SHOCK WAVES ON THE SURFACE AFTER CRATER-FORMING IMPACTS. N. Artemieva[1,2] and V. V. Shuvalolv[2], [1]Planetary Science Institute, Tucson, AZ, artemeva@psi.edu, [2]Institute for Dynamics of Geospheres RAS, Moscow, shuvalov@idg.chph.ras.ru.

Introduction: Impacts of high-velocity cosmic bodies (CB) possess a real hazard for human civilization. The entry of relatively small (~20 m in diameter) Chelyabinsk meteoroid in February, 2013 caused substantial economic problems, severe injuries, and panic among local people. If the Tunguska-like event occurred not in Siberia but above Moscow or any other megalopolis, the city and its population would be totally demolished.

We continue our project [1] and present here the modeling results for crater-forming projectiles (asteroids and comets with a diameter of 0.3-3 km). At least the smallest 300-m-diameter asteroids are still below the detection limit of astronomical observations and can encounter with the Earth anytime. Calculated pressure-wind values are compared with known hazardous effects from [2].

Methods: We use hydrocode SOVA [3] to model the atmospheric entry and the interaction of generated shock waves with the surface. The CB is treated as a strengthless body; its equation of state is either ice or dunite. Details of the atmospheric entry model are presented in [4]. When the CB reaches the surface, 2D distributions are interpolated into 3D mesh to model the interaction of the CB with the surface (crater and ejecta formation) and, then, ejecta and the atmospheric wake interaction with the atmosphere. Due to computer capacity restrictions, 3D resolution is much lower yet it still allows us to conserve the total energy and the momentum of the CB-atmosphere system. As atmospheric shock waves cover areas much larger than the crater itself, the rezoning procedure is applied a few times during each run.

Tracer particles within the target are used to describe ejecta velocities and their physical states, whereas tracer particles in the lower atmosphere allow to record maximum overpressure and wind speed around the impact point.

Results: We have modelled the atmospheric entry followed by the impact for ~50 different scenarios: projectile diameters are in the range of 0.3 – 3 km; their velocities vary from 15 to 50 km/s; impact angles are between 15° and 90° (vertical impact).

Influence of the atmosphere on pre-impact parameters. In contrast to small bodies [1], the atmosphere has minor influence on pre-impact parameters of crater-forming projectiles (Fig. 1): their mass and velocity decrease by <1%. Only 0.3-km-diameter comets at impact angles <30° lose most of their energy in atmosphere producing powerful airbursts, but are unable to form a crater. However, strong atmospheric shock waves generated during the entry change the pattern of pressure distributions on the surface (Fig. 2). Also, the atmospheric wake could change ejecta distributions and plume evolution.

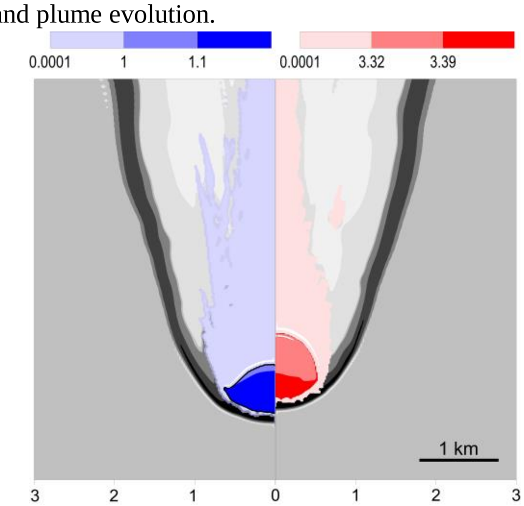

Fig.1. Normalized atmospheric density (gray shades) and densities of a comet (left, blue colors) and an asteroid (right, red colors) at an altitude of 1 km. Pre-atmospheric diameters were 1 km and impact angles were 45° in both cases; comet velocity was 50 km/s, asteroid velocity – 20 km/s. Both bodies are only slightly deformed, the wake is filled by vapor (although vaporization is minor in both cases, M_{vap}/M_0<<1).

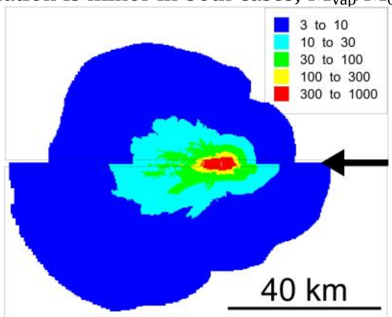

Fig. 2. Distributions of overpressure (P_{max}/P_0) on the surface 50 s after a 45° impact of a 1-km-diameter asteroid at 20 km/s. *Top:* the entry is not taken into account; *Bottom*: 2D-flows resulting from the atmospheric entry (Fig. 1) have been interpolated into 3D calculations. Whereas near the crater pressures are very similar, presence of the wake results in larger are of total destruction both, uprange and downrange.

Distributions of shock pressure and wind speed depend, obviously, on impact energy and, for a given energy, on an impact angle (Fig. 3). In all runs highly oblique impacts result in smallest craters, but in the largest areas of severe damage. Areas with high values of dP/P_0 are usually elongated in the impact direction; moderate values of dP/P_0 are distributed more evenly.

