HAZARDOUS EFFECTS CAUSED BY IMPACTS OF SMALL COSMIC BODIES: SHOCK WAVES ON THE SURFACE. N. Artemieva[1,2] , V. Shuvalov[1], and V. Svettsov[1], [1]Institute for Dynamics of Geospheres, Moscow, Russia, artemeva@psi.edu; [2]Planetary Science Instiute, Tucson, AZ 85719.

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. Impacts of small CBs are much more probable and may occur any time in the nearest future anywhere. Usually these small bodies cannot reach the surface, but instead release all their energy in atmosphere producing airbursts. However, strong shock waves and thermal radiation are capable of causing serious troubles on the surface. Current estimates of airbursts effects [1] either utilize oversimplified analytical models or interpolate the effects observed after powerful nuclear explosions [2]. Specifics of impacts such as the momentum transfer and impact obliquity are usually neglected. A few comprehensive numerical models are restricted to the Tunguska and Chelybinsk airbursts.

To assess hazardous consequences of small (1-200 Mton TNT) CB impacts in a wide range of scenarios (sizes, velocities, entry angles, composition) we combine numerical modeling of the related physical processes with available observations of natural and technogenic catastrophes.

Methods and Initial Conditions: We use hydrocode SOVA [3] to model the atmospheric entry of CBs 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 is totally transformed into a debris-vapor jet, 2D distributions are interpolated into 3D mesh to calculate the interaction of the jet and atmospheric flow with the surface which is treated as impenetrable nondeformable plane. 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 (Fig. 1). If the pressure on the ground is known as a function of coordinates and time, the energy of seismic waves can be calculated using a solution of Lamb's problem of the response to vertical load acting on the surface of an elastic half-space [5].

Results: We have modelled the atmospheric entry for ~50 different scenarios to show that airbursts are typical for a vertical entry of asteroids smaller than 100 m and comets smaller than 150 m. Impact obliquity moves this threshold to larger diameters.

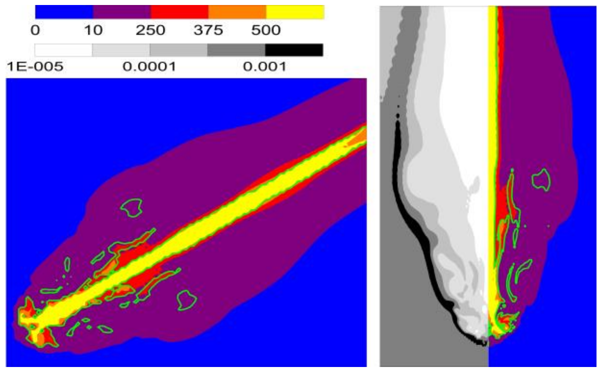

Fig. 1. *Right:* Specific energy (in kJ/g, see the color scale) and density (in g/cm^3, the gray scale) at the end of the entry model. A 100-m-diameter comet entered the atmosphere at 30° to horizon with a velocity of 70 km/s. At an altitude of 8 km it was transformed into an elongated hot jet (green lines show the boundary between the cometary material and air). The resolution of 2D simulations is ~1.5 m near the axis of symmetry and increases outward; the frame size is 6 km×10 km (only the leading part of the jet is shown). *Left:* The same distribution at the beginning of 3D simulations. with spatial resolution of 100 m.

Pressure and winds on the surface: The shape of severely damaged area is almost circular for entry angles >45°; it is transformed into a butterfly with its 'wings' being perpendicular to the trajectory plane if impact angles are below 45°; highly oblique impacts (<20°) result in elongated 'wings' (Fig.2). Relatively short overpressure pulse is followed by a long low-pressure pulse (60-90% of the standard atmosphere). This reduced pressure may be dangerous for people who survived the shock wave. Values of maximum pressure, wind speed and total area subjected to overpressures of a certain value (0.2, 0.1, 0.05, and 0.02 of the standard atmospheric pressures) have been calculated for all 'airburst' scenarios (see Fig.3).

Winds: Gas velocities behind shock waves (commonly known as 'winds') are negligible below the epicenter, then increase quickly to 'hurricane'-like values and, at larger distances, decay slowly in the same manner as maximum overpressure values (Fig.2).

Comets: Effects on the surface after cometary impacts are in general similar to those after asteroid impacts. If comets are of the same size and have the same velocity, effects are smaller due to lower comet density. If energies are the same, maximum pressures and winds are lower after a cometary impact. However, the total area of moderate damage (overpressure of 2%) is usually larger (Fig.3).

