Scouring the surface: Ejecta dynamics and the LCROSS impact event

Brendan Hermalyn a,∗, Peter H. Schultz a, Mark Shirley b, Kimberly Ennico b, Anthony Colaprete b

a Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912, USA
b NASA Ames Research Center, Moffett Field, CA 94035, USA

A R T I C L E   I N F O

Article history:
Received 1 July 2011
Revised 19 December 2011
Accepted 27 December 2011
Available online 18 January 2012

Keywords:
Impact processes
Cratering
Collisional physics
Geological processes
Regoliths

A B S T R A C T

The Lunar CRater Observation and Sensing Satellite mission (LCROSS) impacted the moon in a permanently shadowed region of Cabeus crater on October 9th 2009, excavating material rich in water ice and volatiles. The thermal and spatial evolution of LCROSS ejecta is essential to interpretation of regolith properties and sources of released volatiles. The unique conditions of the impact, however, made analysis of the data based on canonical ejecta models impossible. Here we present the results of a series of impact experiments performed at the NASA Ames Vertical Gun Range designed to explore the LCROSS event using both high-speed cameras and LCROSS flight backup instruments. The LCROSS impact created a two-component ejecta plume: the usual inverted lampshade “low-angle” curtain, and a high speed, high-angle component. These separate components excavated to different depths in the regolith. Extrapolations from experiments match the visible data and the light curves in the spectrometers. The hollow geometry of the Centaur led to the formation of the high-angle plume, as was evident in the LCROSS visible and infrared measurements of the ejecta. Subsequent ballistic return of the sunlight-warmed ejecta curtain could scour the surface out to many crater radii, possibly liberating loosely bonded surface volatiles (e.g., H2). Thermal imaging reveals a complex, heterogeneous distribution of heated material after the LCROSS impact. The details of the impact are of primary importance in understanding the nature of this volatile-rich region on the south pole of the moon, both in terms of the volatility distribution within the regolith and in the properties of the regolith itself.

1. Introduction and background

The Lunar CRater Observation and Sensing Satellite (LCROSS) mission utilized the spent upper stage of a rocket as a kinetic impactor to launch material from a permanently shadowed region (PSR) within Cabeus crater above the 833 m sunlight horizon. A suite of nine instruments onboard the LCROSS shepherding spacecraft (SSc) made measurements of the sunlit regolith and released volatiles, including the identification of multiple species of water ice and hydroxyl molecules (Colaprete et al., 2010) as well as several other volatile components, such as CN, NH, NH2, CO2, and CS (Schultz et al., 2010). Instruments onboard the Lunar Reconnaissance Orbiter (LRO) provided complementary measurements of the liberated volatiles and excavated crater (Gladstone et al., 2010; Hayne et al., 2010). Although limited by non-optimal Earth viewing conditions due to topographic obstruction, evidence for the LCROSS ejecta plume was also reported by ground-based observers (Killen et al., 2010).

While combined observations establish the presence of volatiles in the shadows of Cabeus, interpretation of the source region and initial conditions in the PSR from these data is highly dependent on the specific mechanics of the impact. For example, the amount and approximate excavation depth of the material ejected to sunlight determines the volume percentage and provenance of these volatiles within the PSR. Initial attempts using canonical ejection laws to return the volatiles into the 25–30 m diameter LCROSS crater (e.g., Gladstone et al., 2010) indicate significantly higher concentrations of volatiles by volume compared with other estimates of content (Feldman et al., 1998; Elphic et al., 2010). The details of the impact are of primary importance in understanding the nature of this volatile-rich region on the south pole of the moon, both in terms of the volatility distribution within the regolith and in the properties of the regolith itself.

Prior to impact, several independent studies predicted the ejecta dynamics of the impact event through the use of scaling laws (Schultz, 2006; Heldmann et al., 2007), computational modeling (Shuvalov and Trubetskaya, 2008; Korycansky et al., 2009) and experiments (Schultz, 2006; Hermalyn et al., 2010). Although the Centaur impacted the surface at 85 ± 5° from horizontal (and thus was a rare example of a vertical impact), the cratering event was unique for a number of reasons. First, the geometry of the Centaur upper stage, a thin-walled hollow cylinder with much of the mass located on one end in a spherical steel propellant tank, resulted in a non-standard projectile with an extremely low relative density. Second, the low impact velocity (compared to the Deep Impact mission or natural planetary events) indicates that this was not a true hypervelocity impact. Although the impact speed exceeds
the sound speed in the target, it is lower than the speed of sound in the projectile. Additionally, peak shock pressures at these speeds are insufficient to cause significant shock heating, let alone melting, of the target. Third, while the target lunar regolith was expected to form a crater in the gravity-scaling regime (as with previously observed Apollo S-IVB impacts), the soil does not have the same material properties as the canonical “Ottowa” sand that is commonly used in impact experiments and forms the basis for calibration of many scaling laws. More compressible and/or porous target materials alter the ejecta dynamics and further reduce the peak pressure for bulk material. 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 sunlight horizon of ~833 m above the impact point in Cabeus placed a strict requirement on the minimum ejection velocity for ejecta to reach illumination. This condition severely restricts the amount of material that could be measured. Moreover, these velocities represent an extension into an early-time regime that does not follow the canonical dimensionally predicted velocity decay curves for main-stage ejecta behavior (Housen et al., 1983; Hermalyn et al., 2010; Hermalyn and Schultz, 2010). Because the event was recorded in a time-resolved fashion, interpretation of the dynamics is dependent on temporal data rather than ejecta velocity as a function of launch position.

