

**Ejecta Evolution and Dynamics from Hypervelocity Impacts:
Time-Resolved Experimental Studies and Applications to Planetary
Cratering**

by

Brendan Hermalyn

B.S., Fairfield University, 2007

M.S., Fairfield University, 2007

Sc.M., Brown University, 2009

Sc.M., Brown University, 2011

Dissertation

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This dissertation by Brendan Hermalyn is accepted in its present form by the
Department of Geological Sciences as satisfying the dissertation requirement for the
degree of Doctor of Philosophy.

Date: _____

Peter H. Schultz, Advisor

Recommended to the Graduate Council

Date: _____

Donald W. Forsyth, Reader

Date: _____

John F. Mustard, Reader

Date: _____

E. Marc Parmentier, Reader

Date: _____

David A. Crawford, Reader

Approved by the Graduate Council

Date: _____

Peter M. Weber, Dean of the Graduate School

Curriculum Vitæ

brendan_hermalyn@brown.edu
(401) 863-7526

Brown University Geological Sciences
Box 1846 Providence, RI 02912

Education:

BROWN UNIVERSITY, Providence, RI

Ph.D., Planetary Sciences (5/2011)

- Impact Physics
- Advisor: Dr. Peter H. Schultz

Sc.M., Engineering (5/2011)

- Fluid Dynamics
- Advisor: Dr. Kenneth S. Breuer

Sc.M., Geological Sciences (5/2009)

- Impact Physics/Planetary Science
- Thesis Title: *Early-Stage Ejecta Velocity Distribution from Hypervelocity Impacts into Sand*
- Advisor: Dr. Peter H. Schultz

FAIRFIELD UNIVERSITY, Fairfield, CT

M.S., Mathematics (8/2007)

- Statistics, Numerical Analysis

B.S., Fairfield University (1/2007) Summa Cum Laude. 4.0 GPA. Phi Beta Kappa.

- Majors: Physics, Music; Minor: Mathematics

Professional Experience:

DIXI Science Team Collaborator (2010-Present)

Stardust-NExT Science Team Collaborator (2010-Present)

NASA JPL Planetary Sciences Summer School (August 2010)

CTH Hydrocode Training Class, Sandia National Laboratories (March 2010)

LCROSS Science Team Collaborator (2009-Present)

Deep Impact Science Team Collaborator (2008-Present)

Graduate Research Fellow, Brown University (9/2007-Present)

NASA Reduced Gravity Students Opportunities Program (Spring, 2007)

- Project Leader for *Splashless In Space: The Impact Behavior of Large Droplets on a Rigid Surface in Low-Atmosphere, Low-Gravity Environments*

NASA/Goddard Space Flight Center Internship (Summer, 2006)

- Project: *Radiative Non-Equilibrium at the Lunar Surface*

Independent Study in Biophysics, Fairfield University (Spring, 2004)

Teaching and Community Experience:

Brown University

- RI Space Grant Science Education Outreach (2009-2010)
- Guest Lecturer, GEOL 0810 Planetary Geology. (April, 2009)
- Co-President, Geology Department GeoClub. (2008-2009)
- T.A. for GEOL 0810 Planetary Geology (Spring, 2008)

The Discovery Museum and Planetarium (Summer 2001 → Summer 2007)

- Science instructor, program developer, Challenger Center commander, science demonstrator, exhibit designer

Fairfield University (2004 → 2005)

- Undergraduate tutor for Mathematics and Physics

Awards and Fellowships:

Brown University Dissertation Fellowship (2010-2011)

Alex Charters Student Scholar of the Hypervelocity Impact Society (2010)

Rhode Island Space Grant Fellowship (2009-2010)

Stephen E. Dwornik Planetary Geoscience Student Paper Award: Best Graduate Oral Presentation (2009)

Brown University Travel Grant Award (2009)

Birkmaier Fund Recognition Award (2008)

NASA Cosmochemistry Program Travel Support Grant (2008)

Connecticut Space Grant Consortium Project Grant (2007)

NASA/JSC Reduced Gravity Student Opportunities Program (2007)

Society Of Physics Students Student Leadership/Future Teacher Scholarship (2006)

Honorable Mention, AAPT Barbara Lotz Future Physics Teacher Scholarship (2005)

Knights of Pythias Scholarship (2004)

Fairfield University Fellowship (2003-2007)

Publications:

- Hermalyn, B.;** Schultz, P. H. Time-Resolved Studies of Hypervelocity Vertical Impacts into Porous Particulate Targets: Effects of Projectile Density on Early-Time Coupling and Crater Growth. Submitted. *Icarus*, 2011.
- A'Hearn, M. F.; Belton, M. J. S.; Delamere, W. A.; Feaga, L. M.; Hampton, D.; Kissel, J.; Klaasen, K. P.; McFadden, L. A.; Meech, K. J.; Melosh, H. J.; Schultz, P. H.; Sunshine, J. M.; Thomas, P.; Veverka, J.; Wellnitz, D. D.; Yeomans, D. K.; Bodewits, D.; Carcich, B. T.; Collins, S. M.; Farnham, T. L.; **Hermalyn, B.;** Kelley, M. S. *EPOXI at Comet Hartley-2*. Submitted. *Science*, 2011.
- Hermalyn, B.;** Schultz, P. H. Early-Stage Ejecta Velocity Distribution for Vertical Hypervelocity Impacts into Sand. *Icarus* 209(2):866–870, 2010.
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Selected First-Author Conference Publications and Presentations:

- Hermalyn, B.; Schultz, P. H.; Farnham, T. L.; Bodewits, D.; A'Hearn, M. F. *The Detection and Location of Icy Particles Surrounding Hartley 2*. LPSC 2011.
- Hermalyn, B.; Schultz, P. H.; Heineck, J. T. *The Ejecta Evolution of Deep Impact: Insight from Experiments*. AGU 2010.
- Hermalyn, B.; Schultz, P. H.; Colaprete, A.; Shirley, M.; Ennico, K. *LCROSS Ejecta Dynamics: Implications for Volatile Release*. NLSI Forum 2010.
- Hermalyn, B.; Schultz, P. H. *Effects of Projectile Density on Early-Time Coupling for Hypervelocity Impacts into Porous Particulate Targets*. HVIS 2010.
- Hermalyn, B.; Schultz, P. H.; Heineck, J. T. *Early-Stage Coupling for Oblique Impacts in Granular Material*. LPSC 2010.
- Hermalyn, B.; Schultz, P. H.; Colaprete, A.; Shirley, M.; Ennico, K. *LCROSS Ejecta Dynamics: Insight from Experiments*. LPSC 2010.
- Hermalyn, B.; Schultz, P. H.; Colaprete, A. *LCROSS Impact Conditions and Ejecta Evolution: Insight from Experiments*. AGU 2009.
- Hermalyn, B.; Schultz, P. H.; Heineck, J. T. *LCROSS Early-Time Ejecta Distribution: Predictions from Experiments*. LPSC 2009.

Hermalyn, B.; Schultz, P. H.; Heineck, J. T. *Early-Stage Ejecta Velocity Distribution*. LPSC 2009. Hermalyn, B.; Schultz, P. H.; Anderson, J. L. B.; Heineck, J. T. *Evolution of Impact Ejection Angles: Implications for Early-Stage Coupling*. MetSoc 2008.

Hermalyn, B.; Schultz, P. H.; Anderson, J. L. B.; Heineck, J. T. *Time-Resolved Ejecta Velocity Distribution in Oblique Impacts*. ACM 2008.

Hermalyn, B.; Schultz, P. H.; Anderson, J. L. B.; Heineck, J. T. *Time-Resolved Assessment of Ejecta-Mass Distribution Using 3D-PIV*. LPSC 2008.

Professional Associations:

American Geophysical Union
Meteoritical Society
The Explorers Club
Sigma Pi Sigma (Physics Honor Society)
Alpha Mu Gamma (Language Honor Society)
Pi Mu Epsilon (Mathematics Honor Society)

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Introduction and Motivation

The excavation of mass during an impact is a shock-driven process that shapes the distribution of materials on planetary surfaces. Ejecta velocities reflect the initial conditions and material flow-field inside the transient crater, and control the ballistics and eventual emplacement of material. Studies of ejection velocities during main-stage excavation flow describe the speed and direction of ejected material as a function of time after impact or launch position. Dimensionally predicted scaling laws for impacts (and explosions) into granular targets [Housen et al., 1983] provide a canonical ejecta-velocity distribution: a power law relationship between ejection velocity and time (or ejection position) at a constant ejection angle (Fig. 1). This model is an example of the “late-stage equivalence” concept of crater growth [Dienes and Walsh, 1970], where the details of the impact, i.e., the transfer of the projectile’s energy and momentum to the target, are collapsed into a single coupling parameter C to simplify scaling (e.g., Housen et al. [1983]). Almost all experimental studies have provided spatial descriptions of the launch position due to the difficulties in temporally-resolved in-flight measurement.

The spatial domain allows ejecta velocities for a given launch position to be scaled solely by late-stage parameters, such as the final crater radius and gravitational acceleration (see Fig. 1). At early times, however, while the projectile is still transferring its energy and momentum to the target, the single power-law relationship does not hold. Recent experimental studies of vertical impacts into sand [Hermalyn and Schultz, 2010] reveal an increased ejection velocity above point-source predictions at early times before transition to the expected power-law slope. This early-stage component does not scale according to late-time dimensionless groups relevant once the late-stage equivalence is in effect (such as the final size of the crater), but instead must

be scaled according to the initial shock conditions of the impact. While this early phase represents a very small portion of crater formation time or total ejected mass in laboratory experiments, it should consume a larger percentage of crater growth for planetary-sized events since the cratering efficiency (displaced crater mass over projectile mass) diminishes [Schultz, 1988]. This phase is also relevant for the measurements of the LCROSS mission, which relied on ejecta reaching a sunlight horizon of ~ 830 meters above the impact point. This altitude sets a velocity requirement that corresponds to the earliest stages of growth. Prior studies address the prescribed minimum velocity only marginally, as shown in Fig. 1. Additionally, a temporal (rather than the usual spatial) description of the event is necessary for interpretation of spacecraft data.

Vertical impact events rarely occur on planetary bodies, however. Instead, impacts occur at oblique angles to the target surface, where 45° is the most statistically probable angle [Gilbert, 1893, Shoemaker, 1962]. While the rims of craters on planetary bodies tend to retain circularity for all but the most oblique impacts, asymmetric ejecta patterns, such as the uprange “zone of avoidance” (ZoA), are observed both at laboratory and planetary scales for a much wider range of impact angles. These asymmetries cannot be accommodated by the point-source assumption. When the axisymmetric simplification of vertical impacts is removed, the point-source approximation is insufficient to explain the details of the impact for virtually all of crater growth. Asymmetries in the shock [Dahl and Schultz, 2001] from oblique impacts are manifested through azimuthally dependent velocities and ejection angles in the ejecta flow-field, as well as damage [Schultz and Anderson, 1996]. Such asymmetries persist well into crater growth; considerably after the dimensionally-predicted point-source flow-field would be established in a comparable vertical impact [Anderson et al., 2003, 2004, Anderson and Schultz, 2006] (see Fig. 2). Additionally, the time-dependent spa-

tial variations in the flow field center and ejection position during excavation (and ultimate crater dimensions) complicates scaling considerably. To date, no simple analytical ejection velocity model incorporating impactor obliquity has been proposed.

This dissertation presents new temporally-resolved experimental data of the early- to main-stage ejecta velocity distribution from impacts into granular targets. The tractability and success of these experiments, which were performed at the NASA Ames Vertical Gun Range (AVGR), is in large part due to recent advances in equipment and techniques for high-speed photography and photogrammetry. Overcoming the engineering challenges here provided novel data, but it is essential that these results are taken in the context of planetary cratering. As a result, the structure of this dissertation is developed in pairs of studies, each composed of an experimentally based (more technical) chapter, followed by an application of the findings to planetary events.

Outline of Chapters

Chapter one is an experimental study of the effects of projectile density on the ejecta velocity distribution from hypervelocity vertical impacts into sand targets. This project builds on the 2-dimensional PTV technique initially developed in Hermelyn and Schultz [2010] to present the ejecta velocity distribution as a function of both time and launch position for the first time. The temporal resolution of this technique allows measurement of ejecta an order of magnitude faster (and earlier) than captured in previous studies (see Fig. 1), and reveals early-time, high-speed deviations from the expected point-source behavior. The combination of the spatial and temporal description of the ejecta velocity also provides new insight into the cratering evolution through development of proxies for the early-stage depth and diameter of the transient crater.

In chapter two, we apply these results for the early-time high-speed component of ejecta to the LCROSS mission data. The LCROSS mission used the spent Centaur upper stage rocket that transported the spacecraft (and LRO) to the moon to impact a permanently shadowed region near the south pole. Once illuminated by the sun, volatiles in the regolith matrix were released and measured by a suite of instruments onboard the LCROSS shepherding spacecraft. Interpretation of the nature of these volatiles within the regolith is dependent on the cratering process. The conditions of impact made this a unique cratering event: the geometry of the low-density, hollow Centaur rocket, the relatively slow (2.5km/s) impact speed, and the high minimum ejecta velocity requirements to reach sunlight. These conditions complicate the reconstruction of the event. In this chapter, we present experimental results using both high-speed instruments and LCROSS flight backup instruments in order to examine the mechanics of an LCROSS-like event. These results are then applied to the LCROSS flight data to allow interpretation of the source region and possible excavation depths for the volatiles.

The third chapter presents the first time-resolved experimental studies of the early-to main-stage ejecta velocity for oblique impacts. The pioneering efforts of Anderson et al. [2003], Anderson and Schultz [2006] provided a first look at the velocity distribution in oblique impacts in the spatial domain, and demonstrated asymmetries that persisted to late stages. These studies were restricted to a single discrete velocity vs. launch position measurement (for all azimuths) per impact experiment. Thus, multiple identical experiments were required to build up data for a specific impact condition; as a result, the data is not temporally resolved. In this chapter, a novel high-speed three-dimensional imaging technique is developed for this application at the AVGR to measure the ejecta velocity as a function of time (rather than

launch position, which required complicated correction terms [Anderson and Schultz, 2006]). The temporal resolution afforded by this technique allows the development of an analytical model of ejecta velocity that accounts for the oblique trajectory of the impactor.

Chapter four develops an ejecta propagation model that utilizes the experimentally-determined velocity distribution in chapter three to reconstruct the ejecta patterns resulting from oblique impacts, both in-flight and once emplaced on planetary surfaces. Direct examinations of these effects at laboratory scales are limited to an area only a few crater radii larger than the crater due to the chamber walls. In-flight ballistic ejecta measurements include velocity, the existence and closure of the up-range zone of avoidance, and the flow-field center migration during excavation. These parameters represent a first step toward parametric investigation of the factors controlling uprange ejecta patterns and non-radial emplacement on planetary surfaces. The model is then applied to the Deep Impact mission to permit an experimentally based reconstruction of the event.

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Figure Captions

Figure 1. Ejecta velocity distribution for prior studies. The velocity is presented as a function of launch position x_e (the distance from impact point and crater center), scaled to the final crater radius R . Velocity v_e is scaled to the late-stage, dimensionally-predicted parameter of the square root of the gravity times the final crater radius. Sources for data are listed in the legend. Overplotted is the minimum velocity required to reach the sunlight horizon for the LCROSS event, which demonstrates the need for understanding the faster material from earlier times.

Figure 2. Oblique ejecta velocity distribution for hypervelocity impacts into sand from Anderson et al. [2004]. Velocity v_e is scaled to the late-stage, dimensionally-predicted parameter of the square root of the gravity times the the “adjusted” final crater radius R' . The velocity is presented as a function of launch position x_e (the distance from impact point and crater center), scaled to R' . Data is arranged into bins downrange (in the direction of impact), uprange (antiparallel to the impact vector) and lateral (orthogonal to the trajectory) to the flow-field center. Velocity data from a similar vertical impact is included as a black solid line.

Figures

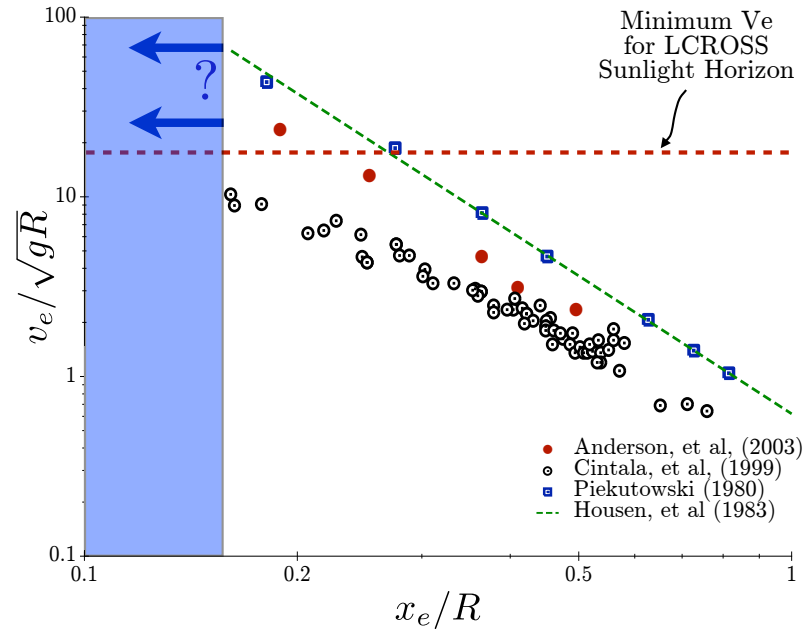


Figure 1

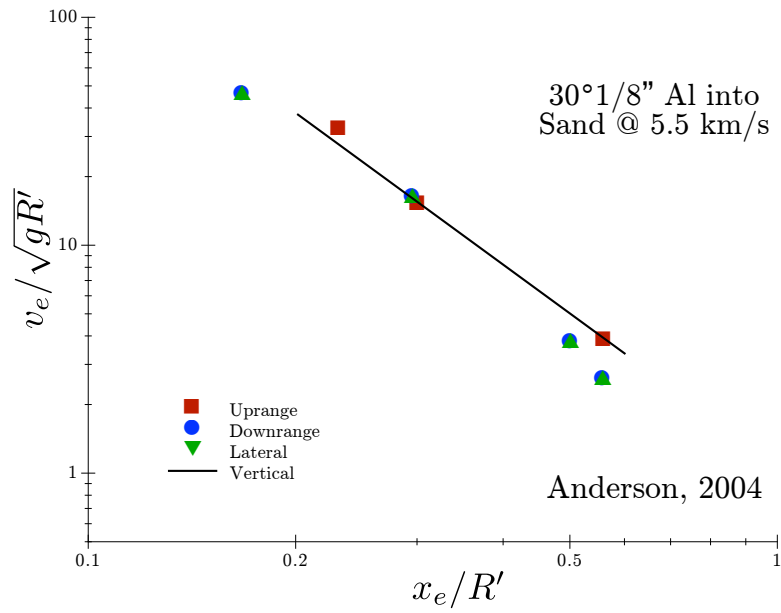


Figure 2

**Chapter 1. Time-Resolved Studies of Hypervelocity Vertical
Impacts into Porous Particulate Targets: Effects of Projectile
Density on Early-Time Coupling and Crater Growth**

Brendan Hermalyn and Peter H. Schultz

Department of Geological Sciences, Brown University

Providence, RI 02912

Abstract

The depth and duration of energy and momentum coupling in an impact shapes the formation of a crater. The earliest stages of crater growth (when the projectile transfers its energy and momentum to the target) are unrecoverable when the event is described by late stage parameters, because the initial conditions of the impact are collapsed into a singular point in time and space. During the coupling phase, the details of the impact are mapped into the ejecta flow field. The goal of this experimental study is to examine the effect of projectile density on coupling depth and location in porous particulate (sand) targets through measurement of the time-resolved ejecta evolution. A non-invasive high-speed imaging technique is employed to capture the velocity of individual ejecta particles from very early in the cratering event. These data reveal that the effects of early-stage coupling, such as non-constant ejection angles, manifest not only in early-time behavior (as initially reported in Hermalyn and Schultz [2010]) but also extend to main-stage crater growth. Time-resolved comparisons with hydrocode calculations provide both benchmarking and insight into the parameters controlling the ejection process. Metrics for the transient depth to diameter ratio demonstrate non-proportional crater growth throughout much of excavation. Low-density projectiles couple closer to the surface, thereby leading to lower ejection angles and higher proxies for the diameter to depth ratio. These results have implications for the ballistic emplacement of ejecta on planetary surfaces.

1.1 Introduction and Background

Granular target materials, such as sand, are commonly used in laboratory-scale experiments as a proxy for both smaller planetary impacts into regolith-covered bodies as well as larger gravity-controlled craters. Prior studies established a canonical ejecta distribution model for main-stage crater growth in granular targets: ejection velocities controlled by the surface gravity launched at a constant ejection angle (e.g., [Housen et al., 1983]). Similarly, metrics for crater growth, such as the crater diameter and depth, are usually approached from either main-stage or final crater dimensions.

