LCROSS EJECTA DYNAMICS: INSIGHT FROM EXPERIMENTS B. Hermalyn[1], P. H. Schultz[1], A. Colaprete[2], M. Shirley[2], and K. Ennico[2], [1]Brown University, Providence, RI 02912-1846 (Brendan_Hermalyn@brown.edu), [2]NASA Ames Research Center, Moffett Field, CA 94035

Introduction: The Lunar CRater Observation and Sensing Satellite (LCROSS) mission impacted the moon in a permanently shadowed region of Cabeus crater on October 9th, 2009. Using the second stage of the LRO/LCROSS launch vehicle as a kinetic probe, the mission was designed to excavate potentially water-ice rich regolith into sunlight. Photographic and spectroscopic measurements from the following shepherding spacecraft (SSc) documented the ejected materials. Prior to impact, several independent studies predicted the ejecta dynamics of the impact event through the use of scaling laws [1, 2], computational modeling [3], and experiments [2, 4]. The unusual conditions of the impact, however, made predictions based on the canonical cratering models difficult. Here we present initial results of an experimental campaign designed to better understand and interpret the LCROSS impact event.

LCROSS Impact: The empty Centaur upper stage of the Atlas V that launched LRO/LCROSS to the moon impacted the lunar surface at $\sim$2.5km/s at an angle of $\sim 85^\circ \pm 5^\circ$ from horizontal. This impact was a unique cratering event for a number of reasons. First, the geometry of the Centaur upper stage was a thin cylinder with the majority of the mass located on the ends, resulting in a non-standard projectile of extremely low relative density. Second, the low impact velocity (compared to the Deep Impact mission or natural planetary impacts) means that this was not a true hypervelocity impact, as the back of the projectile felt the shock prior to reaching the surface. Third, while the target lunar regolith was expected to form a crater largely in the gravity-scaling regime, it does not have the same material properties as sand. Lastly, since the impact took place in a permanently shadowed region, the ejecta needed to reach the sunlight horizon before becoming visible and heating up to dissociate volatiles on grain surfaces. The Cabeus impact area had a sunlight horizon of $\sim$830m, requiring any material reaching this horizon to be ejected at high velocities. Therefore, the early-time, high-speed component of ejecta will be the first to reach sunlight. During the impact event and subsequent excavation of material into sunlight, the trailing SSc recorded visible (VIS), near infrared (NIR), and mid infrared (MIR) images and spectra of the ejecta evolution for approximately 4 minutes before loss of signal (Fig. 1). By combining the measurements from multiple instruments, a time-resolved evolution of the cratering event could be constructed.

Experimental Studies: As part of a study to understand the effect of impact parameters on the early-stage ejecta distribution, a series of impact experiments were performed at NASA Ames Vertical Gun Range (AVGR) designed to explore the characteristics also relevant to the unique LCROSS impact. Hollow aluminum spheres were employed in order to study the effect of underdense projectiles. The hollow nature of these impactors decreases their relative density by a factor of $\sim$4 from solid spheres. These experiments used #20-30 sand and pumice target materials to examine the role of compressibility in the impact. Here, we present initial results for the sand experiments for comparison with prior studies.

The velocity of the ejecta was directly measured using particle tracking velocimetry (PTV), a noninvasive imaging technique that measures the velocities of individual particles in the ejecta curtain profile. The PTV technique enables the determination of very high ejection velocities over a wide range of ejection angles. The data sets were recorded at high speeds ($\sim$11,000 to 500,000 frames per second), thereby allowing for time-resolved examination of the early-time ejecta flow field.

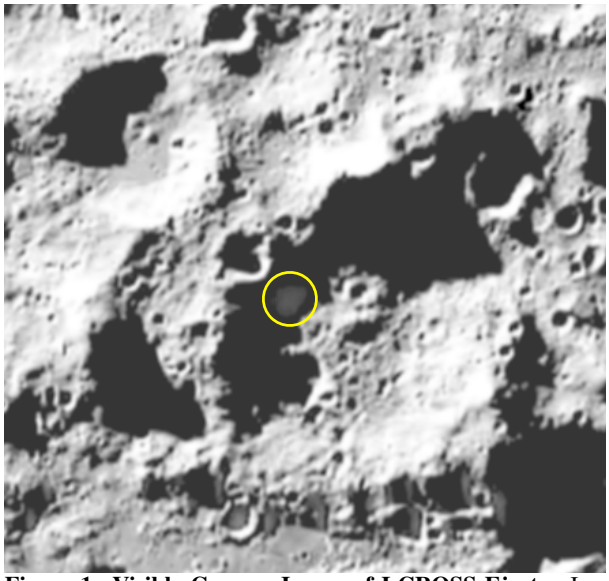

Figure 1: Visible Camera Image of LCROSS Ejecta. Image shows visible ejecta (circled in yellow) reaching sunlight a few seconds after the impact into Cabeus. Image has been processed to enhance visibility of plume.

