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Global and local re-impact and velocity regime of ballistic ejecta of boulder craters on Ceres

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A B S T R A C T

Imaging by the Dawn-spacecraft reveals that fresh craters on Ceres below 40 km often exhibit numerous boulders. We investigate how the fast rotating, low-gravity regime on Ceres influences their deposition. We analyze size-frequency distributions of ejecta blocks of twelve boulder craters. Global and local landing sites of boulder crater ejecta and boulder velocities are determined by the analytical calculation of elliptic particle trajectories on a rotating body. The cumulative distributions of boulder diameters follow steep-sloped power-laws. We do not find a correlation between boulder size and the distance of a boulder to its primary crater. Due to Ceres' low gravitational acceleration and fast rotation, ejecta of analyzed boulder craters (8–31 km) can be deposited across the entire surface of the dwarf planet. The particle trajectories are strongly influenced by the Coriolis effect as well as the impact geometry. Fast ejecta of high-latitude craters accumulate close to the pole of the opposite hemisphere. Fast ejecta of low-latitude craters wraps around the equator. Rotational effects are also relevant for the low-velocity regime. Boulders are ejected at velocities up to 71 m/s.

1. Introduction

Boulders on planetary surfaces are widely studied, because they provide insight into impact processes and the composition of the upper layer of the planetary body. Ballistic models are widely used to describe ejecta emplacement across a planetary surface as well as the material exchange between planetary bodies.

Large ejecta blocks have been identified with imagery of NASA's Dawn spacecraft around morphologically fresh craters (Schröder et al., 2016). In 2015, NASA's Dawn spacecraft arrived at the dwarf planet Ceres to investigate its surface and interior. Onboard instruments include a Gamma Ray and Neutron Detector (GRaND), a framing camera (FC) and a visible and infrared mapping spectrometer (VIR) (Russell and Raymond, 2011). In contrast to pre-Dawn models, mission data suggests that Ceres' heavily cratered crust consists of a ice-rock mixture with less than 40% ice (Bland et al., 2016). VIR data indicates a mixture of ammonia-bearing phyllosilicates, magnesium-bearing phyllosilicates and carbonates (De Sanctis et al., 2016). Ceres exhibits a wide morphologic variety of craters, but basins larger than 300 km are absent (Hiesinger et al., 2016). Furthermore, H_2O was detected, indicating water ice exposure (e.g. Combe et al., 2016). Floor fractured craters, large scale linear structures and domes are interpreted to be an indication for cryovolcanism (Buczkowski et al., 2016; Ruesch et al., 2016).

There are various analytical and numerical studies about the ballistic emplacement of ejecta on bodies of the Solar System. Particle trajectory models provide insight into the correlation between ejecta and existing structures and formations, such as grooves on Phobos (e.g. Davis et al., 1981; Nayak and Asphaug, 2016; Wilson and Head, 2015) and the Moon (Wieczorek and Zuber, 2001), secondary craters (Bierhaus et al., 2012), magnetic anomalies on the Moon (Hood and Artemieva, 2008), tektites on Mars (Lorenz, 2000; Wrobel, 2004) and lunar rays (Giamboni, 1959). Furthermore, ejecta emplacement models provide explanations about observed ejecta geometries and hence the impact process itself, such as for Hale crater on Mars (Schultz and Wrobel, 2012) and Chicxulub crater on Earth (Alvarez, 1996). Studies on global trajectory regimes, the fate of ejected particles and the transfer of particles between planetary bodies, especially between planets and their satellites, have been conducted to examine the interaction between planetary bodies (e.g. Alvarellos et al., 2002; Gladman et al., 1995; Nayak et al., 2016).

Boulders have been investigated with various points of focus, depending on the planetary body and the available data. Size-frequency distributions and shapes of boulders have been studied on the Moon (e.g.

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Greenhagen et al., 2016; Krishna and Kumar, 2016), Mars (e.g. Di et al., 2016b; Golombek et al., 2003), satellites (e.g. Martens et al., 2015; Thomas et al., 2000), comets (e.g. Pajola et al., 2015), but especially on asteroids (e.g. Chapman et al., 2002; Jiang et al., 2015; Lee et al., 1996; Mazrouei et al., 2014; Michikami et al., 2008; Nakamura et al., 2008). Ejection velocities and in some cases ejection sites were estimated for the Moon (Bart and Melosh, 2010a, 2010b; Vickery, 1986), Eros (Durda et al., 2012; Thomas et al., 2001), Lutetia (Küppers et al., 2012) and Ida (Geissler et al., 1996). On Ceres, trajectories of ejection particles have been calculated numerically to test the correlation between ejecta emplacement and linear structures on the surface (Schmedemann et al., 2017).

The purpose of this study is to provide an overview about the ballistic emplacement of ejecta on Ceres, especially for smaller boulder craters. The criteria for the selected twelve boulder craters are the number of boulders, boulder diameters and the crater location. Selected craters must have enough identifiable boulders at a given resolution. Only six craters have enough large blocks that allow size measurements in a sufficient large diameter range. Additional craters were selected to cover all occurring boulder crater diameters and latitudes. At first, we mapped and, if possible, measured boulders of selected craters to analyze their distribution. Initially, we focused on the emplacement of all ejected particles. How do rotation and gravitational acceleration affect ejecta transport of craters in the diameter range of boulder craters? Subsequently, we wanted to know at which velocities boulders were ejected and how their trajectories were influenced by rotation. In addition, we investigate how the choice of impactor parameters alters resulting ejection velocities. We chose a fast and easy implemented analytical approach to calculate re-impact sites introduced by Dobrovolskis (1981).