Implicit in most of these studies is the assumption of proportional crater growth (wherein the crater maintains a constant aspect ratio and shape throughout excavation) and the “late-stage equivalence” [Dienes and Walsh, 1970, Holsapple and Schmidt, 1987]. These assumptions compress the initial conditions of the impact to a singular point in time and space, (i.e., a “coupling parameter” [Holsapple and Schmidt, 1987]), and allow main-stage excavation growth (where the majority of material is ejected) to be scaled over a range of crater sizes and impact conditions. The scaling of main-stage ejection velocity for hypervelocity impacts into granular material during nominal crater growth can be described by dimensional analysis [Housen et al., 1983], as supported by a number of experimental (e.g., McGetchin et al. [1973], Schultz and Gault [1979], Piekutowski [1980], Oberbeck and Morrison [1976], Piekutowski et al. [1977], Cintala et al. [1999], Anderson et al. [2003]) and numerical studies (e.g., Wada et al. [2006]). The details of the initial coupling phase after impact, when the projectile transfers its energy and momentum to the target, have traditionally been viewed as lost when the event is described by main-stage parameters.

While the projectile is still transferring its energy and momentum to the target at early times, however, the standard main-stage scaling laws should not (and do not) apply. Recent time-resolved experimental studies of vertical impacts into sand

reveal ejection velocities higher than extrapolations from point-source predictions at early times [Hermalyn and Schultz, 2010]. The early-stage component does not scale according to the main-stage dimensionless groups relevant after the late-stage equivalence has been achieved (such as the final size of the crater). Instead, this high-speed component reflects the variables (such as the projectile size, impact velocity, projectile density, and target material properties) that control the initial shock conditions of the impact. The ejecta velocity during this phase is the manifestation of the energy and momentum balance in the transient crater. Although this early stage represents a very small portion of the time of crater formation and total ejected mass in laboratory experiments, the phase consumes a larger percentage of crater growth for planetary-sized events [Schultz, 1988].

Previous experimental studies have not, in general, extended into this regime for granular materials, and studies of the effects of projectile density on the impact event have been limited (as pointed out in Housen and Holsapple [2011]). Computational modeling of impacts into granular materials is also not yet fully constrained or calibrated, particularly for this early stage of growth [Brown et al., 2007, Pierazzo et al., 2008], and has only recently been able to incorporate some of the fine-scale physics [Collins and Wünnemann, 2007, Collins et al., 2010]. Almost all prior velocimetry studies (with some exceptions, e.g., Braslau [1970] and Hermalyn and Schultz [2010]) reference ejecta velocities to a spatial dimension, i.e., the distance from crater center. While this approach provides a valid description of main-stage ejection from vertical impacts, the three-dimensional evolution of the flow-field center in oblique impacts convolutes the use of a spatial metric and requires complicated correction terms (as presented in Anderson and Schultz [2006]). Thus, the dependent variable of time of launch is employed.

Measurements of the transient crater have been conducted through the use of quarter-space techniques (where a translucent window vertically divides the half-

space target along the impact plane, thereby permitting a view of the crater interior, e.g., Schmidt and Housen [1987], Schultz et al. [2005]) and more recent non-intrusive investigations utilizing a laser system (e.g., Barnouin-Jha et al. [2007], Yamamoto et al. [2009]). These studies have primarily focused on the transition from main- to late-stage growth and subsequent modification. Extension to the early-time regime using these techniques, however, is problematic due to the temporal resolution required and obscuration of the initial early-time cavity due to the impact flash and ejecta.

In this experimental study, we present new experimental and computational measurements of the ejecta distribution and crater growth extending from early times into main-stage ballistic flow for hypervelocity impacts over a range of projectile densities. We implement a non-intrusive, high-speed, time-resolved imaging technique that allows expression of the ejecta velocities as a function of both time and launch position, thereby permitting comparison to past studies. The temporal nature of the data enables comparison and validation of hydrocode parameters during the critical early stages of cratering (rather than the crater dimensions alone). Since the ejecta distribution is an expression of the flow-field, it also reflects the conditions inside the transient crater. Crater growth metrics are developed for both the time-resolved depth and diameter of the crater. These proxies demonstrate non-proportional crater growth and allow direct investigation of the depth and duration of coupling in porous granular materials and their implications for planetary bodies.

1.2 Experimental Description

As part of a general study to understand the effect of projectile impact parameters on coupling, a series of impact experiments was performed at the NASA Ames Vertical Gun Range (AVGR) in Moffett Field, CA. In this study, we focus on the effects of projectile density by using impactors of variable materials into a quartz sand target

(median grain diameter of $\sim 1\text{mm}$; bulk target density of $\delta_t = 1.7\text{g/cc}$). The Ottawa sand grains used in this study are nearly spherical in shape (in contrast to crushed quartz sand, which exhibits a higher degree of internal friction).

The density of the impactor was adjusted by employing a variety of projectile materials: polyethylene ($\rho=0.9\text{g/cc}$), nylon ($\rho=1.1\text{g/cc}$), pyrex ($\rho=2.2\text{g/cc}$), aluminum ($\rho=2.8\text{g/cc}$), titanium ($\rho=4.4\text{g/cc}$), and steel ($\rho=7.8\text{g/cc}$). In order to constrain the effects of density, the projectiles used here were all 6.35 mm in diameter, and were launched at approximately 5.5km/s (within $\sim 15\%$; with the exception of the slightly slower steel projectile). See Table 1.1 for the full range of impact variables employed in this study. All experiments were performed at a vertical incidence angle (i.e., orthogonal to the target surface), and under vacuum conditions ($< 67\text{ Pa}$ of atmosphere).

1.3 Measurement Technique

A set of high-speed cameras were narrowly focused on the ejecta curtain profile (see Fig. 1.1 for examples of recorded images). A non-intrusive Particle Tracking Velocimetry (PTV) imaging technique provided measurements of ejecta velocities. The PTV method, which is commonly used in experimental fluid dynamics, tracks individual particles between successive image frames at high spatial resolution, thereby determining the instantaneous velocity of each grain in the field of view. This study employs a multi-step implementation of PTV. First, the ensemble motion of multiple particles is computed between frame pairs using an iterative cross-correlation routine (a particle imaging velocimetry technique) to generate an initial reference velocity field. The images are then interrogated to locate individual particles ($\sim 4 - 5$ pixels in diameter). Finally, particle position and displacement is computed using the reference motion as an initial step. The advantage in this methodology is that individual

particles are tracked in a Lagrangian fashion (rather than velocity measurement over an Eulerian grid, as is the case in cross-correlation or Particle Imaging Velocimetry studies), thereby permitting ballistic retraction of discrete grains to the target surface and determination of ejection velocity, time of launch, and launch position.

In most fluidic PTV studies, the measurement plane is established through the use of a thin laser sheet to illuminate tracer particles in the flow field. For this study, the measurement plane was established by long focal length lenses at low f-stops (wide apertures), in order to restrict the depth of field (DoF) of the imaged curtain. Thus, only a few centimeters of the curtain (specifically, the plane that contains the impact vector perpendicular to the camera sensor) is in focus and measurable. Particles that are out of the plane of measurement will not be tracked (e.g., see Fig. 1.1 for example images that demonstrate the difference between in-focus and unfocused particles). By utilizing the profile edge of the curtain, the velocities of the ejected particles are reduced to two components (since there is little motion away from or towards the camera sensor). The radial symmetry of ejecta in vertical impacts justifies the applicability of this measurement over all azimuths in the curtain. The concept of planar measurement of the ejecta has been applied in prior studies [Oberbeck and Morrison, 1976, Piekutowski et al., 1977, Cintala et al., 1999, Hermalyn and Schultz, 2010]. Through the use of high-speed cameras operating at 15,000 frames per second with exposure times of $< 1\mu\text{sec}$ to minimize streaking, the velocity of in-flight ejecta can be determined throughout much of crater growth, extending from the early-time regime through the transition to main-stage flow.

The accuracy of this method depends on the image resolution, impact timing uncertainty, and the error in the 2-dimensional simplification. High spatial resolution compensates for the relatively small number of particles in the region of interest in the curtain profile (compared to fluidic implementations). Impact timing is known to $\mathcal{O} \sim$ a few microseconds for all experiments from either direct calculation (if the projectile

is imaged in flight) or time-of-flight calculation from laser timing stations located on the AVGR launch tube. The out-of-plane velocity error can be constrained by both the DoF, which is maintained at a few cm, and the speed of the particles. The error is greatest ($\sim 20\%$) at early times, when the particles are only in two successive frames, and diminishes at later times. It is important to note that this error would only serve to artificially decrease the measured absolute magnitude of the ejecta (diminishing the measured radial component since the out-of-plane motion would not be captured) and would not affect ballistic regression to the surface calculated from the vertical component.

Since these experiments were performed under full illumination, the impact point (which varies slightly but measurably in both x and y axes between experiments) is always within the measurement plane of the cameras as defined by the DoF. Thus, the particles on the outer edge of the curtain profile will not have an additional out-of-plane component. In contrast, a measurement plane established by a vertical laser sheet may not include the actual point of impact, and quarter-space experiments are necessarily offset to avoid impacting the window. These disparities from the impact point would cause measured velocities to be systematically lower.

1.4 Analysis

1.4 Methodology

Once the positions and displacements of the particles are determined, the grains are regressed to the surface by subtracting the ballistic time of flight and trajectory, thereby determining the ejection velocities (and thus ejection angle), time of launch, and launch position. Particles are assumed to be launched under extension (e.g., no particle interactions) at the pre-impact target surface. From here, metrics of crater growth can be formulated. First, since the launch position (distance from impact point and, in vertical impacts, crater center) is computed simultaneously with time

after impact (after removal of the ballistic time of flight as above), we can determine the diameter of the transient crater in a temporally-resolved manner. Second, an effective maximum scaled-depth of excavation, y' , is derived as the intersection of the particle launch vector at the target surface with the vertical impact vector, scaled to the radius of the projectile (see Fig. 1.2). This proxy is established from the physical constraint that this intersection point represents the absolute deepest location from which material could be ejected for any given time after impact. While other studies [Maxwell, 1977, Croft, 1980] have employed different metrics for excavation depth based on empirical models of hydrostatic flow fields, they include an implicit assumption of proportional crater growth and are not expected to apply at early times. Therefore, we adopt the simplified maximum above with the understanding that it is only a proxy and will overestimate crater depth during main-stage growth.

1.4 *Scaling*

Following common practice in the literature (as defined by dimensional analysis in Housen et al. [1983]), ejection velocity v_e is scaled to the impact velocity V_i at early times, and to the square root of gravity g multiplied by the final crater radius R_c for gravity-controlled craters during main-stage ejection.

The temporal scaling of the early-time component is dependent not upon strength or gravity, but rather by the initial conditions of the impact event [Hermalyn and Schultz, 2010]. The early-stage abscissa is given by:

$$\tau' = \frac{t_{launch}}{(a/V_i)} \left(\frac{\delta_t^\nu c^\mu}{\delta_p^\nu V_i^\mu} \right) \quad (1.1)$$

where t_{launch} is the time after impact that a particle crosses the pre-impact surface, a is the projectile radius, c is the sound speed, and δ_t and δ_p are the target and projectile densities, respectively (as in Hermalyn and Schultz [2010]; derivation is

included in Appendix 1 here for completeness). This can be thought of as the early-stage penetration parameter $\tau = t_{launch}/(a/V_i)$ with an impedance term.

The dimensional exponents found to best scale the velocity data are $\mu = 2/3$ with $\nu=1/3$ [Holsapple and Schmidt, 1987, Holsapple, 1993]. The main-stage dimensionally-predicted velocity dependence on time is given by [Housen et al., 1983]:

$$\frac{v_e}{\sqrt{gR_c}} = k_1 \left(t_{launch} \sqrt{\frac{g}{R_c}} \right)^{(\alpha-3)/(\alpha+3)} \quad (1.2)$$

where k_1 is a constant of proportionality and α is a constant for a given material. We adopt $\alpha = 0.51$, as in Housen et al. [1983], and as supported by our data. Note that $\alpha = 3\gamma/(2 + \gamma)$ [Housen et al., 1983], where γ is a different expression of the constant for a given material; thus, the exponent in the equation above could also be formulated as $-1/(1 + \gamma)$. We employ the α notation for late-stage parameters, and the γ notation for early-stage formulations for continuity with Housen et al. [1983] and Housen and Holsapple [2011] respectively, even though the numerical exponents are identical for a given material.

For scaling of the launch position in the inertial range, we adopt (from Housen and Holsapple [2011]):

$$\frac{v_e}{V_i} = k_2 \left[\frac{x}{a} \left(\frac{\delta_t}{\delta_p} \right)^\nu \right]^{-1/\gamma} \quad (1.3)$$

where x/a defines the non-dimensional launch position. Note that the scaling parameters V_i and a can be replaced with $\sqrt{gR_c}$ and R_c , respectively, to transform into the standard late-time scaling relations. The δ_t/δ_p term is required for matching dissimilar target and projectile materials. In many previous studies of impacts into sand, this term is omitted since it is nearly constant for similar impact conditions (e.g., Holsapple and Schmidt [1987]).

1.4 *Projectiles of Variable Density into Sand*

The measured ejection velocity as a function of time, scaled to both early- and late-stage parameters, is given in Fig. 1.3. All experiments match at late times as expected, but the ejecta velocity distribution departs from the point-source approximation at very early times. Data from prior studies (as indicated in the figure legends) is presented in Fig. 1.4 for comparison. Note that the present study captures material ejected an order of magnitude faster and considerably earlier in the excavation process than previous studies. The same velocity data, when plotted against crater growth parameters (Fig. 1.5), also exhibit departures at early stages of excavation close to the impact point. Higher density projectiles initially eject material from near the crater center and then transition to the expected power-law predicted slope.

The angle of ejection evolves throughout excavation and departs from the commonly assumed value of $\sim 45^\circ$ (Fig. 1.6). Early-stage ejection angles rapidly increase until attaining a maximum value before decreasing. Ejecta from the aluminum projectile (Figs. 1.6b, 1.6d) initially reach an angle of $\sim 50^\circ$ before progressively lowering towards $\sim 40^\circ$ throughout crater growth. The higher density titanium and steel projectiles result in a more gradual increase of 10° to 15° upward, ultimately reaching a progressively higher ejection angle dependent on the density. Ejection angles from the impact of the titanium projectile eventually decrease to merge with the angles from the aluminum impact; ejection angles from the steel impact, however, retain a characteristically higher ($\sim 5^\circ$) ejection angle throughout measurement. In contrast, the low density nylon and polyethylene projectiles produced lower ejection angles (in the 40° range) throughout growth. It should be noted that the ejection angle of individual particles is not necessarily equal to the curtain angle.

1.4 *Computational Comparison*

Hydrocode parameters (e.g., equations of state) can be calibrated for granular materials using these temporal results and can provide valuable insight into the factors controlling excavation of material at early times. Prior attempts at hydrocode validation with experimental data have focused on the final crater dimensions in metals and strengthless targets [Pierazzo et al., 2008] as well as quarter-space experimental data using sand targets [Pierazzo et al., 2010]. While final crater dimensions can be “dialed in” with almost any strength model (as is pointed out in Pierazzo et al. [2010]), the detailed matching of the cratering process is much more difficult and must be based on physical constraints. Here, we present the preliminary results of an investigation to match the velocity and ejection angle in laboratory-scale experiments using Sandia’s CTH code [McGlaun et al., 1989]. These initial results are part of a larger parametric study to address the effects of hydrocode parameters on the ejecta distribution, and are provided here because they impart insight into the mechanics controlling the ejection process; full analysis of these results will be presented in a future contribution.

The use of velocity as a metric constrains the partitioning of energy within the computation; for example, if comminution and compaction of the sand grains robs from the energy balance, the available kinetic energy (e.g., velocity of ejecta) will be correspondingly lower [Braslau, 1970]. Thus, matching the ejecta velocity between experiment and code provides a metric for differences in energy partitioning. This matching extends not only to the absolute magnitude, but to the ejection angles, which reflect the relative kinetic energy partitioning between upward and radial velocity components. Benchmarking the velocity distribution also has practical implications, since hydrocode calculations have been used to assess ejecta emplacement on planetary bodies.

The studies performed mimic the experiments using 3-dimensional, laboratory-

scale computations. Specifically, the main goal was to replicate the ejecta dynamics from the 6.35mm diameter aluminum experiment at 5.59 km/s. Axisymmetric 2-dimensional (2D) models (which assume a cylindrical geometry) are commonly employed to reduce the computational burden, especially for vertical impacts. Such studies, however, suffer from the boundary condition along the origin line, which leads to non-realistic behavior along the center (usually called “center-line artifacts”) and affects the ejection angle and velocity of material. Additionally, ballistic propagation under the 2D assumption is convoluted because ejecta “particles” are actually considered as toroids rather than individual masses. Although computationally expensive (even with the considerable benefit of adaptive mesh refinement or AMR), matching the experimental data requires the full dimensionality of the problem even for vertical impacts, and will be necessary for extension to an oblique impact.

In order to compare the early-stage velocity distribution to the experiments, two different equations of state (EOS) were tested for the target: a tabular EOS for porous quartz (SESAME “dry_sand”), and the recently benchmarked P- λ model for quartz sand (using parameters from [Brown et al., 2007]). In this study, we take a continuum approach to modeling the target surface, rather than the mesoscale approach employed in Barnouin-Jha et al. [2002], Crawford [2005, 2006]. The SESAME studies utilized the P- α model of porosity, which models the collapse of pore space through a single pressure-dependent distention parameter α [Carroll and Holt, 1972]. The P- λ model utilizes a Mie-Gruneisen EOS approximation for shock calculations and is coupled with a non-linear pressure dependent compaction term λ . While the initial benchmarking of P- λ for sand was performed by Brown et al. [2007], these studies were limited to 1-dimensional shock propagation from flyer-plate impacts, and did not include the ejection process or release conditions in two other dimensions. All calculations use Mohr-Coulomb pressure dependent yield strength, available in CTH as the “geo yield” option with a yield strength for the sand of 10e5 Pa.

The computations focused on matching the early-time component (rather than late-stage or final dimensions) in order to complement the regime measured in this experimental campaign. A line of Eulerian tracers record the velocity of ejected material. These tracers are distributed a small distance above the target surface to mimic the PTV technique used for the experimental data. The measured velocities are then similarly retracted to the surface. The velocity and ejection angle on the outside of the curtain can then be plotted for each recorded time step (see Fig. 1.7).

1.5 Discussion

Combining the temporal and spatial evolution of the ejecta provides allows interpretation of the source region and transient crater dimensions. In this section, we develop metrics for lateral and downward growth and evolution of the transient crater. While the absolute magnitude of the ejecta velocities eventually match the late stage predictions, they depart at early times, reflecting the initial conditions of the impact. The paucity of very early-time data for the low-density impactors is reflected in Fig. 1.6. Based on images at this time, this scatter is interpreted to be a function of the projectile failure and partial vaporization, which randomizes early flow. The evolution of the angle of ejection initially is characterized by a downward-migrating flow-field center during the early-time regime, followed by a transition to main-stage growth.

When the same data are presented in relation to the launch position (Figs. 1.6c, 1.6d), the ejecta angle evolution is revealed to occur within a zone very close to the impact point (within a few projectile radii or $< 0.1R$ for the denser projectiles) in all experiments. The assumption of a constant ejection angle during the ballistic flow stage, which would support the proportional growth concept, is inadequate to describe the evolution measured here. The migrating ejection angles reflect the kinetics of the ejected material and the conditions inside the transient crater. Thus, the emerging ejecta vectors can be inverted to describe the flow-field beneath the surface during

excavation. Within the range of projectile densities presented here, a $10 - 15^\circ$ range of main-stage ejection angles is possible by changing the density of the impactor. A change in ejection angle from 45° to 30° , for example, corresponds to $\sim 15\%$ difference in the flat-body ballistic range.

The computational results exhibit the same departure in early-time absolute velocity from main-stage growth for laboratory-scale (over a limited range of time). While the absolute magnitude of velocity could be fairly well matched using either EOS model, the separate velocity components (e.g., ejection angles) from the two models demonstrate differences (Fig. 1.7). The velocity and angle of the ejecta continue to evolve above the pre-impact surface in the models, as higher velocity, low-angle material inside the crater interacts with lower velocity, higher angle material on the outside of the curtain until an equilibrium is reached a short distance above ($\sim 1/10$ of a projectile diameter).

The efficacy of the different EOS models provides insight into the cratering process and the factors controlling ejection. Generally, the SESAME EOS model, which does not treat the reversible compression and compaction of material, does not match the evolution or magnitude of ejection angles observed experimentally. Physically, this indicates differences in the partitioning of the target kinetic energy into radial and upward components during launch. The P- λ model is found to match the experimental ejection angles quite well throughout the measurement period by using the parameters from Brown et al. [2007] and adjusting the porosity to match the density of the sand used in experiments. It should also be noted that the numerical models are not generally calibrated in the tensional regime and thus the SESAME model might not be capturing the extensional behavior as well as the P- λ EOS. Future studies will continue these results out to later times and will include the effect of porosity (as relevant for impacts into regolith materials) and other parameters.

Figure 1.8 shows the maximum source depth y scaled to the projectile radius,

a as a function of scaled time. Ejecta from high-density projectiles initially trace to several projectile radii beneath the surface (at most) at a given scaled time, and quickly achieves main-stage growth, represented by the transition to a more constant downward slope. Ejecta from low-density projectiles, however, comes from relatively shallower depths for a given time, indicating that these projectiles couple closer to the surface. For a given scaled time after impact, the maximum source depth proxy can vary by a factor of almost 3 depending on the projectile density.

