A Comparison of Crater-Size Scaling and Ejection-Speed Scaling during Experimental Impacts in Sand.

Jennifer L.B. Anderson[1], Mark J. Cintala[2], and Molly K. Johnson[1]. ([1]JLAnderson@winona.edu)
[1]Geoscience, Winona State University, Winona, MN 55987. [2]Code KR, NASA JSC, Houston, TX 77058.

1. Introduction

Non-dimensional scaling relationships[1,2,3] are used to understand cratering processes including final crater sizes and the excavation of material from a growing crater. It is assumed that, beyond a few projectile radii from the impact point[2,4], these processes depend only on a combination of the projectile's characteristics, namely its diameter, density, and impact speed, thus simplifying the impact event into a single point-source of energy and momentum.

Laboratory experiments allow these scaling relationships to be tested by controlling initial impact conditions and measuring the resulting processes directly. In this contribution, we continue our exploration of the congruence between crater-size scaling and ejection-speed scaling relationships. In particular, we examine a series of experimental suites in which the projectile diameter and average grain size of the target were varied.

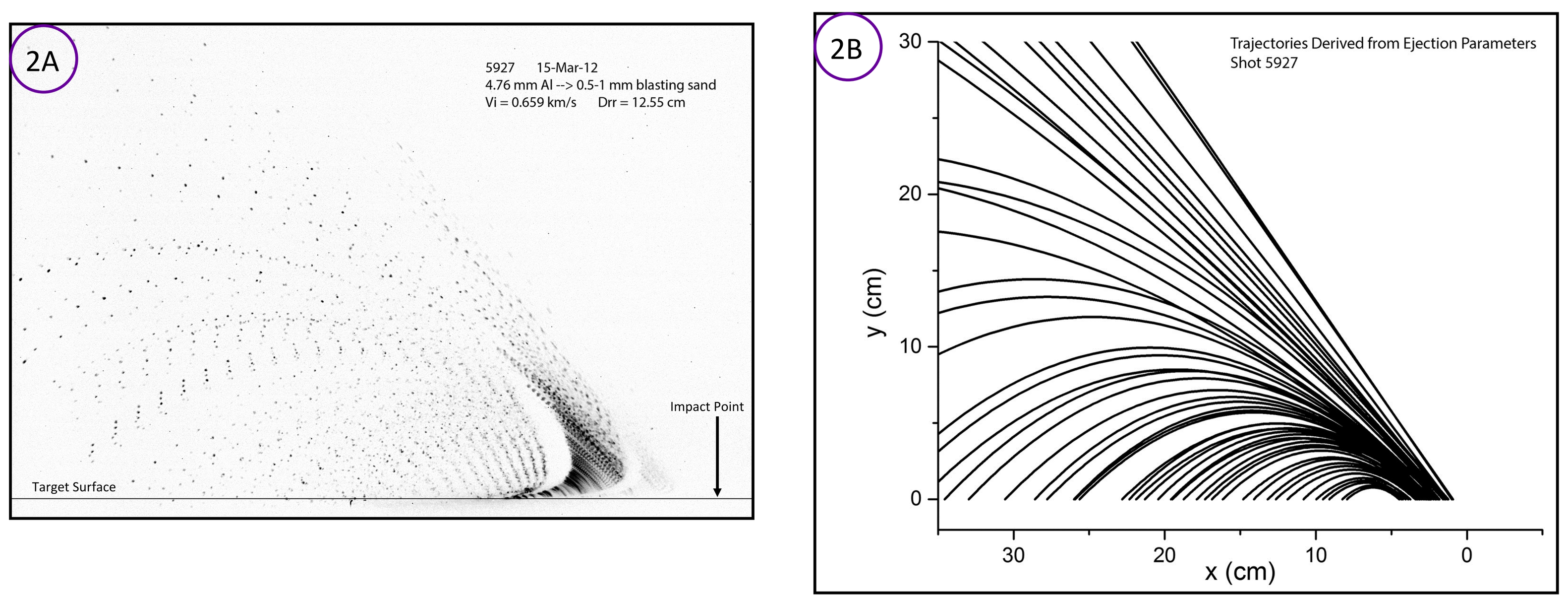
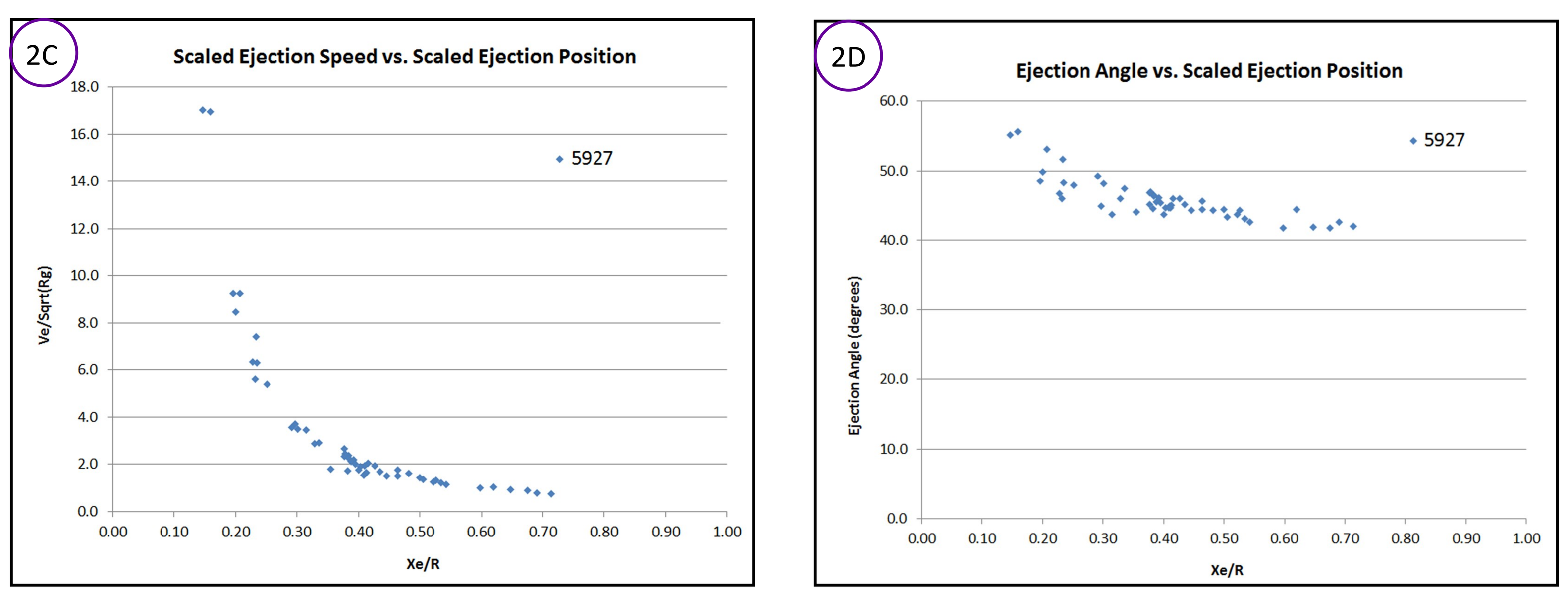


Figure 2. Shot 5927 is an example of the EVMS analysis completed for each shot in each experimental suite. **A.** EVMS image (shown inverted). **B.** Trajectories derived from ejection parameters. **C.** Scaled ejection-speed vs. position. **D.** Ejection angle vs. scaled ejection position.



2. Ejection-Velocity Measurement System (EVMS)

The EVMS projects a "sheet" of laser light through the impact point perpendicular to the target's surface and a camera views the event from a precisely known geometry (Figure 1). The laser is strobed at a known rate, permitting individual ejecta to be traced along their ballistic trajectories (Figure 2A).

Individual trajectories are measured from the EVMS images and extrapolated back to the target surface, yielding ejection position, speed, and angle data for each particle (Figures 2B, C, and D). The final crater dimensions are also measured, thus permitting analysis of both crater-size and ejection-speed scaling relationships.

