Planned Lunar Impacts: Scientific Value and Ground-based Observation Limits

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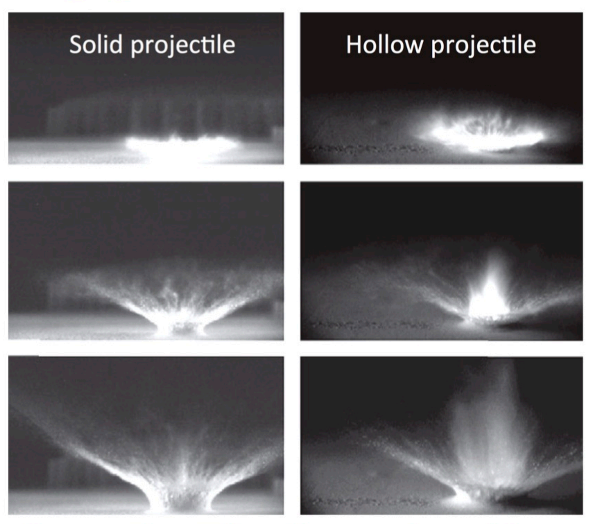
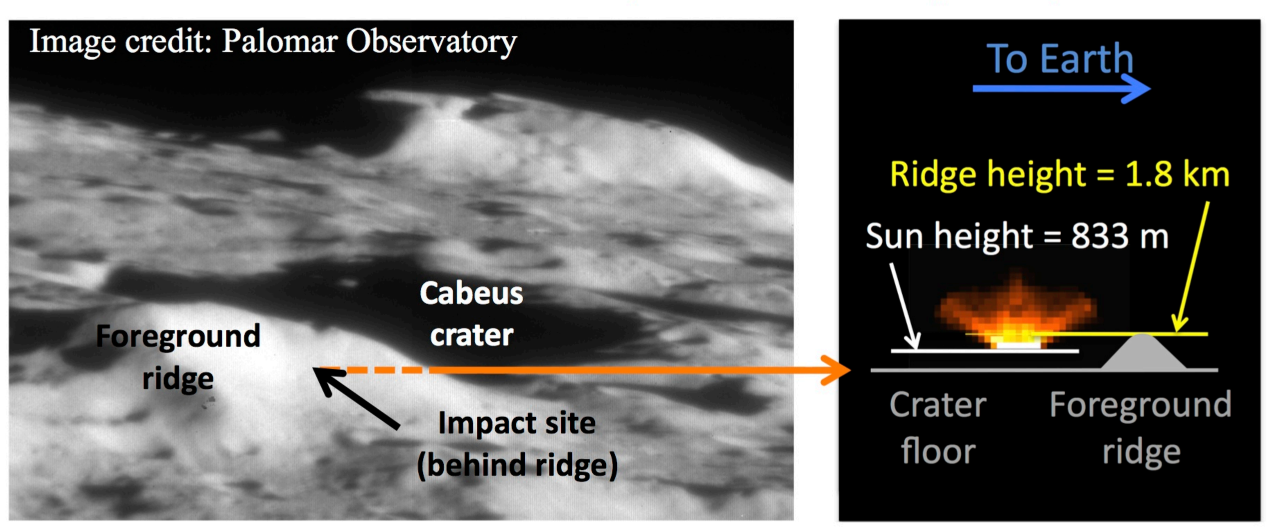
The LCROSS Impact

On October 9, 2009, the LCROSS mission entailed the impact of a 2300 kg Centaur upper stage onto the floor of Cabeus crater at a speed of 2.5 km/s and an impact angle of 85° to the horizontal [1][2][3]. The primary science goal of the LCROSS mission was to verify the presence of water in the lunar regolith thrown up into sunlight by the impact. This goal was achieved with observations from the *in situ* Shepherding Spacecraft that followed the Centaur impactor. A secondary science objective was to observe the time evolution of the ejecta plume from a side perspective from Earth-based observations. Pre-planned lunar impacts allow investigation of several issues through plume imaging:

- Determination of the ejecta mass from an impactor of known size, impact speed and angle.
- Verification of crater formation theories linking crater size and ejected mass to properties of the impactor.
- Comparison of large-scale impact plume morphology to results from laboratory impacts of high-speed projectiles to evaluate impact scaling assumptions.
- Evaluation of lunar regolith properties as a function of depth including albedo, particle size, and compressibility.