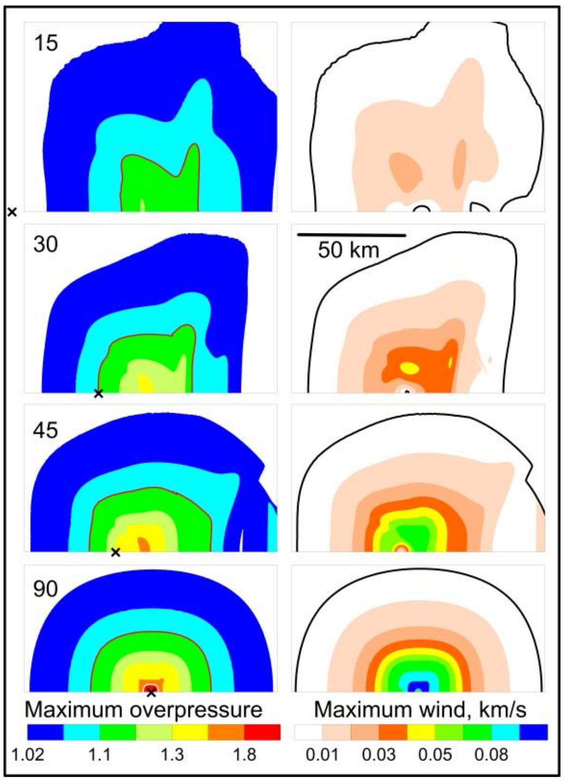

Fig. 2. Distributions of maximum overpressure (P/P_{atm}) on the left and distributions of the maximum wind speed on the right after the entry of a 50-m-diameter asteroid with velocity of 20 km/s at various angles to horizon (15-90°). The impact occurs from right to left and the intersection of the trajectory line with the surface (ground zero) is shown by a crest on each pressure map. Areas with maximal potential damage are shifted from the ground zero uprange to a distance of ~60 km after a highly oblique impact.

Earthquakes: Magnitudes of equivalent seismic sources vary from 4.0 (a 30-m-diameter comet at 20 km/s) to 5.9 (a 100-m-diameter asteroid at 50 km/s). Dependence of magnitudes on the entry angle and the entry velocity (for the same total energy) is rather small and irregular (Fig. 3). Only vertical impacts result in substantially lower magnitudes. Seismic efficiency of surface waves calculated by Guttenberg-Richter equation ranges from 1.5×10^{-5} to 6×10^{-5}.

Discussion: The low resolution of 3D simulations may lead to underestimates of maximum pressure and velocity values. Also, in Eulerian codes the total energy is not conserved; an option to transfer the energy deficiency into the internal energy leads to a slight (2-5%) increase in extreme pressure and velocity values and to a ~20% increase in affected areas. However, much larger effects could take place if the surface is uneven (e.g., high walls can cause shock waves interference and local pressure peaks).

Our models show that accurate estimates of affected areas and local impact effects require precise knowledge of CB's properties which are 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] Collins G.S. et al. (2005) *M&PS, 40,* 817–840. [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 V.V. (2017) *Solar System Research, 51*, 44-58. [5] Svettsov V.V. and Shuvalov V.V. (2014) 40th COSPAR, Abstract B0.4-71-14.

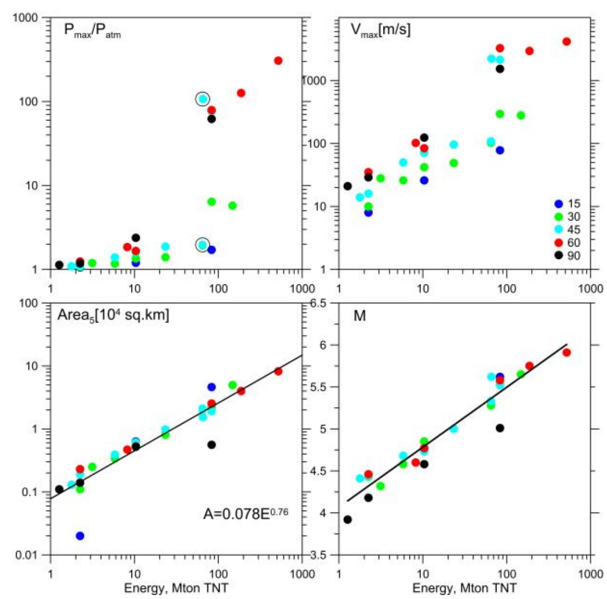

Fig. 3. Maximum pressure (top left), maximum wind speed (top right), the total area with ovepressure >5% (bottom left), and earthquake magnitude for all asteroidal airbursts (bottom right). Different colors correspond to different impact angles (see the insert on the velocity graph). In general, all effects depend mainly on the initial CB energy, whereas the influence of the impact angle is minor at energies <20 Mton and becomes dramatic at larger energies at the threshold of the 'airburst'scenario. Two 45° impacts with similar energies of 65Mton but with different velocities of 20 and 50 km/s (highlighted by black rims on the pressure graph) produce dramatically different effects on the surface because of CBs disruption in the atmosphere.