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The transition from circular to elliptical impact craters

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1. Introduction

The vast majority of impact craters on planetary surfaces is circular. This observation implies that the overall shape of craters formed by hypervelocity impacts is not sensitive to the impact angle and direction as it is known that most impacts occur at an oblique incidence angle. However, 5% of impact craters on planetary surfaces are elliptical, with an ellipticity of 1.1 or greater. The frequency of elliptical craters was found to be consistent assuming that impacts at or below about 12° form elliptical craters [1]. Here we are using the three-dimensional hydrocode iSALE-3D [2] to study highly oblique impacts. In previous studies [3] this code has been successfully used to reproduce formation of elliptic craters from laboratory experiments in metal [4]. Furthermore, it was shown that the cohesive strength strongly influences the threshold impact angle for elliptical impact crater formation. However, this study has been performed for low-energy (small-scale) impacts only. Here we address the question, whether impact energy also affects formation of elliptic impact craters. Furthermore, we study also the role of internal friction and give insight how the crater formation mechanism changes during the transition from circular to elliptical craters.

2. Hydrocode simulations

To investigate crater formation at very oblique impact angles, we carried out a series of 3D simulations by using the multi-rheology hydrocode iSALE-3D [2]. We assumed Earth-like gravity conditions of g=9.81m/s^2 and varied the impact angle between 90° (vertical impact) and 5°, focusing on impacts below 30° where transition from circular to elliptical craters is expected. To avoid the complication of material vaporization impact velocity was kept constant at a relatively low value of U=8 km/s. To study the effect of different impact energies, we varied the impactor size over two orders of magnitude (500m – 5 km). The thermodynamic state of the material was computed by the Tillotson equation of state [5] using granite parameters as stated in [6]. To study the effect of material strength, we varied both the coefficient of internal friction (f=0.2, 0.3, 0.4, and 0.7) and cohesion (Y_{coh}=0, 5, 20, 100, and 200 MPa) assuming a Drucker-Prager strength model ($Y = Y_{coh}+fP$, where P is pressure). We do not take tensile failure into account. Hence, fragmentation of the projectile is excluded in our calculations although it may be an important aspect in highly oblique impacts.

3. Results

Following the definition of Bottke et al. [1], we define an elliptical crater as a crater with an ellipticity (length divided by width) of 1.1 or more. Fig. 1 shows crater ellipticity as a function of the impact angle for different projectile sizes and friction coefficients. At this point, cohesion was kept constant at 5 MPa. Vertical impacts as well as oblique impacts up to 45°-30° generate circular craters, which is in good agreement to observations on planetary surfaces. The critical angle, at which elliptical craters are formed, slightly decreases with projectile size (or impact energy). This may be explained by the fact that the less energy is transferred into the target and is available for shockwave-induced excavation the smaller the crater relative to the size of the impactor and the less the impact may be approximated by a point source. Hence, the impactor's momentum becomes more important causing material displacement and crater formation.

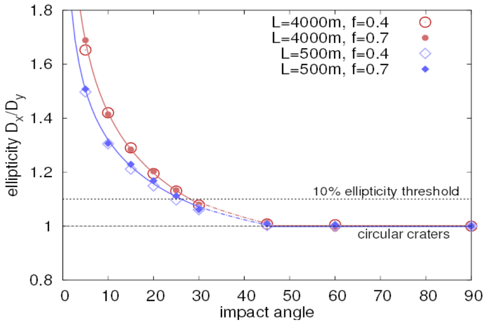

Figure 1: Ellipticity vs. impact angle for different impact energies and friction coefficients. Cohesion was kept constant at 5 MPa.

Next we investigated the effect of target strength by varying friction (Fig. 1) and cohesion (Fig. 2). Our results suggest that internal friction does not affect significantly the formation of elliptical crater (Fig. 1). In contrast, cohesion has a strong effect on the critical angle for ellipticity as shown in Figure 2. The more resistant the target material is against plastic deformation, the larger the required angle of impact at which elliptical craters evolve. This implies that a planetary surface with higher strength would be covered by more elliptical craters than a body composed of weaker material (assuming the same impact rates and angle probabilities for all planetary bodies).

