MASS DEFICIENCY PROBLEM IN LARGE METEORITE FALLS. N. A. Artemieva[1,2] and V. V. Shuvalov[2], [1]Planetary Science Institute (1700 E. Ft. Lowell, suite 106, Tucson AZ 85719, artemeva@psi.edu), [2]Institute for Dynamics of Geospheres (Moscow, Russia).

Introduction: The total mass of recovered Chelyabinsk meteorites does not exceed 2000 kg, <0.02% of its pre-atmospheric mass. The largest fragment and its satellites from the Chebarkul lake made about ~800 kg whereas meteorites recovered shortly after the fall from the strewn field are mainly small (<0.1 kg) fragments [1]. Similar problem of "mass deficiency" exists for other recently observed and well-documented large meteorite falls such as Almahata Sitta and Tagish Lake (Fig. 1). No one meteorite has been recovered after the Tunguska event – the largest impact of 20-th century.

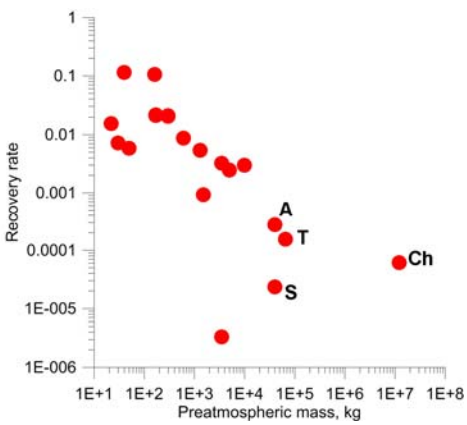

Fig. 1. Ratio of the recovered meteorite mass to the estimated pre-atmospheric mass as a function of the latter. Data points are extracted from [2,3]. **A**: Almahata Sitta (2008); **T** – Tagish Lake (2000); **S**- Sutter's Mill; **Ch** – Chelyabisnk (2013)

Mass deficiency could be explained by a few reasons: 1) dramatic overestimate of the pre-atmospheric mass; 2) low recovery rate: 3) specific structure of large meteoroids (dusty matrix with embedded solid fragments, e.g. [3-4]); 4) intense ablation during large meteorite falls. The first two reasons should be dismissed as these events have been registered by various methods, their landing sites have been predicted and carefully searched. The third idea will remain speculative until detailed asteroid study in situ. Thus, it seems reasonable to check physics of meteoroid/atmosphere interaction using numerical models.

Method and initial conditions: We use the 2D hydrocode SOVA [5] to describe an entry of cosmic body into the atmosphere. At the beginning the meteoroid is represented by a swarm of fragments with prescribed size-frequency distribution; all particles have the same velocity along the trajectory and a small perpendicular component describing expansion of the meteoroid after the fragmentation [6]. Each particle is characterized by its mass-dependent strength and may be subjected to subsequent fragmentations. In addition, fragments change their mass due to ablation. The intensity of ablation depends on the radiative flux which is defined in our approach as the maximum between a fraction of gasdynamic flux (known as the heat transfer coefficient C_h) and the black-body radiation flux [6]. This approach works better if fragments move within a hot wake behind the swarm where their relative velocity is low, but the surrounding gas is extremely hot, with T> 20, 000 K). We use CIRA tables to describe density-temperature stratification of Earth's atmosphere and the equation of state of air [7]. The computational domain is usually 300×3000 cells and it moves down if the shock wave is too close to its bottom. The resolution of 1m (10 cells per projectile radius) is a compromise between the accuracy and the computational time.

We start to model a tight swarm of 1cm – 2 m fragments with the total mass of 10^7 kg at an altitude of 50 km. The entry velocity is 18 km/s; the entry angle is either 90° or 30° (in both cases two-dimensional approach works well as the bolide size is much smaller than the atmosphere scale height).

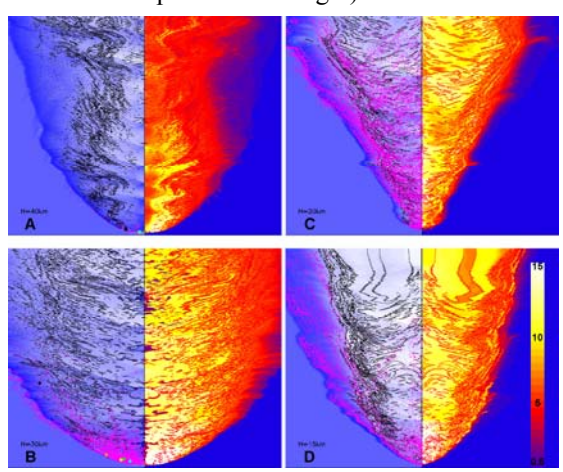

Fig. 2. A vertical entry of a 20-m-diameter meteoroid. R and Z axes scale differently: maximum radial distance is 300 m, distance along the Z-axis (trajectory) is 3 km. The right side of each plate shows temperatures in kK, the color scale is on plate D; the left side shows relative densities (shades of blue), vapors (black lines), and fragments (pink and cyan dots). A-plate: an altitude of 40 km, vaporization starts, all fragments are still within a tight swarm; B-plate: an altitude of 30 km, the cross-section of the bolide increases, intensive fragmentation starts, small fragments (pink dots) slide along the shock wave to the far wake. C-plate: an altitude of 20 km, the swarm has a conical shape with small particles distributed more or less evenly along the trajectory. D-plate: an altitude of 15 km, ablation ceases, mm-sized fragments form a cold outer shell (visible as a smoke train for observers).

