 we demonstrate effect of heat transfer coefficient variation to trajectory parameters (body diameter of \( D = 19.8 \) m, density of \( \rho_m = 3.3 \) g/cm\(^3\), entry velocity of \( V_0 = 19.16 \) km/s, entry angle of \( \theta_0 = 18.3^\circ \), \( C_D=0.1 \) and \( Q = 6.25 \) MJ/kg) determined by (1-4) eqs.
Figure 2. Meteorite mass normalized to its initial mass and stagnation point pressure at different heat transfer coefficients for meteorite atmospheric motion without accounting for fragmentation.

The heat transfer coefficient was varied within the range of values found in the literature. Uncertainty of three orders of magnitude in $C_H$ leads to much greater scatter in meteorite motion parameters than variation of body drag (Fig.1) because essentially lower uncertainty of its value.

The assumptions considered above about permanency of the coefficients in eqs. (1-4) are somewhat voluntary and are not confirmed in the observations of entry of large bolides. One another way alternative to this simple approach is accurate integration of equations describing flow around a meteoroid with consideration of radiation, material ablation, etc. Unfortunately, solution of this problem in its exact formulation without additional simplifications is hardly possible both because its extreme complexity and lack of reliable data on a number of important physical processes accompanying meteoroid entries (first of all spectral characteristics).

Here we will consider results of numerical modeling of 18m meteoroid motion through the atmosphere with velocity of 17 km/s. Full Navier-Stokes equations were integrated for prediction of body flowfield using finite-volume upwind scheme (88-89). It was assumed that the meteoroid has a spherical form, is a stony one and corresponds to ordinary LL-chondrite by its constitution. For the sake of simplification, the constitution of the meteoroid was considered as a mixture of silicates, that are instantly decomposed to three basic oxides: SiO$_2$, FeO and MgO and pure iron (the following molar fractions were selected for the LL-chondrite: 45, 20, 29% for silicates and 6% of iron). Minor admixtures (such as oxides of Al, Ca, Na, sulfides, etc.) were replaced by excess of oxygen. This conditions are appropriate for entry conditions of the Chelyabinsk event of February 2013. Only altitude range of 50-30 km was considered because at higher altitudes ablation is much lower but at lower altitudes meteorite fragmenting have to be accounted for. High level of pressure in the body shock layer permits using assumption of local thermodynamic equilibrium (LTE) both for air species and ablation vapors. In this case all thermodynamic characteristics of the mixture (depending on pressure, temperature and concentration of ablation products blown in the shock layer) can be specified from LTE assumption depending on the thermodynamic properties of individual species (90-91). Radiation-adsorption properties of high-temperature air was taken from table data of (92), a multi-group model was used for description of adsorption dependence on radiation frequency, and radiation transport equation was solved in plain layer assumption (93). Diffusion coefficients of equilibrium gas mixture was evaluated assuming constant Schmidt numbers $Sc = 0.7$.

Temperature fields and streamline pattern for the flow over frontal part of this body are presented in Fig.3 for altitudes of 50, 40 and 31 km. The contact boundary (dashed line, corresponding to total ablation gases fraction of 0.7) is also shown there. This line approximately
corresponds to the boundary between air plasma and destruction products. The near-wall layer of ablation products covers essential part of the shock layer (50-70\% by thickness). It displaces shock layer out of surface increasing a little the body pressure and drag coefficient.

Figure 3. Temperature, streamlines and contact boundary for stony meteorite flow for altitudes of 50 (a), 40 (b) and 31 (c) km.
Figure 4. Heat fluxes and ablation mass flow rate along the meteorite surface for altitudes of 50 (a), 40 (b) and 31 (c) km.
Figure 5. Distributions of temperature and pressure across the shock layer in stagnation region ($\theta=0^\circ$) (a) and at the side surface ($\theta=90^\circ$) (b) for flight altitude of 31 km.
This calculations demonstrates that mass flow rate of ablated gases is greater than mass flow rate of air in the shock layer at such intensive body heating. Distribution of surface radiation heat fluxes and mass flow rate along the meteorite surface is shown in Fig.4 for three altitudes of h = 50, 40 and 31 km. Convective heat fluxes is practically almost shielded by the blown ablation products and their level is more than two order lower than radiation heat flux. This figure also represents approximated distribution of radiative heat fluxes determined by dependence \( q_r(\theta) = q_r(0) \cos^n\theta \) – such dependences are widely used for approximate estimations of ablation of meteoroid bodies (e.g. (18)). For the flow conditions considered the exponent \( n \), following to the estimations of (19), should be equal to \( n \approx 3.8 \), that corresponds to very steep drop of radiation heat transfer with the increase of \( \theta \) angle. Present calculations demonstrates that the best agreement with the accurate calculations will be achieved at \( n = 1.5, 1 \) and 0.3 for altitudes of 50, 40 and 31 km respectively. This considerable difference is explained by the fact that in (19) the radiation heat flux was obtained for non-ablated body. Accounting for effect of ablation products on radiative heat flux dramatically changes the situation. With the decrease of altitude we observe redistribution of the heat flux from stagnation region to peripheral regions due to influence of optically thick vapor layers and readsorption of radiation in it as well as due to flux shielding. It leads to the situation when the region where heat fluxes are close to maximum turns to be wider and wider.

Distributions of temperature and pressure across the shock layer for the altitude of 31 km for two cross-sections of \( \theta=0^\circ, 90^\circ \) are presented in Fig 5. For this trajectory point the thickness of blown gas layer is about 0.2 m for stagnation region (\( \theta=0^\circ \)) and about 1 m for \( \theta=90^\circ \). Results presented in Fig.5 indicate sufficiently smooth distribution of temperature across the shock layer. Re-radiation and diffusion smooth the temperature profile considerably and widely-used two-layer model (isothermal layer of air plasma with the temperature equal to temperature behind the shock and isothermal layer of destruction vapors at wall temperature) appears to be misleading in this situation.
Species molar fractions of ablation products and air plasma for flight altitude of 31 km are presented in Fig. 6 for the same cross-sections of θ=0.90°. Atmospheric molecular oxygen is almost totally dissociated and oxygen formed throughout destruction of the meteorite material dissociates quickly near the surface. Molecular nitrogen is also almost dissociated, only small zone of relatively low-temperature gas exists where atomic nitrogen recombinates to molecules near the mixing region especially near the side surface of the body. Silicon, iron and magnesium oxides also dissociate quickly as moving outward the wall and almost disappear at the half of blow gas layer, consequently, the fractions of atomic species of Si, Fe and Mg grow. At further moving out the wall the fraction of neutral atoms starts decreasing due to ionization and the most part of the shock layer turns to be ionized. For present conditions, a number of double ions is not considerable with maximum total molar fraction ≤ 0.2%.

Table 1. Calculated integral parameters for stony meteorite entry

<table>
<thead>
<tr>
<th>H, km</th>
<th>C_D</th>
<th>C_H</th>
<th>Q, MJ/kg</th>
<th>σ (s²/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.944</td>
<td>0.102</td>
<td>17.5-18</td>
<td>0.0060-0.0062</td>
</tr>
<tr>
<td>40</td>
<td>0.948</td>
<td>0.079</td>
<td>17-18</td>
<td>0.0046-0.0049</td>
</tr>
<tr>
<td>31</td>
<td>0.933</td>
<td>0.039</td>
<td>17-18</td>
<td>0.0023-0.0025</td>
</tr>
</tbody>
</table>

Main integral characteristics (coefficients of drag, heat transfer and ablation) obtained numerically are presented in Table 1. As concern the drag coefficient then we have its small increase (from 0.86 to 0.93-0.95) because of outer inviscid flow displacement by the blown ablation products. To a first approximation this growth is equal to increase of effective body cross-section due to displacement of the contact surface out of the wall. It is worth to note that the heat transfer coefficients are quite great compared to previously reported numerical data (16, 7, 17, 18) and agreed well with the observation data of $C_H \approx 0.1$, because of sufficiently accurate modeling of destruction of stony meteoroid object and radiation processes in air plasma and material vapors in present calculations. On the other hand, the value of destruction specific energy $Q$ is about trice greater than magnitudes usually accepted for ordinary chondrites. Magnitude of destruction energy used here corresponds to equilibrium value of energy consumed by the body heating, fusion and sublimation. It corresponds to the meteorite destruction model adopted here, when heated layer of the meteorite surface sublimates instantly at calculated values of pressure and temperature of near-wall gases. If we will use a destruction mechanism caused not by sublimation but by melting of meteoroid material then the value of $Q$ will be reduced to 5-7 MJ/kg usually employed in approximate calculations. As a result, the value of ablation coefficient will grow up to magnitude of ~0.006-0.02 s²/km², (observations of stony meteorites give values about 0.014 (13), value of 0.016 was used for the Chelyabinsk meteorite (14), hence, in accordance with (7) it will lead to considerable growth of ablation. However, it seems that extremely high levels of heat fluxes to the surface make it doubtful that appreciable amount of the material will be ablated as melt film without its vaporization. It means that one of the most principal problem in theoretical consideration of large meteoroid entry in the atmosphere (at least before starting gross fragmentation) is insufficient understanding of ablation mechanisms of meteoroid bodies.

3 Calculation of fragmentation and deceleration altitudes for asteroids of different sizes impacting the Earth's atmosphere

Earlier theoretical investigations of objects falling from space with different sizes (21) demonstrate that there are four scenarios for the fall of these bodies to the Earth (in order of decreasing body dimensions):
• crater-forming impact (when a cosmic body, perhaps even highly fragmented, reaches the Earth’s surface and forms a crater);
• a surface giant bolide (GB) or, in other words, a surface “meteor explosion” (when a high velocity jet consisting of small fragments and vapors of the meteoroid and air heated in the shock wave reaches the Earth’s surface without forming a crater);
• air GB or air “meteor explosion” (when the products of a completely disintegrated and evaporated meteoroid are decelerated in the atmosphere and do not reach the Earth’s surface but the shock wave and thermal radiation produce noticeable destruction and fires);
• ordinary meteor phenomena (that can be observed from the Earth and from space, but leave no significant traces on the Earth’s surface).

Certainly, there are no sharp boundaries between these modes and intermediate scenarios are also possible.

A typical example of an air meteor explosion is the well-known Tunguska catastrophe (see (22)) which was produced by a fall of a cosmic body with an energy release from ten to several tens of megatons. In this case, only two shock waves occurred: the so-called “explosion wave” incident on the Earth and the reflected shock wave. A more complicated flow occurs during surface meteor explosions and, especially, during crater-forming impacts. In the last case, shock waves are generated upon the flight of a cosmic body through the atmosphere and the emission of material from the crater followed by the fall of ejecta under the action of the force of gravity.

In this report we present the results of a set of numerical simulations to determine what a scenario is realized at different projectile sizes and trajectory angles.