The goal of this study is to examine the unique LCROSS impact conditions through a series of laboratory experiments to understand their effect on the cratering process, and permit interpretation of the LCROSS data. Section 2 describes the LCROSS mission and relevant measurements of ejecta. Section 3 describes the experimental setup and methodology employed and analysis of the data. Sections 4 and 5 provide interpretation of the LCROSS data and discussion.

2. LCROSS impact

The LCROSS mission was comprised of two spacecraft: the uninstrumented Centaur impactor and the Shepherding Spacecraft (SSc), which guided the Centaur throughout the 3 month cruise and bake-out phase to the impact trajectory, and observed the event from above with a suite of instruments. The Centaur, the upper-stage of the Atlas rocket that transported LRO/LCROSS to the moon, is a thin, hollow cylinder 12.68 m long and 1.52 m in radius, weighing 2300 kg at impact. The relative density of theemp-tied Centaur is quite low (~25 kg/m³), with most of the mass concentrated in a spherical steel fuel tank at one end of the rocket, as well as the engine and coupling. The Centaur remained attached to the SSc, performing bake-out rolls designed to minimize any remaining fuel and volatiles (and thus the possibility of spectral contamination), until separation 9.67 h before impact. The impact angle and speed, including local slope effects, was 85 ± 5° at 2.5 km/s. While the exact orientation of the uncontrolled Centaur at impact has not yet been determined accurately, the approximate roll rate was negligible compared to the impact speed; thus the impact is considered as a vertical event.

After separation, the SSc conducted a breaking burn, providing a 600 km separation distance from Centaur. During the impact event and subsequent excavation of material into sunlight, the trailing SSc observed the ejecta evolution for approximately 4 min before loosing communication and joining the Centaur on the lunar surface. Nine science instruments on the SSc provided complementary observations: a set of visible (VIS), two near (NIR1, 2), and two mid (MIR1, 2) infrared cameras, UV–Visible (UV–VIS) and near IR (NSP) spectrometers, and a total luminescence photometer (TLP). The instruments of primary interest in this study are the VIS, NIR2, and MIR1 cameras. Full description of the SSc payload is outside the scope of this work (included in Ennico et al. (2011)); we provide limited details on the instruments used here as required for interpretation of results.

The VIS camera was the primary instrument for recording the size of the ejecta plume above the sunlight horizon. Interlaced NTSC format images were recorded in three colors onto a CCD chip with a Bayer filter and compressed using a lossy algorithm before return to Earth. The camera was set to auto-gain throughout the encounter. As a result of downlink bandwidth limitations, the VIS images immediately before and during the impact were subject to compression artifacts due to wavelet clipping onboard the SSc (Ennico et al., 2011). While processing attempts are ongoing, preliminary results of artifact removal routines are presented here (see Appendix A for brief description of processing routine). The NIR cameras (sensitive to 1.4–1.7 μm and 0.9–1.7 μm, respectively, due to a long-pass filter in NIR1) could be set to specific gains and exposure times; NIR2 is of interest here due to its role in capturing the final crater and increased sensitivity (NIR1 is also slightly out of focus). The MIR cameras (6.0–10 μm and 6.0–13.5 μm, respectively, due to a short-pass filter in MIR1) recorded the thermal evolution of the initial hot spray of ejecta after impact and the warm area surrounding the crater during the final SSc approach. Both cameras were thermally calibrated using LRO Diviner data; however, the sensitivity floor for the cameras was ~200 K, over 150 K higher than the Cabeus PSR (Paige et al., 2010). Although it is less sensitive due to the bandpass filter, we concentrate primarily on MIR1 here because MIR2 is slightly out of focus.

2.1. Ejecta measurements

By combining the measurements from multiple instruments, a time-resolved evolution of the cratering event can be constructed. A thermal pulse was detected approximately 0.3 s after the calculated time of impact by the NSP (which was operating at 72 Hz during this phase); emission lines from the impact event were also evident in the UV/VIS spectrometer exposure that includes the 0.8 s following impact (Schultz et al., 2010). Next, a hotspot up to
several kilometers in diameter was measured immediately after impact in both MIR cameras, persisting for several seconds and decaying with time (Fig. 1). A rise in the overall radiance in the spectrometers indicated the arrival of the curtain into sunlight a few seconds after impact (Colaprete et al., 2010). The first images after impact in the VIS camera sequence (about 8 s post-impact) reveal a visible ejecta plume several kilometers in extent (Fig. 2). The ejecta is also present in the NIR camera sequence (which starts at the same time after impact as the VIS), but due to the gain and exposure setting, the difference between background and illuminated ejecta is on the order of only a few DN; therefore, measurements of the plume extent are less reliable.

The visible ejecta lasted tens of seconds and expanded with time before disappearing from view by about 30 s after impact. In contrast to the standard ejecta curtain formed in many experiments, which would have produced an expanding annulus of sunlit ejecta, the VIS images reveal a relatively symmetric cloud that did not exhibit the expected central void (Schultz, 2006; Korycansky et al., 2009) but was instead filled in (Schultz et al., 2010), as seen in Fig. 2. A continued presence of volatiles (and overall increase over pre-impact background) in the spectrometer measurements persisted for almost 4 min after impact (Colaprete et al., 2010). Towards the end of SSc approach, the fresh Centaur crater region was recorded by the MIR cameras (Fig. 3), revealing an area of about 65 m across emitting above the background temperature. The gain and exposure settings on the NIR2 camera were adjusted in the final seconds of SSc approach, allowing the SSc to image the permanently shadowed floor of Cabeus and revealing the same newly formed crater seen in the MIR cameras at higher spatial resolution, thereby permitting direct measurement of its size (as discussed in Schultz et al. (2010)).

