Using ground based observations of the LCROSS impact plume to investigate water ice stratification within permanently shadowed lunar sediment. K. M. Luchsinger[1], N. J. Chanover[1], P. D. Strycker[2], [1]Department of Astronomy, New Mexico State University, Las Cruces, NM, USA, [2]Concordia University Wisconsin, Mequon, WI, USA.

Introduction: In 2009, the Lunar CRater Observation and Sensing Satellite (LCROSS) mission impacted into Cabeus crater, a permanently shadowed crater near the lunar south pole. This impact produced a debris plume detectable from ground-based observations using principal component analyses (PCA) to extract the light curve resulting from sunlight scattering off of the debris plume [1].

Previous efforts to model the debris plume by Strycker et al. [1] placed constraints on the mass and shape of the plume, specifically establishing the best fit model to be a three component plume, with the bulk of the particles in the lower angled plume, some in a narrower, higher angled plume, and a few in a very narrow, very high angled plume component. with a truncated log linear initial velocity distribution.

The three component plume is consistent with the plume shape and behavior experimentally measured at the NASA Ames Vertical Gun Range by Hermalyn et al. [3]. The truncated initial velocity distribution, however, deviates from the strictly log linear initial velocity distribution measured in that study. The current modeling work holds the Hermalyn et al. [3] experimentally measured plume shape and behavior fixed, and instead allows the albedo of the debris plume particles to vary with depth, simulating stratified layers within the lunar sediment. In this work, we expand upon the previous modeling efforts by investigating stratification of the lunar sediment, specifically examining the effects of higher albedo layers potentially caused by water ice depositions.

Data: The LCROSS debris plume was detected using Agile, a high speed imager, on the Astrophysical Research Consortium 3.5 m telescope at Apache Point Observatory (APO), and was the first ever ground-based detection of an impact plume [1]. This detection was possible only after principal component analysis (PCA) techniques were applied to the data, as initial analysis was not able to detect the plume [1][2]. Further analysis of the Agile data from APO using more advanced image processing techniques resulted in a light curve with increased signal to noise [4]. The increased signal to noise enabled us to analyze the data at finer spatial resolution, and we elected to model the debris plume in a grid of ten spatial locations above the crater as seen from Earth. We use two rows, corresponding to physical heights of 3.4 km and 5.3 km above the crater floor, and five pixels in each row sampling the plume at horizontal intervals of 3.8 km.

Model: After running a χ^2 analysis of the Strycker et al. [1] model as compared to the models used in this work, we can demonstrate that the more physically motivated models produce lower χ^2 values than the truncated initial velocity distribution models. The Strycker et al. [1] best fit model produces an average χ^2 value per pixel of 8.016, compared to the best fit models of the stratified lunar sediment models in this work, which produce average χ^2 values per pixel of 2.546 and 2.552. Therefore, the more physically motivated models do better fit the data, as expected.

For our model, we developed an N-body simulation code that gives us more control over the details of the particles and plume shape than what was previously used by Strycker et al. [1]. The code assigns both radius and albedo individually to a total of 141,000 particles. The radius and albedo are assigned as a function of the maximum height reached by the particles, which we can then translate into a maximum initial depth using Figure 9 from the Hermalyn et al. [3] paper. There is a degeneracy in this method between the radius and albedo of the particles; however, we used a uniform radius of 2.5 μm throughout, and we used the same scaling factor to scale each model light curve to the data in order to limit our study to the distributions of albedo as a function of depth. A step-function distribution of radius or albedo as a function of depth was suggested by [1], but we included the conditions in the lunar crater to inform our selection of possible distributions. We identified four components that produce models that fit well to the observed light curve: a surface layer of dirty ice; a mixing region where the albedo decreases with depth from that of the surface layer to that of pure lunar regolith; a layer of pure lunar regolith; and a boundary depth below which no material is ejected from, which could correspond to lunar bedrock. The best fit models include all four layers, with varying layer thicknesses and mixing regions with varying albedo decreasing behavior.

A sample lightcurve, the center pixel in the lower row, is presented in Figure 1 below. The sample lightcurve includes two four layer models, two double layer models (one with a layer of surface ice and one with a layer of bedrock), and a recreation of the Strycker et al. [1] truncated initial velocity distribution model.

