DEPENDENCE OF SECONDARY CRATER SHAPE ON IMPACT VELOCITY

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Introduction: A large fraction of small impact craters on planetary surfaces were formed in low-velocity, secondary impacts [1]. Understanding how crater shape depends on impact velocity has long been a goal of cratering studies [e.g., 2, 3, 4]. Previous work using secondary craters to address this question have disagreed about the dependence of diameter-normalized rim-to-floor depth (d/D) upon distance from the source primary [5,6,7]. The maximum impact speed for secondary craters is the planetary escape velocity (~ 5 km/s on Mars). In practice, it is difficult to identify the source crater for high-velocity distal secondaries, except where they belong to rays and oriented clusters. We have identified > 75 clusters of secondary impact craters in HiRISE stereo imagery [8] from four well-preserved craters with extensive ray systems visible in THEMIS nighttime IR: Zunil, Tomini, Corinto, and Gratteri [9]. We have generated digital elevation models (DEMs) for > 2,700 craters in these clusters, ranging in diameter from 40 m to 300 m, with estimated impact velocities between 0.4 km/s to 2 km/s (based on downrange distance from the source primary and current atmospheric density). We have used these data to examine the morphometric transition between low-velocity "splash" craters and craters that exhibit features typical of hypervelocity craters, especially with regard to cavity depth, rim height, and rim and cavity symmetry. For comparison, we have also estimated the rim height and depth dependence using iSALE computer simulations [10, 11]. In the observations and models, we find that a transition occurs at ~ 1 km/s, somewhat less than the expected target sound speed (> 5 km/s).

Methods: The crater DEMs were generated using the Ames Stereo Pipeline [12]. These were post-processed using a second pipeline developed in-house to compute morphometric quantities [13]. These quantities include: the ratio of rim height and rim-to-floor depth over rim-to-rim diameter (h/D and d/D) as well as the alignment offset between the azimuth to the source crater and all of the following directions: (a) azimuth to the lowest elevation on the rim; (b) vector sum of radial azimuths weighted by rim height; (c) major axis orientation of ellipse fitted to the rim planform; and (d) direction from rim planform center to the position of lowest cavity elevation. For each secondary cluster, a weight was assigned for all potential source craters. This was computed from the degree of alignment with cluster-associated features in THEMIS night-IR, as well as the orientations of highly asymmetric ejecta blankets. The presence of extensive ejecta blankets was mapped and found to depend on geologic setting.

Results: The average shape of low-velocity secondary craters from the Sedan nuclear explosion was described by [3]: the lowest cavity elevation is uprange of the planform geometric center; the crater rim is lowest in the uprange direction and tallest downrange. By contrast, well-preserved hypervelocity craters exhibit a relatively symmetrical shape, with h/D ~ 0.03 to 0.04 on average, and d/D ranging from 0.15 to 0.25 [e.g., 13]. The aforementioned morphometric quantities (see Methods) were plotted as a function of downrange distance in several ways: unbinned, binned by downrange distance intervals, and grouped by cluster. In the case of nearly all parameters, we find that measured distributions are narrow and agree with expectations for splash craters at proximal distances and low impact velocities ($v_i \ll 1$ km/s), and broaden with increasing velocity until $v_i \sim 1$ km/s. For $v_i > 1$ km/s, the widths of the distributions of morphometric parameter values are relatively unchanged.

Simulations: The impact hydrocode iSALE-2D [9] was used to estimate rim height and rim-to-floor depth as a function of impact velocity. The model's axisymmetry (and hence, *vertical* impact angle) is not realistic; fully 3-D simulations are needed to explore the dependence of cavity and rim asymmetry upon v_i. We have assumed a solid rock strength model and material properties appropriate for the young Amazonian lava plains in which the majority of studied craters reside. The model runs were conducted with and without dilatancy [10], and for a duration of two excavation time scales. The simulations correctly anticipate the morphometric transition as a break in slope of d/D versus v_i at $v_i \sim 0.8$ - 1 km/s. The depths predicted by the model correspond to an upper bound for measured values, except where $v_i > 1$ km/s, in which case model estimates are sometimes exceeded. The comparatively large range in measured values for individual clusters may be the result of variations in secondary projectile strength and integrity.

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