

**SNOW COMPACTION DURING THE CHELYABINSK METEORITE FALL.** R. Luther<sup>1</sup>, A. Lukashin<sup>2</sup>, N. Artemieva<sup>3,2</sup>, V. Shuvalov<sup>2</sup> and K. Wünnemann<sup>1</sup>, <sup>1</sup>Museum für Naturkunde, Leibniz Institute for Research on Evolution and Biodiversity, Berlin (Invalidenstraße 43, 10115 Berlin, Germany, robert.luther@mf-n-berlin.de), <sup>2</sup>Institute for Dynamics of Geospheres, RAS, Russia, <sup>3</sup>Planetary Science Institute, Tucson.

**Introduction:** The Chelyabinsk meteorite fall rose the general awareness of the small impact hazard. In the early morning of February 2013, the bright meteor and several flashes could be observed by the local population near the Ural mountains. The 20-m-diameter meteoroid broke up during its passage through the atmosphere and released most of its energy at an altitude of 40–20 km; its entry angle was quite low with  $\sim 17^\circ$  to the horizon and the trajectory length in the atmosphere exceeded 250 km [1]. Atmospheric shock waves led to more than 1500 injured people (mainly by broken windows) and minor damage in infrastructures of the nearby towns.

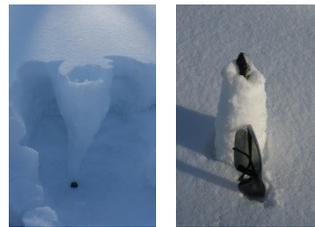
A few days after the meteorite fall small fragments with an average size of 3–6 cm were collected by geologists from the Vernadsky institute. They found about 4 kg of meteorites (450 samples) that were distributed over an area 40 km south of Chelyabinsk [2]. The mass found by the local people corresponds to approximately 0.02% of the estimated original mass, whereas the major part is lost in the atmosphere due to ablation.

The collected fragments were mostly found in holes in the snow (Fig. 1). The funnel walls of the holes showed an irregular topology and consisted of coarse-grained snow. Larger fragments penetrated the 70-cm-thick snow layer and reached the frozen ground surface. Smaller fragments got stuck in the snow, showing a special characteristic: For the bottom 15–25 cm in depth, the funnels narrowed into a cone shape, forming so-called “snow carrots” (Fig. 1). At the tip of the carrots, the meteorite was found surrounded by a dense shell of the similar coarse-grained snow. The mechanism of cone formation is still not clear. Two hypothesis are generally discussed: i) The original fluffy snow is compacted by the impacting small fragment; ii) The fragments are warm (as described by some witnesses [1]) and cause partial snow melting.

In this paper we study the dynamics and thermal evolution of small fragments in the atmosphere after the catastrophic fragmentation and their penetration through the snow cover. We use the point mass approximation and solve the heat transfer equation to find initial conditions (temperature and velocity) of fragments prior their penetration into the snow. Then we model the penetration process using the iSALE hydrocode combined with the  $\epsilon$ - $\alpha$  porosity model [3]. Tillotson equation of state or ANEOS are used to de-

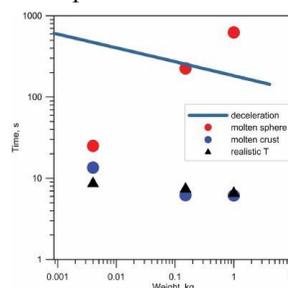
scribe basalt (meteorite fragments) and ice (snow). Implementing a realistic snow model is a sophisticated task due to the wide spectrum of characteristics in mechanical properties and snow microstructure. For the snow, we used a Drucker-Prager rheology model [4, 5]. Snow porosity was set to about 70% (density of 284 kg/m<sup>3</sup>). We varied the model parameters inside realistic boundaries to achieve a good agreement with the observations.

**Results: Deceleration and free-fall time:** All numbers below are for initial masses of 40 g and 10 kg (in parentheses). Shortly after the catastrophic disruption (1–3.5 s), individual fragments lose 90% of their mass and are decelerated below 2 km/s, when ablation ceases. The free fall time in atmosphere is about 8 (3) minutes; fragments reach the surface vertically with a velocity of 28 (74) m/s. The final diameter of a fragment is 1.3 cm (8.5 cm).



