BIMODAL CRATERS ON VESTA: IMPACTS ON SLOPES STUDIED BY NUMERICAL SIMULATIONS.

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Introduction: On July 17, 2011 the Dawn spacecraft [1] approached the inner main belt asteroid 4 Vesta. Stereo-photogrammetric analysis revealed large differences in elevation from -22.3 km to +19.1 km [2]. Thus, many impact craters on Vesta are formed on slopes which might explain their asymmetric interior morphology and ejecta distribution [2].

Most of these unusual craters show a well-formed circular sharp rim on the uphill side and an undefined smooth rim on the downhill side. The latter seems to be mostly overprinted by the ejecta blanket. Ejecta on the uphill rims is detected only sporadically in thin layers. The DTMs and profiles of these craters, such as "Helena" (lat 41.4°S, long 122.5°E; see Fig. 1) normally reveal a steep slope uphill and a shallower one downhill [2, 3].

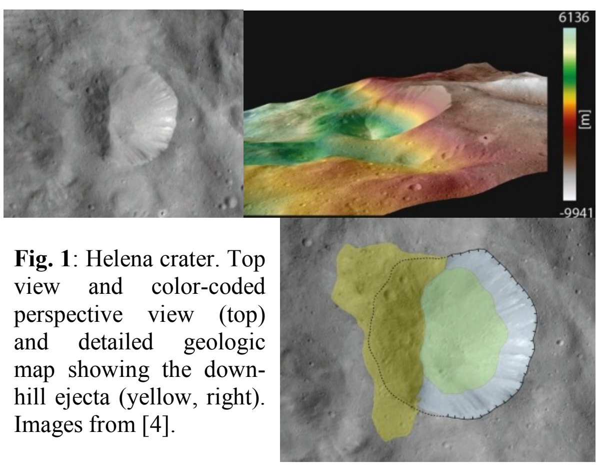

Fig. 1: Helena crater. Top view and color-coded perspective view (top) and detailed geologic map showing the downhill ejecta (yellow, right). Images from [4].

These observations raise the important question, how these unusual craters were formed. We conducted numerical simulations of the formation of a crater similar to "Helena" (see Fig. 1) to investigate, whether the rough pre-impact target topography caused the bimodal shape of this type of craters. In previous studies we demonstrated that the shape of an impact crater and especially its ejecta distribution is the result of a complex interaction of the topography, an oblique angle of incidence, the impact energy (i.e. size, density, and velocity of the projectile), the impact position relative to the topography, and the properties of the target material [5]. In these studies we also showed that the crater shape is only influenced by impacts in tilted targets with a variation in altitude >30% of the projectile's diameter. The distribution of ejected material is affected by even smaller differences in elevation [6]. The range in elevation measured at the Helena impact site (~6 km) is larger than the estimated projectile size (~1 km) to form a Helena-sized crater. Thus, it is likely that the observed unusal crater morphology of Helena and the ejecta distribution have been significantly affected by the slope at the impact site.

Model description: To consider the effect of topography three-dimensional simulations are required. For this purpose, we used iSALE-3D, a three-dimensional, multi-material, multi-rheology hydrocode [7,8]. It has been shown before that iSALE-3D is capable of calculating hypervelocity impacts into topography [5,6]. It follows an ICE'd ALE approach as described in [9,10] to solve the Navier-Stokes equations in a compressible manner and uses finite-differences and finite volume techniques on a staggered Cartesian mesh. Different material models, such as an ε-α-compaction model to consider porosity [11] or a block model to simulate acoustic fluidization [12] are available as well as a number of strength models which include accumulation of damage [13,14] and allow for a realistic calculation of the mechanical response of a geological material under high dynamic load. The thermodynamic behavior of material can be calculated by using a numerous equations of state, such as Tillotson [15] or ANEOS [16].

Simulation setup: We conducted three-dimensional simulations of a Helena-like impact event by using a simple target geometry with a slope angle of 40° and a slope height of 4 km. The projectile had a diameter of 900 m and its velocity was 5 km/s – a probable impact velocity for a low gravity body such as Vesta (gravity g=0.22 m/s^2). We used a dunitic composition of the target assuming a material model that accounts for strength weakening due to the accumulation of damage [13] and an ANEOS equation of state [16] for dunite. We used the ε-α-compaction model as described in [11] with a porosity of 25%. The mechanism of acoustic fluidization [12] has been taken into account, too.