In addition to the instruments onboard the SSc, independent measurements of the impact event were made by the Lyman Alpha Mapping Project ultraviolet spectrograph (LAMP) and the Diviner Lunar Radiometer on LRO (Gladstone et al., 2010; Hayne et al., 2010). The LAMP instrument recorded the UV signatures of volatiles above the lunar limb and revealed species of CO, H2, Ca, Hg, and Mg in significant abundance (Gladstone et al., 2010). Additionally, the measurements place velocity constraints on the leading edge of the ejecta from a time-of-flight analysis between surface and spectrometer slit location above the limb. The Diviner instrument, considerably more sensitive to temperature than the MIR cameras, recorded the sub-pixel (<400 m) thermal signal of the impact crater during the closest approach 90 s after impact and for multiple post-impact orbits.

3. Experimental studies

The experimental studies can be divided into two groups: temporally resolved measurement of the ejecta velocity distribution, and thermal measurements of the evolution of the ejecta and crater.
3.1. Methodology

A suite of impact experiments performed at NASA Ames Vertical Gun Range (AVGR) was designed to explore the characteristics relevant to the unique LCROSS impact. Although a general description of some of the experiments has been presented previously (Schultz et al., 2010), here we provide a more detailed report of the process, including the ejecta-velocity distribution, ejection angles, and excavation depths. The experiments including LCROSS engineering units have not previously been published.

A series of both solid and hollow 12.7 mm diameter aluminum spheres were launched at ~2.5 km/s orthogonal to the target surface to study the effects of non-standard projectiles (e.g., low-density hollow impactors that fail near the surface) and regolith-like target properties on the cratering evolution. While solid aluminum projectiles \( (\rho_p = 2800 \text{ kg/m}^3) \) represent a canonical impactor, the ramifications of density and projectile failure were evaluated through the use of hollow aluminum spheres of the same diameter. The bulk density of the hollow sphere \( (\rho_p = 710 \text{ kg/m}^3) \) is still over an order of magnitude denser than that of the Centaur; however, it serves as a proxy for investigation of process differences. The density of the hollow projectile does approach the effective density of the spherical steel oxygen tank, which comprises most of the mass in the Centaur. The thin-walled aluminum spheres fail on impact. The combined effects of projectile failure and density have previously been observed to significantly reduce the peak pressures and dramatically affect the excavation process, and eject material with both high-angle (Schultz et al., 2010) and low-angle (Hermalyn and Schultz, 2010; Hermalyn and Schultz, 2011) components relative to the horizontal pre-impact target plane.

The experiments were conducted using both #20–30 smooth Ottawa quartz sand \( (\text{grain diameter of} \sim 1 \text{ mm, bulk target density} \delta_t = 1700 \text{ kg/m}^3) \) for comparison to prior studies, and a cohesive, compressible regolith-like target material \( (\text{airfall pumice dust}) \) to examine the role of compressibility in the impact. The airfall pumice dust \( (\text{grain sizes ranging from} \sim 10 \mu \text{m to} \sim 100 \mu \text{m with a bimodal distribution centered at} 25 \mu \text{m and} 85 \mu \text{m; bulk} \delta_t = 1280–1500 \text{ kg/m}^3, \text{depending on compaction}) \) serves as a realistic analog for planetary regolith since it is moderately compressible (further reducing the peak pressures) and comprised of coarse, heterogeneous, agglutinitic particles that exhibit a high degree of cohesiveness under static conditions and lose bulk strength under extension behind the shock (Schultz et al., 2005). All experiments were performed under vacuum conditions \( (<0.5 \text{ Torr of atmosphere}) \).

3.2. Ejecta velocity measurements

A particle tracking velocimetry (PTV) technique was developed to non-intrusively measure the velocity and position of particles in the profile of the ejecta curtain to high spatial and temporal resolution (see Fig. 4). This technique, often employed in experimental fluid dynamics research, has been validated in prior studies of ejecta velocities (Hermalyn and Schultz, 2010), although the concept of planar velocity measurement in vertical impacts has a considerably longer history (Oberbeck and Morrison, 1976; Piekutowski et al., 1977; Cintala et al., 1999). Along the leading edge of the curtain, the velocity of the ejecta is reduced to two components \( (\text{i.e., there is little out-of-plane motion}) \), thereby allowing planar measurement of the ejecta. The measurement plane was optically established by creating a narrow depth of field (DoF) with long focal length lenses at wide apertures, allowing only the particles on the edge of the curtain to be in-focus and measurable. A series of high-speed cameras \( (~11,000–15,000 \text{ frames per second or fps}) \) allow measurement of particle velocities over the large dynamic range required for early-time, high-speed components of ejecta.

The ejecta velocities captured by the system range from \(~700 \text{ m/s for the fastest material to a few meters per second (or until the edge of the curtain is outside the field of view of the cameras). See Fig. 5 for example images.}

Once measured in flight, the ejecta are then ballistically retracted to the target surface, providing the launch velocity as a function of both time and position (see Fig. 4). Intersection of the sand grains with the impact trajectory \( (\text{gray dashed line to blue}^1 \text{ dot}) \) is taken as a proxy for the depth of maximum excavation, thereby allowing estimation of the maximum ejected mass and maximum excavation depth as a function of time.