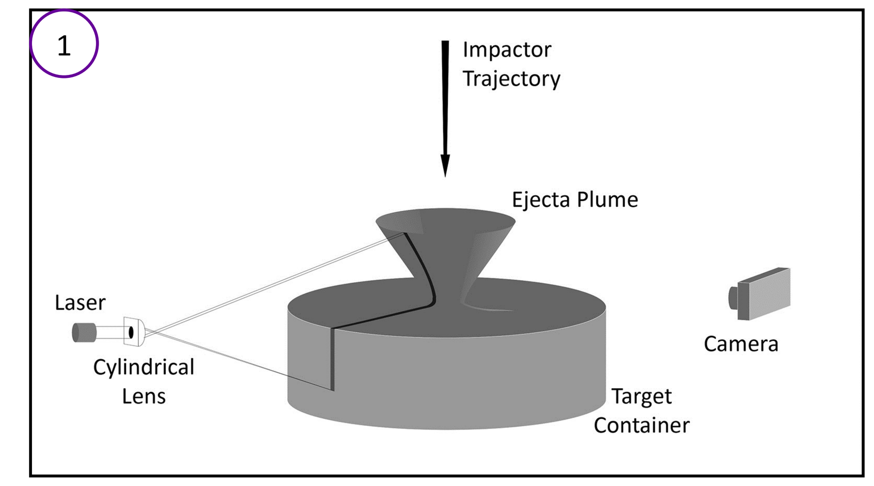


Figure 1. EVMS set-up.

3. Experimental Methods

All experiments were performed at the vertical gun in the Experimental Impact Laboratory at NASA Johnson Space Center. Ejecta were documented using an updated version of the Ejection-Velocity Measurement System (EVMS)[5] (Figure 1). Impact speeds ranged from 0.6-2.4 km/s at vertical incidence angles at pressures < 1 torr. See Table 1 for details of the experimental suites.

Table 1. Experimental Suites			Crater-Size Scaling		Ejection-Speed Scaling		
Projectile (spheres)	Target	γ	α	R^2	α (avg.)	R^2 (range)	Reference
3.18 mm glass	1-3 mm sand	1.8	0.47	0.97	0.69	n/a	[6]
4.76 mm aluminum	1-3 mm sand	2.8	0.45	0.95	0.67	n/a	[5]
3.18 mm glass	0.5-1 mm sand	4.5	0.45	0.93	0.68	n/a	[7]
4.76 mm aluminum	0.5-1 mm sand	6.7	0.46	0.99	0.57	0.77 - 0.97	This study
4.76 mm glass	0.5-1 mm sand	6.7	0.43	0.97	0.58	0.87 - 0.98	This study
6.35 mm aluminum	0.55 mm sand	11.5	0.45	n/a	0.50	n/a	[8]

4. Crater-Size Scaling

Final-crater dimensions have been tied to initial impact conditions through Π-scaling relationships,[2,3] which infer that a single coupling parameter α is related to the slope of the Π_R vs. Π_2 relationship (Figure 3, Eq. 1). Values of α derived for each suite are given in Table 1.