Results: Snapshots of the entry process are shown in Fig. 2. Although the meteoroid is treated as a swarm from the beginning, down to an altitude of 35 km it moves likes a solid body with a slow increase in radius and mass loss mainly due to ablation. At an altitude of 30 km (plate B) small (< 1 cm) fragments begin to slide along the bow shock filling the wake and leaving the computational domain. The most intense fragmentation takes place between 25 and 20 km (plate C). The wake is totally filled by small fragments; a lot of particles decelerated to low velocities leave the computational domain. In the last plate D decelerated fragments move in cold atmosphere (although the center of the wake is still hot) and may be visible as a dusty train.

The mass loss and the velocity decrease are shown in Fig. 3. The total mass of vapor is ~70% of the initial mass, i.e., less than expected 90% for the ablation coefficient in use ($0.014 s^2/km^2$). However, final solid fragments are mainly small, <1cm (Fig. 4). The total mass of larger fragments corresponds to 30,000 meteorites in size range of 3 – 6 cm plus 80 meteorites > 6 cm. We failed to reproduce the largest recovered fragment (600 kg) as it certainly has a higher strength than average statistical predictions.

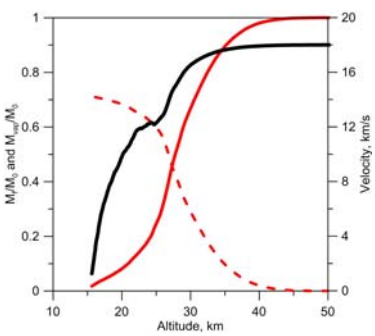

Fig. 3. Mass (red lines and left axis) and velocity (black line and right axis) changes versus altitude. Thick red line: mass of solid particles within the computational domain (300 m in radius, 3 km in length); dashed red line: the total vapor mass.

Discussion: Although the final results (SFD of fragments on the surface and their total mass) are stable for all runs, many peculiarities of the entry process, such as deceleration at low altitudes and energy release in atmosphere, strongly depend on badly known physical parameters and modeling assumptions such as computational mesh resolution, artificial viscosity, etc. The approach is quite expensive from the viewpoint of computational time (and will be even more expensive for smaller bodies). Although we do observe some light flashes (Fig. 5), we cannot correlate them with observations. It means than standard Point Mass Approximation (PMA) trial methods are more efficient allowing to check/reject a lot of variants quickly. However, it should be emphasized that an empirical introduction of "dusty clouds" into these models [8-9] is just a convenient way to describe much more complicated process of ablation/fragmentation and not an inherited property of large meteoroids.

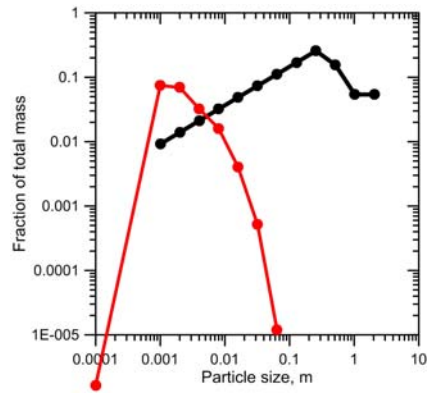

Fig. 4. Size-frequency distribution of fragments in the upper atmosphere (black line) and near the surface (red line). The largest fragment is 2 m in radius, each following bin is twice smaller down to 100 μm.

Conclusions: Whereas meteorite falls are usually described in the frame of PMA models, larger events (Tunguska) require full-scale hydrodynamic modeling. Analysis of the Chelyabinsk event allows us to bridge the gap between Tunguska-like airbursts and 'casual' meteorite falls. We are able to show that the mass deficiency of meteorites could be explained by intense fragmentation and vaporization of large (a few m in diameter) bodies during the atmospheric entry. Although the total survived mass could be impressive, the fragments are smaller than 0.1-1 cm and, hence, not easily identified as "meteorites". In addition, they could be dispersed widely by local winds as their precipitation time may last days and weeks. It would be interesting to find this "meteor" dust on Siberian snow fields. As far as we know the single attempt [10] was not successful because of substantial local pollution.

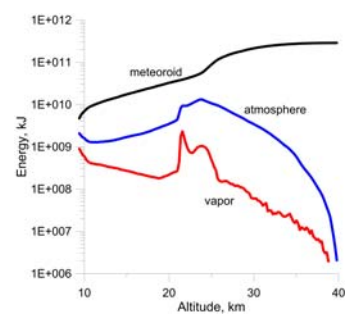

Fig. 5. Kinetic energy of solids (black) and total energies of atmospheric gas (blue) and vapor (red).

Acknowledgements: The study is supported by Russian Science Foundation, grant 16-17-00107.

References: [1] Ivanova M. et al. 76 *M&PS* 48A: 5366. [2] Popova O. et al. 2011. *M&PS* 46: 1525-1550. [3] Borovička J. et al. 2015. eprint arXiv:1502.03307. [4] Goodrich C. et al. 2015. *M&PS* 50: 782-809. [5] Shuvalov V. 1999. *Shock waves* 9:381-390. [6] Artemieva N. and Shuvalov V. 2001. *JGR* 106: [7] Kuznetsov N.M. 1965. [8] Popova O. et al. 2013. *Science* 342: 1069-1073. [9] Borovička et al. 2007. *Astrophysics* 473:661–672. [10] Gindilis L.M. and Shevelev G.N. 2014. In *One year of Chelyabinsk meteorite*: 266-278 (in Russian).