REDUCED GRAVITY EJECTA EMPLACEMENT EXPERIMENTS. K. D. Runyon[1], D. D. Durda[2], C. Tsang[3], V. Klein[2], C. M. Ernst[4], H. T. Smith[4], O. S. Barnouin[4], A. Martin[4], A. Nguyen[5], [1]Planetary Science Institute (krunyon@psi.edu), [2]Southwest Research Institute, Boulder, CO, [3]Boulder, CO, [4]Johns Hopkins Applied Physics Laboratory, Laurel, MD, [5]Vassar College, Poughkeepsie, NY.

Introduction: Impact cratering dominates surface geological processes among solid bodies in the solar system. As a corollary, the excavated and emplaced crater ejecta complement this surface process domination; on even small bodies such as asteroids Ryugu and Bennu, ejecta can be retained [e.g., Richardson et al., 2007; Arakawa et al., 2020; Perry et al., 2022]. Small bodies missions such as Lucy, Psyche, Mars Moon Explorer, and others, and numerous robotic and even human missions to the Moon, will provide abundant opportunities to better characterize the processes and resulting facies related to ejecta emplacement. Crucially, these upcoming missions will all be on worlds with low gravity (<2 m/s^2).

The concept of *scaling* is important when extending the results of laboratory impact cratering to planetary size and velocity regimes [e.g., Schmidt and Holsapple, 1980; Holsapple, 1993; Housen et al., 1983; Housen and Holsapple, 2011]. Two useful parameters for cratering are the cratering (or excavation) efficiency defined as the *removed mass*/*emplaced mass* or

$$M/m; \qquad \text{Eq. 1}$$

and the inverse-Froude number, π_2, as the product of the body's gravity and the size scale (impactor diameter or ejecta curtain width) divided by the square of the impact speed, or

$$\pi_2 = 3.22gr/v^2, \qquad \text{Eq. 2}$$

where 3.22 is a factor used for experimental historical consistency [Schultz and Gault, 1985]. Laboratory results [Runyon and Barnouin, 2018] show that granular ejecta slide, erode, and mix with granular regolith following deposition, leading to geologically complex stratigraphy. Our initial experiments [Runyon and Barnouin, 2018] were not sufficient in number to show whether any scaling rules exist for ejecta deposition; hence more work has been needed.

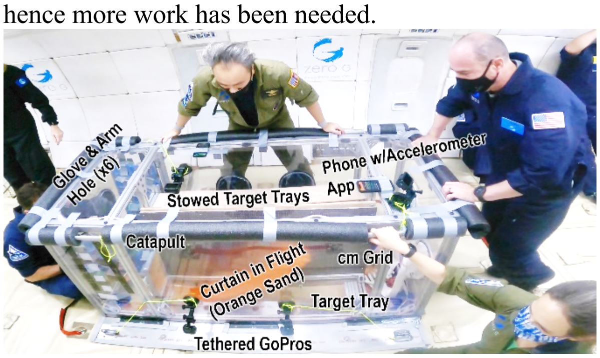

Figure 1. The glovebox with the ejecta catapult in parabolic flight. Note the six armholes (partly obscured). Video still credit: Zero-G/Steve Boxall.

Two questions in our ongoing research are, "How do crater ejecta mobilize regolith on small bodies?" and "Does ejecta emplacement follow scaling rules, especially power laws?" Unlocking the secrets of the evolution of small bodies requires correlating samples and surface units to their provenance and providing geologic context for returned samples. This geologic goal benefits from reduced gravity experiments to understand the interplay between chaotic granularity effects and the slow (few cm/s) deposition and runout speeds expected on small bodies. Our experiments are uniquely tailored to understanding transport histories and dynamics (e.g., implantation, exhumation, mobilization) of geologic materials on small bodies.

Methods: To understand ejecta emplacement on low-gravity worlds, we designed an experimental apparatus for use in reduced-gravity parabolic flight on The Zero Gravity Corporation's ("Zero-G") modified Boeing 727-200 aircraft. A six-arm-hole glovebox contained an ejecta catapult and regolith-ejecta simulant target trays filled with sand (Fig. 1 & 2). The catapult simulates a portion of a granular ejecta curtain using colored sand, and enables studying ejecta dynamics and deposits without needing to also simulate the progenitor crater (Fig. 2); it is based on a much larger, ground-based facility in the Planetary Impact Lab at Johns Hopkins APL [Runyon and Barnouin, 2018].

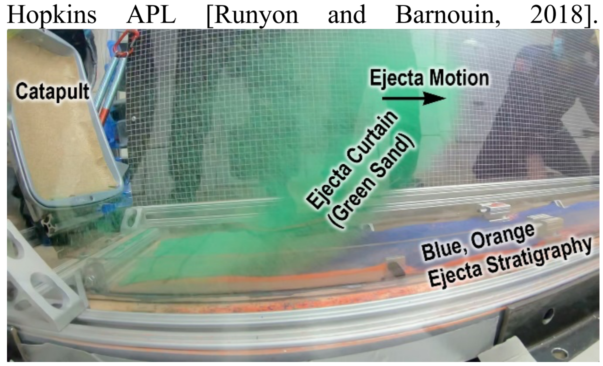

Figure 2. GoPro video still from a Martian gravity (~3.72 m/s^2) parabola showing an ejecta curtain and deposit made of green sand being emplaced over prior deposits of blue and orange sand. The just-fired catapult is seen on the left; the two springs are visible behind it. Reflections of personnel are visible in the glovebox

sides. GoPro camera lens distortion renders the straight metal sides to appear curved.