Numerical method

The SOVA hidrodynamical code (23), was used to model the interaction between a meteoroid and the Earth's atmosphere. In this method, the falling body is assumed to be quasi-liquid (with zero strength), and its deformation due to aerodynamic loading is described by hydrodynamic equations (Euler equations). This approximation was fruitfully applied in simulations of the destruction of the comet Shoemaker–Levy 9 in the Jovian atmosphere. The approximation is suitable for cases of rather large bodies that are destroyed prior to their noticeable deformation. The multimaterial SOVA hydrocode was applied to integrate the Euler equations numerically. This allowed us to define explicitly the boundaries between regions with materials characterized by different equations of state (e.g., between air, vapors, and condensed meteoroid material) in our simulations. Lagrangian equations are solved at the first stage of calculations using (24). At the second step the data are remapped to Eulerian mesh using a second order method described in (25). A procedure described in (26) is used to construct a boundary between different materials. More details can be found in (21, 28).

Last decades numerical differential methods are widely used for simulating interaction of large meteoroids (with sizes of 10 m and greater) with Earth's and planets atmospheres. Deformation, fragmentation and deceleration of the falling body is predicted by numerical integration of hydrodynamic equations. Different numerical models are distinguished by numerical methods used and sorts of state equations utilized for meteoroid material behavior. Pure Eulerian (29, 30, 31), mixed (32-34) and Lagrangian (35-37) methods are used. For description of meteoroid material thermodynamic properties the gas or liquid equations of state (EOS) as well as multiphase EOS of Mie-Gruneisen, Tillotson, ANEOS, etc. are used (exact form of the EOS is not very important in this case because of relatively low contraction). These models were widely used for simulation of such phenomena as Tunguska event, fall of the Shoemaker–Levy 9 comet fragments to Jupiter, and, allow, at least qualitatively, describing all observed features of those unique events. It should be
stressed that nowadays this approach provides the fullest, detailed and accurate modeling of explosions of cosmic bodies within the frameworks of accepted physical assumptions.

For all aforementioned models the meteoroid is considered as quazi-liquid (38) in the sense that it does not possess any strength and stress tensor is exactly spherical (there are no shear stresses). This assumption is based on that remarkable deformation of meteoroids with sizes of 10 meters and greater starts at altitudes where aerodynamic loadings are substantially greater than the strength of falling bodies. Thus, it can be supposed, that deformed body is totally destructed to that moment.

To model the radiative transfer in meteoroid vapors and in air, we applied the approximation of radiative heat conduction. The Rosseland mean-free paths for air at typical temperatures behind the bow-shock front (1–5 eV) are not more than 1 m below 30–40 km; therefore, the approximation of radiative heat conduction is quite reasonable for bodies about 100 m in size.

The radiation incident on the boundary of the condensed material leads to its evaporation. The vapor flux from the unit surface of the condensed material $\Delta m$ is determined by the relation

$$\Delta m = \frac{q \Delta t S}{Q}$$  \hspace{1cm} (8)

where $q$ is the radiation flux, $\Delta t$ is the time step, and $Q$ is the heat of evaporation. The pressure of the outcoming vapors is assumed to be equal to the gas pressure near the surface. The vapor temperature and density are determined from the phase equilibrium curve. The numerical model is described in more detail in (38).

The tabular equations of state and photon path lengths were used for air (39), cometary material (40), and H-chondrites (41).

The results of numerical computations often depend on whether the energy equation is written in divergent or nondivergent form (24). In the first case, the total energy is automatically conserved, but problems with computing internal energy and temperature arise (the resulting values can even be negative). If we use the equation of energy in nondivergent form, the balance between thermal and kinetic energies is described correctly, but there are problems with total energy conservation (especially on coarse grids in the areas of compression). We can overcome the problem of a total energy deficit by introducing a compensating augmentation of thermal energy (26) similarly to that made for inelastic impacts. But this can lead to too high temperatures in the material. Speaking about numerical simulations of mass ejection and spread, we can note that the velocities will be slightly underestimated in the first case (without thermal energy correction) and overestimated in the second. Both approaches were applied in the present study to get upper- and lower-bound estimates.

**Numerical modeling of aerial burst induced by impact of cosmic body**

Figure 7 illustrates the sequential stages of the interaction with the atmosphere of a 60-m-diameter stony asteroid falling onto Earth with a velocity of 20 km/s at an angle of 45° (variant 13). The asteroid density was 3.5 g/cm$^3$; the equation of state for H-chondrites (41) was used to describe its thermodynamic properties. The meteoroid starts its deformation at an altitude of about 30 km; wavelike perturbations arise at its surface due to Rayleigh–Taylor and Kelvin–Helmholtz instabilities. The central part of the trail is filled with vapors because of evaporation.
At higher aerodynamic loadings, the meteoroid is squashed and turns to a panlike structure at a height of 20 km corresponding to classic analytic models (12, 42). The further growth of instabilities results in the fragmentation of the meteoroid, which below 17 km turns to a jet of vapors, shockheated air, and fragments of the falling body. First, the velocity of this jet is nearly the same as the initial velocity of the meteoroid, 20 km/s (see Fig. 8). Thus, the destruction and fragmentation of the falling body occur prior to its appreciable deceleration. The velocity was found from an examination of the motion of the glowing region (meteor), which was in turn determined as a region whose temperature was above 0.5 eV (the temperature of air transparency).

The fragmentation leads to the extension of the evaporating surface and, hence, to an increase in the ablation rate (Fig. 8). At a height of about 10 km, the meteoroid’s fragments completely evaporate and the jet becomes purely gaseous. The jet velocity is still high and differs from the initial velocity of the meteoroid by less than 10%.
Figure 7. The destruction of a stony meteoroid with a diameter of 60 m falling at a velocity of 20 km/s at an angle of 45° (variant 13). The distributions of density (decimal logarithm of density in g/cm³) are shown at different altitudes. The distances along the trajectory are given on the vertical axis, while the distances in the distance perpendicular to the trajectory are on the horizontal axis. The black line indicates the boundary between the meteoroid vapors and the air.
Figure 8. The dimensionless meteoroid mass (related to its initial mass) and the dimensionless bolide velocity (related to the initial velocity of the meteoroid) as functions of height. The bolide velocity is found as the velocity of the motion of the lower boundary of the glowing region (to be more exact, of the region with a temperature of 0.5 eV). The meteoroid has the same parameters as in Fig. 7.

Because of the intense ablation, the average gas density in the high-velocity jet is higher than the density of the ambient air at 10–15 km. The air heated in the shock wave has a high pressure; therefore, the jet expands. In addition, the jet comes down to denser and denser atmospheric layers (i.e., the density of the ambient air increases). That is why, at the moment of deceleration (at a height of about 2 km), the gas density in the jet is much lower than the density of the ambient atmospheric air and something that resembles a “fireball” typical of atmospheric explosions occurs. However, in the case under consideration, the hot rarified volume is cylindrical rather than spherical in shape (Fig. 7). The heated gas starts its upward motion to form an atmospheric plume (38).

At the moment of full deceleration of the meteor, the bulk of the meteoroid material (in the form of vapors mixed with hot air) is concentrated at altitudes from 3 to 10 km (see Fig. 9). This material is later introduced into the atmospheric plume and is ejected to the upper atmosphere, up to 100–1000 km (38).
Figure 9. The height distribution of the meteoroid material (vapors) $f_m$ and released energy $f_e$ at the moment of total deceleration. Both distributions are dimensionless, normalized to the total initial mass and energy of the meteoroid, respectively. The meteoroid has the same parameters as in Fig. 7.

When the meteoroid (and its remnants) is decelerated in the atmosphere, the energy is released along a long portion of its trajectory from 20 km (strong deformation and the beginning of meteoroid fragmentation) to 2 km (the height of deceleration of high-velocity jet of vapors and air). Therefore, the energy release from the meteoroid burning up (evaporation) in the atmosphere is much different from that of a point explosion.

If the size of the falling body is increased in the above-mentioned variants, the high-velocity gas jet, formed after the total evaporation of the meteoroid and its fragments, will not have time to decelerate and will hit the terrestrial surface. However, since the gas density is small in the jet, the pressure induced by its deceleration will be comparable or smaller than the rock strength and either no crater is formed or a very shallow plane crater (without impact melt and impact-modified material) arises and the traces of it are quickly erased.

It is worth noting that, strictly speaking, the computational grid used in our simulations is too crude to accurately describe the processes of radiation transfer in the shock-heated layer (where there are only 5–10 cells) and evaporation. An increase in the grid resolution results in a fast growth of computation time, which makes it impossible to perform computations for a set of cases. The test computations show that with the mesh size half that as the one applied the evaporation rate and the thickness of the vapor layer change by not more than 20–30%. Thus, the results obtained in this study should be considered as a first approximation, which needs further refinement, but even now gives more reliable values than any crude estimates.
The process of deformation and fragmentation of a quasi-liquid meteoroid is accompanied by the development of the Rayleigh–Taylor and Kelvin–Helmholtz hydrodynamic instabilities. The instabilities develop in a stochastic way; that is why the results are different in different runs with identical initial data.

Stony bodies differ from comet-like bodies in their density, heat of evaporation, and initial velocity (we can neglect the strength differences as we consider only rather large bodies, which are destroyed at high altitudes to become quasi-liquid). The numerical results show that the heat of evaporation and the initial velocity only negligibly affect the height of destruction and deceleration of the meteoroid. The effect of density is significant, whereby stony bodies penetrate into the atmosphere deeper than comet-like bodies of the same size. Thus, a stony 80-km-diameter meteoroid falling at an angle of 45° (variants 15–17) is totally evaporated at 7–8 km, and the resulting gas jet reaches the Earth’s surface. The similar comet-like meteoroid (variants 25 and 26) is evaporated at a height of 12–14 km, and the gas jet formed is stopped at an altitude of 4–7 km. Roughly speaking, a 100-m-diameter comet-like body is fragmented, evaporated, decelerated, etc. at the same altitudes as a 60-m-diameter stony body.

**The influence of internal friction on the deformation of a damaged meteoroid**

Even a totally destroyed body is not completely equivalent to a liquid one. For instance, a liquid volume placed on a solid surface spreads out to cover the entire surface, whereas a sand volume (a very strongly damaged body) acquires the shape of a cone, with the cone angle determined by the coefficient of internal friction. Ivanov et al. (43) simulated the initial stage (before the onset of fragmentation and marked deceleration) of meteoroid deformation taking into account strength and showed that the presence of internal friction, i.e., shear stresses proportional to the pressure, may influence the deformation character of the damaged meteoroid and, in particular, may decelerate the development of instabilities on the surface of the meteoroid. In turn, this may delay the fragmentation and mitigate the deceleration of the meteoroid and, accordingly, may change the depth of the penetration of the meteoroid into the atmosphere. To estimate how important the inclusion of internal friction we have performed the simulation of the interaction of a stony meteoroid with planetary atmosphere.

We added to the program a module for the calculation of the Navier–Stokes equations to account for dry friction (Mohr–Coulomb model). The shear stresses are isotropic and are defined as the product of pressure by the friction coefficient. The action of specified shear stresses is equivalent to the action of viscosity, with the viscosity coefficient defined by these shear stresses and the tensor of the deformation rates. The model does not consider the very initial stage of the destruction of the meteoroid (cracking and fragmentation), because for sufficiently large (a few tens of meters and more) bodies the deformation becomes apparent at altitudes where the aerodynamic loads significantly exceed the strength limit (38).