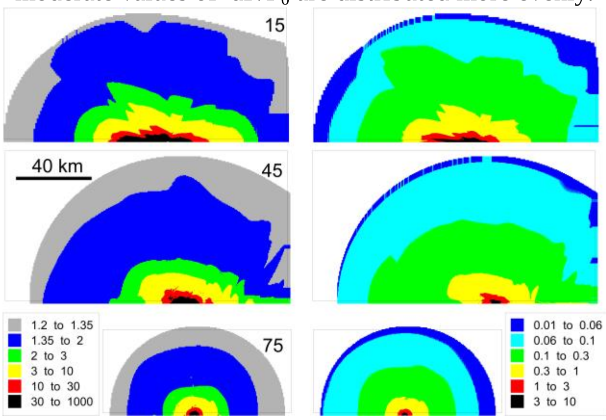

Fig. 3. Maximum overpressure (left) and maximum wind speed (right, in km/s) after a 300-m-diameter asteroid impact with a velocity of 20 km/s and various impact angles (15, 45, and 75°).

Total area of severe damage on the surface (P_{max}/P_0>3) is shown in Fig.4. Highly oblique impacts produce order of magnitude larger areas whereas moderate and near-vertical impacts with the same energy result in similar (and much smaller) areas of total destruction. Areas of substantial damage ((P_{max}/P_0>1.35) are usually 5-10 times larger than totally damaged areas and keep the same dependence on an impact angle. If the impact angle is constant and the energy *E* increases, totally damaged area is proportional to $E^{1/3}$ (green symbols and black dashed line in Fig.4)

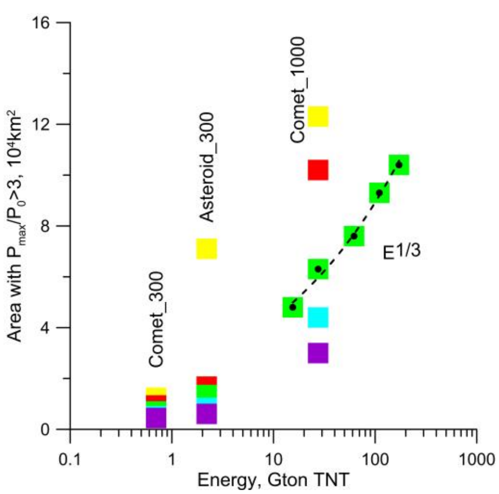

Fig. 4. Area of total damage (P_{max}/P_0>3) as a function of impact energy. Different colors show different impact angles: yellow – 15°, red – 30°, green -45°, cyan – 60°, magenta – 75°. Green symbols approximated by the black dashed line are for a 1-km-diameter comet with velocities of 15, 20, 30, 40, and 50 km/s.

Far-field estimates: As we learned from the Chelyabinsk case even small shock pressures (~1 kPa) still can be dangerous if impacts occur in densely populated area. Calculations of small dP values are quite challenging due to much larger distances, possible reflections of shock waves from the boundaries, growing with time oscillations of the atmosphere, etc. Thus, we try to find reliable extrapolations to these smaller values. Preliminary results for some scenarios are shown in Fig. 5. The exponents depend on azimuths, impact angles, and impact velocities. As a rule of thumb for a 1-km-comet, pressure drops to 20 kPa at a distance of 100 km and exceeds 0.5 kPa up to a distance of 500 km (decay exponent of -2.4).

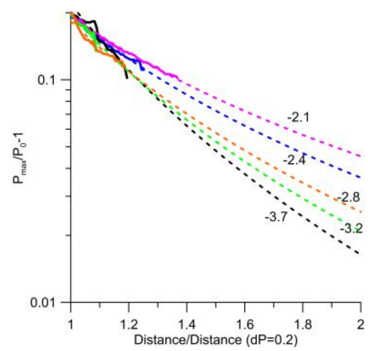

Fig. 5. Extrapolation of shock waves decay in downrange direction after a 1-km-diameter cometary impact at impact angles >45°. Solid lines show calculated results, dashed lines – extrapolations. Distances are normalized to a distance at which shock pressure drops to 20 kPa (0.2 of the atmospheric pressure). This distance varies from 122 km for an impact velocity of 20 km/s at 75° to 144 km for an impact velocity of 50 km/s at 45°.

Conclusions: The consequences of crater-forming impacts are less sensitive to impact obliquity than the consequences of airbursts. Practically for all impact angles except of 15° the affected area is circular. The area of global disruption by atmospheric shock waves is an order of magnitude larger that the crater area (including the continuous ejecta blanket). It means that atmospheric shock waves are the most hazardous consequences of moderate-scale (crater diameter of ~20 km) impacts.

Our models show that accurate estimates of affected areas and local impact effects require precise knowledge of the impact scenario which is usually poorly known (or totally unknown). It means that the results presented above have to be considered as 'rough' estimates prior to the impact, but can be used to evaluate CB properties after the impact.

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References: [1] Artemieva N. et al. (2017) *LPSC*-48, Abstract #1514. [2] Glasstone S. and Dolan P.J. (1977) *The Effects of Nuclear Weapons*. [3] Shuvalov V.V. (1999) *Shock waves,9*, 381-390. [4] Shuvalov et al. (2017) *Solar System Research*, *51*, 44-58.