Our parabolic flight campaign began in December, 2021 and consisted of 30 parabolas: 10 of Martian gravity (3.72 m/s^2), 10 of lunar gravity (1.62 m/s^2), and 10 of near-microgravity. In actuality, variations in the precision of the parabolas flown allow for moments of milli- or centi-gravity with accelerations on the order of 1-10 cm/s^2; this is very nearly the gravity expected on large asteroids. By conducting similar catapult ejecta experiments at a range of gravity levels and deposit speeds, we were able to explore a range of π_2 values and thus test the hypothesis that a *M/m* vs. π_2 power law relationship exists for ejecta emplacement. This experimental setup also allowed us to observe differences in ejecta runout, mixing, and eroding with the sand in the target trays.

Status and Future Work: We are in the midst of analyzing video data for ejecta curtain size and velocity. Preliminary results show that the ground-projected curtain width (*r* in Eq. 2) is 5 ± 2 cm for both martian and lunar gravity and 7 ± 2 cm for mill-/centi-gravity. Acceleration values for the 10 martian and 10 lunar gravity parabolas are 3.46 ± 0.20 m/s^2 and 1.45 ± 0.19 m/s^2 for martian and lunar gravities respectively. For four of the mill-/centi-gravity parabolas the acceleration was 0.21 ± 0.19 m/s^2. Fig. 2 shows orange, blue, and green ejecta layers from subsequent ejecta emplacements. Preliminary π_2 values appear to be 1.7 ± 0.6 and 1.0 ± 0.3 for martian and lunar parabolas, respectively (Figure 3), much larger than previously measured π_2 values in impact or larger ejecta experiments.

Future analysis of existing data and a follow-on flight in spring 2023, will complete the scaling and geologic experimentation and analyses. Our next flight will use crushed colored chalk with a size-frequency distribution more akin to asteroidal regolith, such as on Bennu (power-law slope of -3.0 ± 0.2; Burke et al., 2021).

References: **Arakawa,** M., et al. (2020). An artificial impact on the asteroid (162173) Ryugu formed a crater in the gravity-dominated regime. Science, 368(6486), 67-71. | **Burke**, K. N., et al. (2021). Particle size-frequency distributions of the OSIRIS-REx candidate sample sites on asteroid (101955) Bennu. Remote Sensing, 13(7), 1315. | **Holsapple**, K.A., 1993. The scaling of impact processes in planetary sciences. Annu. Rev. Earth Planet. Sci., 21, 333-373. | **Holsapple**, K.A., Schmidt, R.M., 1982. On the scaling of crater dimensions 2: impact Processes. J. Geophys. Res. 87 (B3), 1849–1870. https://doi.org/10.1029/JB087iB03p01849. | **Housen**, K.R., Holsapple, K.A., 2011. Ejecta from impact craters. Icarus, 211, 856-875, doi:10.1016/j.icarus.2010.09.017. | **Housen**, K.R., Schmidt, R.M., and Holsapple, K.A., 1983. Crater ejecta scaling laws: Fundamental forms based on dimensional analysis. JGR, 88, B3, 2485-2499. | **Perry**, M. E., et al (2022). Low surface strength of the asteroid Bennu inferred from impact ejecta deposit. Nature Geoscience, 1-6, doi: 10.1038/s41561-022-00937-y. | **Richardson**, J.E., et al. 2007. A ballistics analysis of the Deep Impact ejecta plume: Determining Comet Tempel 1's gravity, mass, and density. Icarus, 191, doi:10.1016/j.icarus.2007.08.033. | **Runyon**, K. D., & Barnouin, O. S. (2018). Preliminary laboratory investigations of ejecta emplacement dynamics and morphology with planetary applications. Planetary and Space Science, 160, 39-55. | **Schmidt**, R.M., Holsapple, K.A., 1980. Theory and experiments on centrifuge cratering. JGR 85, B1, doi:10.1029/JB085iB01p00235. | **Schultz**, P. H., & Gault, D. E. (1985). Clustered impacts: Experiments and implications. Journal of Geophysical Research: Solid Earth, 90(B5), 3701-3732.

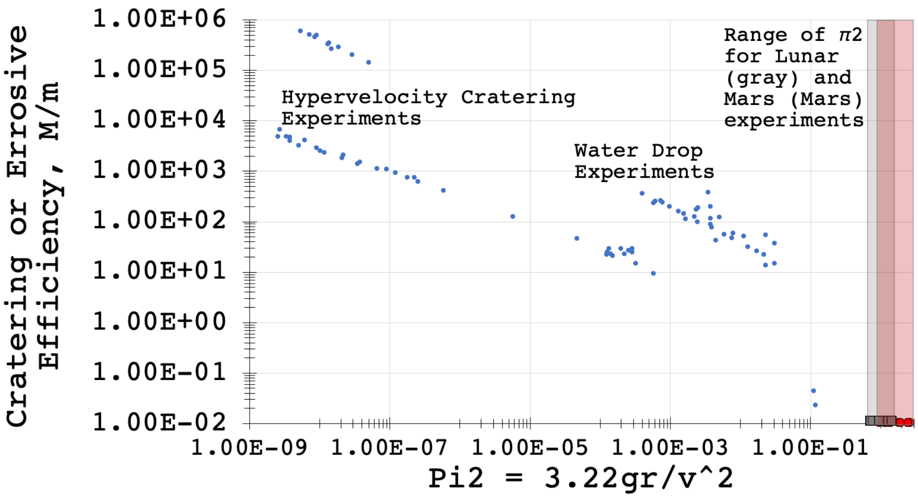

Figure 3. Scaling data from past hypervelocity and water drop experiments (blue dots; Holsapple and Schmidt, 1982; Schultz & Gault, 1985) in context with π_2 values for lunar and martian gravity data. As yet the erosive efficiency is unconstrained for our experiments.