THE FORMATION OF KAALI CRATER, ESTONIA: INSIGHTS FROM NUMERICAL MODELING.

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Introduction: The Kaali crater-strewn-field located on the island of Saaremaa, Estonia (58.37°N, 22.67°E), consists of nine well-preserved craters, with diameters ranging from 110 m to several meters [1, 2]. The Main crater, with diameter of 110 m, was thought to be formed by impact of an IAB iron meteoroid [3, 4], into Silurian dolomite target rocks covered by up to a few meters of glacial till [5], shortly after 1650 – 1400 BC [6]. Although the Kaali craters have been identified a long time ago, the process of their formation has not been properly studied yet. Recent scientific expedition [6, 7, 8], which allowed to date the craters, as well as mapped the crater topography using 3D laser scanning tools and subsurface morphology using groundpenetrating radar and electrical resistivity tomography (ERT), significantly improved our understanding of the Kaali structures, and provided more constraints on this structure formation. In this study, we conduct a series of numerical modeling experiments to constrain the Kaali crater-strewn field meteorioid entry parameters, and then use these information to model the formation of Kaali Main crater using the shock physics code iSALE 2D [9, 10, 11].

Methods: To determine entry parameters of the Kaali meteoroid, we use existing physical models of cosmic body interaction with a planetary atmosphere [12]. First, we integrate numerically standard equations for ablation and deceleration [13]. To simulate the disruption process, we use the modified so-called Pancake approximation [13]. Accordingly, when dynamic loading exceeds meteoroid internal strength, it is transformed into the cylindrical cloud of fragments with increasing mass. We use factor 3.5 relatively to meteoroid initial radius to stop its expansion. The position and mass of every big fragment in the Pancake cloud is defined by Monte Carlo method and standard cumulative mass-frequency distribution. Every large fragment (>0.1% initial meteoroid mass) moves independently to the ground and some of them may be subjected to another fragmentation cycle. To estimate the radiation flux from the bolide in the atmosphere on the surface, we determine the range of energy deposited in the atmosphere. We use standard conversion coefficient [14] assuming that about 10% of energy deposited in the atmosphere is converted into thermal radiation. To estimate craters diameters on the ground we use the pi-scaling laws [15] with material-dependent scaling parameters determined using iSALE2D multi-rheology, multi-material hydrocode.

We then use the calculated vertical velocities and masses of impacting fragments to simulate impact processes. We consider a planar target with two layers (a 2 m-thick porous quartz layer on top of limestone) and iron as the impactor. We use tracer particles to record the shock conditions and determine the angle and velocity of ejection. Subsequently, we calculate the ballistic trajectories for each tracer to work out the deposition distance [16]. For every tracer representing ejecta, we record its temperature induced during the impact cratering process to study the ejecta temperature variation along the distance from the crater center. The observed crater profile and ejecta thickness were used to constrain the model parameters.

Results: Our preliminary results show that the entry mass of the Kaali meteoroid was between 800 and 1500 tons, its velocity varied between 14 and 18 km/s and initial trajectory angle was < 45 degrees. About 90% of its initial energy was released into the atmosphere, and the airburst occurred at the altitude of 8-10 kilometers. For the Kaali Main crater, the rim height is ~ 7 m above the pre-impact surface, and the rim has ~ 2-3 m uplift. The excavation depth is about 10 m. The ejecta thickness at the rim is ~ 3 m and decreases proportionally to a power-law with a decay exponent. The temperature of ejecta, induced by the impact process, has a highest value of ~ 350 K and varies along with the distance from the basin center. These results can be used to analyze the initial locations of the interesting samples and peak shock pressures these samples experienced.

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