These new data also allow tracking the time of launch as a function of launch position (Figs. 1.9a, 1.9b). Near the impact point, the slope of the line is steeper than during main-stage growth. This steeper slope indicates that the crater diameter grows more slowly at early times. A comparison can be derived for the launch position as a function of time. Since ejecta velocity is dimensionally predicted in Housen et al. [1983] for both t/Tc and x_e/R , the two variables should also be tied by a common power-law line by $t/Tc = K(x_e/R_c)^{3.44}$, as shown in Figs. 1.9a, 1.9b. Physically, this relationship defines the launch position (or crater radius) as a function of time. Implicit in this derivation, however, is that the crater undergoes proportional growth throughout time, i.e., all dimensions grow in a self-similar fashion. The data only follow this slope at the earliest stages for the aluminum projectile, however, although the other denser projectiles also follow a steeper slope. This discrepancy indicates that the assumption of a constant aspect ratio (diameter/depth) is not applicable for much of main-stage growth (as presented in [Schultz et al., 1981, Schultz, 1988]).

By combining the two metrics developed above, we can arrive at an effective (proxy) diameter (x) to depth (y) ratio in the transient crater (Figs. 1.10a, 1.10b). In developing this proxy, we emphasize that y represents the “apparent depth,” and will overestimate true vertical extent at later times (by a factor of ~ 2). We can interpret this x/y physically if we make the assertion that y is the maximum depth, and thus x/y is the minimum possible diameter/depth (D/d). At the moment of

contact for the higher-density projectiles, the first stages of excavation appear to be relatively shallow. That is, depth is small compared to diameter, even though material is being ejected from close to the crater center during first contact and compression. Thus, the crater first appears to grow laterally outward while the projectile continues to penetrate. As the projectile progresses farther down into the target, transferring its momentum and energy, the source region becomes deeper, thus reducing the x/y ratio. The source appears to grow relatively shallower with time after reaching the maximum energy deposition as the crater then begins to grow laterally more quickly. At later stages, ejecta come from depths about $1/2$ to $1/3$ of the actual depth (due to displacement); hence the measured $x/y \sim 2.2$ is analogous to an actual diameter/depth ~ 4 . In contrast, the low-density projectiles maintain a relatively constant (and characteristically higher) x/y , thereby indicating that the flow-field center is relatively closer to the surface. This is akin to modifying the equivalent depth of burst (DoB) [Oberbeck, 1971, Holsapple, 1980, Holsapple, 1993].

The effect of coupling depth is seen even in the final crater dimensions (after modification). Here both diameter and depth are referenced to the pre-impact surface, and are termed the “apparent” dimensions. The apparent diameter to depth ratio was measured after each experiment, and while the pyrex, aluminum and titanium projectiles create crater D/d ratios in the 3.6 range (3.6, 3.8, and 3.7, respectively), polyethylene and nylon remain shallow ($D/d \sim 4.2$), thus reducing the efficiency. These differences in crater formation occur even though ejecta velocities appear to scale as expected for main-stage growth.

1.6 Conclusions

Results from this experimental study reveal that the earliest stages of excavation result in high-speed ejecta derived from the upper surface and near the impact point. Dense projectiles penetrate deeper and couple later in the target, whereas under-

dense projectiles couple quickly much closer to the surface. The crater is also found to grow non-proportionally, first exhibiting more relatively downward growth before transitioning to relatively outward expansion. This flow-field center evolution manifests in migrating ejection angles for much of crater formation. While some of these conclusions may seem to make sense intuitively, this is the first time that such details of excavation have been traced to the earliest stages experimentally.

The effect of projectile density on both the depth and duration of coupling has implications for planetary impacts. First, the results affect models of ballistic ejecta emplacement and source depths of ejecta from primary craters (e.g., Apollo samples) and spectral reflectance of distal crater ray systems. Second, these results establish a physical understanding for ejecta produced by artificial impacts, such as the Deep Impact mission and the recent LCROSS impact. Third, temporal (rather than spatial) description of the ejecta dynamics allows investigation of the time-resolved growth of the crater, and is essential for comparison to the azimuthally-varying ejecta velocities from oblique impact events.

Appendix: Derivation of τ'

The derivation of the early-stage temporal scaling parameter was developed in Hermalyn et al. [2010]; it is presented here for completeness.

Take the velocity of the ejecta v to be functionally dependent as (in dimensionless form):

$$\frac{v}{V_i} = F\left(\frac{\delta_p}{\delta_t}, \frac{tV_i}{a}, \frac{c}{V_i}\right) \quad (1.4)$$

for a given time t , projectile radius a , impact velocity V_i , δ_p and δ_t are the densities of the projectile and target respectively, and c is the sound speed in the target (e.g., Schultz and Gault [1990]).

This early-time regime is scaled according to the shock, where time is non-dimensionalized by the shock position τ :

$$\tau \propto \frac{t}{(a/V_i)}$$

The coupling parameter, C , is defined as:

$$C = aV_i^\mu \delta^\nu F\left(\frac{c}{V_i}, \Pi_m\right)$$

where F stands for some dimensionless function of c/V_i and the Π_m dimensionless material set [Holsapple and Schmidt, 1987]. C should be a constant for any given impact event. C has dimensions of (energy) $^{1/3}$ when $\nu = 1/3, \mu = 2/3$, and (momentum) $^{1/3}$ when $\nu = \mu = 1/3$; representing the two endpoints and range of the coupling parameter. [Holsapple, 1993]

Near the impact point, however, as the projectile transfers its energy and momentum to the target, this approximation does not hold. Instead, an impedance term, “ I ,” of form $f\left(\frac{c}{V_i}, \Pi_m\right)$ is defined such that:

$$I = f\left(\frac{c}{V_i}, \Pi_m\right) = \left(\frac{\delta_t^\nu c^\mu}{\delta_p^\nu V_i^\mu}\right)$$

Then

$$C = aV_i^\mu \delta^\nu \left(\frac{\delta_t^\nu c^\mu}{\delta_p^\nu V_i^\mu}\right) = aV_i^\mu \delta^\nu I$$

and

$$a = \frac{C}{V_i^\mu \delta^\nu} I$$

An adjusted dimensionless τ' now replaces τ using a' instead of a :

$$\tau' = \frac{t_{launch}}{(a'/V_i)} = \frac{t_{launch}}{(a/V_i)} \left(\frac{\delta_t^\nu c^\mu}{\delta_p^\nu V_i^\mu} \right)$$

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Table 1.1: Summary of experimental suite performed at the AVGR

Projectile Diameter (<i>mm</i>)	Material	Density (<i>g/cm</i> ³)	Velocity (<i>km/s</i>)
6.35	Polyethylene	0.9	4.21
6.35	Nylon	1.1	5.64
6.35	Aluminum	2.8	5.59
6.35	Titanium	4.4	4.97
6.35	Steel	7.8	3.25

Figure Captions

Figure 1.1. Time series of high-speed PTV images of vertical impact experiment (6.35mm diameter titanium projectile into #20-30 sand at 4.9km/s). Images are focused on half of the ejecta curtain. Red arrow denotes impact point and direction. Note the early-time low-angle ejecta in A and B. The emergence of nominal sand grains in the bottom part of C (near the hinge point) illustrates the transition to main-stage behavior. D shows ejection during the ballistic coast regime. Images were taken at 31.8, 98.5, 165.2 and 2967.9 μsec after impact.

Figure 1.2. PTV measurement and regression of ejecta curtain profile. Individual sand grains are tracked along the profile of the curtain, yielding their velocity and position to high spatial and temporal resolution (vector arrows on left). The particles are ballistically retracted (schematically represented by the yellow line) to the pre-impact target surface (green dashed line). The intersection of the sand grains with the impact plane (black dotted line to blue dot) is taken as a proxy for the depth of excavation, y .

Figure 1.3. Velocity versus time for variable projectile density impact experiments. Early-stage scaling (a) vs. late-stage scaling (b). For early-stage scaling, the ejecta velocity is scaled to the impact velocity (V_i) and launch position is scaled as τ' , as described in the text. Late-stage scaling in the gravity-controlled regime divides the ejecta velocity (V_e) by the square root of gravity g times the final crater radius R ; time is scaled by the time of total crater formation T_c [Housen et al., 1983]. The dimensionally-predicted line (fit to experimental data) of $V_e/\sqrt{gR_c} = 0.28 * (t\sqrt{g/R})^{-0.709}$ (using $\alpha=0.51$) is shown as a black line, and does not account for the early time components.

Figure 1.4. Velocity comparison to prior ejecta velocity studies using early-stage scaling (a) vs. late-stage scaling (b). In gravity-scaled craters, the launch position is nondimensionalized by either the projectile radius a for early-stage ejecta or to R , the final crater radius, for main-stage growth [Housen et al., 1983]. Sources of data are listed in the legend. The Housen et al. [1983] power-law line was fit to small-scale explosion data from Piekutowski [1980]. All other experiments listed are from impacts at lower speeds ($\sim 1\text{-}2\text{km/s}$) using a variety of projectiles. The 6.35mm aluminum projectile impact from this study is used as reference. Most impact experiments fall below the power-law line, including data from this study at early times (although the same data falls above the power-law line in the temporal domain).

Figure 1.5. Velocity versus launch position for variable projectile density impact experiments. Late-stage scaling (a) vs. early-stage scaling (b). In gravity-scaled craters, the launch position is non-dimensionalized by the projectile radius a for early-stage ejecta and to R , the final crater radius, for main-stage growth [Housen et al., 1983]. The dimensionally predicted slope of -2.55 (using $\alpha=0.51$) is shown as a black line, and again does not account for the early time components. For early-stage scaling,

the ejecta velocity is scaled to the impact velocity V_i and launch position is scaled as $[(x/a)(\delta_t/\delta_p)^\nu]^{-1/\gamma}$, as described in the text.

Figure 1.6. Ejection angle versus time (a,b) and launch position (c,d) for variable projectile density impact experiments, separated into low (a,c) and high (b,d) density experiments. Ejection angles are initially 5° to 10° lower than the expected nominal angle of $\sim 45^\circ$ for impacts into sand. The angle of ejection quickly maps upward before reaching a maximum. There is a sorting of ejection angles based on the density of the impactor: ejecta from higher-density projectiles exhibit characteristically higher ejection angles throughout growth, whereas the low-density projectiles cause ejection angles to remain low. 45° canonical model is displayed in dashed black line. In 1.6d, data from a 90° impact of a 6.35mm aluminum projectile into #20-40 sand at 1km/s is included from Anderson et al. [2003] for comparison as a red line.

Figure 1.7. CTH Hydrocode comparison with experiments for the early-time regime. The computational studies used a 2024 aluminum projectile matched to the speed and size of the projectile in the experimental run; the targets presented here include two separate studies using the SESAME and P- λ EOS's (SES and P-Lambda, respectively). Individual tracer points within the ejecta curtain are plotted. The individual lines making up the data are an artifact of the tracer element spacing resolution. The calculations are capable of matching the experimentally determined ejection velocity quite well throughout the measurement (although the strength of the material causes a sharp turn-over at later times as the pressure drops below the tensional yield strength). The early-time departure from main-stage ejection velocity is seen in the calculations as well (a). Ejection angles exhibit a similar increase, and are found to match closely using the P-Lambda model. The SESAME EOS model, under identical elastic-plastic behavior, does not match the shape of the experimental ejection angle evolution.

Figure 1.8. Scaled maximum excavation depth vs. scaled time. Depth y is scaled by projectile radius a for both early-time (a) and main-stage (b) growth. The high-density projectiles couple deeper (i.e., reach a constant slope of y/a) than the lower density projectiles, which couple quickly near the surface. For a given time, ejecta from the steel projectile has a maximum depth of excavation, a factor of up to 2.5 deeper than that from the low-density projectiles.

Figure 1.9. Launch position vs. scaled time. Data is separated into low (a) and high (b) density plots. The black line denotes the dimensionally-predicted relationship of $t/T_c = 2.214(x_e/R)^{3.44}$ as developed in the text. Note transition from early times, when crater grows quickly in the lateral direction before transitioning to a main-stage slope. Also plotted for comparison (in black circles in upper right) is late-time data from Barnouin-Jha et al. [2007] from a low-speed (278m/s) impact into soda-lime glass beads. While the overplotted data is higher than found in this study (possibly due to the uncertainty in impact timing, as identified by the authors), it appears to follow the same late-stage slope.

Figure 1.10. Effective transient crater diameter to depth ratio as a function of time after impact for both low (a) and high density (b) experiments, separated for clarity. The denser projectiles initially grow primarily downward (decreasing x/y), before beginning to grow outward. Low-density impactors maintain a fairly constant, and consistently high, x/y ratio throughout growth.

Figures

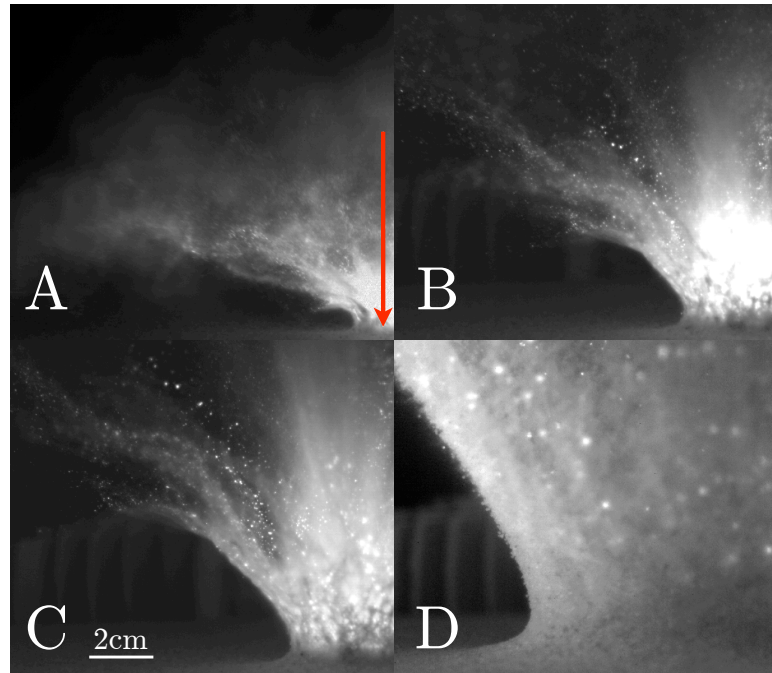


Figure 1.1

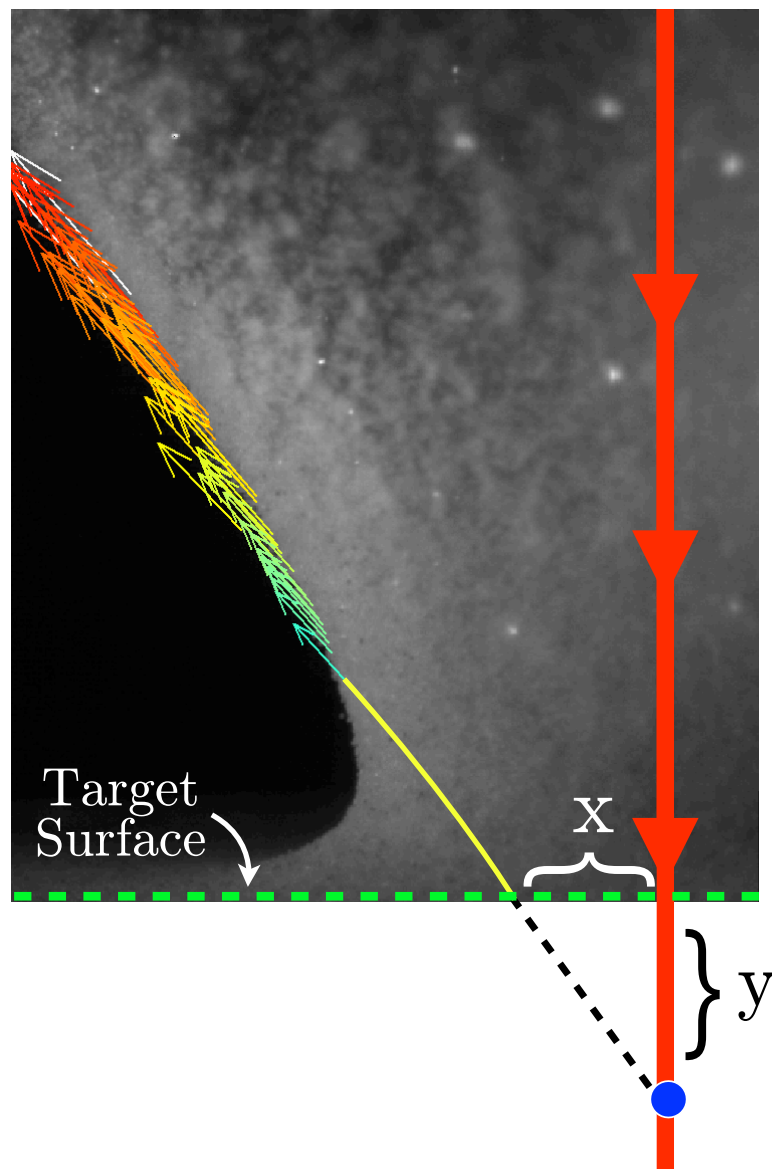


Figure 1.2

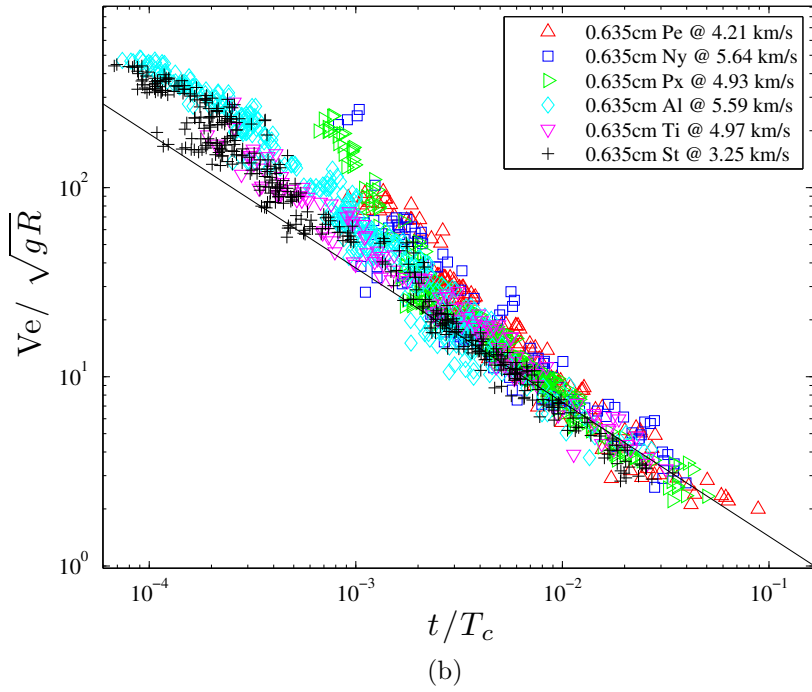
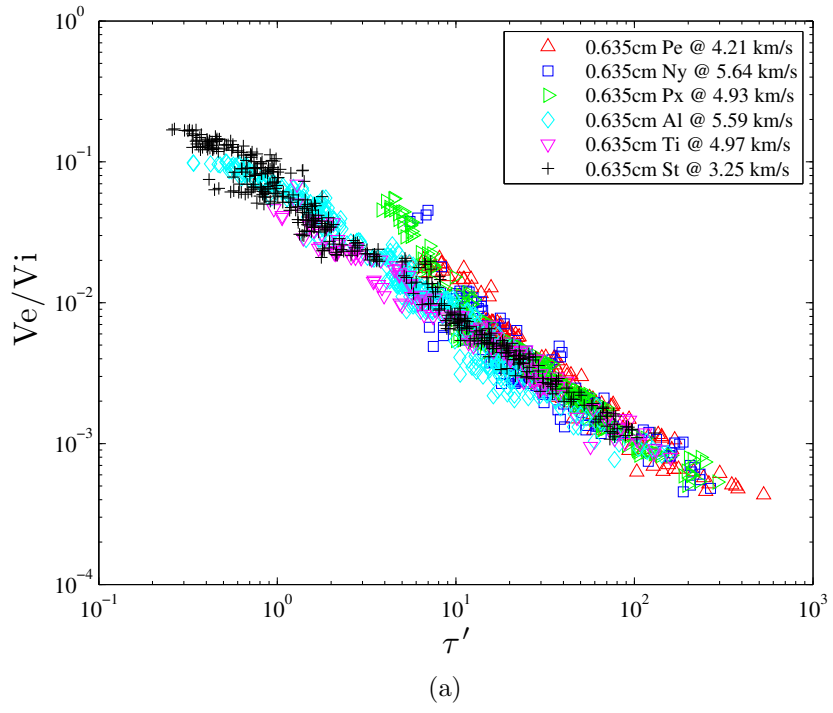
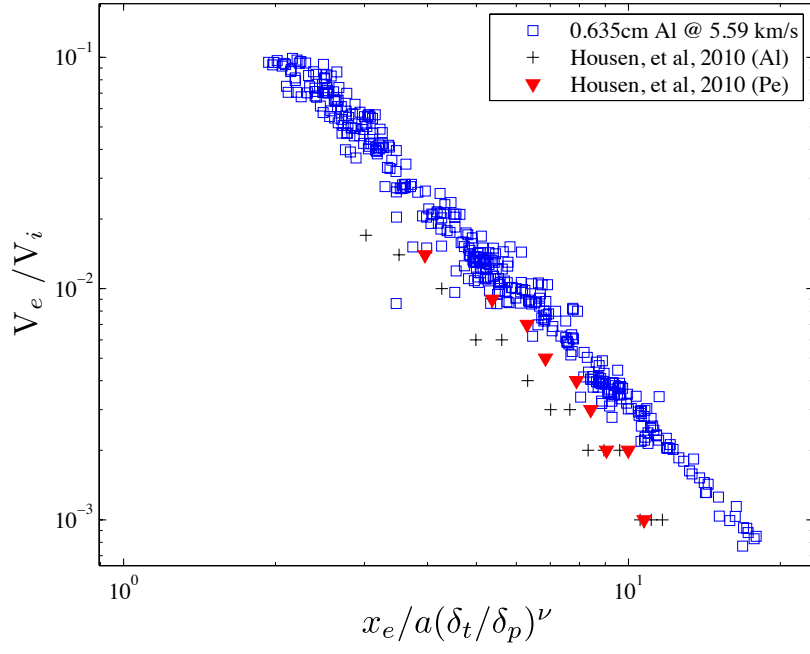
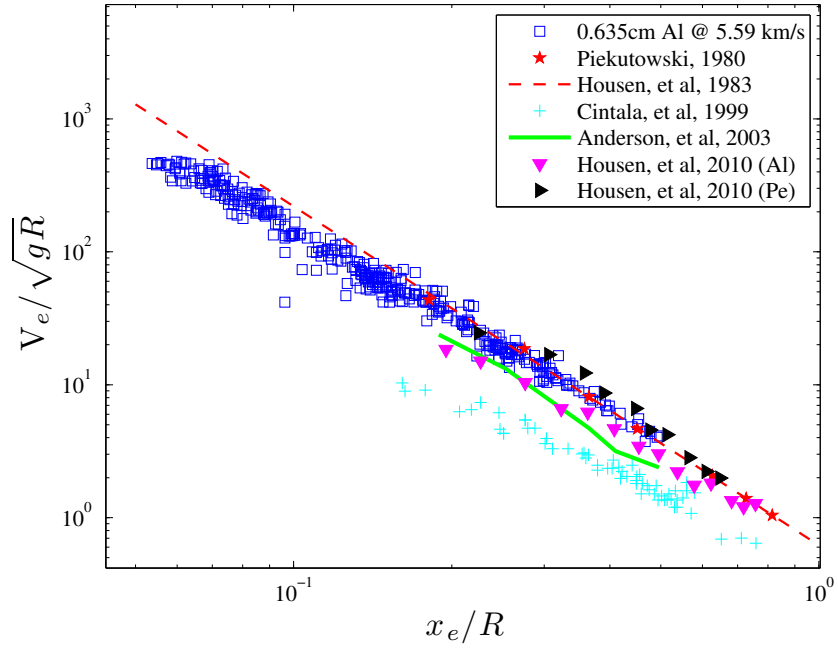