While the individual sand grains are easily resolvable in the images, the fine-grained pumice dust is below the resolution of the images recorded using this setup. To accomplish the same ballistic retraction, these images are further processed to enhance the appearance of small “clumps” or inhomogeneities in the ejecta curtain of the pumice. These clumps are then used as tracer points (similar to optical flow velocimetry techniques). This approach was validated by seeding the top surface with sand-sized neutral density tracer particles in one experiment; the optical flow technique yielded the same velocities and locations as discrete particle tracking.

\(^1\) For interpretation of color in Figs. 1, 3–9, 12, and 14–16, the reader is referred to the web version of this article.
3.3. LCROSS analog and thermal studies

For post-impact analysis of mission data, an additional suite of experiments was performed at the AVGR that combined the high-speed measurements (to temporally resolve the different phases of the event) and LCROSS engineering units of the VSP, NSP, NIR1, and MIR2 instruments. The LCROSS instruments, identical to those flown on the mission (except for lens focal lengths), were positioned on top of the vacuum chamber as close to nadir as possible (<10° off or less) to simulate the viewing conditions during impact. High-speed instruments were used in conjunction with the LCROSS instruments for comparison. This approach allowed a “close up” view of processes that occurred below the resolution of the SSC instruments during the actual impact, and provided insight into the true nature of the event.

These experiments also utilized both solid and hollow projectiles into the same sand and pumice targets. Several additional (non-PTV) high-speed color and grayscale visible cameras (~11,000–500,000 fps) and a thermal camera (137 fps) provided context for the slower LCROSS instruments. Individual parameters, including the addition of a sunlight horizon, alteration of target properties, and projectile effects were controlled to provide a basis for interpretation of the LCROSS flight data.

4. Analysis and results

4.1. Experimental ejecta dynamics

Ballistic retraction of the particles to the target surface permits direct evaluation of both ejection angle and velocity as a function of time after impact. The velocity distribution (scaled to the square root of gravity times the final crater radius) is dimensionally predicted to follow a power–law relationship with time after impact \( t \) (scaled to the time of crater formation \( T_c \)). In the experiments, \( T_c \) can be measured directly (and is on the order of ~60 ms). Following Schultz et al. (2005), an estimate for the crater formation time in the LCROSS event can be calculated from \( T_c = \gamma \sqrt{R_c/g} \), where \( R_c \) is the final size of the crater, \( g \) is the gravitational acceleration on the target, and \( \gamma \) is a constant for a specific material. The LCROSS crater was estimated to form in \( T_c = 1.3 \) s.

Although all experiments converge on a common late stage line as predicted by dimensional analysis toward \( t/T_c \sim 0.1 \), early-time velocities fall above predictions by a factor of approximately 2 (Fig. 6). This departure from power–law behavior encompasses a greater portion of crater growth as projectile size increases (Schultz, 1988; Hermalyn and Schultz, 2010), or with highly porous material (Schultz et al., 2007) (i.e., as cratering efficiency diminishes). The comparative size and low density of the Centaur impactor should further cause deviations from expectations. When scaled to LCROSS dimensions, we find that only material ejected prior to \( t/T_c \sim 0.5 \) has sufficient vertical velocity to reach the 833 m sunlight horizon of Cabeus.

The first measurable particles are ejected at low angles (see Fig. 7) which increase with time towards the expected ~45° for impacts into sand. Hollow projectiles exhibit lower ejection angles initially, but display different trends depending on the target...
angles for both impacts (Hermalyn and Schultz, 2011). Low-density impactors have previously been reported to couple much closer to the pre-impact surface, as manifested in the lower ejection projectile failure (and low-density impactors) results in energy and momentum angles throughout growth, as compared to those from sand targets. The effect of before increasing. Impacts into pumice retain characteristically lower ejection angles than those from the sand and do not achieve a constant angle for main-stage growth (Housen et al., 1983) ejection angle for much of growth after initiation with the impact plane, we arrive at a geometric con-

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mation close to the surface (within a few projectile diameters), the hollow projectiles fail under shear and achieve higher ejection angles (\(\sim 40^\circ\)) before returning to lower angles (\(\sim 5^\circ\)). The greater degree of scatter in the ejection angles from the hollow aluminum projectile (which is also evident in the raw images) is interpreted to be an effect of the failure of the projectile at early times. Ejecta from the compressible pumice dust target, on the other hand, exhibit characteristically lower ejection angles than those from the sand and do not achieve a constant angle throughout the measurement period presented here. Instead, both hollow and solid projectiles result in a continual rise in ejection angles until late times.

By inverting the launch position and angle to find the depth of intersection with the impact plane, we arrive at a geometric con-

straint for the maximum depth of excavation for any given time (see Fig. 4). This simple proxy will overestimate excavation depth, but it is used here instead of other metrics (e.g., the parabolic \"z-model\" (Maxwell, 1977; Croft, 1980) since it is makes no assumptions of proportional crater growth. In addition, the empirical \(\tau\) is not expected to hold at early times or under the unique impactor conditions used here. The maximum depth of excavation (Fig. 8) is scaled to the projectile radius as \(y/\alpha\); the abscissa is given by the early-stage time parameter \(\tau = t/(a/V_i)\) where \(t\) is the time after impact that a particle crosses the pre-impact surface (as above), \(a\) is the projectile radius, \(c\) is the sound speed, \(\rho_t\) and \(\rho_p\) are the target and projectile densities, respectively, and \(\mu\) and \(v\) are constants (as in Hermalyn and Schultz (2010)). This can be thought of as the early-stage penetration parameter \(\tau = t(a/V_i)\) with an impedance term.