The figure above is a time series of images for laboratory impacts of solid and hollow projectiles at the NASA Ames Vertical Gun Range [4]. Hollow projectiles (right), representing the hollow Centaur impactor, produced multi-component plumes.

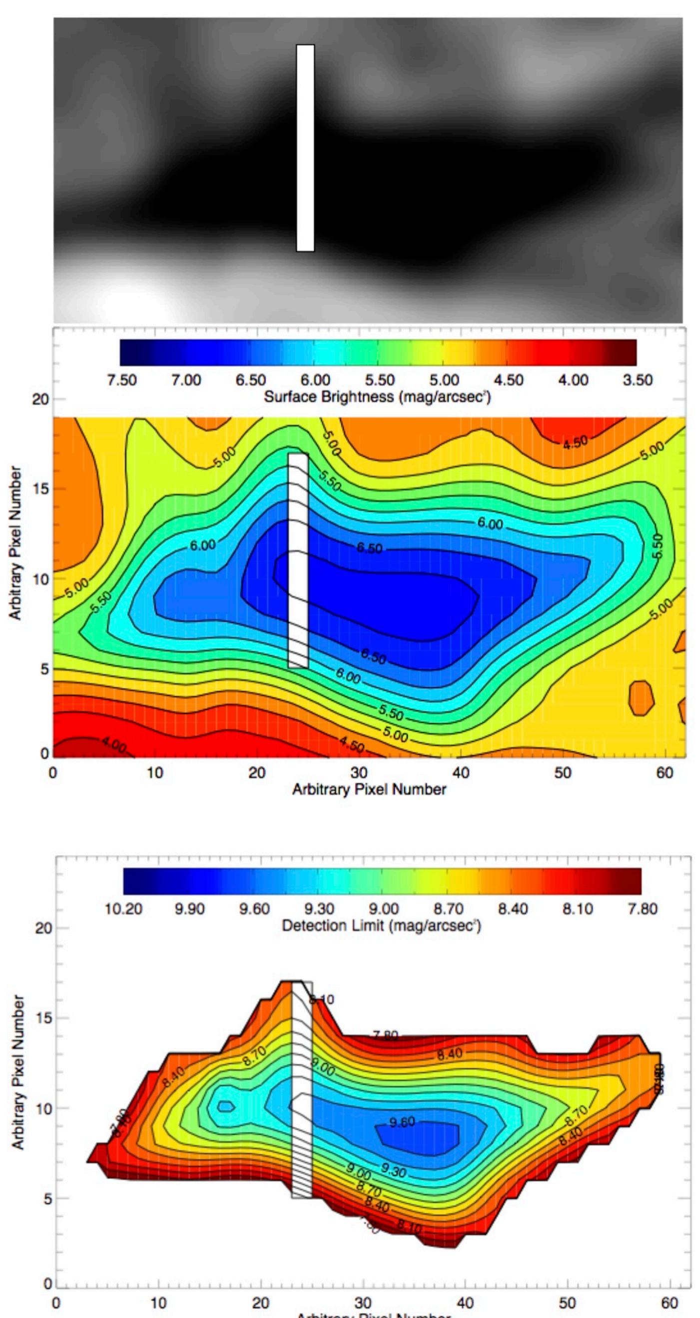


The impact site was optimized for detection of water from the Shepherding Spacecraft and was not ideal for imaging a plume from Earth. Surrounding bright lunar terrain increased the scattered light levels in the dark area of Cabeus. Although the plume was illuminated from a height of 833 m above the impact site, a foreground ridge obscured the view of the plume below 1.8 km. The scattered light from this bright ridge reduced the signal-to-noise threshold from the lower portions of the visible plume.

Ground-based Observation Strategy & Initial Results

We observed the LCROSS impact with the Astrophysical Research Consortium 3.5 meter telescope at Apache Point Observatory in Sunspot, NM. We used the Agile visible light frame transfer camera with a V-filter to obtain a continuous series of 0.5 s exposures throughout impact. We chose an ND=2.5 neutral density filter to reduce images close to saturation of the illuminated lunar terrain in order to maximize the signal-to-noise ratio for a faint plume.