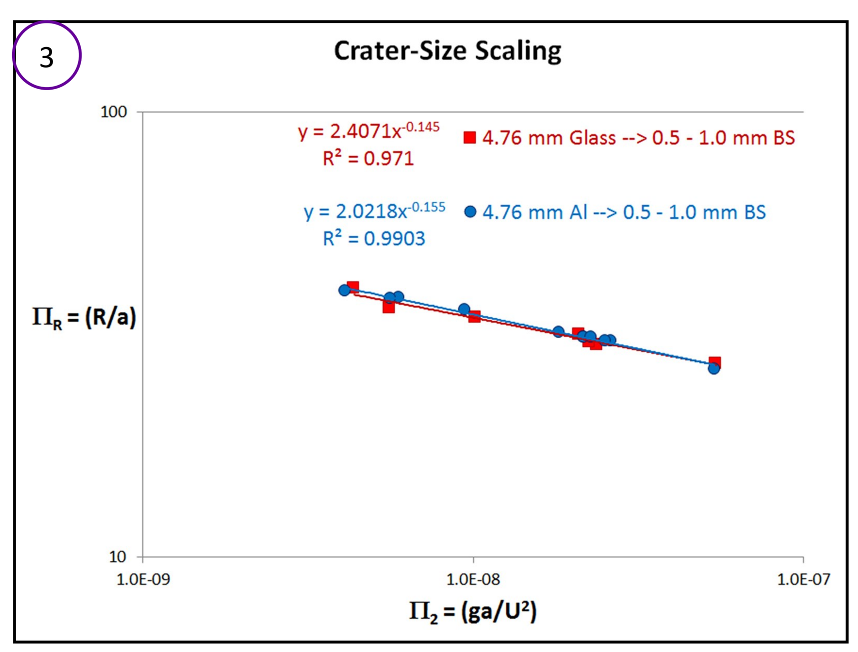


Figure 3. Crater-size scaling.

5. Ejection-Speed Scaling

The scaled ejection-speed is related to the scaled ejection-position by a power law[3] (Equation 2) whose exponent e_x is a function of the coupling parameter, α (Equation 3). These exponents and the derived values of α were calculated for each individual shot (see Figure 4); the average values for each suite are given in Table 1. Note that the α values derived from the ejection-speed scaling are higher than those from the crater-size scaling.

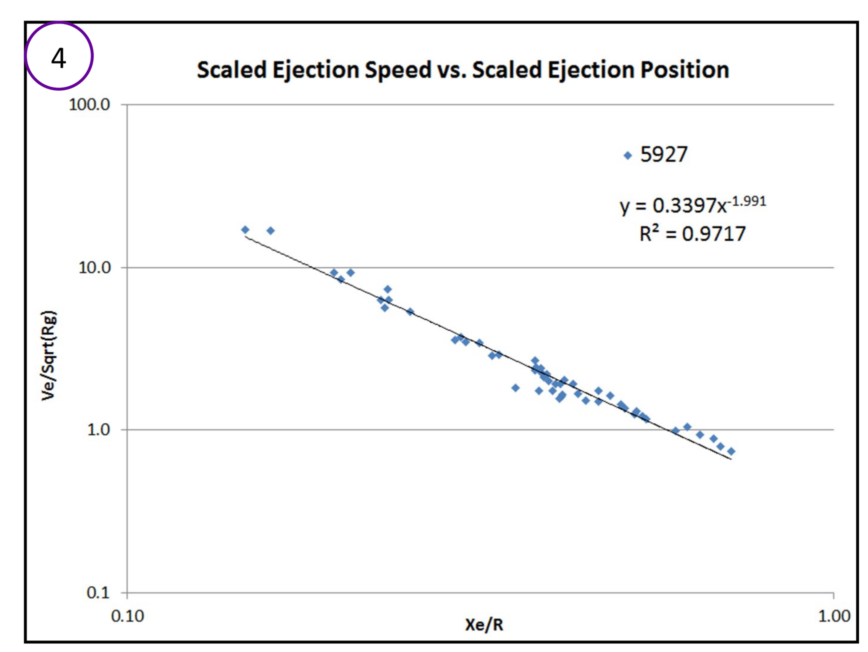


Figure 4. Ejection-speed scaling.

$$\frac{R}{a} = k_2\left(\frac{ga}{U^2}\right)^{-\alpha/3} \quad [1]$$

$$\frac{v_e}{\sqrt{gR}} = k_1\left(\frac{x_e}{R}\right)^{-e_x} \quad [2]$$

$$e_x = \frac{3-\alpha}{2\alpha} \quad [3]$$

$$\gamma = \frac{projectile\ diameter}{avg.\ target\ grain\ size} \quad [4]$$

6. Dependence of Point-Source Solution on Target Granularity

The first EVMS study[5] initially noted that the two scaling relationships yielded different values of the coupling parameter with the α values derived from ejection-speed scaling being higher than those from crater-size scaling. This difference was suggested to be a result of the similarity in dimensions between the target grains and the projectile. Subsequent EVMS studies[6,7] found similar discrepancies between the crater-size and ejection-speed values for α. The data in this study follow this trend. Scaling results obtained using Particle Imaging Velocimetry (PIV) and a much finer grained target[8], however, showed much better agreement between the two values of α. (All data are given in Table 1).