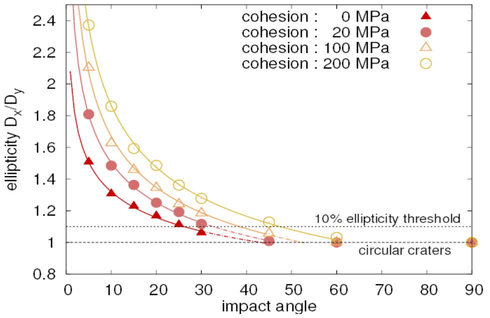

Figure 2: Ellipticity vs. impact angle for L=500 m, f=0.7 and a varied cohesive strength.

4. Conclusions

We identified three different regimes indicating the transition from circular to elliptical impact craters. For a particular strength and impact energy the regimes correspond to impact angles of 20°, 10°, and 5°, as shown in the snapshots in Fig. 3:

a) Transition regime (Fig. 3a: 20°): In many respects, crater growth is similar to moderate oblique impacts (>30°). Note, most of the ejected material moves parallel to the target surface, indicating the transition to the case of a ricochet impact (b). The projectile is completely shocked and crater excavation takes place primarily as a result of shock wave compression. The resulting crater is slightly elliptical.

b) Ricochet regime (Fig. 3b: 10°): The projectile hardly penetrates into the target while it undergoes shockwave compression. Crater formation is initially mainly driven by the momentum transfer from the projectile to target material (the projectile pushes material out of its way) and a highly elliptical crater evolves. Subsequently, the shock-induced relatively symmetric excavation flow (originating from a point source) superimposes the initial processes, resulting in an elliptical, but still relatively deep impact crater.

c) Grazing regime (Fig. 3c: 5°): In this scenario the projectile is more or less sliding along the surface. Only a small amount of energy is transferred into the target and, hence, available for shock-induced crater excavation. Reflections of the shockwave at the surface and the projectile boundary lead to an only partially shocked impactor. Hence, only a small amount of projectile material undergoes vaporization and the projectile probably would disrupt into larger fragments. Crater excavation is dominated by the projectile pushing material out of its way, which eventually results in a highly elliptical and very shallow impact crater.

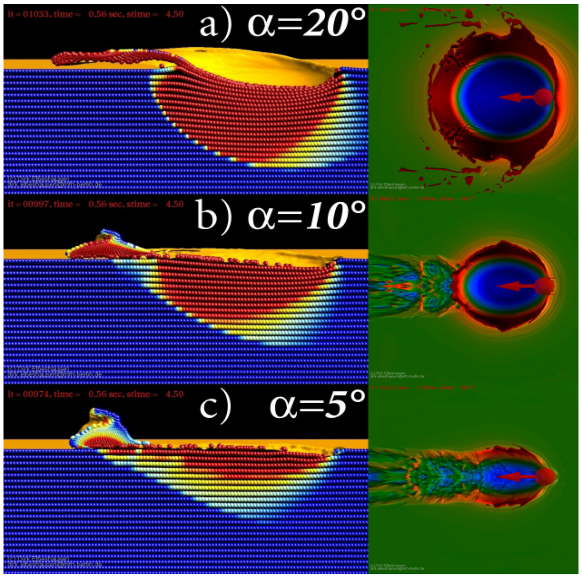

Figure 3: Snapshots of crater formation (*L=1 km*) in a weak target (Y_{coh}=*5 MPa*, *f=0.3*) for selected impact angles. Left: Early stage, front face shows tracers colored by pressure in a range from 0 (blue) to 3 GPa (red) which is close to the Hugoniot elastic limit for most granites and similar materials. Right: Corresponding craters at late stage crater modification (plane view); color denotes elevation above impact surface. Projectile material has been removed from the visualization (see depressed features in downrange direction) to enable an undisturbed view into the crater.

Acknowledgements

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