Our initial inspection of the images revealed no evidence of a visible plume, a negative result obtained by other facilities in the ground-based observation campaign [5]. We also found no visible plume in processed images where we subtracted pre-impact images from post-impact images to search for changes due to an evolving plume.



We subsequently calibrated the post-impact images to produce brightness maps of the Cabeus area and of the 3-sigma noise threshold above the impact site [6].

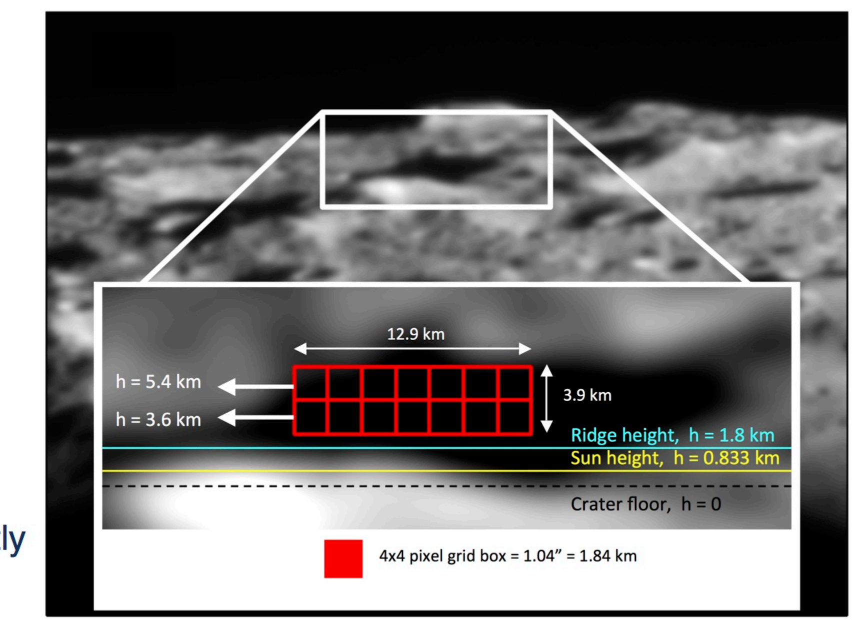
The figure at left is a V-band surface brightness map of the Cabeus crater LCROSS impact site from Agile imaging. The upper panel is a close-up view of the floor of Cabeus crater and the surrounding area. The middle panel is the per pixel V-band surface brightness. The white bar denotes the area directly above the LCROSS impact site. We found the minimum brightness above the impact site to be **6.75 magnitudes/arcsec²**.

The lower panel is the per pixel 3-sigma noise threshold of the data converted to calibrated V-band brightness values. This represents the upper brightness limit of a plume that could be detected through subtraction of pre- and post-impact images. As we found no detection of the plume using this method, we determined the maximum V-band plume brightness to be **9.5 magnitudes/arcsec²** at 4 km above the impact site.