Figures 10-11 show the successive stages of the interaction of a rocky asteroid with the atmosphere; an asteroid 40 m in diameter falls to the Earth at a velocity of 20 km/s at an angle of 45°. The results presented in Fig. 1 are calculated without taking into account internal friction, and the results in Fig. 2 are calculated with accounting for friction. The experimental data for the
friction coefficients of granite are presented in (44). The calculations used $K = 0.7$, close to the experimental value.

Figure 10. Destruction of a rocky meteoroid of 40 m in diameter falling at a speed of 20 km/s at an angle of 45° calculated disregarding internal friction. The density distributions (the darker color corresponds to a larger density) are shown at different altitudes $H$. The vertical axis indicates the distance along the trajectory.

Figure 11. Destruction of a rocky meteoroid 40 m in diameter falling at a speed of 20 km/s at an angle of 45° calculated with an internal friction coefficient of $K = 0.7$. The density distributions (the darker color corresponds to a larger density) are shown at different altitudes $H$. The vertical axis indicates the distance along the trajectory.
The qualitative pattern of the evolution of the meteoroid is similar in both cases. Initially, the meteoroid starts to deform, and wavelike perturbations appear on its surface due to the development of Rayleigh–Taylor and Kelvin–Helmholtz instabilities. An increase in the aerodynamic load causes the deformation of the meteorite into a prolate (pancake) shape in accordance with the classic analytical models (12, 42). The further development of instabilities causes the fragmentation of the meteoroid and its conversion into a jet consisting of vapors, air, and fragments of the falling body heated in the head part of the shockwave. However, the presence of internal friction leads to the marked deceleration of both the meteoroid deformation and the development of instabilities on the surface of the meteoroid. As a result, the conversion to a pancake shape, the fragmentation, and the deceleration of the meteoroid take place at much lower altitudes. In other words, the inclusion of friction leads to the fact that the asteroid penetrates 10–20 km deeper into the atmosphere than it does in the case of no friction or, equivalently, the inclusion of friction leads to a smaller size of the meteoroid penetrating to a given height in the atmosphere.

Use of the above-described model with dry friction to calculate the formation of large (about 10–100 km in diameter) impact craters showed that to obtain the correct (i.e., coinciding with that observed) crater shape, a much smaller friction coefficient is needed (45). This is because of the so-called “acoustic fluidization”. The oscillations of ground particles, initiated by the shockwave, lead to a reduction in friction and make the ground damaged by the shockwave “more liquid.” Seemingly, the phenomenon of acoustic fluidization should also be observed during meteoroid deformation, since the pressure variations caused by the development of instabilities at the vapor–air interface, the nonuniformity of evaporation, the increase in the density of the incoming air, etc., constantly generate acoustic waves in the meteoroid matter. Melosh and Ivanov (46) considered two possible mechanisms of the reduction of friction: shorter (than the meteoroid size) and longer wave variations. In the case considered by us, pressure variations in a very wide frequency range are present. The highest frequency variations are generated by vortices near the small inhomogeneities on the surface and during the detachment of small particles (mechanic ablation). The long-wave oscillations are caused by the global rearrangement of the current induced by the hydrodynamic instabilities, the possible body rotation, the nonuniformity of evaporation, etc. Which mechanism leads to the reduction in friction is difficult to identify, and it is not quite clear even in the case of the more carefully studied process of crater formation.

The most highfrequency oscillations are generated by eddies near small nonuniformities and at separation of small particles (mechanical ablation). Long-wave oscillations are induced by global flow restructuring resulting from hydrodynamic instability, possible rotation of the body, vaporization nonuniformity, etc. It is hardly saying what mechanism brings about the reduction in friction, it is not clearly seen even for the case of the process of cratering that is much more investigated.

Ivanov and Deutsch (45) observed a reasonable coincidence with the observed crater shape in the case of a simple decrease of the friction coefficient down to a value of K = 0.1. We examined how such a decrease in friction influences the process of the deformation and fragmentation of the meteoroid. Figure 12 shows the calculations of how this same rocky asteroid 40 m in diameter interacts with the atmosphere when K = 0.1. In this case, the body is decelerated at a height of about 7 km; i.e., even at this small value of the internal friction coefficient, the deceleration height turns out to be 6 km lower than for the liquid (K = 0) meteoroid.
Figure 12. The destruction of a rocky meteoroid 40 m in diameter falling at speed of 20 km/s at an angle of 45° calculated with the internal friction coefficient $K = 0.1$. The density distributions (the darker color corresponds to a larger density) are shown at different altitudes $H$. The vertical axis indicates the distance along the trajectory.

**Dependence of impact scenario on impactor parameters**

We have performed a set of numerical simulations of asteroidal impacts to determine what kind of impact scenario is realized at different projectile sizes and trajectory inclinations. The simulations show that the results only slightly depend on impact velocity.

The results of all computations are summarized in Table 2. A decrease in the trajectory inclination (an angle of $90°$ corresponds to the vertical fall) infers a growth of the air mass along the meteoroid path and an increase of the period when the resistance force and the aerodynamic loadings act. This results in the earlier (i.e., occurring at higher altitudes) deceleration and fragmentation of the falling body. In a vertical impact of an asteroid 60 m in diameter, the vapor jet reaches the Earth’s surface; after $45°$ oblique impact, the jet is stopped at altitudes from 2 to 5 km, and after $30°$ oblique impact even an asteroid 80 km in diameter decelerates at an altitude of 6-9 km. Accordingly, larger bodies evaporate in the atmosphere and do not reach Earth at smaller trajectory inclinations.
Table 2. Stony meteor bodies. The first column gives the variant number; $D$ is the diameter of the meteoroid; $V$ is the initial velocity of the meteoroid; $\alpha$ is the inclination of the trajectory (with respect to the horizon) in degrees; $H_{min}$ is the minimal height of the lower boundary of the glowing region (when the vapor jet does not reach the Earth's surface); $U$ is the velocity at which the vapor jet hits the Earth's surface (if it reaches the surface); and $H_{evap}$ is the height at which the meteoroid material is completely evaporated.

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Stony projectiles differ from cometary-like ones by their density, evaporation heat and impact velocity (the strength can be neglected because we consider rather large projectiles which disrupt and become quasi-liquid at high altitudes). The simulations show that the evaporation heat and impact velocity only slightly influence a fragmentation and deceleration height. The influence of density is much more important. Stony projectiles penetrate much deeper into the atmosphere than cometary-like ones.

In all variants presented in Tables 2, the altitudes of the total evaporation of the meteoroid material are from 5 to 10 km higher than the altitudes of the meteor deceleration (that is, the altitudes where the glowing region, the gas jet, or meteoroid vapors are stopped). This means that there is quite a wide range of the falling bodies’ parameters at which the high-velocity jet impacts the terrestrial surface without forming a crater, that is, surface aerial bursts are realized.

Figure 13. Scenarios resulting from cometary (a) and asteroidal (b) impacts. Light region corresponds to crater-forming impacts, dark region marks aerial bursts, intermediate region corresponds to surface GBs. White ellipse show possible parameters of the Tunguska projectile.

Fig. 13(b) illustrates the results described above for the case of stony bodies. Cometary body impacts (Fig.13a) are described in the next section.

4. Determination of breakup and deceleration altitudes of comet-like bodies of various sizes

Comets attract attention of researches during long times, but unfortunately the properties of comets are still not clearly understood. From the viewpoint of comet hazards and assessment of the altitudes of breakup and deceleration of cometary bodies, first of all it is necessary to know sizes, densities, typical velocities, thermodynamic properties and composition of cometary material. But while the properties of stony bodies striking the Earth have been studied both in numerous meteoritic researches and using many observational data on the falls of stony bodies in the atmosphere (in particular quite recent flight and airburst of
Chelyabinsk meteor), identification of the falls of bodies of cometary origin with sufficient assurance has not met with success. On the other hand, cometary meteorites either are lacking or could not have been identified because of the lack of information about their properties.

Typical sizes of the nuclei of observed comets range from kilometers to tens of kilometers, but the nuclei hundreds of meters in size have been also found in space. Like this, the effective radius of comet 147P/Kushida-Muramatsu is about 200 meters (47). Debris of these nuclei with much smaller sizes and different properties can hit the Earth. However, only small particles up to tens of centimeters in size are observed in meteor showers which represent the remnants of certain comets. These particles vaporize and decelerate high in the atmosphere.

Ceplecha and McCrosky (48) have analyzed data on the falls of more than two hundred meteoroids and came to a conclusion that the meteoroids can be divided into three large groups depending on the altitudes of termination of light radiation. Ordinary chondrites, which are found among stony meteorites more often, form group 1 with the lowest altitudes where they become dim. Carbonaceous chondrites form group 2 which is characterized by higher altitudes of flashes. The make-up of the first group is confirmed by radiation spectra as well as by the cases of recovery of meteorites after registrations of their falls. The third group, which is divided into two subgroups 3A and 3B, comprises meteors with the highest altitudes of luminosity. According to a viewpoint established since then, group 3 consists of fragile bodies of cometary origin, although the vast majority of these falls reveal meteor spectra which correspond to the composition of stony meteorites and do not have lines or bands of volatiles typical for comets only. Higher rates of ablation in the atmosphere and lower density are also attributed to group 3 bodies, but these values were calculated using a simplified method based on ordinary differential equations for the variation of a speed and body mass, and such approach can give significant errors. The possibility to accurately determine the meteoroid density from the observations of meteoroid motion is particularly questionable, but nonetheless, it was believed that the subgroup 3B is formed by bodies more porous and lighter in weight than in subgroup 3A – with a density of about 0.1 g/cm³. Since then the separation of meteoroids into three groups and the interpretation of these groups as bodies with different composition was established practice among some observers.

Later, after analyzing several hundred meteoroids with an estimated size from 0.1 to 1 meter, Ceplecha (49) found that the relative number of meteoroids in group 3 increases with the size of the bodies and, furthermore, by extrapolating the number of meteoroids in the groups according to their sizes, he concluded that among ten-meter bodies which hit the Earth 70% should be the bodies of cometary composition. This conclusion is in strong contrast with the astronomical observations. On the other hand, those properties which are distinctive for the meteoroids of group 3 may be inherent for a fall on the Earth of an ordinary chondrite if the flow around the body moving in the atmosphere occurs in a non-standard regime and large-scale vortexes are formed behind the shock front (50, 51).

The most probable velocity of the impacts of parabolic comets on the Earth is 54 km/s, and of periodic comets – 20 km/s (52). Comet nuclei are composed of water, silicate dust, frozen gases – CO, CO₂, etc., and a certain amount of organic material (53), but the ratios of these components can be different. The density of comet nuclei is in the range 0.5 – 1.2 g/cm³ (54).

Estimates based on astronomical observations show that the comets hit the Earth much rarer (approximately 3-6 times) than asteroids (see (55)), however, they represent a very serious threat. Most of the dangerous asteroids and periodic comets can be found in advance by astronomical observations and one can try to prevent the cosmic threat in good time. But the long-period comets may appear suddenly, and to prevent a possible impact on the Earth of such object with very high speed is extremely difficult if for no other reason than the lack of data on the physical properties of a dangerous object.
Since cometary nuclei have plenty of water, comet-like bodies are usually modeled as objects with a density of 1 g/cm$^3$ and with the equation of state and other properties of water.