Results: We identified properties of the lunar sediment that produce the best fit models, which we use to derive the distribution and quantity of water ice required to replicate those properties. We use the changing albedo with depth to trace the volume, mass, and concentration of water ice within a column of lunar sediment below one square meter of lunar surface. We use values of 0.17 for the albedo of lunar regolith and 0.8 for the albedo of pure water ice; however, as there is no measurement of the albedo of pure water ice under permanently shadowed lunar conditions, the choice of water ice albedo could result in an over or under estimation of the volume, mass, and concentration of water ice.

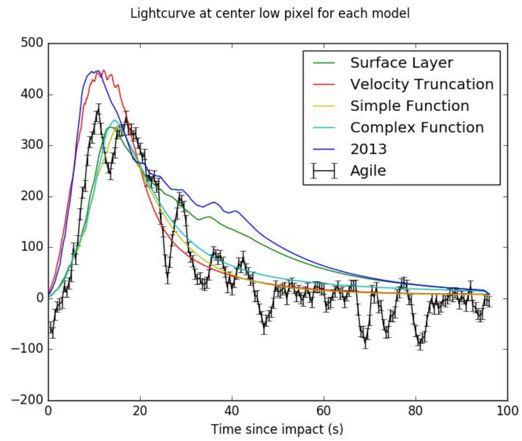

Figure 1: A family of synthetic plume lightcurves with the PCA filtered Agile data in black, the surface ice layer in green, a reproduction of the Strycker et al. [1] model in dark blue, a velocity truncation (bedrock) model in red, and two four layer models, simple function and complex function, in yellow and cyan.

In order to compare the results of our more complex models with what was done previously we recreated the velocity truncation model from Strycker et al. [1], and found that our best models produce a lower χ^2 value when summed over all ten pixels, with a total value of 80.16, for an average χ^2 value per pixel of 8.106, compared to the values for the best fit models, 25.52 and 25.46, for average χ^2 values per pixel of 2.552 and 2.546, thus confirming that the layered lunar sediment models do produce models which better fit the data than the truncated initial velocity distribution models.

Using the albedo distributions which produced our two best fit models, we calculate water ice concentrations of 20.71% and 24.91% - that is, within a column of lunar sediment below one square meter of surface area, either 20.71% or 24.91% of the material is water ice, and the remaining 79.29% or 75.08% is lunar regolith. We also calculate the corresponding volume and mass of water ice, although these values are upper limits due to a possible overestimation of a factor of two in our method of calculating the initial depths, arising from an uncertainty in the flow physics of large impacts [3]. The volume and mass values we calculate for the two best models are presented in Table 1 below.

	Surface Layer	Simple Function	Complex Function
χ^2	54.91	25.52	25.46
Volume of water	1.48 m^3	1.81 m^3	1.69 m^3
Mass of water	1384.89 kg	1694.08 kg	1587.16 kg
Concentration of water	17.49%	20.71%	24.91%

Table 1: Properties of water for the three best fit models

Although we found the properties that produce the best fit versions of the stratification of lunar sediment models, the difference in χ^2 value per pixel of each model is insufficient to make any claims about the likelihood of a given set of layers being physically present. However, the layers we used were chosen due to their being physically realistic. We determined the light curves that would have resulted had the LCROSS mission impacted into layers of surface dirty ice, mixing regions where the water ice content falls off with depth, pure lunar regolith layers, and bedrock layers. We determined the combinations of these layers and the properties of the layers that are necessary to fit the data, namely that, in a stratified sediment model, layers with a higher albedo (surface ice), followed by a lower albedo (regolith), followed by a lack of material (bedrock) must all be present, with varying thicknesses depending on the other constraints of the model. Finally, we measured the concentration of water ice within a column of lunar sediment that corresponds to the best fit properties of models. These measurements represent the water ice concentration within the lunar sediment of a permanently shadowed crater with layers of surface ice, lunar regolith, and bedrock. The LCROSS data are consistent with Cabeus crater being a permanently shadowed crater with layers of surface ice, lunar regolith, and bedrock, but the stratified lunar sediment model is likely not the only model that could reproduce the LCROSS data. Future studies into the geomorphology of permanently shadowed lunar craters will be needed to determine if this more physically realistic model does indeed describe what is actually present in Cabeus crater.

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References: [1] Strycker, P. D. *et al.* (2013) *Nat. Commun.*, 4:2620, doi:10.1038/ncomms3620. [2] Chanover, N. J. *et al.* (2011) *J. Geophys. Res. (Planets)* 116, E08003. [3] Hermalyn, B. *et al.* (2012) *Icarus*, 218:654. [4] Strycker, P. D. *et al.* (in prep)