The low-density hollow projectiles launch material from half the excavation depth of solid projectiles in both target materials. Low-density impactors have previously been reported to couple closer to the surface in prior studies (e.g., Hermalyn and Schultz, 2011), and the hollow nature of these projectiles further reduces the depth of penetration and excavation. At these low speeds (sub-sonic in aluminum), the hollow projectiles fail under shear and tension close to the surface (within a few projectile diameters), which accelerates (and absorbs) the coupling of projectile energy and momentum to the target and reduces the peak shock pressures.

Scaling this proxy to the LCROSS event implies that the low-angle ejecta sampled to a maximum of \(\sim 10\) m below the surface (Fig. 9). This maximum is an overestimate (up to a factor of 2) if the late-stage parabolic flow-field is assumed (e.g., Croft, 1980). Additionally, the material with the deepest origin will only be illuminated for a short period of time; this period is potentially insufficient to warm up material to dissociate volatiles. The ejecta that remains in the FOV's of the spectrometers for tens of seconds, on the other hand, comes from no more than a few meters below the surface.

\subsection{4.2 High-angle plume}

In addition to reducing ejecta angles and coupling depths, projectile failure leads to an additional component of ejecta termed...
the “high-angle plume” (Schultz et al., 2010). This element of the ejecta evolution, ejected at high speeds and angles of >75°, is separate from the canonical “inverted lampshade” low-angle ejecta. High-angle reverse plumes have been observed experimentally and at planetary scales for high-speed oblique impacts into low-density, high-porosity materials (Schultz et al., 2007). Under the LCROSS impact conditions, however, it is the failure of the projectile that allows material from directly beneath the impact point to eject upward; in standard impacts, the deformed projectile is spread out on the bottom of the transient cavity and prevents rarefaction from the center of the growing crater.

The high-angle plume is more difficult than main-stage ejecta to characterize experimentally. The leading edge of this component, which is thermally self-luminous, emerges at high velocities (≈1.25 km/s) soon after impact (Fig. 10). Material continues to release upward throughout much of crater growth (Fig. 11). Due to the high speed and launch angle of this component, the ballistic flight time is much longer than that of low-angle ejecta. Material remains aloft for multiples of the crater formation time. Although the plume is more evident for impacts into pumice dust, hollow impactors also cause formation of this feature in sand. Images of ejecta from impacts into sand targets illustrate that the plume is comprised of extremely fine dust (similar to early-time ejecta) rather than the intact sand grains of main-stage growth. This “dusty” nature implies that the initial shock beneath the impact point crushed and compacted the material prior to ejection. The comminuted dust also indicates that the maximum excavation depth is on the order of a projectile diameter due to the extent of compaction in sand. Experiments designed to characterize excavation depths failed to eject tracers from a projectile diameter underneath the surface. The fine-grained and optically-thin (from the side) nature of this component makes measurement using either PTV or the pumice dust optical flow technique difficult with the implementation employed here.
This evidence supports the role of frictional heating. In addition, abrasions and a thin lamina of partially melted target on one side of impacts. Even at laboratory scales, significant portions of the floor of Cabeus. In this section, we focus on the ejecta-driven effects of heating; a separate contribution will present analysis of the impact flash and initial vapor plume.

During the contact and compression phase of the impact, projectile and target material are compressed and comminuted by a shock wave. At high impact velocities, this compression drives portions of the materials close to the contact point into a high pressure–temperature state that lies above the melting isentrope; the amount of melt is found (for planetary impact scale computations) to follow an energy scaling law (O'Keefe and Ahrens, 1977). As the amount of melt is found (for planetary impact scale computations) to follow an energy scaling law (O'Keefe and Ahrens, 1977). As the energy and momentum of the impact event decrease, however, significantly less shock melting is produced.

It is difficult to generate large amounts of melt at laboratory scales (without using a proxy target material). Studies attempting to measure the partitioning of impact energy directly have found ~26% of impact energy is partitioned to target heating in high speed (>6 km/s) laboratory experiments into granular media (e.g., Braslau, 1970; Schultz and Gault, 1990). This is not an appropriate relation for lower-speed impacts, however, since they result in greatly reduced shock strength. Porous compressible material, such as lunar regolith, further reduce the peak pressures of impact at these speeds since a significant portion of energy is partitioned into compaction of pore space.

Impact heating has been shown to occur under low peak pressures due to the effects of frictional shear heating between the projectile (and fragments) and target (Schultz, 1996). This type of heating is not well modeled by computational shock hydrocodes, and is limited to the region immediately in contact to the projectile rather than extending beyond to shock pressure isobars for vertical impacts. Even at laboratory scales, significant portions of the projectile (both solid and hollow) survive the impact, displaying abrasions and a thin lamina of partially melted target on one side. This evidence supports the role of frictional heating. In addition, internal shear heating of the projectile due to deformation will further increase the temperature of the remaining impactor.

Prior studies of the thermal evolution have primarily addressed shock heating (as above) or the temperature profile of the impact flash (e.g., Ernst and Schultz, 2007) rather than the thermal history of subsequent excavation flow. The thermal evolution of the ejecta was assessed using a series of cameras sensitive to different time intervals and temperatures. Early-time low-angle ejecta is comprised of both finely crushed target and thermally self-luminous material. Color cameras reveal that this material is ejected between 600 and 1000 K from the color temperature (Fig. 5). Top views of this early-stage material (Fig. 12) reveal that much of the initially heated material is ejected from the crater, leaving portions of the surviving projectile spread on the inside of the transient crater a few microseconds after impact. After this initial phase, the vast majority of main-stage material is ejected at close to room temperature.