In this report, we focus on the impacts of comet-like bodies with sizes from 50 to 300 meters. The bodies of this range are destroyed and decelerated in the Earth's atmosphere. Furthermore, from the standpoint of the asteroid and comet hazards, these bodies fall on the Earth more often than unbroken comet nuclei and pose a real threat. The average time interval between the impacts of kilometer sized periodic comets on the Earth is about 3 million years (see (55). Smaller body hit the Earth much more often, but there are no precise estimates of the frequency of their impacts. Among dangerous objects, in particular in the main asteroid belt, some bodies can be found with the properties of comets but with the orbits typical for asteroids. While the approach of the comet to the Sun is usually accompanied by the glow of its coma and tail, a smaller body, that is a residue of a "dead" comet the surface of which does not vaporize, can approach the Earth without being noticed.

**Numerical simulations of the falls of comet-like bodies in the atmosphere**

The same approach that was used for simulation of stony asteroid body falls (see previous section) is used here for numerical modeling of cometary body falls.

We present the results of numerical modeling of comet-like bodies falling in the atmosphere, taking into account the real dependence of atmospheric density on the altitude.

Fig. 14 shows the pattern of the flow around a disintegrating meteoroid of cometary origin with a density of 0.9 g/cm$^3$, a diameter of 100 m and an initial speed of 50 km/s. The characteristic sequence of processes accompanying the fall of the body is as follows. First, the icy body begins to evaporate, then deforms, and splits into fragments. After vaporization of fragments a gas stream (or jet) moving down and consisting of vapor and air heated in the shock wave is formed. High speed jet continues to move along the trajectory at a speed close to the initial velocity of the meteoroid, then expands and decelerates, forming a cylindrical cloud of hot and rarefied gas, which in turn begins to rise up, forming an atmospheric plume.
Figure 14. Destruction of a comet-like meteoroid falling in the atmosphere. The temperature distribution (left) and density (decimal logarithm density expressed in g/cm$^3$) at several altitudes H are shown. The vertical axis shows the distance along the trajectory. The black line is the boundary between vapor and air.

The altitude of about 45 km corresponds to the beginning of the deformation of the icy meteoroid. On its surface there are wavelike perturbations due to the development of Rayleigh-Taylor instabilities at the front surface and the Kelvin-Helmholtz on the side. Evaporation leads to infill of the center of the wake by the vapor. Destruction and fragmentation of the falling body at altitudes of 20-30 km occur before it begins to decelerate markedly. Fragmentation leads to an increase in the evaporating surface and an increase in the rate of ablation; at an altitude of about 20 km meteoroid fragments completely evaporate. The jet (or cloud) of vapor and gas moves down. At
first jet velocity remains high, almost the same as the initial velocity of the body entry to the atmosphere.

At altitudes of about 20 km the average gas density in the high-speed jet is still high, a shock wave moves in front of the jet, and the air heated in the shock wave has a higher pressure than the undisturbed surrounding air. But in the moments of intense braking at altitudes of 7-10 km the density of the gas in the jet is noticeably lower than the density of the ambient air because the jet expands. During the process of intense deceleration the kinetic energy of the jet is converted into thermal energy of the air. This makes the final step of braking similar to a high-altitude explosion, but more cylindrical than spherical.

The process of deformation and fragmentation of a quasi-liquid meteoroid, as already noted, is accompanied by the development of Rayleigh-Taylor and Kelvin-Helmholtz hydrodynamic instabilities. Development of instabilities is random, so the results of different variants of calculations with the same initial data can be obtained different. Fig. 15 shows the height dependence of the velocities of comet-like bodies for different simulations of the same event – the fall of a cometary body with a diameter of 100 m at an angle of 45 degrees. These curves differ, and the variation of deceleration altitudes of the same spherical bodies which enter the atmosphere at the same speed is 3 – 5 km. Fig. 15 also shows the results for the initial velocity of 20 km/s. Comparison of the results for two initial velocities of the meteoroid 20 and 50 km/s shows that in this range the difference between the altitudes and the degrees of deceleration obtained at different initial velocities of the falling body is relatively small, at least it is not much larger than the difference between the results obtained in various computations for the same speed.
Figure 15. Dependence of the velocity on the height during the fall of comet-like bodies with a diameter of 100 m at an angle of 45° to the Earth's surface at speeds of 50 km/s (solid lines) and 20 km/s (dashed). Body velocity was calculated as the velocity of motion of the lower boundary of the luminous region (more precisely, an area with a temperature of 0.5 eV).

When braking, the energy of the meteoroid and its residues is intensively released in the atmosphere on a long section of the trajectory with a length of about 5 km, while the transverse size of the jet is much smaller. Thus, the energy release during evaporation and braking of an icy meteoroid in the atmosphere is significantly different from the energy release at a high-altitude spherical explosion.

If we will increase the size of a falling body, the high-speed gas jet formed after the complete evaporation of the meteoroid fragments does not have time to slow down and the jet hit the Earth's surface. However, the density of gas in the jet is low, pressure during its braking will be comparable or less than the strength of rocks, and therefore either the crater is not formed or there will be a very shallow flat crater (without impact-melt and shock metamorphosed material) traces of which rapidly disappear. And when hitting the water, the jet produces small temporary water crater.

Comet-like bodies differ from stony bodies in density, heat of vaporization, and, in the case of long-period comets, in the initial velocity (strength can be ignored, since we consider large enough bodies that are destroyed at high altitudes, becoming quasi-liquid). Calculations show that the heat of vaporization and the initial velocity have a weak effect on the height of the destruction and deceleration of a meteoroid. But the effect of the density at the same sizes is very significant, stony bodies intrude much deeper into the atmosphere than comet-like ones of the same size. For
example a stony meteoroid with a diameter of 80 m, falling at an angle of 45 degrees, completely evaporates at an altitude of 7-8 km, and the resulting gas stream reaches the Earth's surface. A comet-like meteoroid of the same size evaporates at an altitude of 12-14 km, and the formed gas jet stops at an altitude of 4-7 km. According to our calculations, we can estimate that a comet-like body with a diameter of 100 m fragments, evaporates and is decelerated at the same altitudes as a stony body with a diameter of 60 meters. The masses of these bodies, if we take the density of a stone body 3 g/cm³, differ by about 1.4 times. And if the comet speed is by 20% higher than the speed of the stone body, they will have the same energies. Thus, we find that such stony body and the body of cometary origin create an "explosion" of the same energy at the same height. For this reason, we cannot determine the nature of the Tunguska cosmic body in the event of 1908 (22) on the basis of the simulations of destruction and deceleration of bodies in the atmosphere, knowing only the equivalent height and energy of the event.

**Classification of impacts of comet-like bodies versus their parameters**

We have carried out a large series of calculations of comet impacts at different angles of trajectory inclinations with a purpose to determine the characteristic features of such events. Does the impact result in air explosion, explosion at the surface or formation of a crater? From this viewpoint, according to our calculations, the difference between the results obtained at different initial velocities of an impacting body is small, at least no more than the difference between the results obtained in various computations for the same speed. Therefore, we restricted ourselves to two speeds typical for the periodic and parabolic comets.

Table 3. Variants of simulations of the impacts of comet-like bodies. $N$ is the variant number, $D$ is the diameter of the meteoroid, $V$ is the initial velocity of the meteoroid, $\theta$ is the angle of a trajectory inclination (to the horizon) in degrees, $H_{\text{min}}$ is the minimum height of the lower boundary of the luminous volume (when the vapor jet does not reach the Earth's surface), $U$ is the speed of a vapor jet when it hits the Earth's surface (if it reaches the ground), $H_{\text{vap}}$ is the height where the meteoroid material is completely vaporized.

<table>
<thead>
<tr>
<th>N</th>
<th>$D$, m</th>
<th>$V$, km/s</th>
<th>$\theta$</th>
<th>$H_{\text{min}}$, km</th>
<th>$U$, km/s</th>
<th>$H_{\text{vap}}$, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>50</td>
<td>45</td>
<td>4.5</td>
<td>-</td>
<td>13.5</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>50</td>
<td>45</td>
<td>7.2</td>
<td>-</td>
<td>12.8</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>50</td>
<td>90</td>
<td>-</td>
<td>9.1</td>
<td>3.2</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>50</td>
<td>90</td>
<td>-</td>
<td>6.2</td>
<td>4.1</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>50</td>
<td>45</td>
<td>2.6</td>
<td>-</td>
<td>9.2</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>50</td>
<td>45</td>
<td>0.80</td>
<td>-</td>
<td>7.5</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>50</td>
<td>45</td>
<td>4.9</td>
<td>-</td>
<td>11.3</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>20</td>
<td>45</td>
<td>3.1</td>
<td>-</td>
<td>9.3</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>20</td>
<td>45</td>
<td>6.1</td>
<td>-</td>
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</tr>
<tr>
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<td>100</td>
<td>50</td>
<td>30</td>
<td>8.66</td>
<td>-</td>
<td>15.5</td>
</tr>
<tr>
<td>11</td>
<td>100</td>
<td>50</td>
<td>30</td>
<td>9.96</td>
<td>-</td>
<td>15.8</td>
</tr>
</tbody>
</table>
Table 3 shows the results of the calculations for comet-like bodies. Reduction of the trajectory inclination angle (90 degrees corresponds to the vertical impact) means an increase in the mass of air in the path of the meteoroid, increasing duration of the drag force and duration of the aerodynamic loads. This leads to earlier (i.e. at higher altitudes) fragmentation and deceleration of an impacting body. When a comet-like body with a diameter of 100 m falls vertically, the vapor jet reaches the Earth's surface. At a trajectory inclination of 45 degrees the jet is braked at an altitude of 1-3 km, and at a trajectory inclination of 30 degrees – at an altitude of 6-9 km. Accordingly, if the angle of trajectory inclination decreases, the size of the bodies which evaporate in the atmosphere before they reach the Earth's surface increases.

Comet-like bodies with diameters of 100 and 400 m are decelerated approximately at the same height (near the Earth's surface) if the angles of trajectory inclination are 45 and 15 degrees respectively (Table 1). When the angle of inclination is 5 degrees, even a kilometer-diameter comet-like body is completely vaporized in the atmosphere and reaches the Earth's surface in the form of a gas jet at a speed of about 10 km/s. We note the important result that the altitudes of complete evaporation of the meteoroid material are by 5-10 km higher than the altitudes of meteoroid braking or stopping of the luminous volume.

There is a certain range of parameters of comet-like bodies in which a high-speed jet of vapor and gas strikes the Earth's surface, but does not form a crater. Then a surface explosion occurs. Fig. 9 shows the boundaries between different types of impacts both for comet-like (9a) and stony bodies (9b). Possible parameters of impacting bodies which could cause the Tunguska event in 1908 are shown. On the results of numerical simulations, as already noted, it could be both an icy and a stony body.

The analytical theory (1)-(4) compared with the numerical calculations gives substantial errors. Compare the results of the numerical simulations with the results which an elementary analytical model gives, we obtained the latter with the help of the computer code (4) available online at the internet site http://impact.ese.ic.ac.uk/ImpactEffects.

