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Asymmetric craters on Vesta: Impact on sloping surfaces

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ABSTRACT

Cratering processes on planetary bodies happen continuously and cause the formation of a large variety of impact crater morphologies. On Vesta whose surface has been imaged at high resolution during a 14 months orbital mission by the Dawn spacecraft we identified a substantial number of craters with an asymmetrical shape. These craters, in total a number of 2892 ranging in diameter from 0.3 km to 43 km, are characterized by a sharp crater rim on the uphill side and a smooth one on the downhill side. The formation of these unusual asymmetric impact craters is controlled by Vesta's remarkable topographic relief. In order to understand the processes creating such unusual crater forms on a planetary body with a topography like Vesta we carried out the following work packages: (1) the asymmetric craters show various morphologies and therefore can be subdivided into distinct classes by their specific morphologic details; (2) using a digital terrain model (DTM), the craters are grouped into bins of slope angles for further statistical analysis; (3) for a subset of these asymmetric craters, the size-frequency distributions of smaller craters superimposed on their crater floors and continuous ejecta are measured in order to derive cratering model ages for the selected craters and to constrain possible post-impact processes; (4) three-dimensional hydrocode simulations using the iSALE-3D code are applied to the data set in order to quantify the effects of topography on crater shape and ejecta distribution. We identified five different classes (A–E) of asymmetric craters. Primarily, we focus on class A in this work. The global occurrence of these crater classes compared with a slope map clearly shows that these asymmetric crater types exclusively form on slopes. We found that slopes, especially slopes $>20^\circ$, prevent the deposition of ejected material in the uphill direction, and slumping material superimposed the deposit of ejecta on the downhill side. The combination of these two processes explains the local accumulation of material in this direction. In the subset of asymmetric craters which we used for crater counts, our results show that no post-impact processes have taken place since floors and continuous ejecta in each crater show comparable cratering model ages within the uncertainties of the cratering chronology model. Therefore the formation, or modification, of the asymmetric crater forms by processes other than impact can be excluded with some certainty.

1. Introduction

Observations on planetary surfaces have revealed that a large majority of impact craters have a shape that is circular in-plane. The reason why even the most oblique impacts produce circular craters is because of the hypervelocity nature of these events. During impact, a significant amount of energy is released into the target within a short period of time. The physical process of crater excavation is, thus, similar to the detonation of an explosive source and, therefore, results in a symmetric excavation flow and crater growth. This simplification, the so-called “impact and explosion analogy” (Holsapple, 1980; Oberbeck et al., 1977), only provides an explanation for the formation of circular and symmetric craters.

However, many observations have revealed evidence for the asymmetric crater growth of some impact structures, such as on the Moon (Plescia, 2012), on Lutetia, and on Vesta (Jaumann et al., 2012).

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The origin of these asymmetries is manifold and in most cases is still ambiguous. Generally, the formation of impact craters is treated for the case of more or less planar surfaces for simplicity but it can be assumed that asymmetries in the crater forms are a result of projectile trajectory (e.g., Plescia, 2012). Shallow impact angles could produce asymmetric ejecta distribution, often in a butterfly pattern with little or no ejecta on the uphill side. At very shallow angles, the crater becomes elongated (Gault and Wedekind, 1978). Additionally, topography (Elbeshausen and Wünnemann, 2011) or heterogeneous stratigraphy (e.g., Collins et al. 2008; Gulick et al. 2008) is often discussed as conditions capable of supporting asymmetric crater formation. Additionally, post-impact modification by volcanism (Schultz, 1977), tectonics (Gurov et al., 2007) or erosion (Simonds and Kieffer, 1993) might also overprint an initially circular impact structure and change it to an asymmetric shape.

The Dawn spacecraft (Russell and Raymond, 2011) entered the orbit of the inner main belt asteroid Vesta on July 17, 2011, and conducted an approximately 14 month science operation to characterize the geology, mineralogical composition, topography, shape, and internal structure of Vesta (Jaumann et al., 2012). The image data show many asymmetrical craters on Vesta.

Because there is no significant erosion and no tectonic activity on Vesta, the impacts should be oblique and/or topographically influenced. However, this still needs to be demonstrated. Thus, the major goals of this paper are twofold: First, we describe the morphology of these asymmetric craters. Second, we investigate whether topography played a dominant role in the formation of these craters.

After describing the methods used in Section 2, we present detailed information about the morphology of these asymmetric craters and attempt to classify their shapes. We use age-determination techniques to show which of the observed morphological features can be associated with the impact crater. By comparing the distribution of the slopes within the spatial distribution of the asymmetric craters, we examine whether topography played the dominant role in the formation of the impact structures. Finally, we use three-dimensional numerical hydrocode modeling to gain insight into the crater formation process.