The LROSE flight backup NIR and MIR cameras, which are much more sensitive to thermal radiation but were operated at lower frame rates of 30 and 3 Hz respectively, capture the later stages of the thermal evolution (Fig. 13). While the thermally self-luminous early-time ejecta saturates the cameras, later stages (after the crater has finished forming) display a heterogeneous distribution of emitters emplaced around the crater, rather than a homogeneously warm ejecta blanket. In two experiments, the temperature of the Cabeus crater floor was simulated by freezing the target material with liquid nitrogen (~70 K) before impact. While this had a slight effect on the final crater temperature (the thermal extent of warmed material surrounding hot projectile fragments was slightly decreased), it had no discernible effect on the initial thermal history.

Many of the emitting particles could be identified after impact, and most were found to include a projectile component. By inverting the trajectory of these particles (using high-speed cameras) after the emitters have been identified in the post-impact images, the warm chunks of material can be seen riding the inside of the curtain up and out of the transient cavity (e.g., Schultz et al., 2005). The largest radiating point in the center of the images is primarily composed of the remains of the inverted projectile and takes up only a small portion of the overall crater size. Due to the size of the AVGR vacuum chamber, some early-time hot

4.3. Thermal effects

The thermal history of the impact is important for interpretation of the volatile content in the data, and can be divided into three areas: heat generated during the impact event (including partitioning into a high-speed, high-angle vapor cloud and low-angle ballistic ejecta), the effects of heat input from solar irradiation on sunlit ejecta, and the role of the remaining heated material on the thermal history.

During impact heating has been shown to occur under low peak pressures due to the effects of frictional shear heating between the projectile and hot ejecta. During impact (A2), the cool projectile top is visible nested inside the transient crater and high-speed thermally emitting ejecta annulus. By the final image, the hottest component inside the crater is seen; this portion was later retrieved and found to be the inverted hollow projectile. (B) is a time-series of a color images (nominally at 6200 fps) that demonstrate the color temperature of the early-time ejecta and the thermal decay inside the transient crater. Ejecta is streaked due to long exposure times.

Fig. 12. Early-time self-luminous material. (A) is a time series of high-speed images (nominally at 500 fps) taken from above (approximating LROSE viewing conditions) showing the initial contact of the projectile and hot ejecta. During impact (A2), the cool projectile top is visible nested inside the transient crater and high-speed thermally emitting ejecta annulus. By the final image, the hottest component inside the crater is seen; this portion was later retrieved and found to be the inverted hollow projectile. (B) is a time-series of a color images (nominally at 6200 fps) that demonstrate the color temperature of the early-time ejecta and the thermal decay inside the transient crater.
material bounces off the walls and returns to the target bucket. Thus, this distribution actually overestimates the amount of near-crater heated material since some emitters would be ballistically transported to large distances on the Moon.

5. Discussion and interpretation

The first MIR images after the LCROSS impact show an expanse of thermally hot material several km wide. Yet at the altitude of the SSc (600 km), the crater itself should have comprised only a fraction of a pixel. Since this warm material has not yet reached sunlight (there is no change in the integrated intensity of the spectrometers), this is interpreted to be the early-time, high speed component of ejecta which decouples from main-stage growth and quickly moves outside the field of view in the laboratory. As this component of hot ejecta travels ballistically from the crater, the fill factor in the MIR pixels rapidly decreases and falls below the sensitivity of the instrument.

The ejecta curtain did not appear as an expanding annulus at the sunlight horizon (as expected from canonical cratering predictions) but instead was filled in. When viewed from above, the ejecta curtain dimensions would be described by the material just reaching the sunlight horizon (forming the radius of the “inner” ring), and faster material that has already passed the horizon and is continuing to expand in radius (the outer extent of the annulus). This outer component is comprised of the earlier time material and would become increasingly diffuse with time and distance.

By scaling the early-time experimental data, the dimensions of an inner ring of ejecta can be estimated (Fig. 14). Material ejected at ~30° from the surface at ~350 m/s (beyond the early-time ejecta-sparse period) compares well with the first few measurements of the LCROSS plume. This represents a minimum speed. Ejecta launched above this velocity (or at lower angles) would form a larger diameter curtain, but would be less optically thick due to reduced mass.

While the low-angle ejecta fit the extent of the LCROSS plume, it does not account for the “filling in” of the center annulus. Similar to the outer edge of the low-angle curtain, a high-angle component ejected 500 m/s at 75° is both consistent with experiments and sufficient to explain the absence of a central void. Again, this represents a minimum; higher velocities and angles are expected in the high-angle component. By ~25 s after impact, no new material reaches sunlight from the low-angle component; thus this period should represent the largest diameter and the greatest amount of material in the FOV’s of the spectrometers (Fig. 14). As the material above the horizon continues to expand, the apparent size of the curtain is diminished, which corresponds to the reduction of both the measured VIS curtain diameter and intensity in the VSP. By ~40 s after impact, the curtain has disappeared from the VIS images, indicating that the low-angle ejecta has dispersed or fallen below the sunlight horizon and the spectrometers are sampling only the material remaining aloft in the high-angle component.