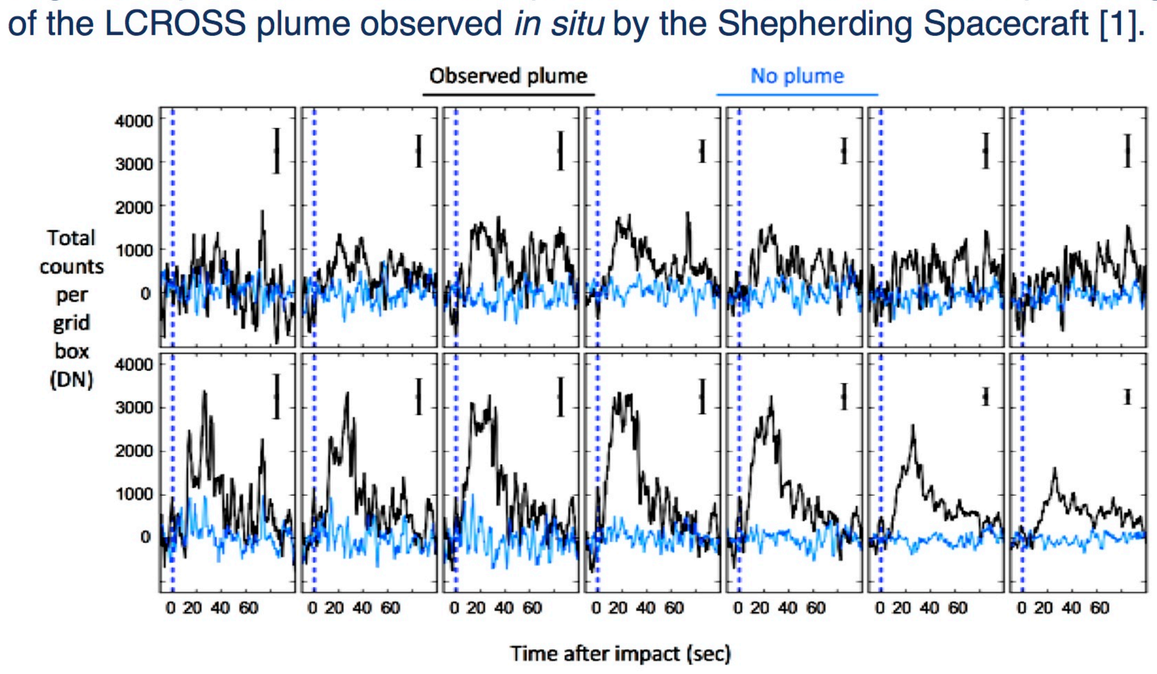
Plume Signal Detection Using a Principal Component Analysis Filter

In order to probe below the 3-sigma noise threshold, we employed a Principal Component Analysis based filtering method on our Agile image sequence. This involved removing the first 4 principal components that represented time-varying seeing distortions and sub-pixel horizontal and vertical image registration errors. We further increased the signal-to-noise ratio by co-adding 4x4 pixel arrays in a grid centered above the impact site and boxcar averaged over 5 frames or 2.5 s.

The diagram at right illustrates the examination grid used to detect the LCROSS plume using the PCA filtering method. The bottom row is centered at 3.6 km above the impact site. This was the darkest region in Cabeus crater in the Agile images. The scattered light from the foreground ridge reduced the signal-to-noise of the LCROSS plume significantly for heights below 3.6 km above the crater floor.

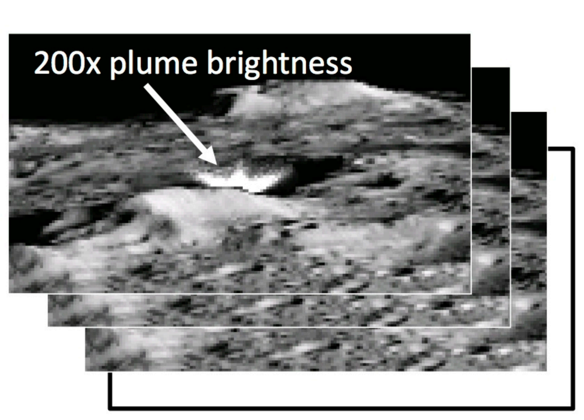


The figure below shows the measured brightness of each 4x4 pixel array in the examination grid as a function of time after LCROSS impact. The vertical bars are the 1-sigma noise values for each respective grid array. We found a detectable increase in brightness directly above the impact site (middle of bottom row). The brightness peaked at 17 s after impact, consistent with the time of peak brightness of the LCROSS plume observed *in situ* by the Shepherding Spacecraft [1].



