

DSMC Modeling of the LCROSS 3-Component Impact Plume through Observations of Lunar Dust from the Shepherding Spacecraft's Near-IR Spectrometer 2 (NSP2) Camera. William Jo¹, David B. Goldstein¹, Philip L. Varghese¹, Laurence M. Trafton², Jennifer L. Heldmann³, Anthony Colaprete³, ¹Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, ²Department of Astronomy, The University of Texas at Austin, ³NASA Ames Research Center, Moffett Field, Mountain View, CA. (williamjo@utexas.edu)

Introduction: In 2009, NASA's Lunar Crater Observation and Sensing Satellite (LCROSS) was launched to study water ice in Cabeus Crater. The LCROSS mission was comprised of two major components: a large but empty rocket upper stage (Centaur) for impact plume generation, and a smaller Shepherding Spacecraft (S-SC) for data collection. Centaur impacted the moon at a velocity of 2.5 km/s almost normal to the lunar surface, lofting almost 200,000 kg of lunar regolith and water ice trapped in Cabeus Crater [1]. The S-SC followed Centaur's descent toward the lunar surface, and impacted 250 s later.

The research herein will examine the three-component Centaur debris plume model through simulation of the NSP2 sun viewing near-infrared spectrometer instrument located on the S-SC and compare computational simulations of dust grain column density with those obtained from the LCROSS mission. Recreation of the plume will follow crater ejecta scaling laws [2] and experimental data of hollow impactors into sand and pumice [3]. This research will refine simulation parameters such as launch angles and velocities and grain sizes to replicate the column density of dust grains as seen through the NSP2 instrument at times 200 – 250 s after Centaur impact. The information attained will be useful for further simulations to better understand the subsurface distribution of water at the Cabeus impact site.

Methodology: *Impact Cratering Mechanics – Low Angle Plume:* The velocity of ejecta v_e from an ejecta plume can be written as: $v_e = f(R, \rho, Y, g, x)$, where R is the final crater radius, ρ is the target regolith density, Y is the target cohesion strength, g is the gravitational acceleration of the moon, and x the radial distance from the point of impact [2]. Through dimensional analysis, there are three Π variables that describe the relation for the ejecta velocity v_e . To simplify the expression, the Π variable containing the target strength Y can be neglected; from literature, the cohesion strength for lunar regolith (~3 kPa) is weak in deep lunar regolith [4]. As Centaur is estimated to have excavated most lunar material up to ~5 m below the lunar surface [5] and median regolith depths in non-mare regions are around 6 – 8 m deep [6], it is assumed that only the fined-grained surficial regolith was displaced and layering below this top layer was not disturbed by Centaur's impact. Therefore, we can reasonably model the ejecta physics of the LCROSS mission within the gravity regime alone. This

leaves us with the a power law scaling equation for normalized ejecta velocity, where α is an experimental parameter [2]. Using a time T_c , defined as the time for ejecta mass to be completely lofted out of the crater, and the term x/R , defined as the normalized origin radius of the material which sources the plume, the equation for v_e can then be written in terms of normalized time after Centaur impact t/T_c [2]. This leaves us with the following relation between non-dimensionalized ejecta velocity and non-dimensionalized time after impact, shown in eq. (1).

$$\frac{v_e}{\sqrt{gR}} \propto \left(\frac{t}{T_c}\right)^{\frac{\alpha-3}{\alpha+3}} \quad (1)$$

To model the hollow Centaur cylindrical body, a best fit line is fitted through the 'hollow' points from figure 6 in Hermalyn et al. (2012), describing a log-log scatter plot of normalized experimental ejecta velocity vs. time. The corresponding equation generated from the best fit power equation will determine the value of α . Using an expression for the volume of ejecta launched before time t from Housen et al. (1983), a cumulative distribution function (CDF) of the mass lofted during crater formation can be derived [2]. In the case of simulation parameters associated with LCROSS, and under the assumption that dust grains are uniform in density and radius, the CDF of the number of grains lofted during crater formation is represented in equation 2. f is defined as the probability that a grain was ejected out of the crater before time t . In the case of LCROSS, the time t is bounded by $0 < t < 1.3$ s [3].

$$f_{\text{grains lofted}} = \left(\frac{t}{T_c}\right)^{0.3158} \quad (2)$$

The CDF is used via a random number draw to assign computational grains a 'pseudo' simulation time, which in turn is used to obtain a launch velocity and launch angle based on Hermalyn et al. (2012) [3].

Spike Plume Estimation: For the central spike component of the plume, distributions of ejecta velocity and angle have been difficult to characterize experimentally, and data characterizing the relationship between ejecta angle and velocity with ejecta time are absent [3]. Strycker et al. (2013) separates the central spike into two components: a medium and high-angled plume. From baseline values from Strycker et al. (2013), we characterized the medium-angled plume with random launch angles between 55 – 75° and launch velocities between 150 – 400 m/s, and the high-angled plume with

random launch angles between $75 - 90^\circ$ and velocities between $300 - 500$ m/s [7].