The relative concentrations of volatiles appear to be considerably higher than expected for such a small crater. The LAMP instrument derived abundances of ~570 kg of carbon monoxide, ~140 kg of molecular hydrogen, ~160 kg of calcium, ~120 kg of mercury, and ~40 kg of magnesium (Gladstone et al., 2010). Seemingly reasonable relative abundances in the regolith are found by requiring 10⁶ kg of lunar soil to be heated to 1000 K. Raising such a mass from the 40 K pre-impact temperature to 1000 K, however, would require more than the total kinetic energy of the impact. While solar radiation can add to the energy balance, particles will only warm to the temperature defined by their radiative equilibrium. Thus, either the relative concentrations of these species is significantly higher than presented or a more efficient release mechanism is required.

The vast majority of ejected material is deposited thermally unaffected within a few crater radii of the impact point. Distal (tens of radii) roughness effects of low angle “scouring” by the early-time
ejecta have been observed in infrared and radar data (Schultz and Mendell, 1978; Thompson et al., 1981; Ghent et al., 2010) and in albedo (Schultz, 1976). While the initially hot, early-time, high-speed LCROSS ejecta curtain would have contributed little mass to the event and would have been ballistically emplaced beyond the fields of view of the spectrometers, this component could play a significant role in re-mobilization of volatiles a considerable distance from the crater. Late-stage ejecta, which comprises the greatest portion of excavated material, is emplaced a few radii away from the crater, inverting the stratigraphy and helping to blanket volatiles from exposure and hopping. The early and main-stages of ejecta, however, do not form continuous blankets, instead returning to the surface at hundreds of meters per second.

As ejecta particles are lofted above the sunlight horizon, they warm radiatively. Simple models of radiative equilibrium indicate that regolith particles of sizes <10 μm (using properties from Heningway et al. (1973) and Paige et al. (2010) and assuming spherical particles) attain an equilibrium temperature within a few seconds of flight. The addition of H2O or other volatiles increase the albedo and heat capacity in addition to cooling the particle by evaporation. These effects can add ~10 s to the warmup time, but would be eliminated after the volatiles have been liberated from the grain surface. Once the particles return below the sunlight horizon, they cool radiatively.

The ballistic return of ejecta to the surface should therefore augment the thermal and mechanical energy delivered to the undisturbed top layers of regolith surrounding the LCROSS impact. After warming in sunlight, re-impacting ejecta would disrupt the surface hundreds of crater radii away from the Centaur crater. This process could serve to enhance mobilization of metastable species in the topmost layer of the regolith, and may provide an additional source region for volatile species measured minutes after the event by Colaprete et al. (2010).

The high-angle component of the LCROSS ejecta follows a similar pattern much closer to the crater center, as warm dust returns to the surface at tens to hundreds of meters per second. Fig. 15 presents the ballistic range, or diameter of re-impacting ejecta, as a function of the ballistic time of flight or time after impact. The greatest effect would be seen from high-speed, sunlight-warmed ejecta that return to the surface within the field of view of the spectrometer. It should be noted that the 75° ejection angle for the high-angle component represents a minimum of the range of angles exhibited by this component; actual ejection angles extend to vertical (as seen in Fig. 11). Thus, the ballistic extent for the high-angle case is a maximum, with higher-angle components returning to the surface much closer to the crater center. As is seen from the VIS images of the ejecta, the entire area surrounding the crater would have been covered with a thin dusting of sunlight-warmed ejecta. If the topmost layer of regolith in the PSR is comprised of a weakly bound “hoarfrost” of volatile species (Schultz et al., 2010), the effect could be significant.

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**Fig. 15.** Ballistic extent of re-impacting ejecta vs. time after impact. The experimental data (utilizing the pumice target with a hollow impactor) for both low-angle (red diamonds) and high-angle (blue dotted line) are scaled to LCROSS dimensions and ballistically traced to the surface; thus the ballistic extent is the diameter of the re-impacting ejecta. For illustration purposes, a minimum ejection angle of 75° is assumed; the actual range of ejection angles extends upward to vertical. The approximate field of view of the spectrometers is plotted as a solid black line; thus, only material that has a ballistic extent less than the spectrometer field of view for a given time will be measured. The sunlight cut-offs for the low angle (black dashed) and high angle (blue dash-dotted) denotes the minimum ballistic range of ejecta that reached above the sunlight horizon; extents below these respective lines were thus not heated by solar radiation.

**Fig. 16.** High-angle plume data comparison with simulation from telemetry. Time series of the final four NIR2 images including the high-angle plume (indicated by dotted white arrow). A disk of arbitrary dimensions (orange) is centered 833 m directly above the calculated impact point (red ×) from Marshall et al. (2011) and projected in the reference frame of the NIR2 camera. While the plume and simulation qualitatively match in the final three images (within the range expected from phase-angle look-direction differences and launch angle (Schultz et al., 2010)), the first image (which corresponds to the first appearance of the high-angle plume) is significantly offset. In addition, the proposed impact point (illustrated in the final two images) does not match with the visible crater.
To evaluate the location and description of the high angle plume identified in the final few NIR2 images before SSC impact (as described in Schultz et al. (2010)), a reconstruction of the NIR2 field of view and look angle was developed based on the spacecraft telemetry and compared to the flight data using AGI’s Satellite Tool Kit (Fig. 16). The plume was modeled as a disk centered 833 m (the sunlight horizon) directly above the calculated impact point from Marshall et al. (2011), and was reprojected into the NIR2 perspective. The size of the disk in this evaluation is arbitrary. While the identified plume falls close to the model in the last three images (within the range expected from phase-angle look-direction differences and launch angle (Schultz et al., 2010)), the first image (which corresponds to the first appearance of the high-angle plume) is significantly offset. When reprojected in this fashion, the proposed impact point (illustrated in the final two images) does not match with the visible crater. The hot spot in the MIR images, however, corresponds more closely to the identified crater rather than the calculated impact point. This discrepancy may account for some of the offset. Additionally, an offset of only a few degrees in the expected look angle of the NIR2 could account for the misalignment. If the viewing geometry and calculated impact point are assumed to be correct, these differences may expose details of the impact. Because the Centaur is not a perfect sphere, it should realistically be expected to create asymmetric mass concentrations (strings, or chains of ejecta clumps) depending on the attitude and location of impact. Even a small local slope at the point of impact could affect the appearance of the high-angle plume.