For comet diameter of $D=100$ m (the density of a comet is taken to be $1 \text{ g/cm}^3$), $V = 50 \text{ km/s}$ and $\theta =90^\circ$ this code gives the following answer. The body begins to break up at an altitude of 98 km and is transformed into a cloud of fragments at an altitude of 0.5 km, the speed of the fragments at this height is 3 km/s, and large fragments can fall on Earth's surface, i.e. there is no complete evaporation. According to our calculations, as can be seen from Table 2, the body with the specified initial parameters completely evaporates even at altitudes of 4-5 km, and a vapor-gas stream hits the surface of the Earth at a speed of 6-9 km/s.
For $D=80$ m, $V=50$ km/s and $\theta=45^\circ$ the code (4) gives an explosion with formation of a fragment cloud at a height of 9.5 km and a speed of motion of 10 km/s (and in Table 3 – complete evaporation occurs at a height of ~ 13 km), and the fragments can fall on the ground (from Table 3 the jet vapor does not reach the surface of the Earth).

The third example – $D = 400$ m, $V = 50$ km/s and $\theta=15^\circ$ the code predicts a blow of scattered fragments on the surface at a speed of 2.8 km/s with formation of a crater field with a size of 3 km x 11 km. The numerical calculations give a complete evaporation at an altitude of 7 km and a blow of the gas jet on the surface at a speed of ~ 2 km/s without cratering.

5. Catastrophic consequences of cosmic bodies impacts (50-500 m in size)

There are several approaches of the consequences estimates. The first relies on usage of the approximate dependences obtained based on explosions of different nature. These estimates are very simple, but not very accurate and may in some cases lead to qualitatively incorrect results. The second approach includes complex numerical simulations based on model, which takes into account many physical processes accompanying impact. These models are constantly evolving and currently can adequately predict the main effects of the impact of cosmic body, depending on its size, velocity, density, structure, slope of the trajectory, etc. However, these calculations are very complicated and time consuming (tens of hours even using modern powerful computers). The third and most promising in terms of rapid response to emergencies is the gradual approach (rather long and laborious) study and modeling of different variants of the asteroid hazard and building on the basis of numerical experiments approximate interpolation relations (or tables) in order to quickly assess the dangerous consequences for potentially dangerous cosmic object with the specified parameters.

Evaluation of the consequences of the cosmic body explosion in the atmosphere

The explosion of a cosmic body in the atmosphere – has became a commonly used term, which implies that the cosmic body is disrupted, melted, evaporated and decelerated in the atmosphere. As the result the most part of its initial kinetic energy is deposited in the atmosphere at a certain altitude the form of thermal energy. Usually this term is used in relation to a fairly large bodies whose kinetic energy is comparable to the energy of air blasts, about 1 kt TNT and more. The deposition of the energy in the atmosphere leads to effects that are typical for air blasts: a shock wave propagates through the atmosphere, thermal radiation comes to the earth's surface, the shock wave, reaching the ground creates seismic waves. The appearance of electromagnetic disturbances is possible, but they are insufficiently investigated and are not considered in this section.

Shock waves action onto objects located on the earth's surface

Shock wave is formed due to cosmic body's energy deposited in the atmosphere, which in a first acts like blast wave from a point source. Therefore, effects of the impacts can be evaluated by comparison with the blasts of the same energy. Here it should be mentioned that the explosion of a
cosmic body in the atmosphere is not the actual explosion. Area of energy deposition can be rather long, that causes asymmetric distribution pattern of the overpressure produced by the shock wave on the Earth surface. At an early stage of the research the energy deposition was often considered as a combination of point and linear explosions (56). Currently there is possibility to model the energy deposition in the frame of the hydrodynamic models (for example, (38), which can be applied to the bodies of more than a few tens of meters. In this case, a falling body is considered to be quasi-liquid, and its deformation due to aerodynamic loading is described by the hydrodynamic equations (Euler equations). Then three-dimensional gas-dynamic problem is solved starting with the determined energy release and availability of the trail formed by cosmic body in the atmosphere.

Direct calculations of the overpressure for a variety of options (especially for oblique impacts) require a very long time, but approximate approach is possible. First, an example of vertical impact (which is calculated in two-dimensional approximation) demonstrated that a meteor explosion and point explosion of the same energy produce approximately the same overpressure on the surface, if the point explosion is produced at a height, where the velocity of meteoroid material (or jets of vapor and hot air) falls to one-tenth of the initial velocity of the meteoroid. Then there was a series of calculations of point explosions of different initial energies (corresponding to the energy of the incident of comet-like and stony bodies). For each energy of explosion the height $h_I$ was determined, for which the overpressure at the surface reached a value $0.21p_0$, where $p_0$ is the normal atmospheric pressure (see Figure 16). According to (57) excessive damage of industrial constructions begins at such level of loading.

Figure 16. The dependence of maximal altitude of explosion, at which the damage on the surface occurs, on the impactor diameter (assuming comet entry velocity of 50 km/s and asteroid entry velocity of 20 km/s).
Seismic effect due to the meteoroid explosion in the air

The shock wave formed due to meteoroid explosion in the air reaches the surface and generates a seismic wave. Seismic waves were recorded after the Tunguska event in 1908 at stations in Irkutsk, Tashkent, Tbilisi and Jena (58). Registration data were analyzed in (58, 59), and it was determined that all stations recorded Rayleigh surface waves.

Methods for measuring and calculating the energy of surface waves were developed (61). But in the actual calculations of energy of seismic waves triggered by explosions in the atmosphere (60, 62), only rather crude approximation of the shock wave overpressure on the surface were used. Currently developed numerical schemes and computer resources allow us calculating the overpressure with sufficient accuracy. On the other hand, parameters of powerful explosions in the atmosphere have been published (63) as well as the magnitude of the earthquake induced (63, 64). Therefore, there is an opportunity to perform mathematical modeling of explosions in the air, to calibrate the results of calculations on the experimental material, to simulate the impact of large meteoroids, and to determine the seismic effect caused by the (65).

Using the solution of the Lamb problem for a halfspace, with a pressure $p(r,t)$ dependent on the radius $r$ and time $t$ being applied at its boundary [Ошибка! Источник ссылки не найден.], it is possible to determine the relation between the energy of the explosion-excited surface waves $E_R$ and this pressure in the form of the following integral over the frequency $\omega$ (60, 61)

$$E_R = C \int_0^\infty p(\omega, \frac{\omega}{c_R}) \omega^2 d\omega$$

(9)

where $c_R$ is the Rayleigh wave phase velocity, $C$ is a dimensional coefficient depending on the material properties at the epicenter (the phase velocities of seismic waves and the Lamé coefficient), and the pressure spectrum is

$$p(\omega, k) = \frac{1}{2\pi} \int_0^\infty \int_0^\infty (P(r,t) - P_0) r J_0(\omega r) e^{-i\omega t} dr dt$$

(10)

here, $J_0$ is the Bessel function, $P_0$ is the atmospheric pressure at the surface, and $k = \omega/c_R$ is the wave number. The coefficient $C$ can most easily be determined from calculations for explosions with known parameters.

The required data of a good quality (Table 4) are provided by a series of the most powerful explosions fired in 1961–1962 at the Novaya Zemlya test site, for which data were published (63). The pressure spectra calculated for a series of nuclear explosions are shown in Fig. 17 in the form normalized to the pressure on the surface. They are stabilized over 1–2 min. In the case of nuclear explosion tests, the measured energy of the fundamental Rayleigh mode $E_{R1}$ (expressed in ergs) is approximated well by the following dependence (63)

$$\lg E_{R1} = 2M_s + 7.4$$

(11)
where $M_S$ is the earthquake magnitude determined by the vertical component of displacement.

Figure 17. Spectra of the pressure at the Earth’s surface for a series of atmospheric explosions. The numbers at the curves correspond to the explosion numbers in Table 4.

### Table 4 – Parameters of the most powerful air explosions

<table>
<thead>
<tr>
<th>N</th>
<th>Date</th>
<th>$E$,$Mt$</th>
<th>$h$, km</th>
<th>$M_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.10.1961</td>
<td>50</td>
<td>3.6</td>
<td>5.4</td>
</tr>
<tr>
<td>2</td>
<td>05.08.1962</td>
<td>21.1</td>
<td>3.6</td>
<td>5.2</td>
</tr>
<tr>
<td>3</td>
<td>23.10.1961</td>
<td>12.5</td>
<td>3.5</td>
<td>5.1</td>
</tr>
<tr>
<td>4</td>
<td>22.10.1962</td>
<td>8.2</td>
<td>3.23</td>
<td>4.9</td>
</tr>
<tr>
<td>5</td>
<td>27.08.1962</td>
<td>4.2</td>
<td>3.0</td>
<td>4.7</td>
</tr>
<tr>
<td>6</td>
<td>06.10.1961</td>
<td>4.0</td>
<td>2.7</td>
<td>4.7</td>
</tr>
<tr>
<td>7</td>
<td>20.08.1962</td>
<td>2.8</td>
<td>2.5</td>
<td>4.6</td>
</tr>
<tr>
<td>8</td>
<td>10.09.1961</td>
<td>2.7</td>
<td>2.0</td>
<td>4.6</td>
</tr>
<tr>
<td>9</td>
<td>08.09.1962</td>
<td>1.9</td>
<td>1.725</td>
<td>4.4</td>
</tr>
<tr>
<td>10</td>
<td>22.08.1962</td>
<td>1.6</td>
<td>1.7</td>
<td>4.4</td>
</tr>
<tr>
<td>11</td>
<td>18.09.1962</td>
<td>1.35</td>
<td>2.0</td>
<td>4.3</td>
</tr>
</tbody>
</table>

The amplitude of vibrations and the earthquake magnitude should apparently be related to the value $\omega p(\omega, \omega/c_R)$, integrated in a certain spectral interval. In the mathematical modeling, the value $A_R$ was calculated, whose logarithm should supposedly be proportional to $M_S$

$$A_R = \frac{1}{P_0(\omega_2 - \omega_1)} \int_{\omega_1}^{\omega_2} p(\omega, \omega/c_R) \, \omega \, d\omega$$

(12)

where the integration limits $\omega_1$ and $\omega_2$ were varied within the range of recorded frequencies of the surface wave. We found that the best fit to experimental data is ensured with $\omega_1 = 0.25$ and $\omega_2 = 0.42$, which corresponds to the periods $T = 2\pi/\omega$ ranging from 15 to 25 s. As shown in Fig. 18, the relation between the results of calculations and experimental data is well approximated by the formula

$$M_S = \log(A_R) + 4.92$$

(13)
where $A_R$ is measured in km$^2$. This interval of periods lies within the limits of the fundamental Rayleigh mode (the $M_1$ wave – (63) and includes the period of the maximum sensitivity of seismographs that were used for recording nuclear explosions (58). All of the four seismographs that recorded the Tunguska event yielded wave periods ranging from 15 to 25 s (59). Thus, the selected frequency range is fully consistent with both the explosions considered and the Tunguska phenomenon.