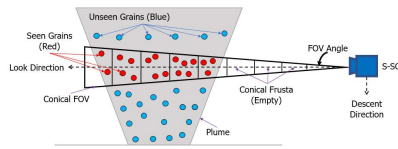


Figure 1: A two-dimensional representation of the S-SC NSP2 FOV as it views a sample impact plume. The FOV is separated into sections called frusta and different grain counts are tabulated within each frusta of the FOV.

Computation of Grain Count Column Density: The sun viewing NSP2 instrument was designed with the spectrometer entrance fiber adjoined to a diffusion plate, preventing the instrument from being oversaturated from the sun. This light would first enter the diffuser and then feed into the entrance fibers of the NSP2 instrument. However, the addition of the diffuser to the NSP2 has an effect consistent with a Lambertian surface: The light signal falls off as the cosine of the angle with the surface normal. For a suitable model accounting for the behavior of the diffuser, a small conical FOV of 0.52° is appropriate as a sampling beam for detecting computational grains of dust in the simulation [8]. This simulation will require a large number of computational grains of $> O(10^6)$ to attain an attenuated simulated NSP2 signal.

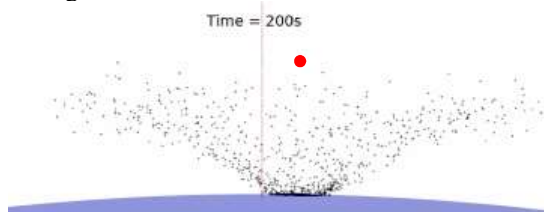


Figure 2: Snapshot of a low angle plume impact governed by the ejecta scaling relations from Housen et al. (1983) and data from Hermalyn et al. (2012) at time after Centaur impact $t = 200$ s on a simulated moon. Dust grains are colored black while the S-SC is colored in red.

To compute the grain count column density, the conical FOV is separated into several different conical frusta separated along the direction of the line of sight, portrayed in figure 1. Dust grains would enter the volume of the conical FOV during the descent of the S-SC and the number of dust grains in each frusta are tabulated at each simulation step. The number density of grains in each frusta are computed and are assigned a position along the line of sight of the FOV. Integration of the number density along the line of sight yields the simulated column density.

Model: Figure 2 provides a snapshot of the low angled plume at time = 240 s, as the S-SC is about to impact the surface of the Moon ~ 10 s later, and figure 3

compares dust grain column density vs. time for the three component plume and the NSP2 measurements. In figure 3, column density contribution must be increased between $247 - 250$ s for the medium-angled plume, and $220 - 240$ s for the high-angled plume to have simulation dust column density to match that of experimental data. This can be done by means of grain diameter decrease, hinting at the theory that spike ejecta is comprised of extremely fine, small dust grains rather than intact, larger ones [3].

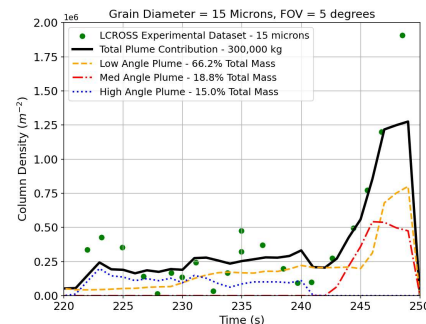


Figure 3: Plot of a sample case of dust grain column density ($\#/\text{m}^2$) vs. time (s) for the computational and NSP2-observed LCROSS plume using a 15-micron diameter grain size and 5° FOV, following dynamics of pumice ejecta [3].

Conclusion: Comparing experimental results of dust column density vs. time on the NSP2 S-SC with simulation results from the 3-component impact plume can help us attain two different goals to improve the physics of the impact plume modeling and understanding the subsurface distribution of dust and water. With defined mathematical constraints governing of the simulated low angle plume from Housen et al. (1983), we can attain an improved estimate of the ranges of angles, velocities, and CDF of the number of grains lofted during crater formation for the plumes comprising the central spike, better characterizing impacts similar to LCROSS. Furthermore, a layering profile of dust grain sizes and densities can be derived through fitting of simulated to experimental dust column density. Using depth of origin correlations from Hermalyn et al. (2012), we can improve the compositional detail of the subsurface regolith layer at the Cabeus impact site.

References: [1] Colaprete, A., et al., *Science* 330.6003 (2010): 463-468. [2] Housen, K. R., et al., *JGR: Solid Earth* 88. B3 (1983): 2485-2499. [3] Hermalyn, B., et al., *Icarus* 218.1 (2012): 654-665. [4] Sánchez, P. and Scheeres, D.J., *MPS* 49, no. 5 (2014): 788-811. [5] Luchsinger, K.M., et al., *Icarus* 354 (2021): 114089. [6] Richardson, J.E., and Abramov, O., *PSJ* 1, no. 1 (2020): 2. [7] Strycker, P.D., et al., *Nature communications* 4.1 (2013): 1-9. [8] Colaprete, A., Personal Communication (2020)