Figure 1.3



(a)



(b)

Figure 1.4

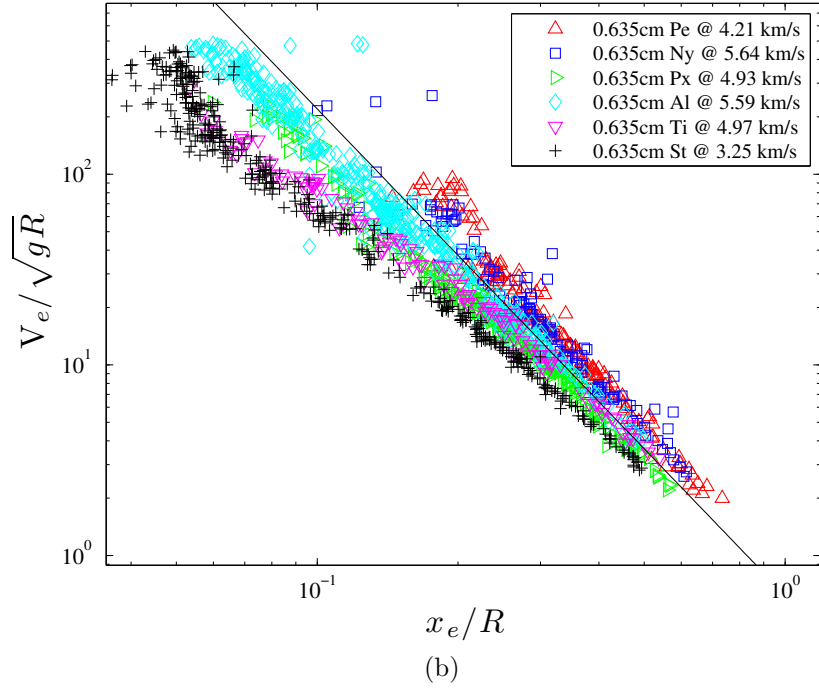
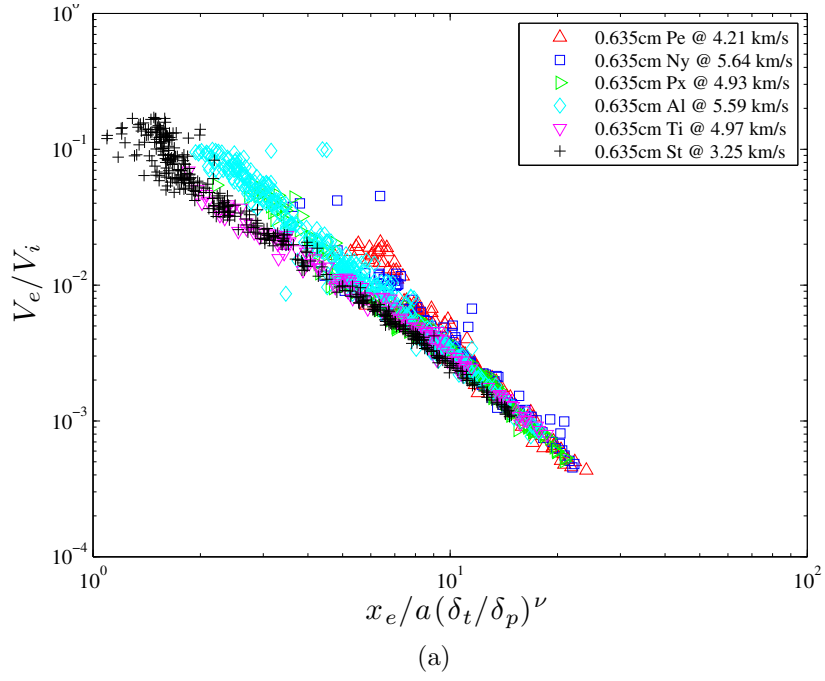


Figure 1.5

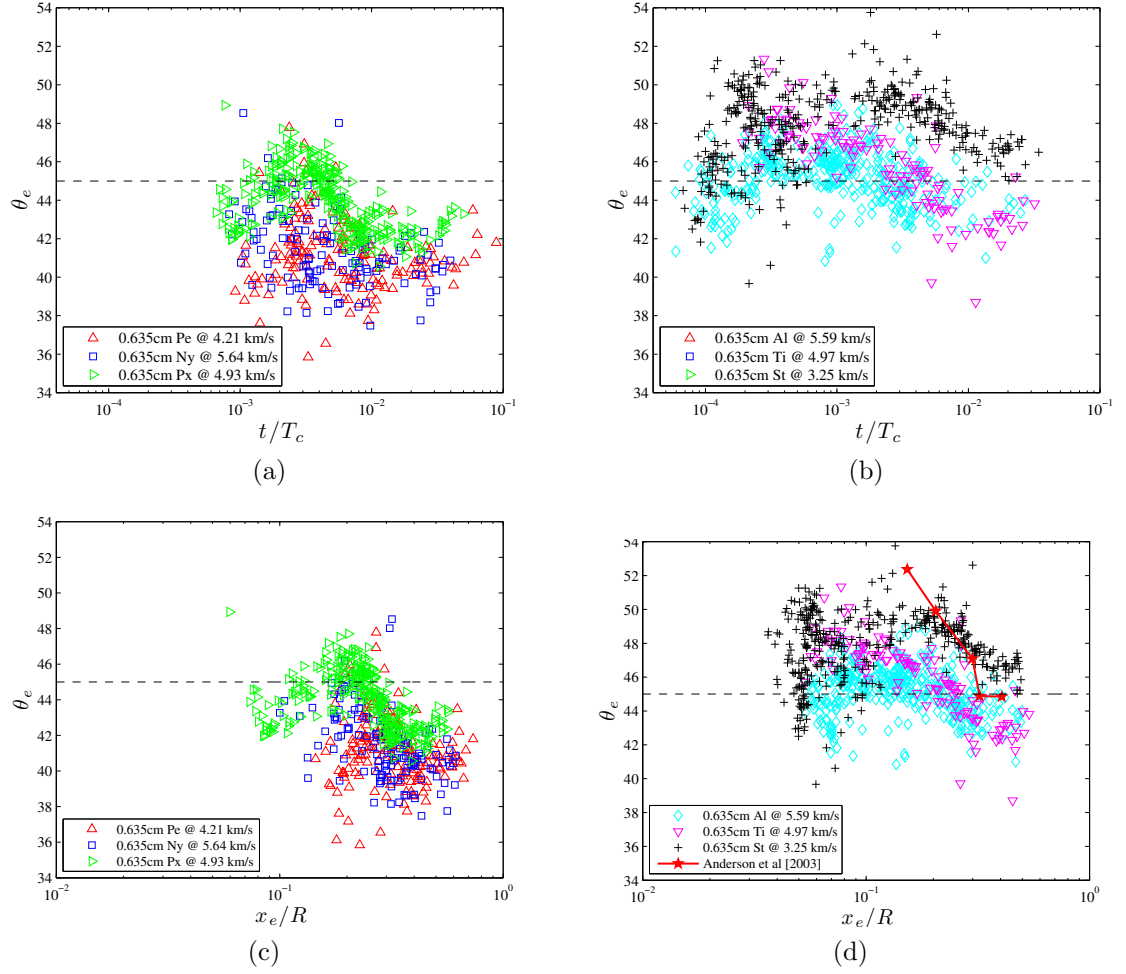
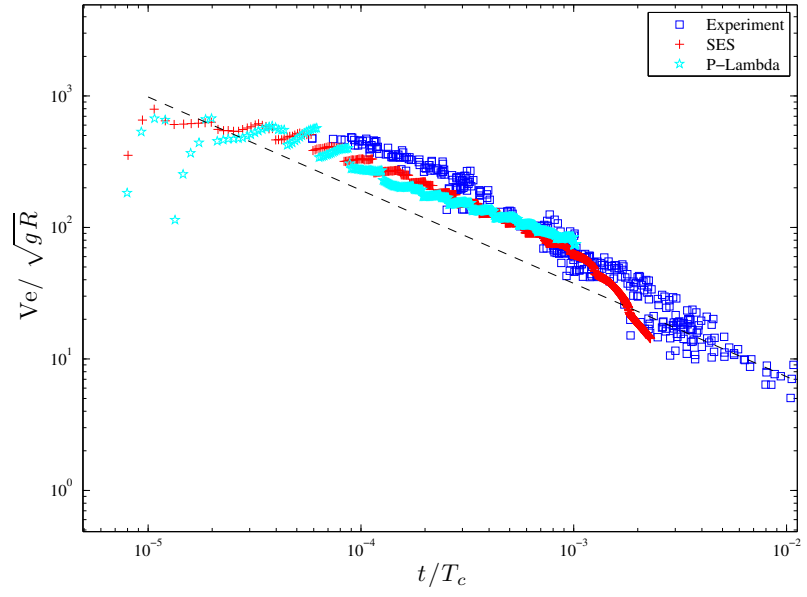
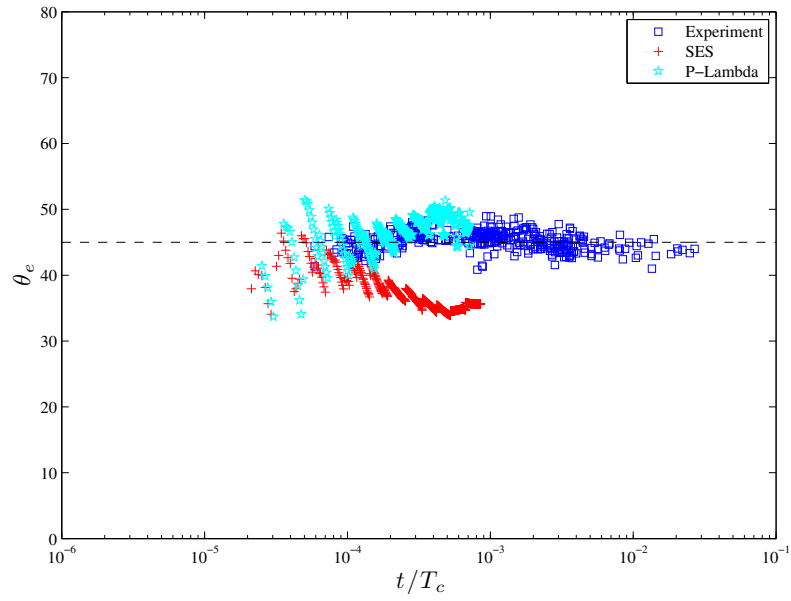


Figure 1.6



(a)



(b)

Figure 1.7

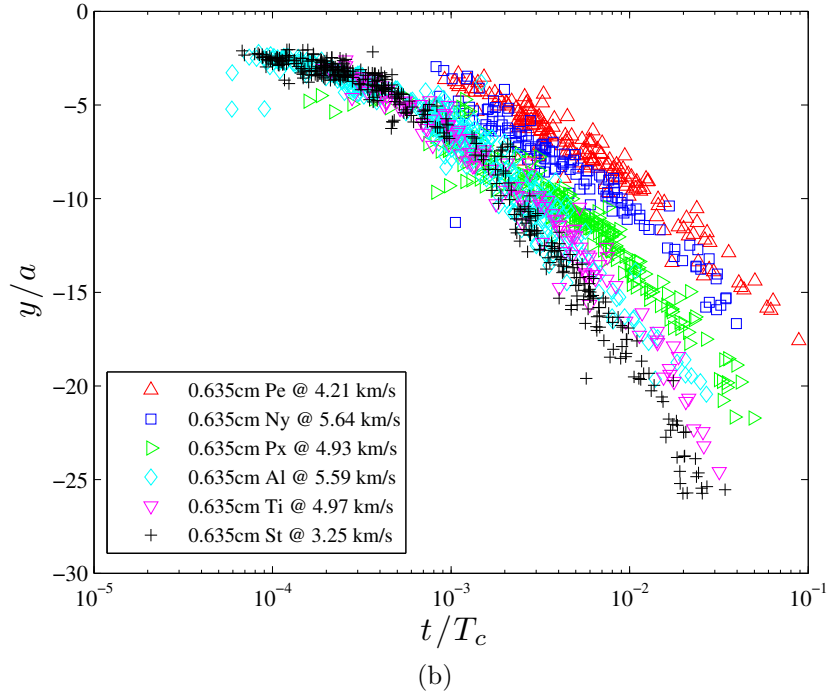
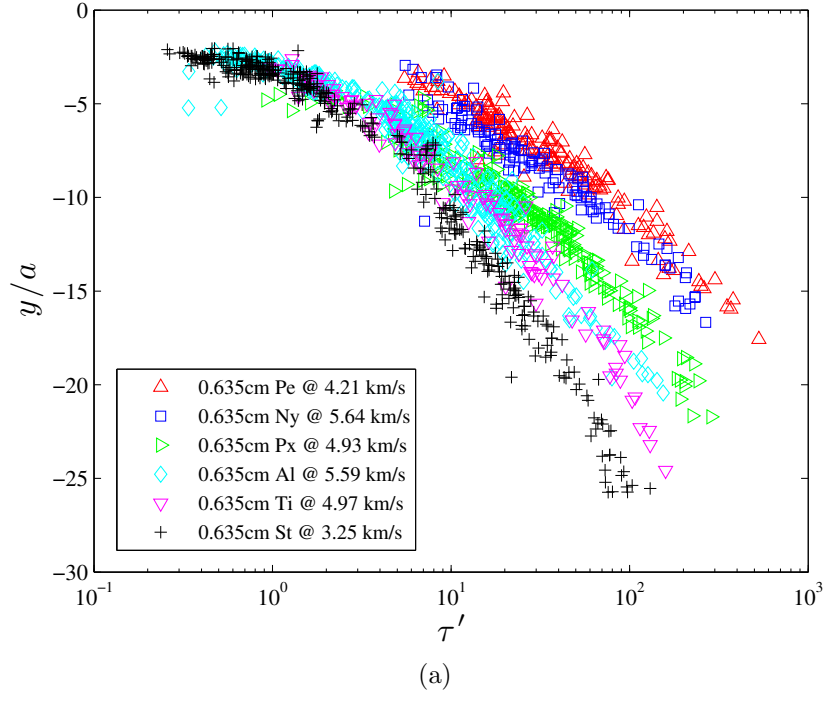


Figure 1.8

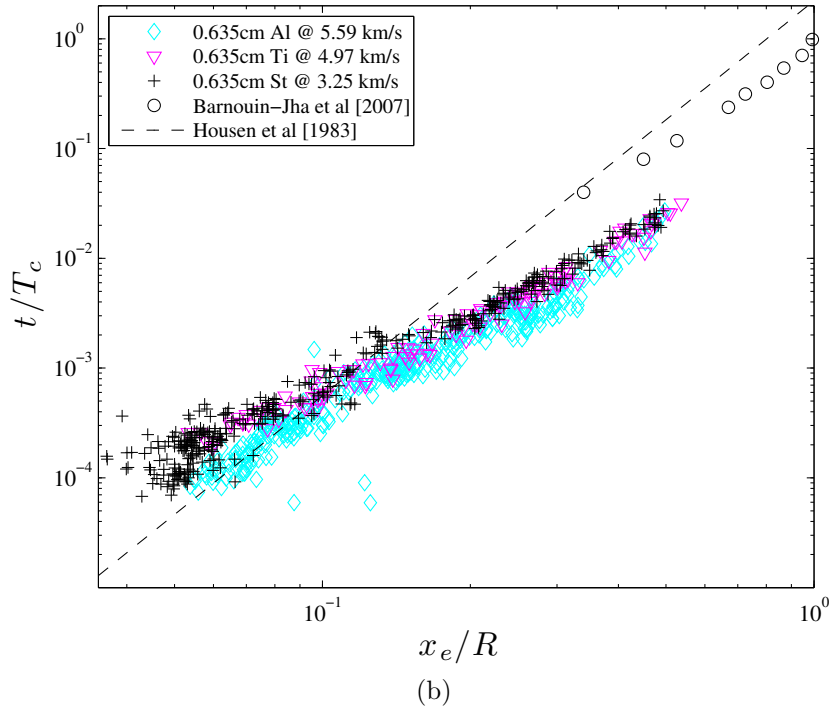
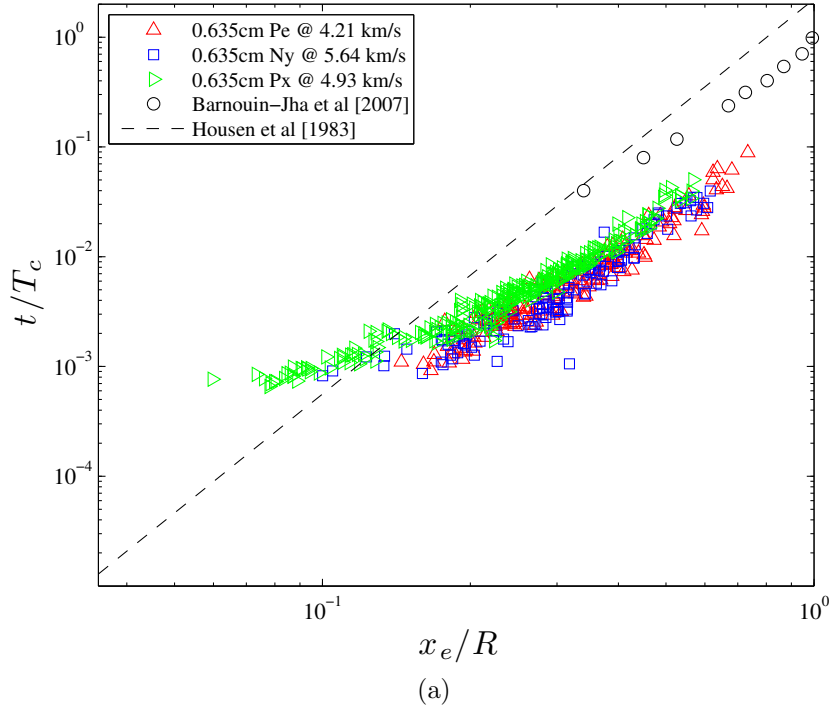