2. Data and methods

Both the Dawn Framing Camera data (FC;Sierks et al. (2011) and the HAMO digital terrain model (DTM; see supplemental material of Jaumann et al. (2012) for further description) were used for the analysis of the asymmetric crater distribution, mineralogy and ejecta distribution on Vesta. During the orbital phases, the FC mapped the surface with image scales of $\sim$260 m/pixel (FC) in the Survey phase, $\sim$60 m/pixel (FC) in the High Altitude Mapping Orbit (HAMO) and $\sim$20 m/pixel (FC) in the Low Altitude Mapping Orbit (LAMO). The topography of Vesta is derived from Dawn FC Stereo images (Jaumann et al., 2012). Dawn arrived in the Vestan southern summer, which allowed for a complete survey of the south polar and equatorial regions for Survey and HAMO data (Denevi et al., 2012).

For our investigations, we primarily used the HAMO, DTM, and LAMO data. The high-resolution LAMO data nearly covers the surface of Vesta, approximately 90% of the surface from 90°S up to $\sim$50°N. With the complete coverage of HAMO data, we can observe the asymmetric craters quite well.

2.1. Geologic investigations

FC-LAMO images with resolutions of 20 m/pixel were used to identify asymmetric craters. To complete the survey, areas that lack FC-LAMO coverage were examined based on the FC-HAMO data with a resolution of 60 m/pixel. Due to the resolution of 20 m/pixel for the FC-LAMO data, we can clearly identify asymmetrical craters with diameters $\geq$ 300 m. Craters with diameters less than 300 m cannot definitively be identified as asymmetric.

Asymmetric craters are morphologically characterized by asymmetrical shapes on sloping surfaces, e.g., mixtures of sharp and smooth crater rims, asymmetric interior morphology and ejecta distribution.

For our investigations, we (a) prepared a geomorphologic map to determine the ejecta distribution with the help of clear filter and multispectral color filter images derived from FC-LAMO data, (b) identified and digitized the outline of each asymmetric crater using the ESRI software package ArcGIS, (c) measured the crater diameters with the help of CraterTools (Kneissl et al., 2011), and (d) created a slope map with the ArcGIS slope tool using the DTM with 450 m/pixel resolution. To create the slope map, we used an ArcGIS tool to calculate the maximum rate of change in value from each cell to its neighbors. The steepest downhill descent from the cell is represented by the maximum change in elevation over the distance between the cell and its eight surrounding neighbors.

2.2. Three-dimensional hydrocode simulations

Numerical simulations are powerful tools that can be used to obtain insights into the dynamics of the cratering process. 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 (Elbeshausen et al., 2009; Elbeshausen and Wünnemann, 2011a). iSALE-3D is capable of calculating hypervelocity impacts into topography (Elbeshausen and Wünnemann, 2011; Elbeshausen et al., 2012). It follows an ICE'd ALE (Implicit Continuous-Fluid Eulerian (ICE) and Arbitrary-Lagrangian-Eulerian (ALE)) approach, as described in Harlow and Amsden (1971) and Hirt et al. (1974), to solve the Navier–Stokes equations in a compressible manner; it uses finite-differences and finite-volume techniques on a staggered Cartesian mesh. Here, we are utilizing iSALE-3D in the Eulerian mode, which additionally requires the reconstruction of interfaces to allow for a precise calculation of material flows. This reconstruction can be performed with an adaptive approach using volume-of-fluid techniques (Benson, 2002; Gueyffier et al., 1999; Hirt and Nichols, 1981) as described in Elbeshausen and Wünnemann (2011). The code has been successfully validated against both laboratory experiments and other numerical codes (Davison et al., 2011; Pierazzo et al., 2008).

To study whether slopes may influence the cratering process of the observed asymmetric craters, we conducted some simulations of oblique impacts into slopes. The effect of topography on impact crater morphology is still far away from being understood and it is not the intention of our study to provide a fully quantified answer to all these effects. Previous numerical studies (Elbeshausen and Wünnemann, 2011b; Elbeshausen et al., 2012) revealed that it is a huge effort to obtain a quantitative description, even when assuming a simplified topography: crater morphology is influenced by (a) the height of the slope, (b) the slope angle, (c) the point of impact relative to the slope, (d) the impact direction and angle compared to the slope, (e) impact velocity, (f) rheology and properties of the slope material, and (g) many other constraints. Thus, trying to generate a quantitative description of the topographical effects would require several thousands of full 3D-simulations at a reasonable resolution. This is far away from being possible, even on today's computer infrastructures. Instead, our intention is here to investigate numerically whether the observed asymmetries in the crater shape and ejecta deposits can be – in principle – explained by the existence of a slope.