Calculations with thresholding for $P(r,t)$ were also performed in the numerical modeling of nuclear explosions. The pressure $P(r,t)$ was set equal to zero whenever its value became less than 5% of $P_0$. The resulting values of $A_R$ are somewhat smaller, and the magnitudes of earthquakes, as shown in Fig. 18, are well approximated by the formula

$$M_S = \lg(A_R) + 5.05$$

(14)

The deceleration of a meteoroid in the atmosphere is not a point source: the velocity drop and energy release occur within a certain range of altitudes that can be of the order of the homogeneous atmospheric scale height. The modeling of an oblique impact allows one to calculate the earthquake magnitude but, in order to determine the pressure spectrum in this case, formula (10) should be replaced by the following integral over the surface and time:

$$p(\omega, k_x, k_y) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int (P(x, y, t) - P_0) e^{i(k_x x + k_y y - \omega t)} \, dx \, dy \, dt$$

(15)

Models of the light pulse and fires

The fall of the Tunguska cosmic object generated fire over an area that lies within the 2,000 km$^2$ area of forest devastation by blast waves. The fire covered >500 km$^2$ (22), that is 4 times smaller than blast wave forest devastation.
According to the results obtained by (67) it is possible roughly to estimate that about 10% of initial kinetic energy of incoming meteoroid is irradiated. Assuming the isotropic propagation of radiation it the energy flux per unit square on the Earth surface may be estimated if the altitude of explosion is known. Or, given the critical for fire ignition value of energy density $e_{cr}$ the limiting altitude, at which the ignition is started, may be found. According to (57), the critical energy density is about $e_{cr} = 35$ J/cm$^2$, corresponding limiting altitudes are given in Figure 19.

![Figure 19](image.png)

**Figure 19.** The dependence of maximal altitude, at which the fires on the Earth surface can occur, on energy of the explosion given in impactor diameters (cometary impactor has velocity 50 km/s; asteroidal - 20 km/s).

A shock wave velocity, above which the emitted radiation is substantially high, is about 6 km/s. The velocity of plume expansion is higher and the shock wave intensely radiates. For example, for a shock wave velocity in the water of 5 km/s the pressure is ~25 GPa, and the temperature in the water shock wave is about 1,700 K (65). After adiabatic release of the water to the atmospheric pressure the velocity of a water vapor plume and shock wave in air is about 6 km/s. The temperature of air behind such a shock wave is about 10,000 K (69), and radiation emission from the shock wave front is much more intense than the radiation of shock-compressed water. It seems more reasonable to use for estimates data on radiation efficiency obtained in the nuclear tests, 30–50% (57), or values of radiation efficiency calculated for the entry of cosmic bodies with sizes 1–100 m, about 10% (67).

During the fall of a cosmic object into the atmosphere, air is heated to high temperatures in the shock wave in front of the body. Thermal radiation from the heated air comes to the meteoroid surface and causes melting and vaporization of its material. The meteoroid vapor also gets hot and emits thermal radiation. The radiation from the heated air and vapor in front of the body and in a
wake behind it reaches the Earth’s surface. The closer the meteoroid comes to the surface, the higher becomes air drag, and a greater amount of energy is released in the atmosphere. The energy release grows both due to the increase in the air density and enlargement of a meteoroid cross-section because of fragmentation. However, if the body has a relatively small size and strongly decelerates, its velocity and air temperature decrease; consequently, the released energy and radiation flux decrease as well. As a result, there is a peak in energy release and radiation. The altitude range of major energy release at the final stage of deceleration typically is relatively narrow; therefore, the process of energy release is similar to explosion. For this reason, energy absorbed by an object located at the Earth’s surface may be estimated, as

$$Q = f \frac{E \cos \alpha}{4\pi r^2} \exp\left(-\frac{r}{L}\right)$$

(16)

where $Q$ is the energy of thermal radiation coming to the object’s surface, $E$ is the explosion energy (meteoroid’s kinetic energy), $r$ is the distance from the explosion to the point on the surface, $L$ is the atmospheric visibility, $\alpha$ is the angle between the normal to the irradiated surfaces and the vector directed from the object to the radiation source, and $f$ is the coefficient of explosion energy conversion to that part of thermal radiation that passes through the atmosphere. Typical values of $f$ are from 10 to 30% (67, 70, 71).

The radiation flux on the surface can be obtained with greater accuracy by calculation of energy release in individual small segments of meteoroid trajectory, using formulas analogous to Equation (16) and integration of the contributions of each segment. The trajectory of a disintegrated meteoroid can be calculated approximately using simple models taking into account the enlargement of a meteoroid cross-section under aerodynamic load (18). The energy release is determined by drag and heat transfer coefficients. These coefficients, and also $f$, are functions of altitude, velocity, and size of a body; these variables change during the flight. Special calculations are necessary to obtain exact values of these coefficients.

For the Tunguska fall, radiation fluxes on the Earth’s surface were calculated in this way (72-74), where the Tunguska cosmic object was treated as a 30-m-radius asteroid that entered the atmosphere with a velocity of 15 km/s at an angle of 45º to horizon. Figure 20 shows isolines of energy input to a unit area on the Earth’s surface for atmospheric visibilities equal to 40 and 20 km in the assumption that the orientation of an irradiated object provides maximum heat absorption. The value of an energy input necessary for ignition varies from 35 J/cm² for dead leaves to 90 J/cm² for pine needles if the radiation comes from a 20 Mt explosion (57). These values are determined with about 50% accuracy. They strongly depend on atmosphere moisture. For a visible tree burn 40–65 J/cm² is necessary. A 15–20 km radius of tree burning determined for Tunguska explosion is in good agreement with the calculated isolines of input energy equal to 65 J/cm² and 35 J/cm² if the visibility was 20–40 km. At a distance of 35 km the light energy per unit area varies from 8 to 13 J/cm² for visibility at 40 km and from 0.8 to 2 J/cm² for visibility at 20 km. This is in reasonable agreement with eyewitness reports.

The calculations of thermal effects produced by the Tunguska meteoroid on the Earth’s surface were carried out in (75-76), where the energy release was approximated as a combination of spherical and cylindrical explosions. The obtained size of the tree burn and ignition area was
noticeably smaller despite the fact that light absorption and dispersion in the atmosphere were neglected: isolines 69 and 34 J/cm² confined areas with radial dimensions 7.5–12.5 and 12.5–19 km, respectively. Probably, this results from the smaller energy explosion assumed by the authors; the calculated energy of radiation emitted by the fireball was also smaller, only 12%.

A shock wave can quench a fire if it falls on the place after ignition. Estimates show that in the Tunguska event the shock wave likely extinguished the fire beyond a 10-km radius area (74). Inside this area the radiation impulse lasted longer than the time of a shock passage, and if the shock put out the fire there, ignition arose again.

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Figure 20. Isolines of radiation energy absorbed by a unit area in J/cm². It is assumed that the irradiated surface is at the sea level and is best oriented to accept the maximum radiation. Results of computations are shown for atmospheric visibility 40 km (a) and 20 km (b). The coordinates start at the epicenter—the Z-axis meets the trajectory at an altitude of 7 km. The Y-axis is a projection of the meteoroid trajectory to the Earth’s surface.
Chelyabinsk bolide of 15.02.2013

February 15 2013 Chelyabinsk event demonstrated consequences, which can be caused by relatively small cosmic object (16-20 m in diameter) (11, 77-79).

The shock wave created by the meteoroid entry caused damage on large area. According to official information about 7320 buildings were damaged and 1613 persons asked for medical assistance. According to the phone query (500 respondents in Chelyabinsk) 20% of respondents reported damage of their property and 9% of them reported that they or/and their relatives or got some injuries (80). Many people didn't visit hospitals for medical assistance. The Chelyabinsk event is an outstanding phenomenon in the series of meteoroid penetrations due to (i) large zone of disturbance (broken windows, ceilings, frames, etc.) and (ii) much varied evidence—including instrumental data such as video and photo records, satellite onboard monitoring, infrasound and seismic response, dusty trace observations (both space-based and ground), and an extensive field of meteorite residue. From March 9 to 25, 2013, a field expedition to the area was organized by the Institute for Geosphere Dynamics of the Russian Academy of Sciences (RAS) and the Institute of Astronomy RAS, and was supported by Chelyabinsk State University and the Yuzhnouralskiy Federal University in Chelyabinsk. Goal was to network and safeguard as much as possible perishable information from various sources.

The entry velocity of Chelyabinsk meteoroid is estimated as 18.9 – 19.3 km/s based on analyzed videorecords (78, 77, 81, 11). The energy and the mass of meteoroids may be evaluated by different methods. The analysis of infrasound records, the data on irradiated energy and the size of the damaged area allowed to conclude that the initial kinetic energy of the object is about 400–600 kt TNT (77, 82, 78, 11). This energy corresponds to meteoroid mass of about 7000 – 14000 t. The diameter of the body is about 16-20 m for bulk density of 3.2 g/cm³. All energy values are uncertain by a factor of two, mainly due to lack of calibration, similar conditions in past events or/and open questions in used approaches (83).

Seismic vibrations caused by the bolide entrance into the atmosphere have been also detected by a large number of seismic stations at distances within hundreds and thousands of kilometers. Approximate coordinates of the source of seismic oscillations (55.150°N, 61.410°E; USGS website: http://comcat.cr.usgs.gov/earthquakes/eventpage/us2013lra1#summary) are rather far from the approximate trajectory of bolide motion. The corresponding earthquake magnitude was rated 2.7–4 according to various estimates.

Shock wave

The shock wave continued to travel out to 90-120 km from the meteoroid trajectory, perpendicular to the trajectory, but quickly lost its destructive power in directions along the fireball path. In forward direction, the shockwave was experienced as loud, but not as sharply peaked and no glass damage resulted in Timiryazevsky (84). A number of numerical simulations were conducted that attempted a more realistic release of energy along the trajectory. The gasdynamic code SOVA was applied. Realistic atmospheric densities, pressures, and temperatures were used as input to the model. In each model, the total kinetic energy of the entering asteroid was fixed at 300 kT TNT. An entry angle of 16.5 degree with respect to the horizon was assumed (observed: 18.3°).
The observed fireball had three main moments of fragmentation and corresponding flares, hence three principal moments of energy release were considered. The last part of the trajectory below 21 km was not taken into account, because the radiation was fainter in this part of trajectory and the meteoroid mass and velocity had decreased significantly.

Three different cases were considered. In all cases the energy was released along the trajectory with a time delay corresponding to the meteoroid motion. For these models, the numerical grid has 500×250×250 points along the X, Y and Z axes. The X axis was taken along the trajectory in a direction opposite to the meteoroid motion, Y was taken perpendicular to the trajectory, while Z was vertical in upward direction.

In case I, all energy was released in one point X,Y = (+20, 0) km at Z = 31.7 km altitude, which corresponded to the main flare.

In case II, all energy was released along the trajectory between points (+100, 0) at 55 km altitude and (-16, 0) at 21 km altitude, and this energy release was taken to be proportional to the air density. Such energy release corresponded to a meteoroid flight with constant cross section, no disruption and negligible ablation, and without deceleration.