Figure 1.9

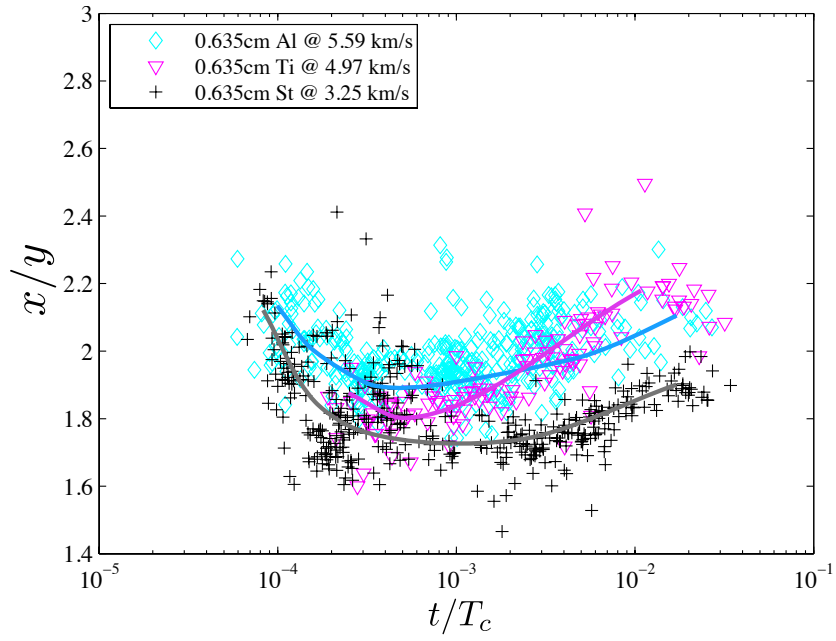
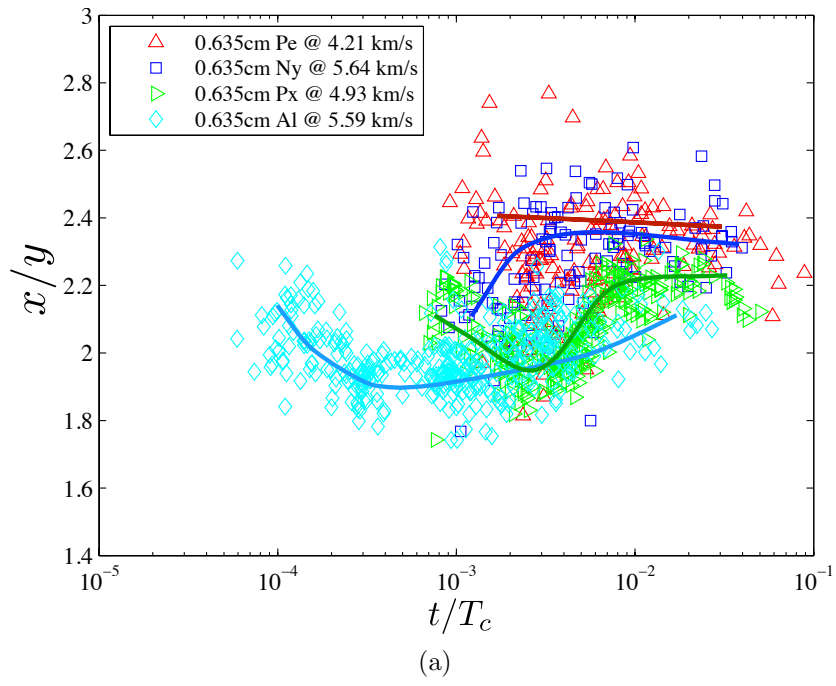


Figure 1.10

Chapter 2. Scouring the Surface: Ejecta Dynamics and the LCROSS impact event

Brendan Hermalyn, Peter H. Schultz
Department of Geological Sciences, Brown University
Providence, RI 02912

Mark Shirley, Kimberly Ennico, and Anthony Colaprete
NASA Ames Research Center
Moffet Field, CA 94035

Abstract

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 interpretation 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. These results reveal that high-speed, early-stage material (capable of reaching LCROSS sunlight horizon) is ejected from shallow depths at low angles in LCROSS-like impacts. Subsequent ballistic return of the ejecta curtain could scour the surface out to many crater radii, possibly liberating loosely-bonded surface volatiles (e.g., H_2). The hollow geometry of the Centaur led to the formation of a high-angle plume, as was evident in the LCROSS visible and infrared measurements of the ejecta. Thermal imaging reveals the complex distribution of heated material that is present but unresolved in LCROSS data. Impact-heated material is emplaced in rays beyond the crater, potentially serving as an additional source of energy for volatile release.

2.1 Introduction and Background

Impact-induced excavation is one of the few methods available that allows remote measurement of planetary subsurfaces. 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 sunlight horizon of 833m from the surface. 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]. Approximately 90 seconds after impact, 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 25-30m 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 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 $85\pm5^\circ$ (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 the 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 surface. Third, while the target lunar regolith was expected to form a crater in the gravity-scaling regime (as expected from previously observed Apollo S-IVB impacts), the soil does not have the same material properties as the canonical “Ottawa” sand, commonly used in impact experiments, which forms the basis for 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 $\sim 833\text{m}$ 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 and computational studies 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 4-5 provide interpretation of the LCROSS data and discussion.

2.2 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 2300kg at impact. The relative density of the emptied Centaur is quite low ($\sim 0.025\text{g/cc}$), 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 remaining fuel and ice (and thus the possibility of spectral contamination), until separation 9.67 hours before impact. The final impact angle, including local slope effects, was $85\pm 5^\circ$ at 2.5km/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 600km 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 minutes before loss of signal and ultimately 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 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 1 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 low-pass filter in NIR1) used identical InGaAs sensors and 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 high-pass filter in MIR1) utilized uncooled vanadium oxide microbolometer sen-

sors to record 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 $\sim 200\text{K}$, over 150K higher than the Cabeus PSR [Paige et al., 2010]. Although it is less sensitive due to the bandpass filter, we focus primarily on MIR1 here because MIR2 is slightly out of focus.

2.2 *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 seconds 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 seconds 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. 2.1). 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 (~ 8 seconds post impact) reveal a visible ejecta plume several kilometers in extent (Fig. 2.2). 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 a few tens of seconds and expanded with time before disappearing from view by ~ 30 seconds 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]. A continued presence of volatiles (and overall increase over pre-impact background) in the spectrometer measurements persisted for almost 4 minutes after impact [Colaprete et al., 2010]. Towards the end of SSc approach, the fresh Centaur crater region was recorded by the MIR cameras (Fig. 2.3), revealing an area of about 65m across emitting above the pre-impact 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 with 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]. To enable these measurements, the orbit of LRO was slightly altered to allow the spacecraft to pass almost directly over the impact site approximately 90 seconds after impact. The LAMP instrument recorded the UV emissions from volatile release 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 (<400m) thermal signal of the impact crater during the closest approach 90 seconds after impact and for multiple post-impact orbits.

2.3 Experimental Studies

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

2.3 Methodology

A suite of impact experiments performed at NASA Ames Vertical Gun Range (AVGR) were 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 12.7 mm diameter aluminum spheres were launched at $\sim 2.5\text{km/s}$ 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 ($\rho_p = 2.8\text{g/cc}$) 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 ($\rho_p = 0.71\text{g/cc}$) is still over an order of magnitude denser than that of the Centaur, but 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 failure and density of the projectile have previously been observed to significantly reduce the peak pressures and dramatically affect the excavation process, with both high-angle [Schultz et al., 2010] and low-angle [Hermalyn and Schultz, 2010, Hermalyn and

Schultz, 2011] components.

The experiments were conducted using both #20-30 smooth Ottawa quartz sand (grain diameter of $\sim 1\text{mm}$, bulk target density $\delta_t = 1.7\text{g/cc}$) for comparison to prior studies, and a cohesive, compressible regolith-like target material (airfall pumice dust) to examine the role of compressibility in the impact. The airfall pumice dust (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 $\delta_t = 1.28$ to 1.5g/cc , 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 that loose bulk strength under extension behind the shock [Schultz et al., 2005].

2.3 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. 2.4). 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 (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 ($\sim 11,000$ to $15,000$ frames per second or fps) allow measurement of particle velocity over the large dynamic range required for early-time, high-speed components of ejecta. The

ejecta velocity bounds captured by the system ranges from ~ 700 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. 2.5 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. 2.4). Intersection of the sand grains with the impact trajectory (white dotted line to blue 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 ($\sim 4 - 5$ pixels in diameter), 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.

2.3 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. The 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 ($\sim 11,000$ to $500,000$ fps) and a thermal camera (137fps) 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.

2.4 Analysis and Results

2.4 *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 the 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 t (scaled to the time of crater formation T_c). 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. 2.6). 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 deviate from expectations. When scaled to LCROSS dimensions, we find that only material ejected prior to $t/T_c \sim 0.5 \times 10^{-3}$ has sufficient vertical velocity to reach the 833m sunlight horizon of Cabeus.

The first measurable particles are ejected at low angles (see Fig. 2.7), and increase

with time towards the expected $\sim 45^\circ$ for impacts into sand. Hollow projectiles exhibit lower ejection angles initially, but display different trends depending on the target material. Solid impacts into the canonical sand target (which is relatively incompressible in this regime) remain slightly above the expected main-stage 45° ejection angle for much of growth after initially rising $\sim 5^\circ$. In contrast, hollow aluminum projectiles into sand result in considerably lower ($\sim 10^\circ$) ejection angles initially and achieve even higher ejection angles ($\sim 50^\circ$) before returning to lower angles ($\sim 40^\circ$). 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 constraint for the maximum depth of excavation for any given time (see Fig. 2.4). 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 makes no assumptions of proportional crater growth. In addition, the empirical z-model is not expected to hold at early times or under the unique impactor conditions used here. The depth of excavation (Fig. 2.8) is scaled to the projectile radius as y/a ; the abscissa is given by the early-stage time parameter $\tau' = \frac{t}{(a/V_i)} \left(\frac{\delta_t^\nu c^\mu}{\delta_p^\nu V_i^\mu} \right)$, where t is the time after impact that a particle crosses the pre-impact surface (as above), a is the projectile radius, δ_t and δ_p are the target and projectile densities, respectively (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 [Hermalyn and Schultz, 2011], and the hollow nature of these projectiles further reduces the depth of penetration and excavation. At these low speeds (subsonic 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 $\sim 10\text{m}$ below the surface (Fig. 2.9). 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, possibly insufficiently to warm up to dissociate volatiles. The ejecta that remains in the FOV’s of the spectrometers for tens of seconds, on the other hand, comes from a few meters below the surface.

2.4 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 $>75^\circ$, 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, preventing 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 the component, which is thermally self-luminous, emerges at high velocities ($\sim 1.25\text{km/s}$) soon after impact (about the time it takes for the back of the projectile to reach the target surface) (Fig. 2.10). Material continues to release upward throughout much of crater growth (Fig. 2.11). 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 main-stage intact sand grains. This 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.

2.4 *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 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 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 $\sim 26\%$ of impact energy is partitioned to target heating in high speed ($> 6\text{km/s}$) laboratory experiments (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. Impacts into 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 600-1000K from the color temperature (Fig. 2.5). Top views of this early-stage material (Fig. 2.12) 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 LCROSS NIR and MIR cameras, which are much more sensitive to thermal radiation but were operated at lower frame rates of 30 and 3Hz respectively, capture the later stages of the thermal evolution (Fig. 2.13). 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 (63K) before impact. While this had a slight effect on the final crater temperature (thermal extent of warmed material surrounding hot projectile fragments was slightly decreased), it had a negligible effect on the initial thermal history.

Many of these 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 emitters 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 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.

2.5 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 (600km), 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. 2.14). Material ejected at $\sim 30^\circ$ from the surface at $\sim 325\text{m/s}$ (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 500m/s at 80° is both consistent with experiments and sufficient to explain the absence of a central void. Again, this represents a minimum speed; higher velocities are expected in the high-angle component. By ~ 25 seconds after impact, no new material reaches sunlight from the low-angle component; thus this period should represent the largest diameter and the largest amount of material in the FOV’s of the spectrometers (Fig. 2.14). 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 seconds 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 10^5 kg of lunar soil to be heated to 1000K. Raising such a mass from the 40K pre-impact temperature to 1000K, 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 cohesive 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 the sizes $< 10\mu\text{m}$ (using properties from Hemingway et al. [1973], Paige et al. [2010] and assuming spherical particles) attain an equilibrium temperature within a few seconds of flight. The addition of H_2O or other volatiles increase the albedo and heat capacity in addition to cooling the particle by evaporation. These effects can add ~ 10 seconds 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 [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. 2.15 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 80° ejection angle for the high-angle component represents a minimum of the range of angles exhibited by this component; actual ejection angles increase to vertical (as seen in Fig. 2.11). 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.

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. 2.16). The plume was modeled as a disk centered 833m (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 (stringers) 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 65m 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 emitters indicate that the distribution of warm material proposed by Hayne et al. [2010] is inconsistent with the LCROSS data during the final approach. A first-order example of this behavior would be that the 30 to 200 m² areal 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

400K for this component would also cause a much higher subpixel temperature than the measured $\sim 230\text{K}$ 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 LCROSS 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 at most a few meters deep. High-angle ejecta excavation depth, on the other hand, seems to be restricted to the immediate subsurface (less than $\sim 3\text{m}$) and is comminuted more than the low-stage component. Both components are expected to sample beneath the $\sim 70\text{cm}$ 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.

2.6 Conclusions

The unique conditions of the LCROSS impact created a two-component ejecta plume: the usual inverted lampshade “low-angle” component and a high speed, high-angle

plume. These separate components excavated to different depths in the regolith, ejecting material from < 10 meters in the low-angle ejecta and $< \sim 3$ meters 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 “warm” 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.

2.7 Appendix 1: 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 already 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 x 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 6 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.)

Acknowledgements

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 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 #NNG05GG71H.

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Figure Captions

Figure 2.1. LCROSS thermal impact signature. Time-sequence of the MIR1 camera before (1) and after (2-4) the impact event. The first image after the calculated impact time (2) shows an ejecta plume multiple pixels in diameter (corresponding to several km), and decays in brightness over time. Yellow circle denotes impact location and approximate location of the NSP/VSP fields of view. Images are taken at a rate of about 1 Hz. Insets are calibrated images displaying the pixel-averaged temperature. Calibration bar is in units of degrees Celsius. “Hottest” pixel corresponds to -27.8° C. Note that background temperature (within the PSR of Cabeus) is simply displaying the camera sensitivity floor; actual background is ~ 40 K.

Figure 2.2. Visible camera time-series of ejecta cloud. Images have been registered and processed (as described in the text). First image is from ~ 20 seconds before impact; image first displaying the ejecta cloud is the first in the VIS series after impact, taken at ~ 8 seconds after impact. Context image (stretched for surface visibility) is shown in the lower right hand corner. Although the processing has not been able to account for all noise, the ejecta cloud dimensions can be seen to grow over time. The ejecta do not form the canonical ejecta cone (e.g., the “inverted lampshade”) but instead appear filled in by the high-angle plume.

Figure 2.3. LCROSS thermal view of final crater. A is a time series of MIR1 images showing the warm crater against the cold floor of Cabeus. Apparent motion of the crater is due to the spacecraft trajectory towards the upper-left of the images. Thus, the FOV and spatial resolution of the crater changes. B is a closeup of the final MIR1 image of the crater before it left the FOV at an altitude of approximately 10km; spatial resolution is ~ 17 m/pix. Calibration bar is in units of degrees Celsius.

The minimum temperature to which the camera is sensitive is around -60° C ; thus, although the background level appears to be in the -70° C range, it is over 160° C colder (40K) in reality [Hayne et al., 2010].

Figure 2.4. PTV ejecta measurement example. Using successive frames from high-speed cameras, the PTV technique permits the particle displacement to be measured. The particles are ballistically retracted (schematically represented by yellow line) to the pre-impact target surface (green dotted line). The intersection of the grains with the impact plane (white dotted line to blue dot) is taken as a proxy for the depth of maximum excavation, thereby allowing estimation of the maximum ejected mass as a function of time.

Figure 2.5. High-speed color images of solid aluminum projectile into sand. Original framing rate was 11kfps with an exposure of $10\mu\text{sec}$. Early-time high-speed material is ejected while thermally self-luminous (1 and 2). Crushed material is evident in the initial ejecta before transitioning to main-stage excavation of intact sand particles (4). Images are from approximately 90, 180, 636, and $3453\mu\text{sec}$ after impact.

Figure 2.6. Experimental ejecta velocity vs time for sand (a) and pumice targets (b). Time is scaled to the time of crater formation T_c on the bottom abscissa, and then scaled to the LCROSS impact on top. Velocity is non-dimensionalized by the square root of gravity g times the final crater radius R ; LCROSS-specific scaling is provided on the right hand side. Gray dashed line represents the dimensionally-predicted main-stage ejection velocity. The slight velocity variation between experiments will have a negligible effect on R . By using late-stage scaling parameters, the difference in mass and momentum of the impactors should be accounted for via the coupling parameter. Although this study only extends to $\sim 10\%$ of crater formation (in the temporal

domain; this time corresponds to a non-dimensional launch position from the impact point of $x_e/R \approx 0.8$), it extends beyond the scaled minimum velocity required to reach the sunlight horizon.

Figure 2.7. Ejection angles vs. time. Time has been scaled to the LCROSS event using late stage parameters (on top abscissa). Ejection angles start out lower than the commonly-assumed 45° angle for main-stage growth [Housen et al., 1983] before increasing. Impacts into pumice retain characteristically lower ejection angles throughout growth, as compared to those from sand targets. The effect of projectile failure (and low-density impactors) results in energy and momentum coupling much closer to the pre-impact surface, as manifested in the lower ejection angles for both impacts [Hermalyn and Schultz, 2011].

Figure 2.8. y/a vs. scaled time. The maximum geometric excavation depth y is scaled to the radius of the projectile a for the low-angle ejecta. The early-stage time parameter $\tau' \propto t_{launch}/(a/V_i)$ is employed to present the early-time behavior. The low-density hollow aluminum impactors excavate material from less than half the maximum depth for solid projectiles.

Figure 2.9. Maximum ballistic height vs. the maximum depth of excavation for low-angle ejecta. The depth has been scaled to the effective projectile radius for LCROSS. The low-angle material excavates material from a maximum of ~ 10 m under the pre-impact surface to the sunlight horizon; the vast majority of material present in the fields of view of the spectrometers was thus from a few meters depth. Since shallower material is launched at higher velocities than deeper material (as it is derived from closer to the impact point), it attains a greater ballistic height and therefore has a greater residence time in sunlight.

Figure 2.10. Hollow vs. Solid Projectile Experiments. High speed images (recorded at 500,000 frames per second; selected frames are temporally matched in this figure) of solid (left) vs hollow (right) 12.7mm diameter hollow aluminum projectiles into pumice at $\sim 2.5\text{km/s}$. The first high-speed ejecta to emerge is extremely low angle and thermally self luminous for both. The ejection angles progress upward toward nominal values. In addition, the hollow projectile also exhibits a characteristic high-speed, high-angle plume immediately after impact. This component persists into main-stage crater growth and remains aloft well after the crater has finished forming.

Figure 2.11. Time series of low- and high-angle plume components from a hollow aluminum projectile into sand at 2.1km/s . Images are matched in time and are taken from an oblique view (left) and top view simulating LCROSS viewing conditions (right). The central high angle plume, which is composed of crushed fine material rather than intact sand grains, fills in the central portion of the ejecta curtain and persists in ballistic flight after low-angle main-stage ejecta has returned to the surface. Frames are taken at 809, 6128, 18870, and 188865 μsec after impact.

Figure 2.12. Early-time self-luminous material. A is a time series of high-speed images (nominally at 500kfps) taken from above (approximating LCROSS viewing conditions) showing the initial contact of the projectile and hot ejecta. During impact (second frame on left), 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 6200fps) 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.

Figure 2.13. Time series of selected NIR camera frames (nominally at 30 Hz) from a hollow 12.7mm diameter aluminum projectile impact experiment into pumice at 2.45km/s at the AVGR. The thermal camera clearly shows the hot ring of high speed, low-angle material expanding rapidly outward and then decaying thermally after emplacement on the surface. Note that the vast majority of heated material is ejected out of the crater (outlined by yellow dotted circle in the final frame), leaving only a small amount of thermally emitting material after impact. Post-impact analysis and imaging found that this material is predominantly composed of projectile, with a thin veneer of target melted on one side. Also, while the early-time component hits the walls of the vacuum chamber in the lab (and thus bounces back towards the crater, artificially increasing the amount of heated material in the FOV during the experiment), it would extend a great distance on the surface of the moon, raking up the regolith as it ballistically returned. Heated material is distributed heterogeneously.

Figure 2.14. LCROSS curtain diameter as a function of time after impact. Blue squares indicate measured LCROSS curtain diameter in the VIS camera. Also plotted is the low-angle ejecta curtain diameter at the sunlight horizon (black squares), the diameter from material ejected at 30° at 350m/s (red), and that of material ejected 80° from the surface at 500m/s (cyan). The VSP/NSP spectrometer's fields of view (which are approximately collinear) are overplotted for comparison (black line).

Figure 2.15. Ballistic extent of re-impacting ejecta vs. time after impact. The experimental data for both low-angle (red triangles) and high-angle (80° blue solid line) are scaled to LCROSS dimensions and ballistically emplaced on the surface; thus the ballistic extent is the diameter of the re-impacting ejecta. For illustration purposes,

a minimum ejection angle of 80° 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. Additionally plotted is the sunlight cut-off for the low angle (black dashed) and high angle (blue dashed), which 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.

Figure 2.16. 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 833m directly above the calculated impact point (red x) 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.