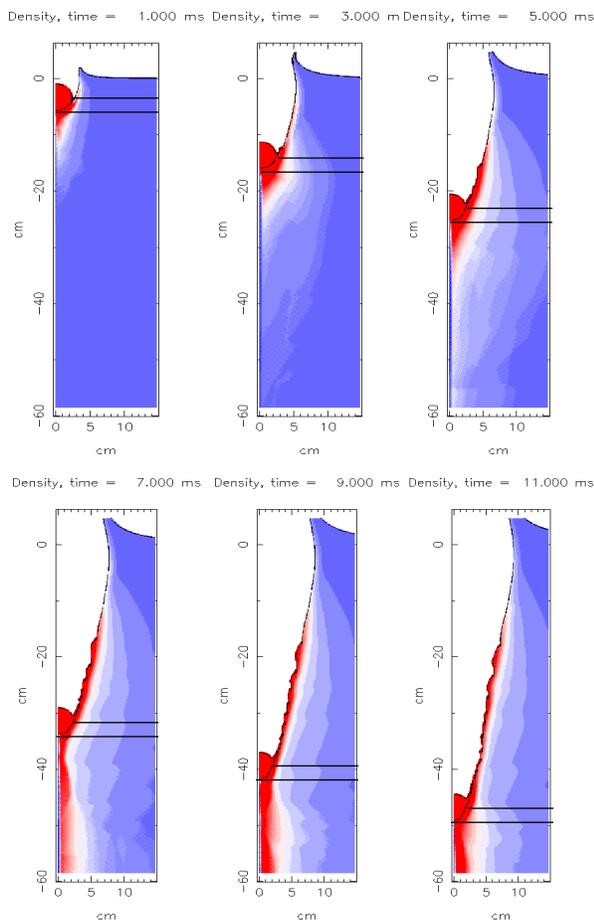
**Fig. 1:** Snow carrots. Left - in situ; right - the lowest part is shown upside down with sunglasses for scale (Images courtesy to C.Lorenz).

**Thermal history:** First, we model the heating of the fragments in the hot cloud immediately after the catastrophic disruption. We found that each fragment has an ablation crust that is about 1 mm thick and its interior (84 and 21% of the final mass) is heated above 300 K. We also modeled simplified T-distributions: A fragment is heated up to the melting point or a cold fragment is surrounded by a molten 1-mm-thick crust. Then all fragments cool down during their free fall in the atmosphere (250 K). In all but one case (molten large sphere) the cooling time interval is substantially shorter than the time interval of free fall (Fig. 2). Hence, fragments reach the surface being at thermal equilibrium with the lower atmosphere ( $-20^\circ\text{C}$ ).



**Fig. 2:** Comparison of cooling time and free-fall time for 3 fragments with various final masses. Red - totally molten fragments; blue - cold fragments; black - the most realistic temperature distribution.

*Fragment penetration into snow target:* The projectile encounters the snow, pushes material out of its way forming a funnel-shaped crater. The fluffy and highly porous snow is compressed as a consequence of the penetration of the projectile into the snow. For estimating the snow compaction, we studied the density in the horizontal cells directly beneath the projectile and in the horizontal cells adjacent to the projectile (as indicated in Fig. 3). In both cases we see an increase of density of up to 13–18% (adjacent to and beneath the projectile, respectively). The funnel wall thickness (the snow layer with higher density) is  $\sim 3.4$  cm (Half Width of Half Maximum, HWHM). At the same time we do not see any significant increase of temperature or internal energy that could lead to a partial snow melting.



**Fig. 3:** Snapshot series from hydrocode modeling of the penetration of the fragment into the snow layer. The time interval between each frame is 2 ms, starting at 1 ms. Red colour corresponds to higher density, blue to lower density. The black lines indicate the density profiles investigated. The propagating tail beneath the projectile along the symmetry axis is a numeric artefact.

**Discussion and future applications:** The formation of the funnel-shaped craters in snow and the occurrence of “snow carrots” at their tip is due to the compaction of the porous, fluffy snow by fragments with initial speeds of up to 80 m/s. The walls of the penetration funnel show an up to 18% increase in density up to 3.4 cm from the crater wall. Although we do not observe a significant temperature increase due to compression, we can not exclude the formation of a thin veneer of partial melt due to friction between the projectile and the snow, as this process is not included in our models. It is possible that some dense part of the funnel walls collapse on top of the projectile, forming the observed snow shells above the projectile. The volume of slumped part of the funnel walls equals the volume of the snow shell.

Although the present study was inspired mainly by our curiosity it has an important application for planetary science. For example, similar problems (penetration of a dense projectile through a highly porous target) occurred during the Stardust space experiment [6]. Although the impact velocity was much higher (6.1 km/s) the observed tracks of cometary dust in aerogel resemble the snow carrots. The accurate interpretation may provide additional information about properties of the collected particles (e.g., their initial strength and porosity) prior to the capture. By the successful Rosetta mission a lot of high-resolution images of the comet nucleus including crater-like structures were obtained. To model these impacts we need a reliable representation of the target material. Hence, we may consider the Chelyabinsk fragments and their snow carrots as a validation test of the iSALE hydrocode including strength models of highly porous materials.

**References:** [1] Borovicka J. et al. (2013) *Nature*, 503, 235-237. [2] Ivanova M.A. et al. (2013) *MetSoc*, Abstract #5366. [3] Wünnemann K. et al. (2006) *Icarus*, 180, 514-527. [4] Haehnel R.B. and Shoop S.A. (2004) *Cold Regions Science and Technology*, 40, 193-211. [5] Lee J.H. and Huang D. (2014) *Journal of Terramechanics*, 55, 1-16. [6] Greenberg M. and Ebel D. (2012) *M&PS*, 47, 634-648.