Results: We were able to reproduce the bimodal shape of unusual craters like "Helena". Our calculations showed that this special type of craters can be formed if the projectile hits the slope at the bottom, coming from downhill direction (see Fig. 3a). Furthermore, a low angle of incidence (here: 15°), is required to reproduce the characteristic ejecta pattern.

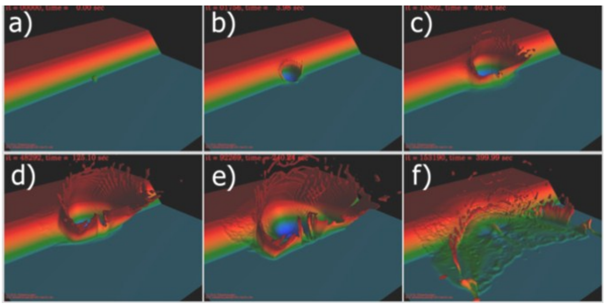

Fig. 2: Numerical simulation of an impact event forming a "Helena"-like crater: perspective view. The surface is colored by its initial height.

Fig. 2 shows a series of different time steps of this impact event. The angle of the ejecta curtain, especially in downrange (uphill) direction is significantly influenced by the slope. In this particular scenario, the downrange ejecta curtain stands up almost vertical - much steeper than in the case of a planar target. As shown in Fig. 2c-e, the ejecta curtain leans inward and deposits material inside the crater. At steep slopes and/or low impact angles (as shown in the example model in Fig. 2) it is possible that material from the downrange/uphill ejecta curtain is deposited at the uprange position outside the crater and overlays the deposit of ejecta from the initial uprange ejecta curtain (Fig. 2e and f). This mechanism explains why no or only a small amount of ejecta deposit can be observed in impact craters like Helena.

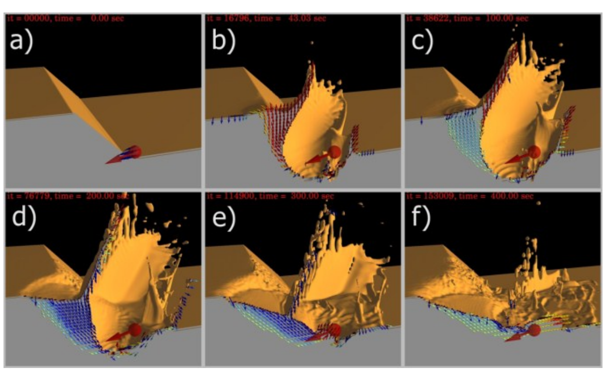

Fig. 3: Numerical simulation of a Helena-like impact event: Side view. Red arrow indicates the initial projectile size, position and trajectory. Small arrows illustrate material motion during the impact event (red: upwards material motion; blue: downward motion).

Fig. 3 shows the same simulation in a cross-section. The slope causes a crater collapse directed downhill, as seen in Fig. 3c. This results in sagging of the uppermost part of the slope towards the crater center, which forms a sharp edge of the crater in the uphill direction. This finding is in good agreement with observations at Helena-type craters on Vesta. The slumped material accumulates in the crater. If the momentum of material motion is sufficiently high, some material may be transported beyond the rim of the crater in downhill direction and deposited outside of the crater, as demonstrated in Fig. 3e and f.

Conclusion and outlook: By conducting numerical simulations we could demonstrate that topography can influence both the ejection angles and the crater collapse. Our results allow for an explanation of the formation of some unusual craters, such as Helena, observed on Vesta. Additionally, we could identify the point of impact relative to the slope and the impact trajectory as important properties controlling the cratering process in topographically rough terrains.

This might be an explanation for some significant variations in the morphology and ejecta distribution of the different unusual craters found on Vesta [17]. Further studies are intended to explain the formation of these different types of craters observed on asteroids.

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