In case III, half of the energy (150 kt TNT) was released along the trajectory as in case II, 30% of energy (90 kt) was released in the first flare at (+20, 0) at 31.7 km altitude, 15% of energy (i.e. 45 kt) during the middle flare at (0, 0) at 25.8 km altitude and the final 5% (i.e. 15 kt) was released during the small flare at the end of the considered trajectory (-16, 0) at 21 km altitude. These altitudes correspond to early estimates of the entry trajectory.

The relative pressure distribution in the plane (X, Z) is given in Fig. 21 for case III at three different time steps. Time t=0 corresponds to the end of energy release. At all times, the spherical shock waves from the three individual flares and the ballistic shock wave caused by the meteoroid's subsonic flight are well distinguishable.
Figure 21 The relative pressure $P/P_0$ distribution ($P_0$ is the pressure at the surface) for case III, case of 300 kt TNT continuous energy release with three flares (see text).

The ballistic shock wave has a conical shape with a small opening angle due to the high meteoroid velocity (taken at 18-19 km/s) compared to the sound velocity (0.3 km/s), at which
speed the quickly decaying shock wave is spreading. It is important to note that the moment of the shock wave arrival at some point on the ground does not depend on the position of the main flare along the trajectory. To a good approximation, sound arrives at a location from the nearest point to the trajectory (but see below).

Projected to the Earth surface (X, Y plane), the overpressure contours of $\Delta p > 500$ Pa and $\Delta p > 1000$ Pa are shown in Fig. 22. This pattern should reflect the observed area of broken windows.

In all three considered cases, the surface area on the ground that was affected by the shockwave is very similar, determined mainly by the total amount of energy released. The shape of the overpressure distribution is determined by the details of the energy release along the trajectory. This may be explained by the fact that in all cases the main part of energy is released at a similar high altitude and the size of the energy source is comparable (or even smaller) than the distance to it. In the case of a point energy source (case I) the damaged area has a circular geometry. In both cases considered where the energy source is stretched along the trajectory (cases II and III) the area of damage is elongated in the direction perpendicular to the trajectory. Non-constant energy release (case III) is needed to match the observed pattern (11, 82).

Eighteen time-calibrated video records (at 10 frames per second) provide a record of the arrival times of the shockwave in the Chelyabinsk/Kopeysk area as well as a number of occasional records (11, 82). We have compared estimates of arrival time from the conical wave with observed values.

![Figure 22. The surface area corresponding to overpressures of $\Delta p > 500$ Pa (relative overpressure >0.005; colored grey) and $\Delta p > 1000$ Pa (relative overpressure >0.01, colored black) for three considered cases.](image)

For a given entry velocity and angle, the blast wave arrival time is dependent on the assumed terminal altitude of energy release ($z_0$). Comparing the arrival times from conical sources with different terminal altitudes to those observed at different locations demonstrated that a conical source can satisfactorily describe the observed blast wave arrival times, but only if the energy deposition continued down to 23 km altitude. The deposition of the energy, which is responsible
for the formation of the blast wave, occurred spread along the trajectory. Only a negligible fraction of the initial kinetic energy (and mass) was probably deposited below 23 km.

**Comparison with other events**

The satellite observational system registers about 30 light flashes in the atmosphere per year at altitudes 30-45 km over the globe. Duration of these flashes is about 1-3 s, the irradiated energy is about 0.01–1 kt TNT. The total raw of optical data 1994-1996 (51 events) were analyzed in (67), and allowed to determine the kinetic energy of corresponding meteoroids to be in the range 0.06-40 kt.

![Diagram](image)


Among the data of onboard monitoring systems available previously, the maximum kinetic energy amounted to ~40 kilotons TNT (85), which is significantly lower than most of the energy estimates for the Chelyabinsk meteoroid. For the period of 1960–1974, infrasound waves have been detected for some bolides by microbarometer systems deployed at that time in the United States(86). The most intense of these events for 14 years (August 3, 1963, Prince Edward Islands,
South Africa) had an estimated energy of 300–1000 kiloton TNT (87), which is comparable with the energy estimates for the Chelyabinsk meteoroid (Fig.23).

**Assessing crater-forming impacts**

This section presents the results of applying the model described above to calculate the vertical impact of a spherical asteroid with a diameter of 300 meters over a solid (composed of granite ) the Earth's surface at a velocity of 18 km/s. Figure 24 shows the most initial stage of impact (first 3 seconds). Initial parameters of the shock wave propagating along the surface are determined by the interaction of a shock wave occurring due to the motion of a falling body with the emitted products of cratering. In the later stage (t > 30 s), the secondary shock waves may occur when crater ejecta is falling on the ground. Trail left by a meteoroid during its pass through the atmosphere significantly affects both the shock wave propagation along the surface and the ejecta distribution. Figure 24 clearly shows the separation of condensed particle size. Larger particles are weakly decelerated and fly faster than smaller particles. The largest fragments can even fly beyond the shock wave and the meteor trail. Smaller fragments (less than 1 cm) decelerated near the shock front, where the air density (and resistance) increases.

![Figure 24. Initial stage of asteroid 300-m in diameter impact (velocity 18 km/s). Black-condensed matter of target and impactor, light-grey - vapor (bounded by thin black curve), grey - air (the darker the larger its density). Black points corresponds to ejecta fragments with size 0.03 mm-3 cm, light-grey points - fragments smaller 0.03 mm.](image)

Fig. 25 shows a later stage of the impact (120-600 s). At this point, the main part of the ejecta (with fragments larger 1 cm) has fallen to the ground at a distances up to 200 km. Millimeter particles also begin to precipitate. Smaller ones reach a maximum height of 30 km, creating a dust cloud. Further evolution of this cloud is determined by turbulent diffusion and wind field. This dust can remain in the atmosphere for weeks and even months because cloud rises significantly above the tropopause. Evaporated material of the target and the impactor rises higher and gradually condenses to form a huge cloud of microparticles at altitudes of about 100 km.
Total mass of ejecta reaches about 1000 times the mass of the asteroid $M = 3.5 \times 10^{13} \text{g}$, however, the most part of it quickly falls back to the surface. In 10 min after the impact the mass of ejecta still being in the air is only about $10M$, long-lived atmospheric aerosol mass is comparable to the mass of the asteroid. Vapor mass at a height of about 100 km is about $0.01M$.

![Figure 25. Final stage of asteroid 300-m in diameter impact (velocity 18 km/s). Black- condensed matter of target and impactor, light-grey - vapor (bounded by thin black curve), grey - air (the darker - the larger its density).Black points corresponds to ejecta fragments with size 0.03 mm - 3 cm, light-grey points - fragments smaller 0.03 mm.](image)

The scenario described above didn't take into account the disruption of the asteroid during the flight. In fact, even 300-m sized body is fragmented during its passage through the atmosphere although is not decelerated essentially. Figure 26 shows the results of modeling, which takes the fragmentation into account. These calculations are particularly important for smaller bodies (100-200 m) which can be significantly decelerated in the atmosphere. The shock wave propagation along the surface is seen on Figure 26. Damage effects of the shock wave is usually correlated with the maximum overpressure behind the shock front. Results of nuclear tests (57) show that brick wall of 24-36 thickness cm begin to crumble under positive pressure of 20 kPa, the concrete block...
walls of 24-36 cm thick totally destroyed by an excess pressure of 35 kPa. We used these values to assess the damage.

![Figure 26. The flow pattern in the vertical impact of the asteroid with a diameter of 300 m. The distribution of the relative density $\rho/\rho_0(z)$ where $\rho_0(z)$ the equilibrium density of air at height $z$. Distances along the horizontal and vertical axes are in kilometers.](image)

The size (diameter) of the area, in which the maximum overpressure exceeds 35 kPa, is 52 km, the area is about 2120 km$^2$. The size of the area in which the maximum excess pressure is higher than 20 kPa is 84 km, the area is about 5540 km$^2$. Dependence of the maximum overpressure on the distance is shown in Figure 27.

The dynamic pressure is another important factor of the damage, it determines the damage caused by strong winds occurring behind the shock front. Size (diameter) of the region where the wind speed reaches hurricane (30 m/s) at which trees are broken and can be pulled out by the roots, is about 115 km, the area of this region exceeds 10000 km$^2$. Wind speed dependence on the distance is shown in Figure 28.
Figure 27. Dependence of the maximum relative pressure $\frac{p}{p_0}$ on the surface at different distances from the impact point for the impact of an 300m asteroid.

Figure 28. Dependence of the maximum wind speed on the surface at different distances from the impact point for the impact of an asteroid of 300 m in diameter.
Figure 29 shows the results of modeling of 300 m in diameter asteroid impact into the ocean of 4 km deep at an angle of 45 degrees. An intermediate water crater with depth of about 2 km and diameter and about 5 km is formed. The ocean wave formed is short enough and quickly fades. Tsunami waves can be considered as an important factor in striking only when the fall of the larger (> 1 km) asteroids. Figure 30 shows the formation of tsunami waves due to impact of 1 km in size asteroid at angle of 15 degrees to the horizon. Despite the very strong slope of the trajectory, the tsunami is symmetric, although the initial stage of formation water of the crater is strongly asymmetric.

Figure 29. The formation of water crater due to impact of asteroid (300 m diameter) in the ocean with depth of 5 km.
6 Determination of the optimal level of the resources of protection in case of short warning time or unexpectedly large NEO. Possibility of fragmentation and the strategy of protection

It follows from the results above that the shock wave is the main damaging factor of an asteroid fall. The “classical” hazard protocols like sheltering and evacuation could only be organized in case of short warning time or unexpectedly large NEO. It seems to be the only protection measure. The problem is to minimize the risk zones. Together with evacuation plans of population available in each country there are needed enough exact forecast of the landing sites and pressure levels. The region of the urgent evacuation of people can be determined using the pressure (in excess of atmospheric pressure) in the shock waves from a falling asteroid given above.
The external boundary of man injuries is the conditional line on the surface of asteroid landing sites where the excess of atmospheric pressure is of 10 kPa.

The easy traumas were found if the excess pressure is of 20-40 kPa (0.2-0.4 kgf/cm²). There are dislocations, temporary loss of hearing, contusions.

The medium traumas answer to the excess pressure of 40-60 kPa (0.4 – 0.6 kgf/cm²). There are contusions, dislocations of extremities, bleeding from nose and ears, injuries of hearing organs, rupture of ear-drums.

The heavy injuries are if the excess pressure is of 60-100 kPa (0.6-1.0 kgf/cm²). There are heavy contusions, breaking of extremities which are often open ones, heavy bleeding from nose and ears.

The very heavy injuries are for the excess pressure over 100 kPa (greater than 1.0 kgf/cm²). There are heavy fractures of bones, breaks of interior organs (liver, spleen, buds, lings), open fractures of extremities, breaking of vertebral column.

The main cause of the distraction of rigid constructions (stone and wooden buildings) is an initial shock just after reflection of the shock wave by the building (it is the pressure of reflected wave). The reflection is essentially enhances the impact effects. For example, in Chelyabinsk in several buildings the lower windows were broken, while upper windows remained intact.

The crude estimations for buildings are made below.