Figures

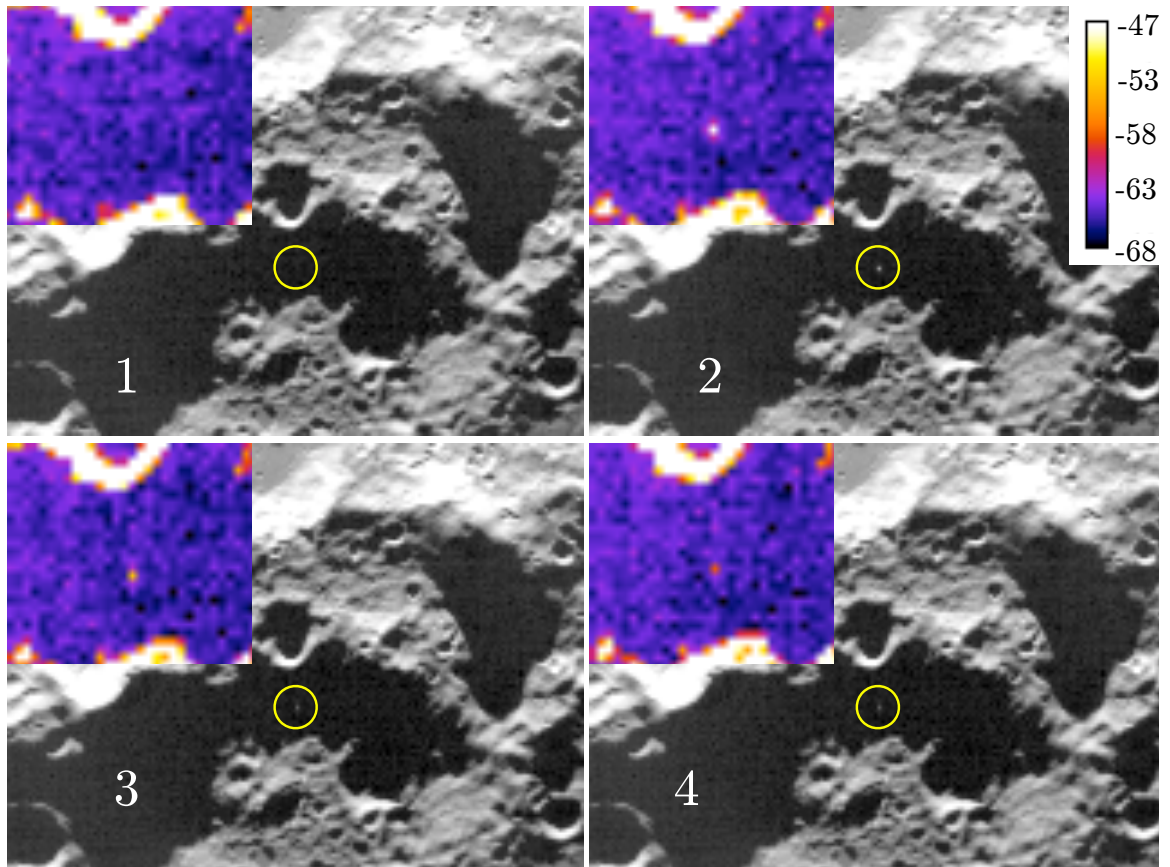


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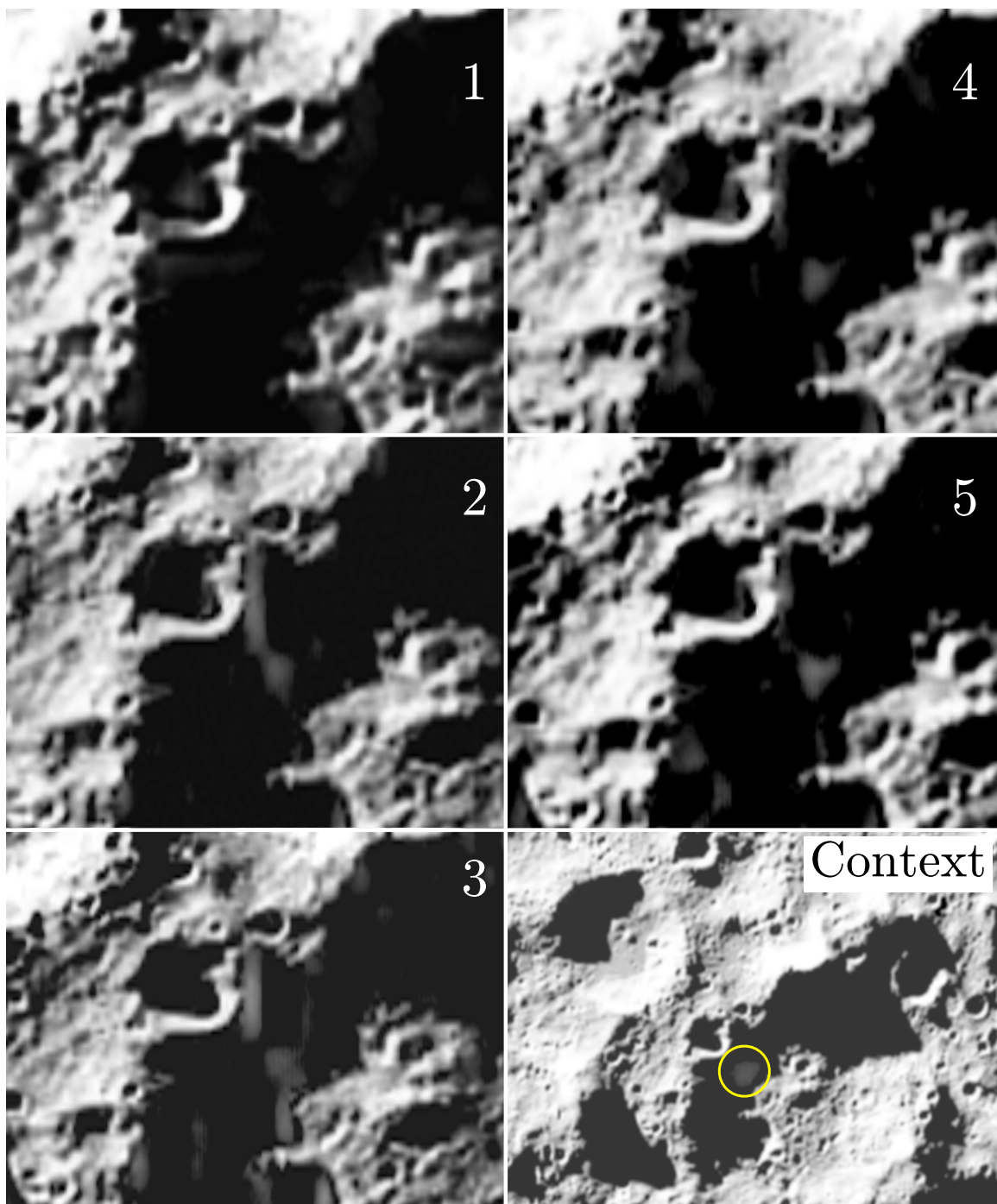
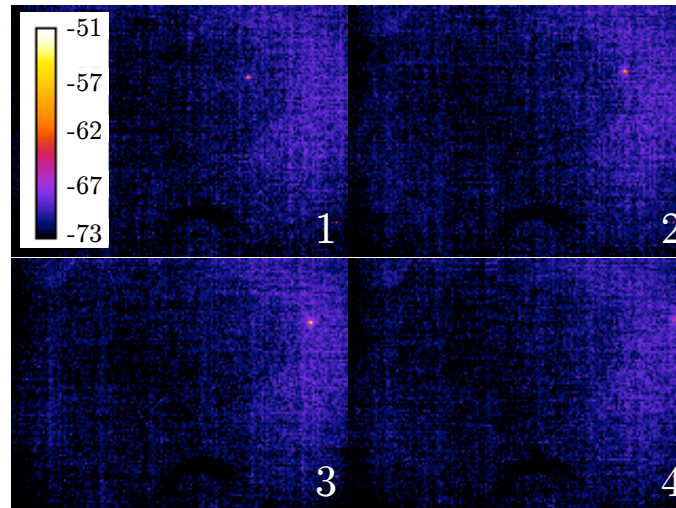
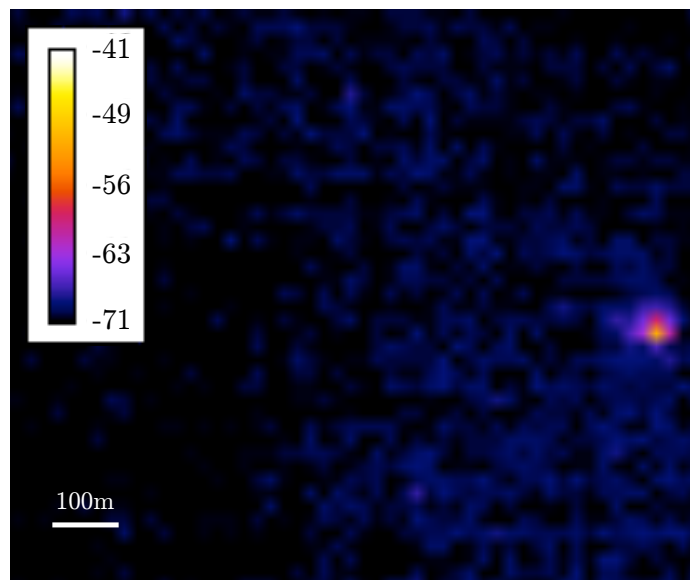


Figure 2.2



(a)



(b)

Figure 2.3

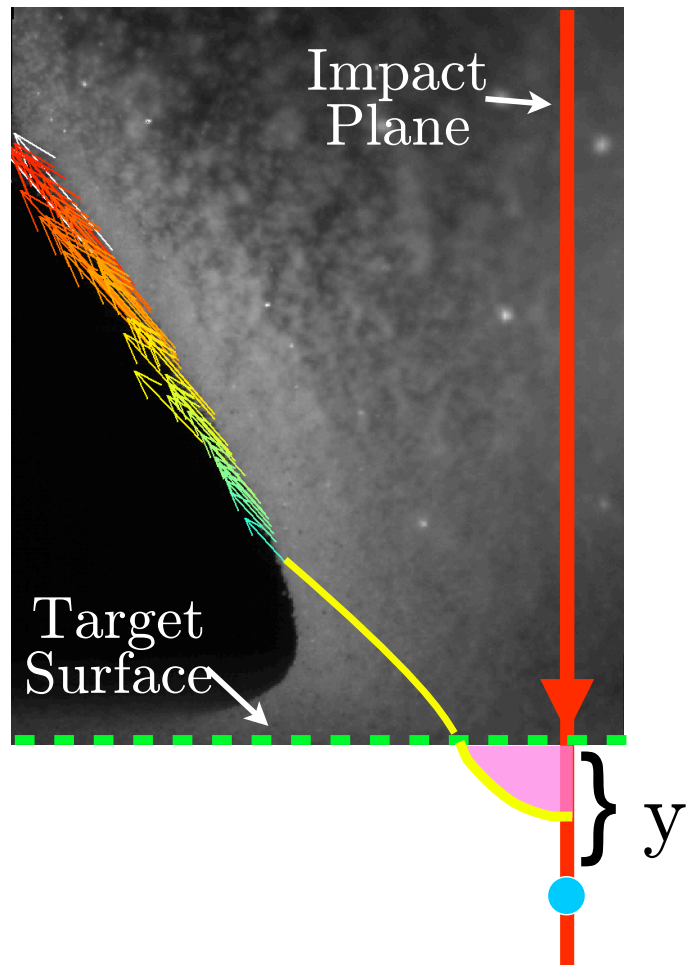


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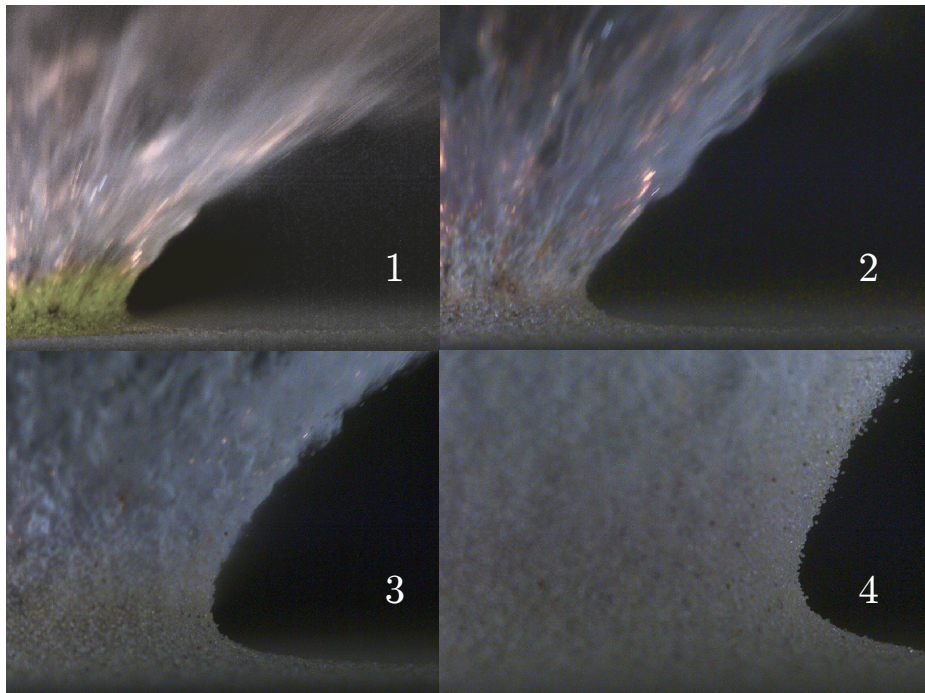


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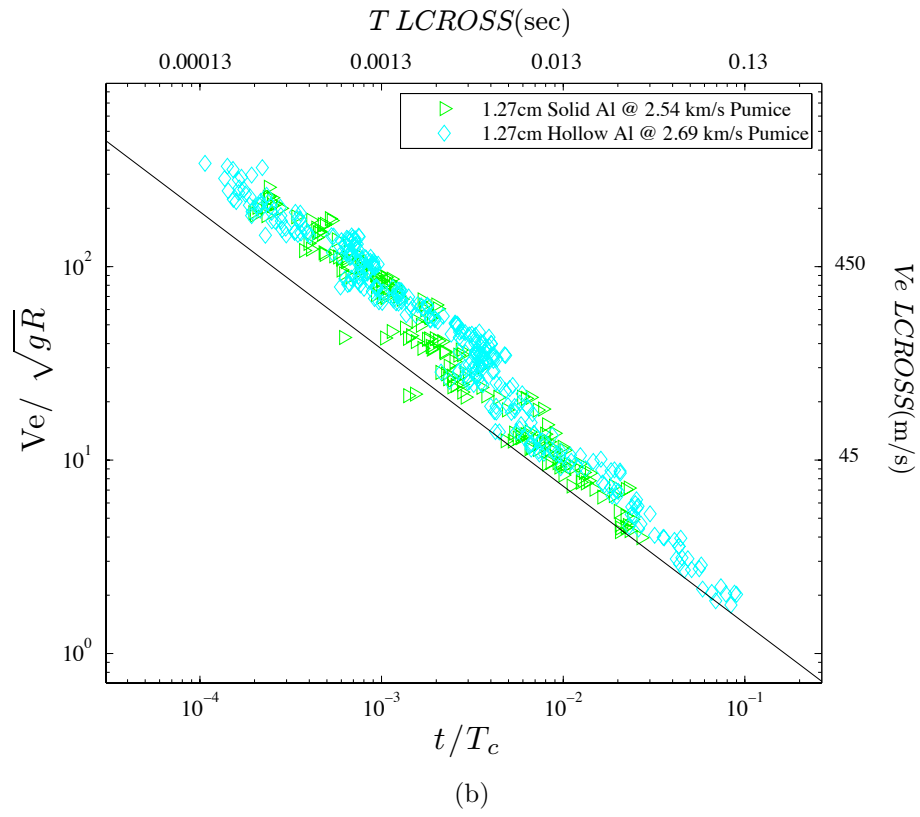
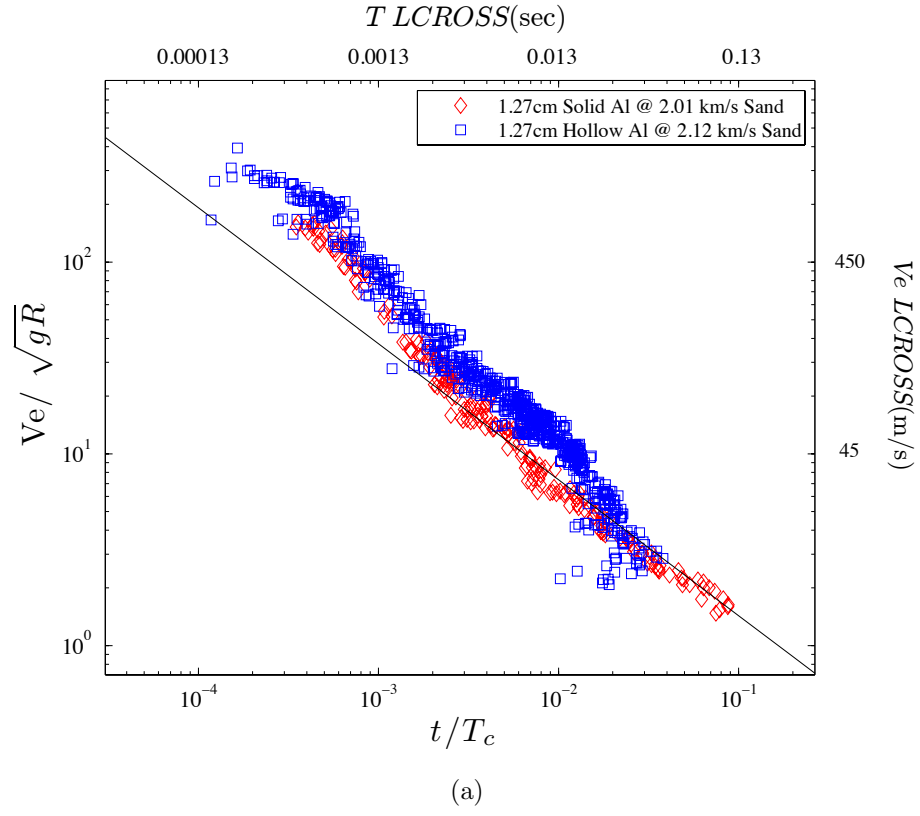


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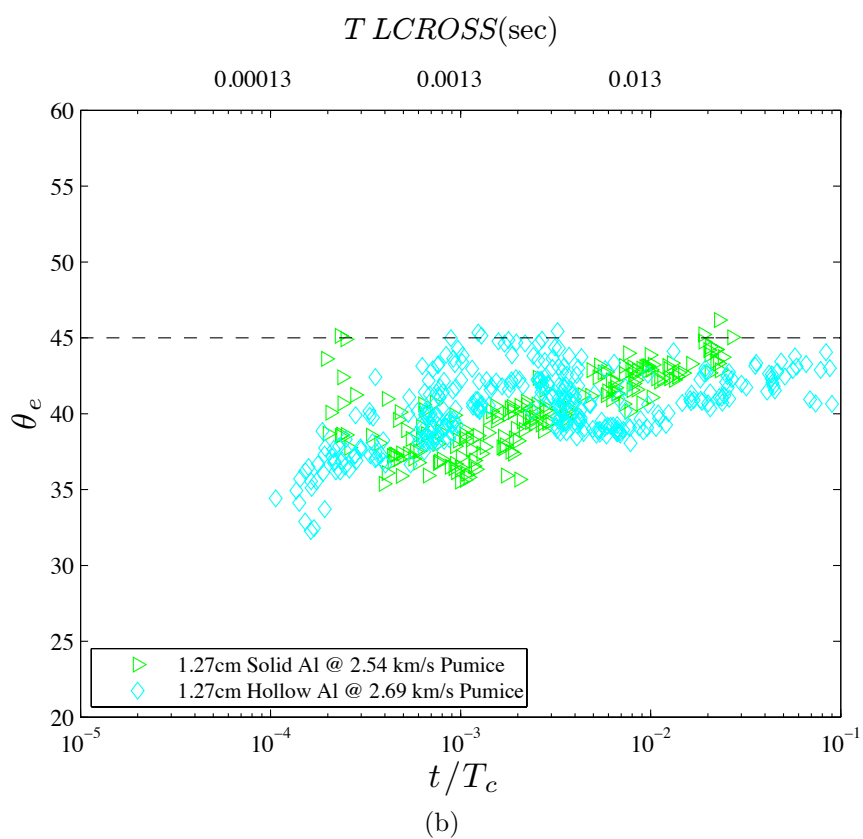
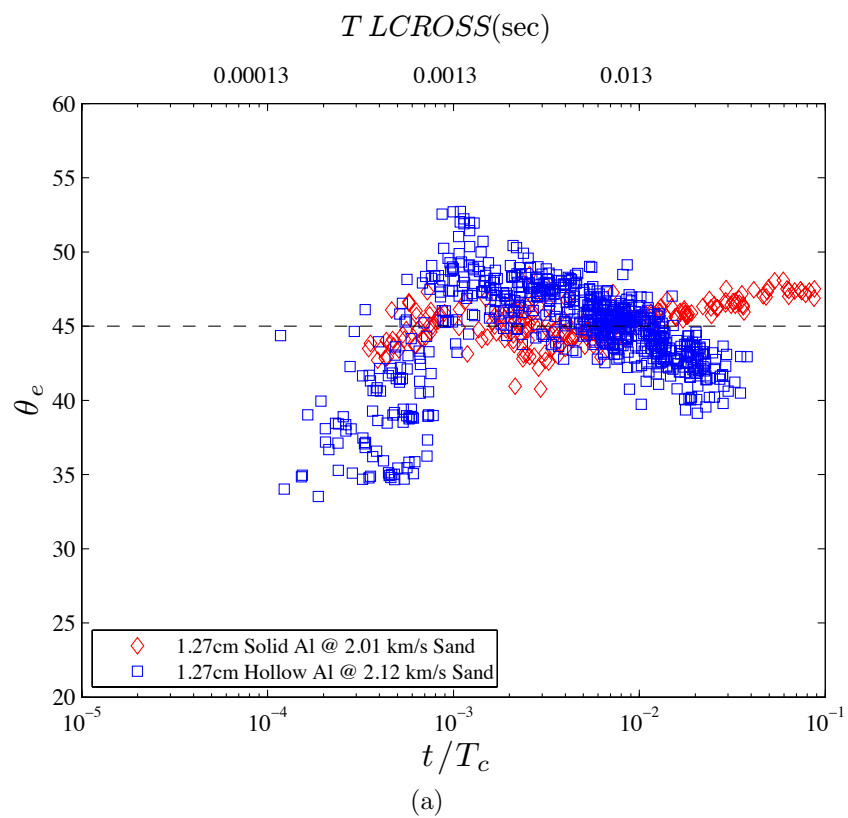