2. Methods

2.1. Measurement and analysis of boulder and crater diameters

Boulder locations, boulder diameters and the diameters of unnamed craters were measured using the ArcGIS Add-In CraterTools (Kneissl et al., 2011), which allows the determination of diameters of circular features independent of image and data frame map projections. Measurements were conducted on mosaics based on data from Dawn's Low-Altitude-Mapping Orbit (LAMO) with a resolution of 35 m/pixel (Roatsch et al., 2016). Because of the non-circular outline of boulder craters, several circles were fitted to each crater to find average values for diameter and location of unnamed craters. Like boulder craters, boulders are of irregular shape and therefore the longest observable elongation of a block was used to define its diameter. Boulders larger than ~100 m could be distinguished morphologically. Close to the resolution limit, positive and negative topographic features can only be identified by the direction of the shadows they cast. We estimate the error for size measurements to be up to one pixel, which correspondents to 35 m. The separation of single boulders was additionally complicated by dense clustered blocks. In consequence, we decided that only measurements above ~100 m object size are reliable and were therefore used for interpretation. In addition, we identify the largest boulders for 30 craters on Ceres to compare the relation between the maximum block size and the crater diameter.

To analyze the linear relation between block distances and block diameters, we calculated the correlation coefficient, using the Scipy statistics package (Oliphant, 2007). The correlating coefficient *coeff* is defined as $coeff \ = \sum xy/\sqrt{\sum x^2 \sum y^2}$, with $x = x_i - \overline{x}$ and $y = y_i - \overline{y}$, in which $\overline{x}$ and $\overline{y}$ are the mean values (e.g. Bewick et al., 2003). Coefficients close to ± 1 indicate a strong positive or negative linear relationship. Coefficients close to 0 indicates no linear relationship (e.g. Vo.T.H et al., 2017). We decided not to derive p-values for a null hypothesis test that is used to test the significance of the correlation, because a larger number of data points is recommended.

2.2. Size-frequency distributions

Rock fragmentation has been shown to follow a power-law behavior (Hartmann, 1969). Power-law distributions are widely used to describe boulder distributions (e.g. DeSouza et al., 2015; Li et al., 2017; Michikami et al., 2008) and were therefore fitted to our diameter data sets. To fit the distribution, estimating uncertainties and plot results, we use a Matlab implementation of the statistical methods described in Clauset et al. (2009). Closely following their description, a data series follows a power-law distribution, if it satisfies the probability distribution $p(x) \propto x^{-\alpha}$, where α is the exponent or scaling factor. We have a continuous data set, whose complementary cumulative distribution function (CCDF) $P(x)$ is defined by equation (1).

$$P(x) = \int_x^\infty p(x')dx' = \left(\frac{x}{x_{min}}\right)^{-1+\alpha} \tag{1}$$

The lower bound of the power-law behavior is described by x_{min}. Maximum likelihood estimators are used to fit the power-law distribution to the data set. The lower cutoff of the scaling region is estimated with the goodness-of-fit method, based on Kolmogorov-Smirnov statistics. Uncertainties for the constants x_{min} and α are calculated as well.

Goodness-of-fit tests provide so-called p-values (not the same p-value as in statistical hypothesis testing in section 2.1), which describe whether the hypothesis of a power-law distribution is suitable. For this purpose, the “distance” between the data and the model is calculated. That deviation is compared to distances of synthetic data sets. The p-value is the fraction of synthetic data sets that has a larger distance than the empirical ones. It takes values between 0 and 1. Values close to 1 indicate that the model is a good fit for the data. Discrepancies arise from statistical fluctuations. A rule-of-thumb threshold for a good fit is 0.1. Values below that threshold indicate that the power-law distribution is not a good fit for the data. If the number of samples is low, the test is not reliable. To rule out power-law behavior, a large number (~>100) of samples is needed for the p-value to fall off below the threshold.

Sometimes, rock fragmentation is also described by the Weibull distribution (stretched exponential) (Weibull, 1951). It is used, for instance, to describe the size distribution of volcanic ashes (e.g. Gouhier and Donnadieu, 2008). Because of its characteristic rollover at smaller sizes it can be well suited to describe the size-frequency distribution of secondary craters (Ivanov, 2006; Werner et al., 2009) and can therefore be applicable for ejecta blocks as well. We focus on power-law fits because they are more commonly used to describe the size distribution of ejecta blocks and therefore make our results comparable. Nevertheless, we tested whether a stretched exponential distribution would be a better fit for our data with a likelihood ratio test (Clauset et al., 2009). We used the implementation by Alstott et al. (2014). If that ratio is sufficiently positive, the first distribution is considered to be the better fit, if negative the second one. Another p-value is introduced to describe the significance of such ratios. The chosen threshold for the second p-value is 0.1. For values above the threshold, no statement about a favored model can be made.

2.3. Scaling laws

Impact crater scaling laws defined by theory and laboratory experiments describe the relationship between impactor, target and the resulting impact crater (Werner and Ivanov, 2015). For a detailed derivation analysis, we refer to Ivanov (2001) and Werner and Ivanov (2015). The transient crater diameter is the diameter of the initial cavity before crater modification sets in (Melosh and Ivanov, 1999). The transient crater diameter for complex craters is defined as $D_t = D_{sc}^{0.15}\, D^{0.85}$ (Croft, 1985) and for simple craters as $D_t \approx D/1.25$ (Werner and Ivanov, 2015). D is the crater diameter and D_{sc} is the simple-to-complex transition diameter. On Ceres, Hiesinger et al. (2016) calculated a simple-to-complex transition diameter of 10.3 km. Holsapple (1993) distinguishes between strength and gravity regime. The choice of regime