Analysis and Results:

At very early times after impact, a high-speed departure over widely accepted dimensional scaling laws is measured in the laboratory (Fig. 2). This initial high-speed component (primarily composed of fine material) is characterized by a fairly small amount of mass relative to the total ejected volume, and appears thermally self-luminous. The ejection angles of this early-time component start out quite low ($< 25°$) and sweep upward to the nominal ejection angle of $\sim$45° for sand during the excavation stage of cratering for the solid projectile. Hollow projectiles exhibit lower ejection angles, consistent with a shallower coupling depth [5]. This early-time component is particularly important for the LCROSS conditions, as this will be the material that has sufficient velocity to emerge from shadow into sunlight. Since the location and velocity of the ejected particles is known with high precision, each particle can be ballistically retracted to its launch position on the surface. This provides a metric for the size of the transient crater, allowing calculation of a maximum amount of ejected mass as a function of time (Fig. 3). In addition to the early-time low-angle particulate ejecta curtain, hollow projectiles form an early-stage high angle plume of high speed fine material in compressible targets, which remains aloft and visible well past the end of crater growth [6].

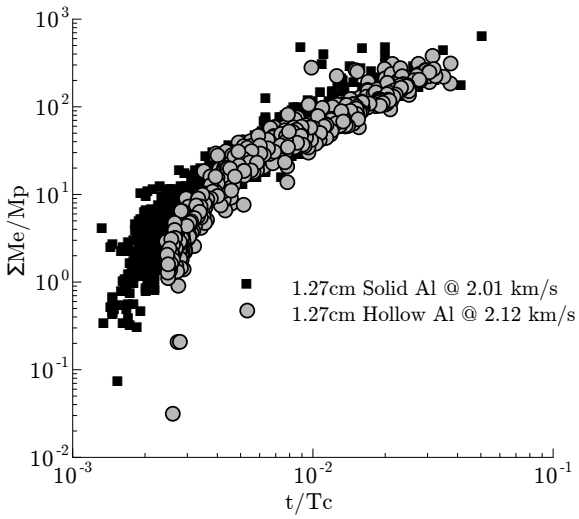

Figure 3: Cumulative Ejected Mass vs. Time for experimental studies. Cumulative mass ejected is scaled to the mass of the projectile; time is scaled to the time of crater formation. Mass is geometrically calculated as an upper bound of excavated material. Experiments are 90° impacts of hollow aluminum (H. Al) and solid aluminum projectiles in #20-30 sand.

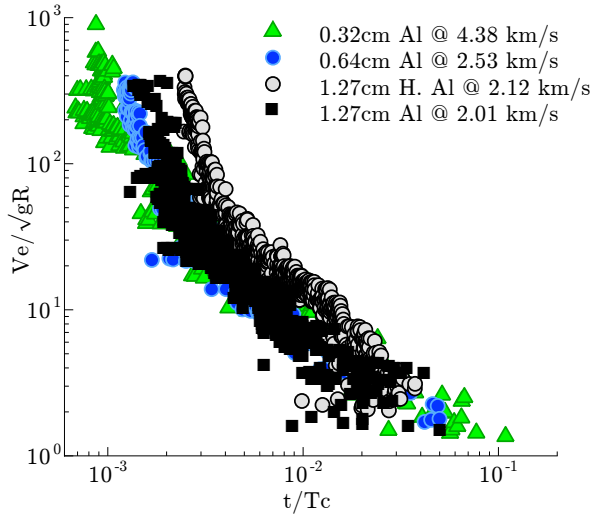

Figure 2: Scaled Velocity vs. Time for experimental studies. Velocity is scaled to the square root of gravity times the final crater radius; time is scaled to the time of crater formation. Although all experiments converge on a common late-stage line, as predicted by dimensional analysis, early-time velocities fall above predictions. This departure from power-law behavior encompasses a greater portion of crater growth as projectile size increases. Experiments are for 90° impacts into #20-30 sand; all impactors are solid except the 1.27 diameter Hollow Aluminum (H. Al).

Conclusions: The experimental studies conducted provide better understanding and interpretation of the ejecta dynamics of the unique LCROSS impact event. Analysis of the LCROSS data suite allows comparison with the experimental campaign to estimate the amount of mass ejected into sunlight in the different ejecta components, providing crucial tie-points for the in-situ abundances of volatiles measured in the spectrometers.

References:

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