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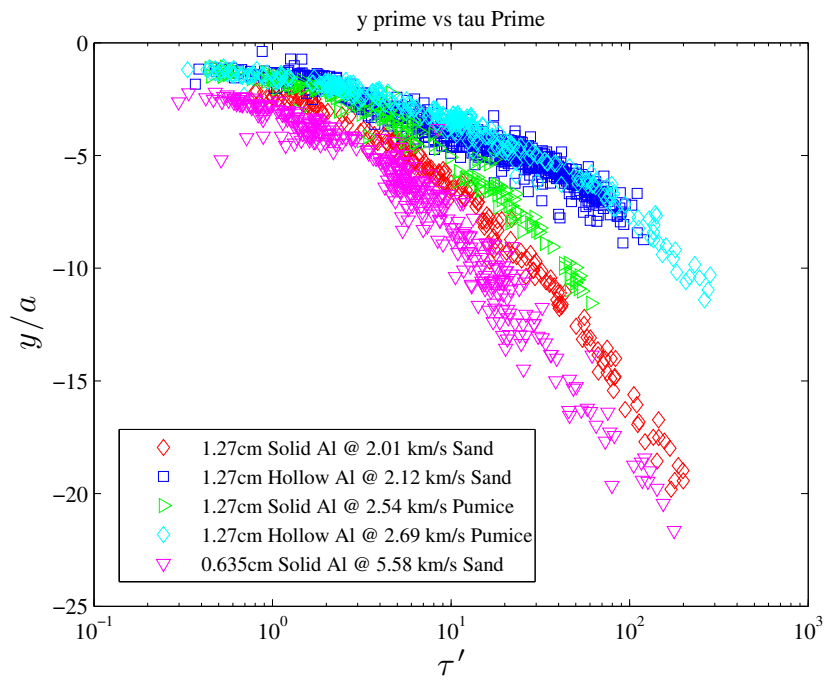


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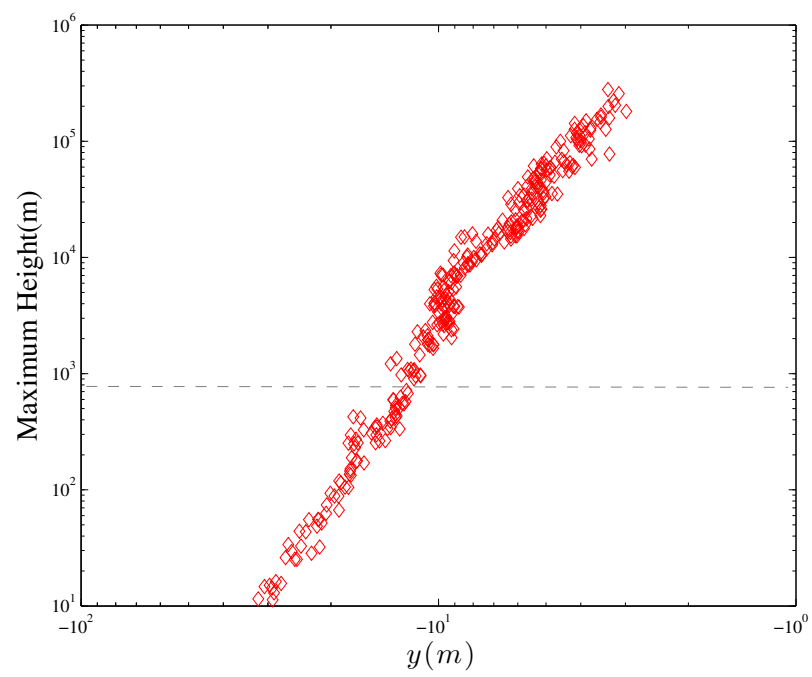


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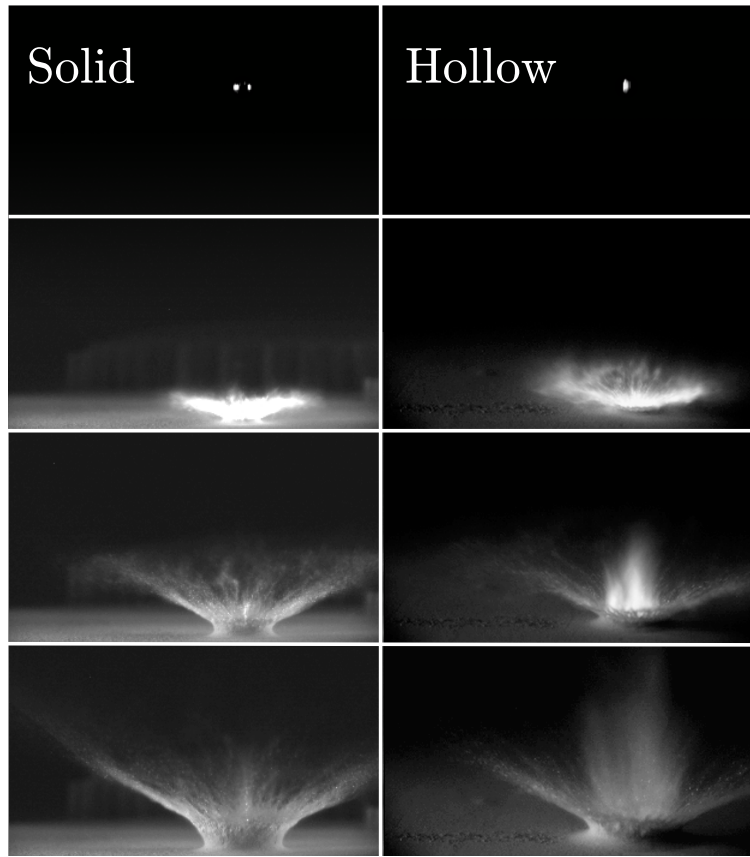


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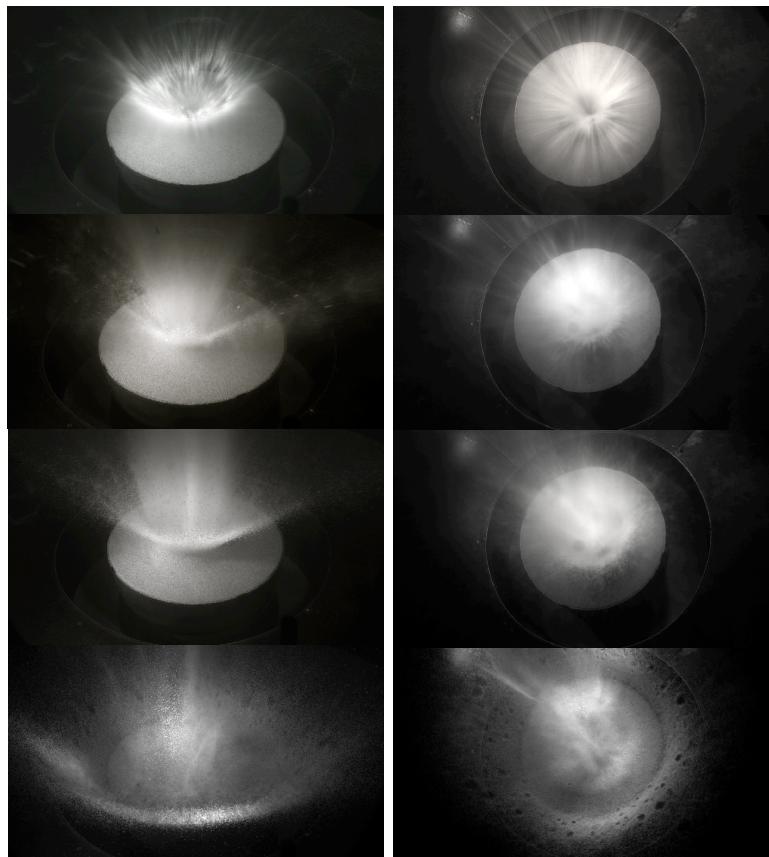


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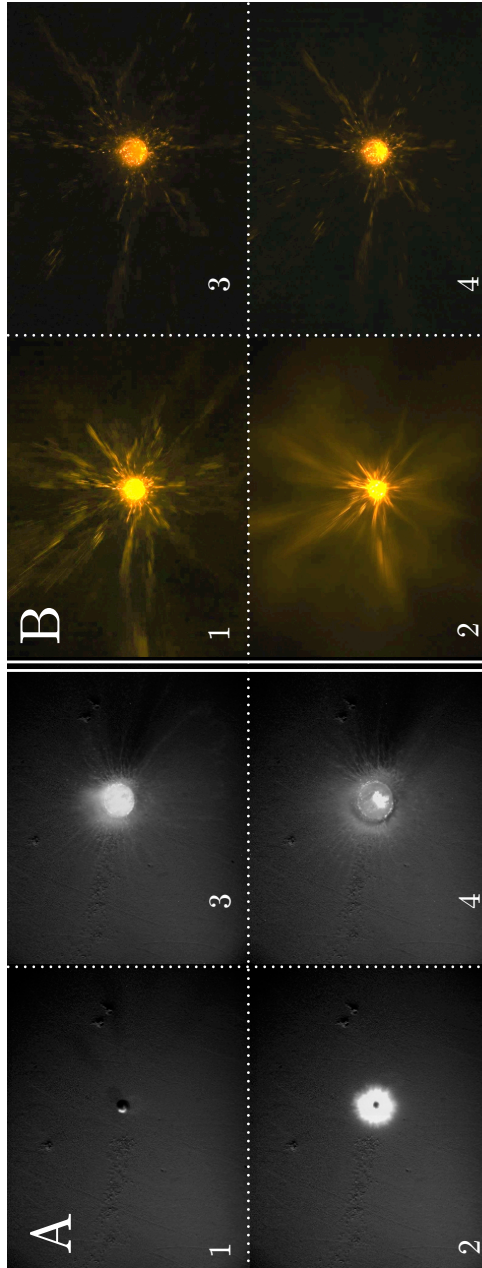


Figure 2.12

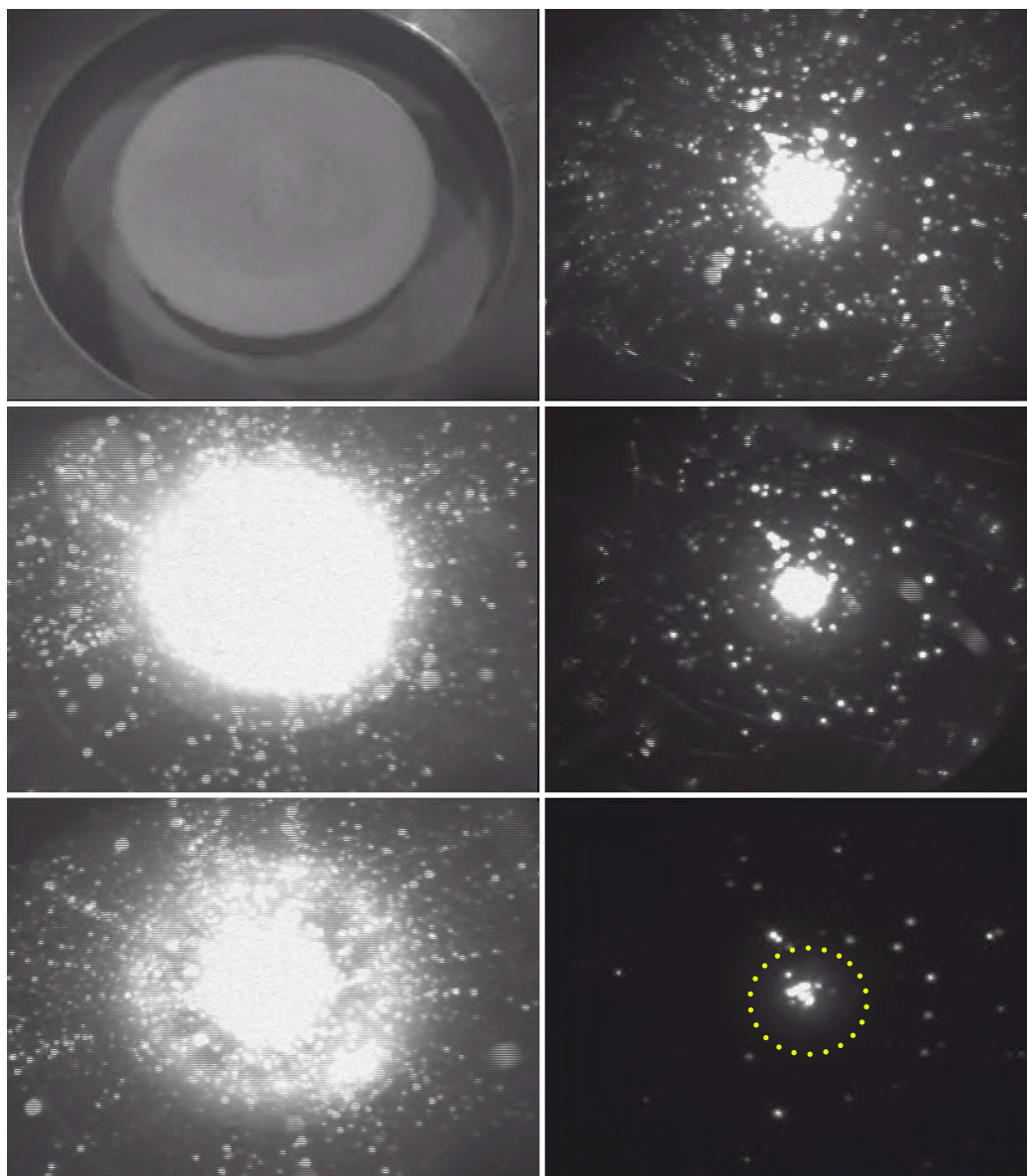


Figure 2.13

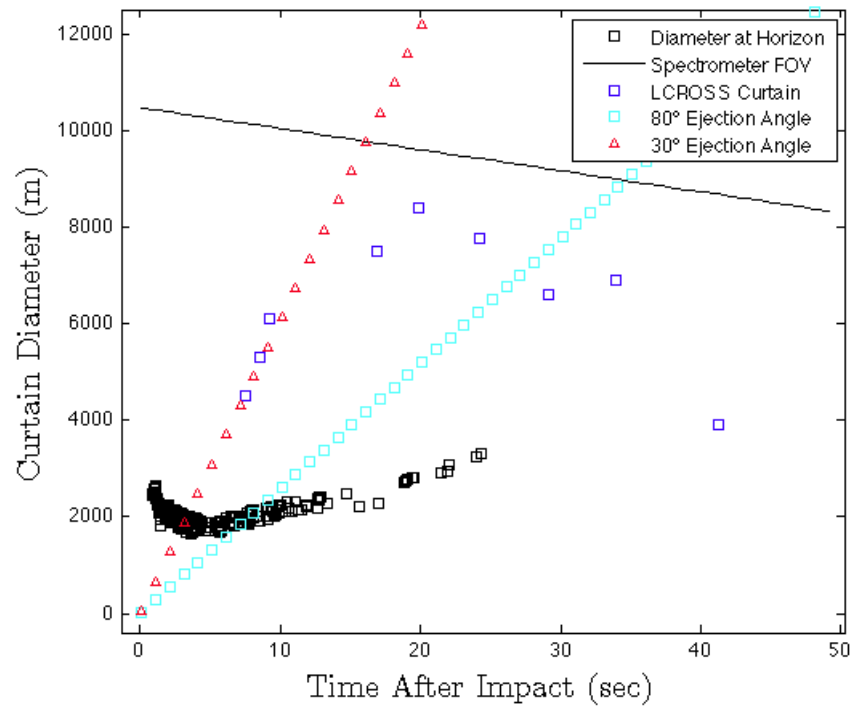


Figure 2.14

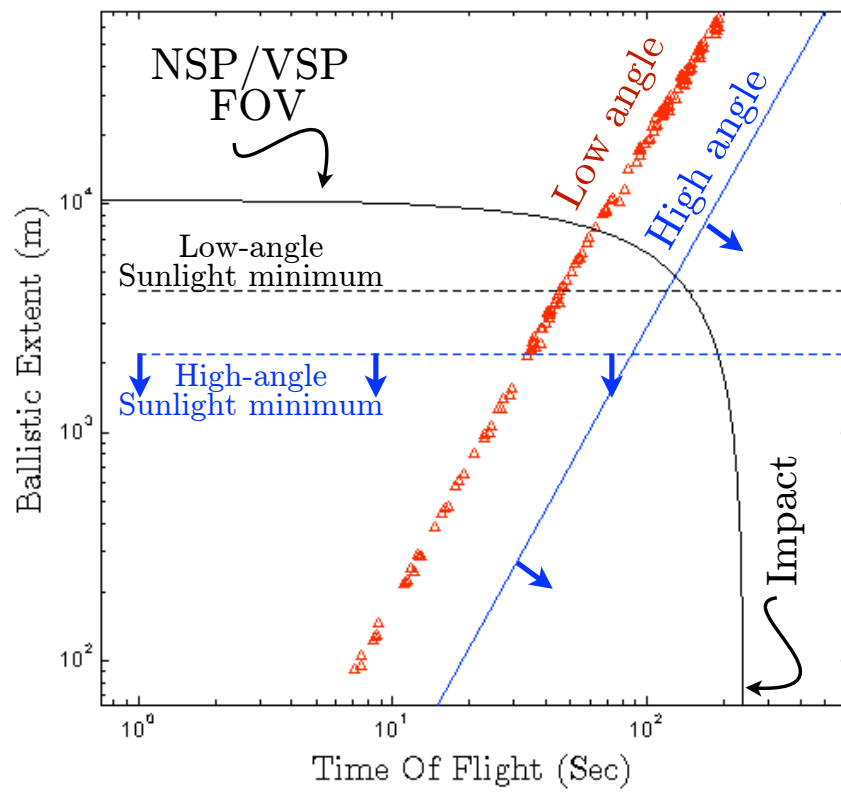


Figure 2.15

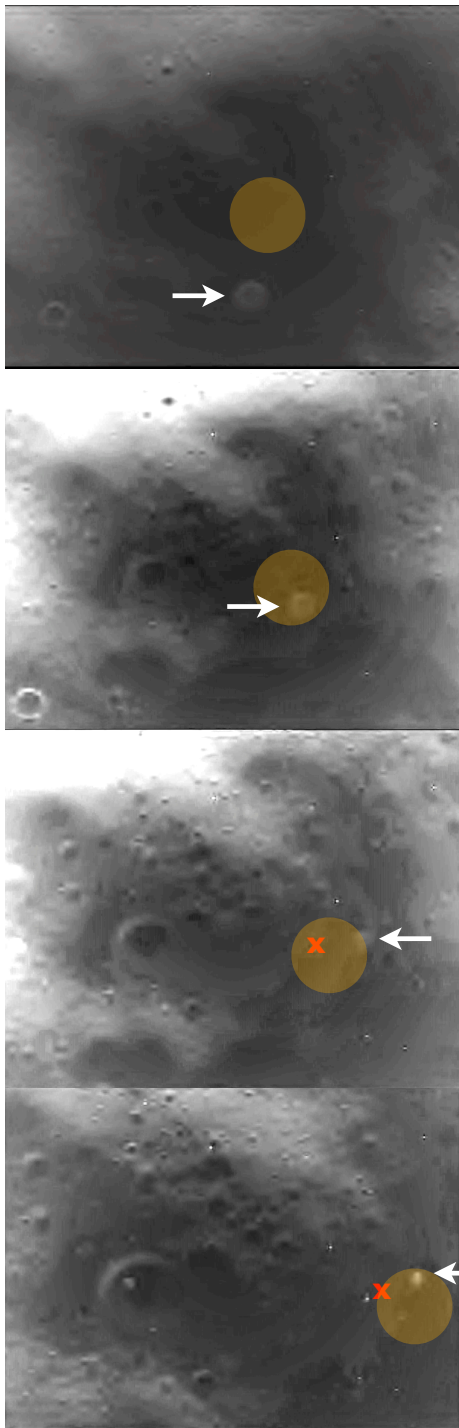


Figure 2.16

Chapter 3. Experimental Studies of the Ejecta Velocity Distribution from Oblique Impacts

Brendan Hermalyn and Peter H. Schultz

Department of Geological Sciences, Brown University

Providence, RI 02912

Abstract

Impacts on planetary surfaces occur almost exclusively at oblique angles. Generally, the shape of the final crater retains circularity for all but the lowest angle impacts, and vertical incidence is often assumed to greatly simplify the dynamics. The ejecta distribution deposited on the surface, however, belies the obliquity of the impact. At early times, the projectile is still coupling its energy and momentum to the target. This regime affects the emplacement of distal ejecta and plays a greater role at larger planetary scales. These effects are especially apparent in oblique impacts because the zone of coupling is extended laterally along the impact trajectory (rather than in the downward direction alone, as in the case for vertical impacts). In a series of studies, Anderson and Schultz presented the first in-flight measurements of ejecta velocities from oblique impacts, revealing asymmetries in the ejection process that persist to late times. The measurement technique captured a single discrete velocity vs. launch position data point (for all azimuths) per impact experiment, and was not designed to be temporally resolved. In this chapter, a novel high-speed three dimensional imaging technique is developed to measure the ejecta velocity as a function of time (rather than launch position, which requires complicated correction terms [Anderson and Schultz, 2006]). These data provide a time-resolved view of the ejecta evolution for the first time, and allow development of a simple analytical description of the velocity distribution as a function of time and azimuth.