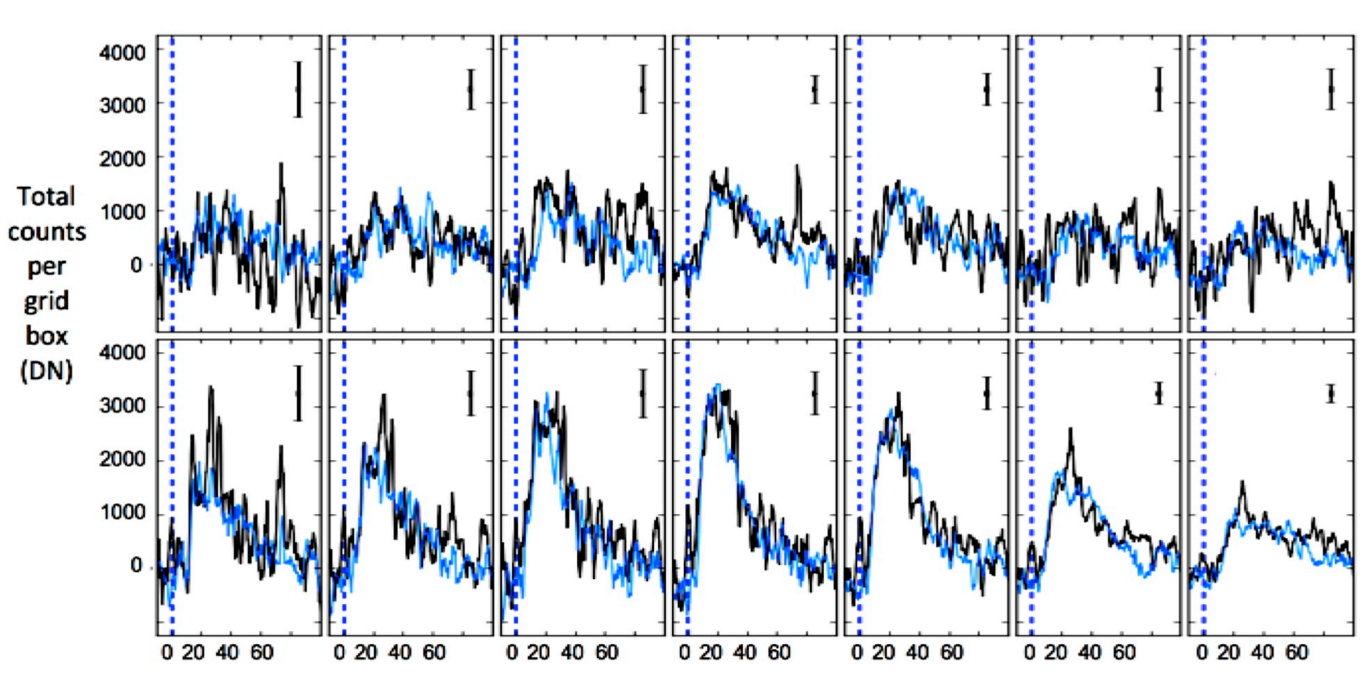
Plume Modeling & Characterization

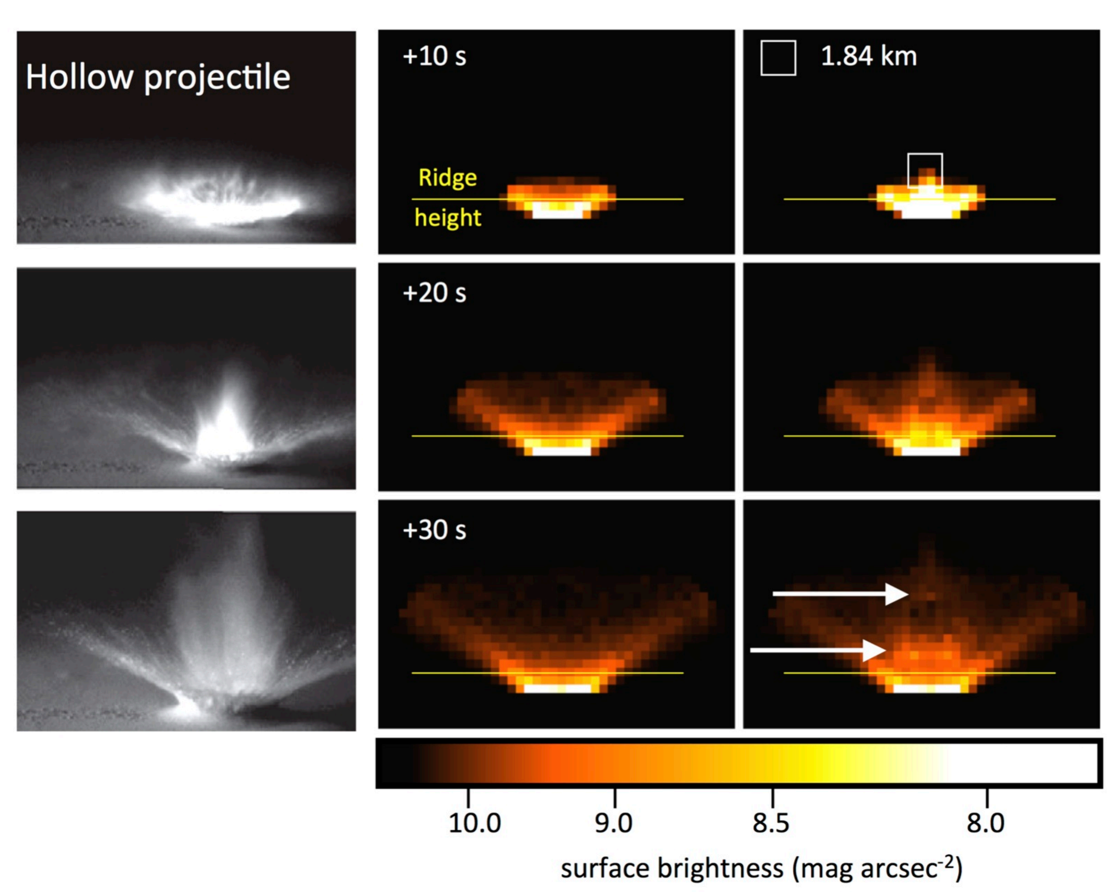
To establish that the signal found after PCA filtering was caused by an impact plume, we created a series of images incorporating output from an n-body ballistic particle plume model. We adopted the following procedure to create a synthetic image sequence and generate model brightness curves for comparison to our observations:



1) Ran 3-D n-body ballistic particle plume simulations and extracted plume brightness maps at 0.5 s intervals corresponding to the Agile image cadence.
2) Created a "perfect" sequence of plume capture maps combined with a computer generated lunar landscape (illustrated at left with plume shown 200x brighter than the actual best match result).
3) Added seeing distortions, frame alignment mismatches, and noise, then generated brightness curves using the same PCA filter and binning as with the observed data.

Below is an overlay of the brightness curves from our best match plume model (blue curves) with the curves extracted from out Agile image sequence after PCA filtering (black curves) [7].





The figure above shows a simulated single-component plume (middle column) and the best-match multi-component plume (right column). The best-match simulated plume resembled laboratory plumes produced by impacts of hollow projectiles (left column). The ejection angle of the LCROSS plume low-angle component suggested a regolith more compressible than pumice material used in lab experiments [3][7]. The white arrows highlight a brightness reduction seen in the best match model high-angle plume that may be due to either a mass reduction for particles with ejection speeds below 150-300 m/s or albedo variations with depth.

The maximum brightness of the best-match simulated plume was **10.0 +/- 0.1 magnitudes/arcsecond²** at 3.6 km above the impact site. Therefore, this analysis demonstrated the ability to detect and characterize a resolved ejecta plume **3.25 magnitudes/arcsecond²** fainter (20x dimmer in radiance) than the scattered light background using a PCA filtering technique. Simulation results indicated that the portion of the plume blocked by the foreground ridge was as bright as **8.0 magnitudes/arcsec²** at the sun height of 833 m above the impact site.

Implications for Future Impact Experiments

We used a PCA filtering method to detect and characterize a lunar ejecta plume with an estimated mass of 2000-4000 kg above the sun height of 833 m [1][7]. Other spacecraft of similar mass to the 2300 kg LCROSS impactor have been considered for lunar impacts at their end-of-life. A lunar impact site choice that would result in improved plume signal-to-noise ratio, either from increased visible plume brightness or reduced background scattered light, would allow for a more detailed characterization of plume dynamics and regolith properties.

Recommended impact site considerations are as follows:

- Impact as near as possible to the lunar limb – This provides a side-on view of the ejecta plume necessary for the evaluation of multi-component plume dynamics. Also, minimizing the area of illuminated lunar terrain in the impact site images reduces the intensity of the scattered light background.
- Clear line-of-sight from Earth and a solar illumination height of no higher than 1 km above the impact site.
- Lunar phase illumination – The solar phase angle at time of LCROSS impact was 65° (with lunar illumination of 71%), which was well suited for plume imaging. A higher lunar illumination phase would produce more scattered background light. A lower lunar illumination (with corresponding higher solar phase angle) would reduce scattered light with a possible tradeoff of a higher sun height at the impact site.

References & Acknowledgments

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