During the final approach of the SSC, the MIR cameras revealed a thermally warm region approximately 65 m in diameter. This region is interpreted to be composed of the unresolved frictionally heated material analogous to the distribution exhibited in the laboratory studies. In all probability, these are crumpled Centaur pieces, thinly veneered by melted lunar regolith, radiating on the floor of Cabeus. This interpretation also allows for the dark “cooler” crater identified in the NIR2 images, which are of higher spatial resolution than the MIR cameras. The effect of discrete emitting chunks, rather than an area at an average temperature, can be equivalent in the thermal images (and Diviner data) but will restrict the thermal wave to much smaller localized regions with greater penetration depths. Initial results of modeling the MIR1 camera response to these sub-pixel elements indicate that the distribution of warm material proposed by Hayne et al. (2010) is inconsistent with the LRO data during the final approach. A first-order example of this behavior would be that the 30–200 m² arial extent of “hot material” utilized in Hayne et al. (2010) could be contained within a single pixel and may be divided among a maximum of four pixels (depending on the location in the sensor). The lowest expected temperature of near 400 K for this component would also cause a much higher subpixel temperature than the measured ~230 K if concentrated into a single pixel.

After formation, the walls of newly created experimental craters collapse to the angle of repose. As the walls fill in the center of the crater, they can cover heated material. The material that forms the walls of the crater is room temperature, as it has not been in frictional contact with the projectile (during penetration) and experiences low peak pressures due to the distance from impact. For the LRO event, this regolith is expected to be near the temperatures of the surrounding terrain and similarly enriched in volatiles. Infilling and covering of the Centaur remains on the floor of the crater allow for rapid quenching of any thermal energy, and may provide an additional contribution to the budget of liberated volatiles.

The source regions and depths for the different components of ejecta can provide insight to the character of the measured volatiles. The early- to main-stage components of the low-angle curtain come from a thin surficial layer a few meters deep at most. High-angle ejecta excavation depth, on the other hand, seems to be restricted to the immediate subsurface (less than ~3 m) and is comminuted more than the low-stage component. Both components are expected to sample beneath the ~70 cm depth measured by the Lunar Prospector and LEND instruments, allowing the possibility that deeper material is significantly higher in volatile content than previously expected. The measurements of volatiles minutes after the impact, which require high ejection angles to remain aloft and in the spectrometer fields of view for this period, are probably derived for the upper surface, as well as contributions from warmed grains landing on the top lamina of soil.

6. Conclusions

The unique conditions of the LCROSS impact created a two-component ejecta plume: the usual inverted lampshade “low-angle” curtain, and a high speed, high-angle component. These separate components excavated to different depths in the regolith, ejecting material from <10 m in the low-angle ejecta and <~3 m in the high-angle plume that remained aloft for minutes after impact. Extrapolations from experimental studies match the VIS data and the light curves in the spectrometers. The impact caused only small amounts of vaporization or shock heating. Warm material is manifested at early times by sparse ejecta launched at high speeds and heterogeneously around the crater at late times, rather than a simple “hot” ejecta blanket. The crater interior was probably cooled quite rapidly, leaving only localized warm areas surrounding frictionally-heated portions of the crushed Centaur. Additionally, the ballistic return of sunlight-warmed ejecta surrounding the crater could have caused a significant increase in the surficial source region for volatiles measured by the LCROSS spectrometers.

Acknowledgments

We wish to acknowledge the work of the technical crew at the NASA Ames Vertical Gun Range: Donald Holt, Rick Smythe, and Donald Bowling. We also thank two anonymous reviewers for their helpful feedback, and J.T. Heineck and E.T. Schairer for advice and expertise with the imaging techniques used. This study could not have been possible without experiments and analysis carried out through NASA Planetary Geology and Geophysics Grant #NNX08AM45G. BH was supported by a NASA Rhode Island Space Grant Fellowship #NN05GG71H.

Appendix A. Processing routines for VIS data

The VIS images suffered from wavelet compression artifacts due to the complexity of the scene in the period immediately surrounding impact. Although attempts at filtering these artifacts are ongoing, the procedure used in this work is presented here.

The technique used relies on the facts that (1) the noise is not the same between two interlaced images and (2) the color temperature of noise is different than the plume or the moon surface.

(1) De-interlacing the images and constructing even/odd pairs (images should be resized to get square pixels).
(2) Sub-pixel registration of the pairs using a cross-correlation routine.
(3) Filter based on color (2 images × 3 colors) so that if the color balance differs from lunar histogram, reject pixel value.
(4) Construct a minimum image by taking the minimum value of each pixel through the six layers.
(5) Unsharp masking.
(6) Re-interpolating the image to full size.
(7) Various processing as above (e.g., power-law stretching, brightness and contrast, subtracting a noise floor, etc.).