The zone of great destruction corresponds to the excess pressure from 30 to 50 kPa. Many-storied buildings are destroyed at 25-30 kPa, low buildings are destroyed at 25-35 kPa, industrial buildings can be broken by shock waves leading to the excess pressure of 30-50 kPa. The moat part of bearing constructions are changed their form. Partly there are stayed walls and covering of the lower stores. Obstructions are created.

The zone of total destruction is characterized by the excess pressure greater than 50 kPa. There are fracture of heavy deformation of all bearing constructions end elements of buildings. There are total blockages, Underground and basement structures are less susceptible. About 70% of airtight sheltering and about 90% of underground electrical and communal nets stay able to work.

The shock wave penetrates into the building through windows, vent channels, flues, technological chinks and other holes. When the shock wave enters into a room, there is a sharp growth in pressure that leads to different failures. The diffraction of shock waves in a complex geometry should be calculated with special codes.

There are also the next elements of the world infrastructure susceptible to the shock wave from an asteroid:
- aircraft
- electrical power lines
- railways
- water and motor transport
- dams.

There are also seismic waves. Such waves are created by the asteroid impact directly onto the surface of Earth and also by air shock wave. The seismic wave can lead to damage of underground communications (subway, communication lines, water pipes, etc.). The great danger can be from damaged dams.

But the range of seismic waves is less than that of air shock wave due to high damping.

**Critical warning terms.**
Let $T_{00}$ is a time between the initial observation of hazardous space body and its collision with Earth.

$T_{01}$ is a time between the accurate calculation of the orbit of the body and the collision,

$T_{02}$ is a time between the attempt of deflection and the collision.

All these values could be named as a warning time depending on a solved problem. For example in (94) the $T_{02}$ is a warning time that used for estimation of different methods of deflection of an asteroids. But in this work the $T_{01}$ is taken as a warning time.

Assuming that the space industry and space launch sites are sustained in the best readiness there are following abilities to defend Earth depending on the warning time $T_{01}$. Here we have in view that the asteroid is about 50 – 300 m in size.

$T_{01} > 10$ years. It is a timeline warning, the best measure is a calm resettlement of population from a hazardous sites. Also the attempt of deflection by kinetic impact can be done, and there is a time for preparations for a well-timed nuclear deflection. But we should mention that any failure in deflection attempts can seriously complicate the situation.

$1$ year $< T_{01} < 10$ years. Immediate resettlement is needed. Asteroid can be still deflected if we have already prepared infrastructure to launch a nuclear charge.

$T_{01} < 1$ year. In this case also immediate resettlement should be realized. The asteroid could be fragmented. The fragmentation should be made no later than several hours before the collision. If the fragments and tremendous mass of dust have no time to go away from each other, then the cumulated effect is unpredictable.

The asteroids of mentioned sizes can be also deflected by a series of nuclear explosions or can be fragmented. In the both cases about a partway fragmentation and the danger from larger pieces remains. It makes this approach very hazardous.

In the case of unexpectedly large NEO there are only two possibilities to lower the serious damage on the ground and probable injuries.

1. At least to try to slightly change the trajectory of the asteroid to avoid it from a most vulnerable site. Such regional withdrawal was studied in our previous report on D7.3 (94). It is a distance of deflection is about 2000 km that allows to take away the falling body from any large city to a sparcely populated area now. There is a place to minimize risks. Mote that in a critical situations even less avoid distances can have a sense.

   For such minimization we need
   - more accurate data and methods for numerical calculations of the influence of nuclear explosions,
   - detail information on available nuclear charges,
   - detail information on appropriate launching sites, their disposition and the dynamics of rocket motion in the vicinity of Earth.

2. To break the asteroid to pieces before his entering into the atmosphere of Earth. But we should consider self-gravitational forces. And any way the distances between pieces will be not enough large to avoid cumulative effects. If the matter of an asteroid will move in the atmosphere as a hypervelocity clot the great danger for ground structures remains.

   Note that the fragmentation of an asteroid requires to do deepened nuclear explosions. The means for deepening should be rigorously studied. The most serios problem is to sure workability of the nuclear charge.
Collision with an asteroid less than 150 m in size is most real. The volume is about $1.4 \times 10^7$ m$^3$ and mass of $2.8 \times 10^{10}$ kg. There should be developed the protection of Earth should be developed against such bodies.

Asteroids larger 200 m (of $2.4 \times 10^{11}$ kgm) should be classified as large. And such mass can unexpectedly large due to errors in determination of the asteroid size and mass.

Collision with a space body larger 1 km in size should be consider as an incredible event because the most part of such asteroids and short-period comets are already known and none of them is going to impact the Earth. Nevertheless such situation can be considered also.

In Table 5 there is given a classification of resources and methods to protect the population of Earth. This table is developed on the base of estimations of the mechanical momentum due to nuclear explosions and appropriate changes of asteroid orbits given in (94).

Table 5. The minimal level of resources needed to prevent serious damage and injuries of the population on the ground depending on a warning time and the size of space body.

<table>
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<th>Warning time $T_{01}$</th>
<th>The size of a space body, m</th>
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<tbody>
<tr>
<td></td>
<td>100-200</td>
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<tr>
<td>&lt; 1 year</td>
<td>Deflection and fragmentation of a space body using series of nuclear explosions of 100 – 1000 kt power.</td>
</tr>
<tr>
<td>1-10 years</td>
<td>Deflection of a space body with a nuclear explosion of 100 – 1000 kt power.</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>Deflection of a space body using one kinetic impactor or series of such impactors.</td>
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Possibility of fragmentation and the strategy of protection

Undeliberate fragmentation of an asteroid due to the deflection attempt using a nuclear explosion or a kinetic impact represents a great danger for the population of Earth. The only method of protection is the timeline of control of asteroid shape and diagnostic of its destruction. Investigations on a mission (D7/4) show that nowadays the most reliable diagnostic of asteroid destruction can be made using a multichannel range-finder aboard a spacecraft at a distance at most 300 km.

7 Implementation

The following implementation we proposed in this report/
1. There is given the classification of warning times for the collisions of asteroids with Earth.
2. The main assumptions of the “physical” theory of meteors are studied. It is shown that the uncertainty in heat transfer gives the main spreading of trajectory parameters (up to the first fragmentation instant). The available theoretical values difference is shown to be much lower, by one to two orders of magnitude, as compared to that for results of meteor observations.
3. The numerical modelling of the entry of hazardous rocky and comet-like meteoroids which are dangerous by serious damage on the ground, is done which allows to calculate the real coefficients of drag, heat transfer, and ablation.
4. The altitudes of deceleration, destruction, and total evaporation solid rocks from 40 m to 100 m in diameter at speed of 20 km/sec and such comet-like bodies at speed of 20 and 50 km/sec at different angles are calculated.
5. Due to the random character of hydrodynamic instabilities on the surface of destructed (quasiliquid) body there is the essential spreading of deceleration altitudes for the same parameters of a falling body.
6. It is shown that the heat of vaporization and initial speed have slight effect on the altitudes of destruction and deceleration but the difference in density is very essential, stone bodies penetrate much deeper into the atmosphere than comet-like bodies of the same sizes.
7. The altitudes of the full vaporization of an ice or stone meteoroid are above the altitudes of body deceleration or the stop of a luminous region by 5-10 km.
8. There is done classification of types of the entry of rocky and comet-like bodies depending on their size and entry angle.
9. It is shown that elementary half-analytical theory have great errors in description of entry of the bodies of the our interest.
10. There are given the dependences to evaluate the magnitude of earthquakes caused by coming shock wave as a function of the distance from epicenter of explosion. The seismic wave is generated even by the air explosion of a large bolide, not only by crater-creation (4).
11. The areas of fires (forest and other highly inflammable objects) caused by light pulse of a bolide.
12. Having the Chelyabinsk event as an example the regions of destruction from coming shock wave from the air explosion of a meteoroid are analyzed for different scenarios of energy-release along the trajectory of flight.
13. There are given results of calculations of cratering impacts both for land and sea surfaces. There are given the intensities of tsunamis.

Conclusions

The study of the cosmic impacts of the different sizes bodies shows that there are possible one of the four scenarios (in order of decreasing in body size):

- a crater-forming impact (when the cosmic body, even highly fragmented, reaches the Earth's surface and forms a crater);
• a giant surface bolide (GB) or, in other words, the surface "meteor burst" (when a high-speed jet, consisting of small fragments of the meteoroid, vapors and air heated in the shock wave reaches the Earth's surface without forming a crater);
• air GB or air "meteor burst" (when the products of the completely destroyed and vaporized meteoroid are decelerated in the atmosphere and mostly do not reach the Earth's surface, but the shock wave and, in some cases, thermal radiation produce noticeable damage and fires, shining example of this case is the Chelyabinsk meteoroid);
• ordinary meteor phenomena (which can be observed from the Earth and from space, but do not leave visible traces on the surface of the Earth).

Of course, there are no sharp boundaries between all these regimes and intermediate scenarios are possible.

The impacts of cosmic bodies 10 – 300 meters in size are of particular interest According to the probability-danger criterion.

The following issues are considered in the report

1. Basic assumptions of "physical" theory of meteoroid entry are considered. It was demonstrated that main scatter in trajectory parameters of meteoroids (up to fragmentation) resulted from heat transfer coefficient uncertainty. The heat transfer coefficients obtained by theoretical analysis can be 1-2 orders lower than values extracted from observations of meteoroid falls.
2. Numerical modeling of initial phase of a large stony meteoroid entry have been done. Theoretical values for drag, heat transfer and ablation coefficients have been extracted using destruction model accepted here.
3. Numerical simulations of the falls of stony asteroids and comet bodies in the atmosphere have been carried out in the range of their sizes which poses a threat of significant damage to the Earth's surface.
4. We have obtained the altitudes of deceleration, breakup and complete vaporization of comet-like and stony bodies entering the atmosphere with typical for comets velocities 20 and 50 km/s at various angles.
5. Because of the random nature of hydrodynamic instabilities on the surface of a falling body that can be assumed as being heavily fragmented or quasi-liquid, there is a marked variation of deceleration altitudes for the same initial parameters of a body entering the atmosphere.
6. Destruction energy and entry velocity affect meteoroid destruction and deceleration altitudes only slightly. To the contrary, density effect is much more pronounced and stony bodies penetrate considerably deeper to the atmosphere than cometary bodies of the same sizes.
7. The altitudes of complete evaporation of stony and icy meteoroids are by 5-10 km higher than the altitudes of body braking or stopping of the luminous region.
8. The types of the impacts of asteroid and comet-like bodies have been defined as a function of their sizes and entry angles to the atmosphere.
9. It has been shown that a simple semi-analytical model gives large errors in the case of predictions for the falls of cometary bodies.
10. Dependences enabling to estimate magnitudes of earthquake induced by ongoing shock wave have been presented for difference distances from the explosion epicenter. The seismic effects of an air burst of a giant bolide can be greater than from a cratering impact.
11. Fired areas, resulted from burning of easily-fired substances ignited by bolide airburst light pulses, have been specified.
12. Areas of damage due to shock wave at air explosion have been analyzed for different scenarios of energy release along trajectory of the Chelyabinsk bolide.
13. Numerical results of crater-forming impacts have been presented for both land and sea falls. Intensities of tsunamis arisen from ocean impacts have been presented as well.
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