To examine whether this variation in α might be a result of the target's granularity, we defined a parameter, γ, to be the ratio of the projectile diameter to the mean dimension of the target grains[7] (Equation 4); γ is given for all experimental suites in Table 1. The updated EVMS with its higher-resolution camera permits detailed analysis of much finer-grained targets than was possible previously, thus increasing the range in γ available for EVMS study.

The derived values of α as a function of γ for the six experimental suites are shown in Figure 5. Crater-scaling values are all near the theoretical minimum. However, at small γ (similar sized projectile and target grains), the values derived from the ejection speeds are much higher. As γ increases, the ejection-speed values appear to converge with the crater-scaling values, as expected for a continuous material. It is notable that this trend appears to be independent of projectile material. Future work will attempt EVMS analysis of an even finer-grained target material to achieve larger γ values for direct comparison with the results of the PIV study[7].

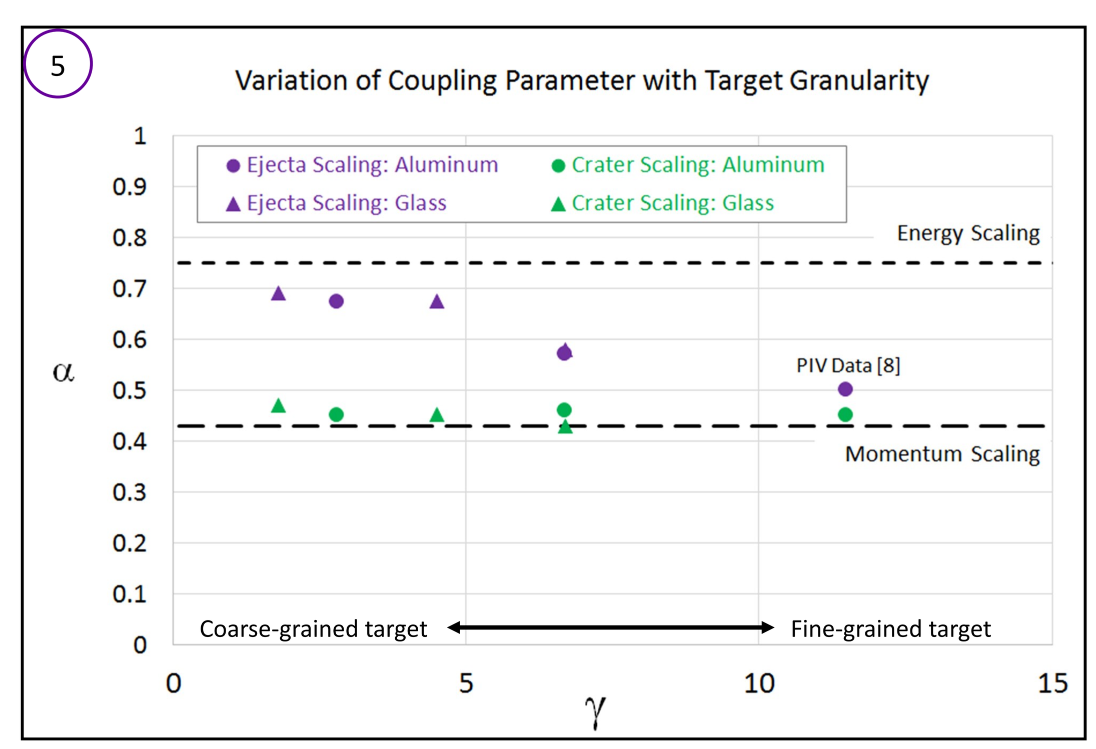


Figure 5. Values of α derived from ejecta-scaling relationships (purple) and crater-scaling relationships (green) as a function of target granularity, γ. Note that as the grain size of the target decreases (and γ increases) the two different methods appear to converge on the same coupling parameter value.

7. Implications

While the assumption is commonly made that a planetary-scale target surface would present a uniform continuum to incoming projectiles, high-resolution images are showing the true diversity of surfaces and the number of fragments embedded in regoliths. Such large fragments may present complexities in subsurface structure that could violate the point-source assumption inherent to crater-scaling relationships.

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