3.1 Introduction

Virtually all planetary impacts occur at incident angles oblique to the target surface. Statistically, $\theta=45^\circ$ is the most probable impact angle for airless bodies (assuming an isotropic flux of impactors) and 50% of impacts are expected to occur between 30° and 60° from horizontal [Gilbert, 1893, Shoemaker, 1962]. While the majority of craters on planetary bodies tend to retain circularity for all but the most oblique (or large) impacts, asymmetries in ejecta patterns are observed at both laboratory and planetary scales as the impact angle decreases from 90° [Gault and Wedekind, 1978, Schultz, 1992]. These deviations from the ejecta distributions created by vertical impacts include a downrange focusing (in the direction of impact) of material and an uprange “zone of avoidance,” or ZoA (e.g., Fig. 3.1). As the crater nears the end of growth, however, the asymmetries presented in distal, high-speed material generally transition to more relatively symmetric ejecta distributions near the rim. The effect of impact angle on the ejecta flow field controls the emplacement and distribution of excavated material on the surface of planetary bodies. Asymmetric ejecta patterns emplaced on planetary bodies are commonly used as diagnostic features since the uprange ZoA is characteristically antiparallel to the projectile trajectory, and may provide clues to the initial conditions of impact. No simple analytical ejecta velocity model that incorporates the effects of obliquity has yet been proposed.

Vertical impacts result in axial symmetry and enable simplification of experimental or theoretical analyses, as well as comparison to explosively-formed craters. The ejecta velocity distribution during main-stage excavation flow (when most material is launched from the crater) has been explored for normal impacts in granular materials through dimensional analysis [Housen et al., 1983], numerical simulations (e.g., [Wada et al., 2006, Collins and Wünnemann, 2007, Pierazzo et al., 2008]), and experimental studies [Piekutowski, 1980, Oberbeck and Morrison, 1976, Piekutowski et al., 1977,

Cintala et al., 1999]. These investigations accommodate the predicted main-stage trend fairly well at later stages, consistent with the “late-stage equivalence” assumption for crater growth [Dienes and Walsh, 1970] where the details of the impact (such as the impact velocity and properties) are collapsed to a singular point in time and space (e.g., Chabai [1959], Orphal [1977], Housen et al. [1983], Holsapple and Schmidt [1987], Housen and Holsapple [2011]). Experimental studies of in-flight ballistic ejecta [Anderson et al., 2003, 2004, Anderson and Schultz, 2006] demonstrated time-varying ejection angles, which imply a spatially-migrating point source. Recent high-speed studies of the ejecta velocity distribution from vertical impacts, however, reveal that the single power-law relationship does not apply while the projectile is still transferring its energy and momentum to the target at early times [Hermalyn and Schultz, 2010, Hermalyn and Schultz, 2011].

When the axisymmetric simplification of vertical incidence is removed, the complexity of the ejection process increases significantly. Asymmetries in the shock from oblique impacts [Dahl and Schultz, 2001] are manifested in azimuthally dependent velocities and ejection angles in the ejecta flow-field [Anderson et al., 2003, 2004, Anderson and Schultz, 2006]. These effects persist well into crater formation, and the emplaced ejecta patterns map out the asymmetric flow-field onto the surface. The point-source approximation is unable to predict ejecta distributions for much of growth.

Previous studies have examined oblique impact ejecta distributions from the ballistic deposition of material on the surface [Gault and Wedekind, 1978] and ballistic capture in discrete azimuths [Schultz, 1999, Schultz and Mustard, 2004]. The three-dimensional, time-varying nature of the flow field vastly increases the difficulty of in-flight ejecta measurement. No scaling laws have yet been proposed that accommodate a description of oblique impacts. Several ad hoc models have been employed to attempt to account for obliquity (e.g., [Wieczorek, M. A. and Zuber, M. T., 2001]),

but these have not been based on experimental or planetary evidence. As a result, planetary cratering applications are either simplified as vertical impacts, or individually require computationally-expensive 3-dimensional (3D) modeling efforts (which have yet to be fully validated for granular materials [Brown et al., 2007, Pierazzo et al., 2008]).

Pioneering experimental studies of the oblique ejecta velocity distribution utilized a 3-component particle imaging velocimetry (3C-PIV) technique [Heineck et al., 2002] adapted from methods commonly employed in experimental fluid dynamics to capture the three-component velocity of groups of particles over all azimuths [Anderson et al., 2003, 2004, Anderson, 2004, Anderson and Schultz, 2006]. This technique used a laser light sheet projected parallel to the target surface to illuminate cross-sections of the particles in the ejecta curtain while in flight. These studies recorded a single discrete pair of stereo images per impact experiment (i.e., one velocity vs. launch position or time “data point” per experiment) to reconstruct the 3-component velocity; thus, multiple identical experiments were required to build up data for a specific impact condition. As a result, the data is not temporally resolved and the current understanding of the ejecta velocity in oblique impacts comes from discrete snapshots of the event (usually 3 or 4 per impact condition) rather than a continuum approach. Presentation and scaling of the velocity data in a spatial fashion required complicated correction terms due to flow-field center migration and time-varying launch position [Anderson and Schultz, 2006].

In this study, we present results from new high-speed experimental studies performed at the NASA Ames Vertical Gun Range (AVGR) designed to measure the effect of obliquity on the time-resolved ejecta velocity distribution for impacts over a range of incidence angles. These results utilize a novel 3D photogrammetric technique to detect and track individual particles, permitting the use of time (rather than launch position) as the independent variable. The transitional evolution from early-

to main-stage growth is captured and compared for different impact angles. Our overall goal is to develop an analytical model of the ejecta velocity distribution for oblique impacts.

3.2 Experimental Description

3.2 Methodology

In order to address and constrain the effects of oblique impact conditions on the early-time ejecta distribution, a suite of impact experiments into Ottawa quartz sand (nominal grain diameter of $\sim 1\text{mm}$) was conducted at the AVGR under vacuum conditions ($< 67\text{Pa}$). The strategy involved varying impact angle (30° , 45° , 60° , 90°) while keeping other parameters (size, density, and, within the limitations of the facility, velocity) constant by using 6.35mm diameter aluminum projectiles launched at 5.18, 5.66, 5.46, and 5.51 km/s, respectively.

3.2 Technique Development and Implementation

The technique employed in this study is an outgrowth of the initial work at the AVGR by [Anderson et al., 2003, 2004, Anderson and Schultz, 2006]. In order to measure the early- to main-stage excavation flow transition in oblique impacts, fundamental changes are required to overcome technical barriers introduced by the new high-speed system. The method developed for this application (High-Speed Two-Frame Hybrid 3-Dimensional Particle Tracking Velocimetry, or “3D-PTV” in this work) appears qualitatively similar to the experimental setup previously employed by Anderson and Schultz, but the measurement is inherently different. In this section, we present the basic concept of the system as necessary for interpretation of the results; full description of the technique developed will be presented in Hermalyn et al., [2011].

Particle imaging velocimetry (PIV) is a common technique in fluid dynamics research for determination of the flow field. Most standard implementations use digital

cameras to record images of laser-illuminated tracer particles seeded into the flow [Raffel et al., 2007]. The cross-correlation of small interrogation windows is computed between images pairs of a flow field taken at different times. The correlation peak location yields the spatial displacement of the windows. Extension to 3-component velocity measurements is accomplished through stereoscopic reconstruction of the displacements in two (or more) cameras of known orientations.

The Eulerian nature of PIV connotes that velocity measurement is averaged over an interrogation area or volume (ideally comprised of ~ 9 particles about 2 pixels in diameter). No spatial information regarding the position of the particles (such as location within the illumination volume) is produced. In fluidics, this generally poses no problem as the desired measurement is the instantaneous velocity (sometimes including out of plane motion); particles are seeded into the flow exclusively to enable flow-field visualization. In measuring the velocity of ejecta, however, reconstruction of the actual particle position and displacement is the goal. The PIV technique employed in prior studies was sufficiently accurate to allow spatial interpretation of the ejection velocity, but was not designed for temporal studies.

For the present study, we adopt a Lagrangian (particle tracking, or PTV) approach. Although this tactic adds considerable complexity to the experimental implementation, it has numerous benefits ideally suited for our application. PTV allows increased spatial resolution, permits individual particle positioning, and does not suffer from velocity averaging due to gradients within interrogation areas. Precise identification of particle location (within the laser plane) is important because the ejecta must be ballistically regressed to the target surface to describe the ejection process.

A high-speed, dual-head Nd:YLF pulsed laser provides the sole illumination of the measured particles. The beam is optically spread to a light sheet (7mm in thickness) and is projected horizontally a few centimeters above the target surface parallel to

the pre-impact plane (see Fig. 3.2). Cross-sectional slices of material launched by the impact into the light sheet are illuminated by the laser pulses and imaged by a set of four synchronized high-speed cameras from arbitrary (e.g., non-collinear) locations through viewing ports in the vacuum chamber. The lens/camera combination is decoupled to allow for Scheimpflug arrangement. The instantaneous Euclidian location (e.g., x, y, z) of each of the particles can be determined within the laser plane photogrammetrically. In order to achieve the spatial resolution required for accurate particle location (~ 3 pixels/particle diameter) while not drastically sacrificing spatial extent, we take advantage of the bilateral symmetry of the ejecta curtain and image only one half of the curtain (with some overlap; see Fig. 3.3 for example images of one time-step).

A new software package developed at Brown to determine the location and velocity of the particles is a hybrid extension of both traditional 3D particle tracking methods (e.g., [Maas, 1992, Maas et al., 1993]) and the PIV technique described above. The difficulty in direct application of these methods lies in the unique conditions of the experiment: low spatial resolution of the particles (as compared with many PTV studies), two-frame particle tracking needed for the 3D reconstruction of the velocity (compared with multiple frame tracking methods, which permit the use of predictor-corrector algorithms), and the inherently lossy characteristic of the data (since a significant percentage of imaged particles leave the field of view between successive frames).

The initial reconstruction of the 3D particle locations is accomplished after image processing by first locating the particles in one of the cameras (a top-view camera) and then mapping the epipolar line swath into the images from the other cameras. A line-search combinatorics algorithm finds the most likely particle match on the epipolar line in each camera image. The particle locations are first located in world coordinates (e.g., the 3D Euclidian position) using the direct linear transform (as

described in Schairer and Heineck [2010]) and then refined using a nonlinear least squares polynomial regression (in the manner of Soloff et al. [1997]) to account for and minimize distortion errors. Each detected particle is fit with a two-dimensional 3-point Gaussian to locate the center to sub-pixel accuracy. This methodology is adopted because it does not lead to image reprojection errors (which are significant in the arbitrary camera positions required by the optical port placement on the AVGR). The over-resolved nature of this measurement (due to each particle being located in ≥ 3 cameras) allows for both uniqueness in identification and increased accuracy in positional reconstruction (Fig. 3.3).

Two-frame 3D tracking methods have previously been employed in fluidic studies (e.g., Pereira et al. [2006]), but have not extended to the high-speed, low-resolution regime of interest here. In addition, most PTV/PIV studies align the measurement volume with the direction of principal motion, thereby allowing detection of particles in subsequent or multiple frames with minimal losses. Since the laser plane is parallel to the target surface in this study (as required by the geometry of the ejection process), the laser plane is oriented $\sim 45^\circ$ away from the launch vector direction; thus, 50% or more of the ejecta particles can move outside the field of view between frames. Once the particles are located in world coordinates in the first frame of each camera, an iterative cross-correlation PIV routine between successive frames allows identification of displaced particles in each camera (similar to super resolution techniques, e.g., Cowen et al. [1997]). Velocity is determined through the difference in location divided by the time interval between pulses. Particles not located in subsequent frames are discarded. As the ejected mass increases with time, the curtain grows optically thick and the laser can illuminate only the outside edge of the lateral component (e.g., the azimuth closest to the laser). This opacity also leads to “shadowing” of the uprange and downrange portions of the curtain. Thus, at late times, the measurable range of azimuths that include illuminated particles is restricted.

The time-resolved nature of the data set allows investigation of the ejecta flow field in a regime much earlier than examined in prior oblique experimental studies (e.g., Anderson and Schultz [2006]). The logarithmic decrease in ejection velocities, however, further complicates continuous temporal measurement of the ejecta. The timing between laser pulses and thickness of the light sheet must be tuned to measure the ejection velocities at early times, whereas the time between successive images (e.g., by skipping one or several images) allows for greater particle displacement at later times when the ejecta are traveling slower. In this study, a time of $15\mu\text{sec}$ between the two laser heads is employed; each laser head operates at 6kHz. This procedure allows a relatively seamless transition from early-stage to main-stage measurement (as controlled by the 6kHz data rate) without a significant data gap. Such a gap occurs when particles are not moving sufficiently between laser pulses to be measured reliably, but too much to remain in the illumination volume for successive frames. Measurements here record ejecta traveling from $\sim 200\text{m/s}$ at early times to $\sim 1\text{m/s}$ at the end of measurement. The non-linear decay of velocity is captured by over-resolving the event. The laser sheet is projected with its bottom 7.8 to 8.1cm above the pre-impact target surface to allow ejecta to spread out slightly, but the volume of illumination (linearly related to maximum upward particle velocity) is sufficient to allow the curtain to become optically dense at later times when most material is ejected. See Fig. 4.3 for examples of the images.

3.2 Error Analysis and Validation

The main source of error in this study is the uncertainty in position reconstruction, affecting both the measured velocity and the calculated launch time. To evaluate the accuracy of particle detection, a calibration plate with particle-sized spheres located at known positions was mapped through the illumination volume, imaged, and then processed as data. This validation demonstrated a standard deviation of 0.05mm

in the in-plane (radial) and 0.08mm in the out-of-plane (upward) direction, which is consistent with the error for the Gaussian sub-pixel interpolation scheme (e.g., Nobach et al. [2005]). Errors appear to follow a normal distribution (according to a Lilliefors test).

While this error is quite small ($<10\%$ of the particle radius), it must be taken in context of the required measurement. Once the particles are located and the displacements are measured, the particles must be ballistically retracted to the target surface from their height in the laser plane to determine ejection velocity and time of launch (as well as launch position). The ballistic time-of-flight to the laser plane, which must be subtracted to yield the time of launch, is very sensitive to errors in location. Error in the “ z ” location of the particle within the illumination volume is proportional to the square of the error in ballistic flight time.

At early stages, the time between successive laser pulses (dt) is $15\mu\text{sec}$; thus, a 0.1mm error in position can yield an error in velocity of $\sim \pm 13\text{m/s}$ or about 10%. Velocity errors are approximately proportional to the difference in ballistic flight time. Generally, errors in the velocity come primarily from the same positional error described above and are not related to the error in the PIV step (since the final reconstruction is from the location of the displaced particle). Some of the displaced particles are incorrectly identified, which leads to an error in velocity. Generally, because the measured velocity tends to strongly deviate from the trend, these errors can be easily filtered. At later stages, the absolute velocity error decreases linearly as the time between images increases. The positional error remains constant, but becomes less important at longer times after impact.

Additionally, a two-dimensional velocimetry technique (or 2D-PTV, as described in Hermalyn and Schultz [2010], Hermalyn and Schultz [2011]) was independently employed to measure the velocity distribution on matching 90° and 30° impacts to provide an independent validation of measurements. These experiments utilized high-

speed cameras mounted orthogonally to the impact plane to image ejecta in the profile of the curtain. Although this technique permits a higher degree of time resolution and a greater dynamic measurement range in velocity than the 3D-PTV system used here, the measurement area is restricted to the one discrete azimuth bin (on the order of $\sim 5^\circ$) per camera. While this limitation is acceptable for ejecta measurement in vertical impacts (due to azimuthal symmetry), only selected components can be measured in oblique impacts. Therefore, its utility here is as a validation tool. We focus on the downrange and uprange azimuths using two separate cameras. These studies are referred to as “2D data” in the text to distinguish from the principal 3D measurements.

3.3 Analysis and Results

After the located particles have been regressed to the target surface by subtracting the ballistic motion and flight time from the positions measured in the laser sheet, the ejection velocities can be presented as a function of time and azimuth. In this study, we adopt a cylindrical coordinate system for presentation and analysis, where the ejection velocities are defined by time of launch t , azimuth ϕ , radial (or “in-plane”) velocity, and upward (“ W ”) velocity components. The azimuth convention adopted here is downrange (in the direction of the impactor) is defined as 0° with uprange at 180° ; the “lateral” component is taken at 90° (e.g., orthogonal to the impact direction); see Fig. 3.5. Although this deviates from the nomenclature utilized in Anderson et al. [2003, 2004], Anderson and Schultz [2006], the physical basis for this convention comes from the physical interpretation of the impact momentum. Under this definition, the impact vector and the downrange direction are aligned in the $x-y$ plane. This formulation leads to a general description of the momentum transferred to the target material. Some of the data plots are simplified to display only the averaged downrange, uprange, and lateral components (binned in 20° increments) for clarity

(e.g., Fig. 3.6). The origin of the reference system is taken to be the center of the final crater rather than impact point or flow-field center, which migrates throughout growth [Anderson and Schultz, 2006]. This translation will only affect the definition of the lateral component. A 5cm shift of flow-field center downrange shifts the lateral component by only $\sim 15\text{-}20^\circ$, or approximately the size of the bin. Presentation of the data as a function of time frees us from the spatial issues attached to the flow-field migration.

The ejection angles vs. time (Figs. 3.6, 3.7) demonstrate significant differences between downrange and uprange azimuths throughout much of measured crater growth for all oblique experiments. The lateral component of ejecta, however, appears to follow the main-stage trend for vertical impacts. The downrange ejecta emerge at $\sim 30^\circ$; the launch angles progress upward with time until joining the lateral component. The uprange component exhibits the opposite behavior, as ejection angles are initially high ($> 50 - 55^\circ$) and decrease with time, consistent with earlier results [Anderson et al., 2003, 2004, Anderson and Schultz, 2006]. The lateral component mirrors the ejection angles for the vertical impact. The extent and duration of the deviation from the late-stage equivalence (where the ejection is expected to be symmetric) is dependent on the impact angle: the 60° impact quickly resembles the vertical impact, whereas the 30° impact exhibits significant asymmetry throughout measurement.

The radial and upward velocity components also can be presented separately as functions of time after launch (Figs. 3.8, 3.9), where $\tau = t/(a/V_i)$ is the scaled time (as presented below). In addition, the decomposition of velocity vectors permits direct scaling of the two components (rather than attempting to scale the ejection angles and absolute magnitude of the velocity). Early-time deviations are evident in the in-plane component by increased velocities in the downrange direction and diminished velocities uprange (e.g., 30° and 45° impact angles) but data from all azimuths tend to merge towards the end of measurement. The dimensionally-predicted late-stage

power law line from Housen et al. [1983] (fit to temporal data from Hermalyn and Schultz [2010]) is superimposed. The lateral component for all impacts generally approximates the velocity distribution for a similar vertical impact (matching the behavior in ejection angle). No clear difference in the upward components appear between the azimuths over this measurement range.

3.3 *Physical Model and Scaling*

Separation of the velocities by component as a function of azimuth at discrete times provides further insight into the ejection process (Figs. 3.10, 3.11). The upward velocity component appears to exhibit no functional dependence on the azimuth regardless of impact angle (Fig. 3.10), whereas the radial velocity component exhibits a sinusoidal dependence on azimuth (Fig. 3.11). Both components at a given time of launch are found to be well-fit by:

$$\left. \frac{v}{V_i} \right|_{t=t_{\text{launch}}} = A + B \cos \phi \quad (3.1)$$

where ϕ is the azimuth and A and B are constants. This provides an empirical description of the velocity distribution at any given time. The physical basis of this form of the regression will be discussed below; however, an F-test demonstrates no significant improvement in fit by adding an additional quadratic term. Fitting the same equation (or a linear regression) to the upward component reveals that the magnitude of the sinusoidal component or “slope” B is statistically indistinguishable from 0 in all cases using a Student’s t-test. Confidence intervals for the amplitude of the sinusoidal component B bracket 0 down to a minimum of 80% confidence intervals; most time intervals extend to the 50% confidence level or below, implying that we cannot reject the null hypothesis of zero slope.

To scale the ejection velocity in the early- to main-stage regime, we cannot rely

on the point-source coupling parameter commonly employed to simplify the cratering process (e.g., Housen et al. [1983], Holsapple and Schmidt [1987], Holsapple [1993]). Instead, we must return to the complete dimensional dependence on early-time parameters.

Following [Holsapple and Schmidt, 1987], the ejecta velocity field v passing through the plane of the target surface at a given azimuth and time for an impact into a homogeneous target under vacuum conditions is determined by a functional dependence F :

$$v = F(\theta, V_i, a, \delta, \rho, t_l, \phi, g, r, K_t, K_p, \eta_t, \eta_p, \Pi_t, \Pi_p) \quad (3.2)$$

where the newly-introduced variables are: the impactor velocity, V_i ; the impactor and target densities δ and ρ , respectively; the projectile radius a ; gravitational acceleration g ; launch radius r ; and the bulk moduli (K_t, K_p) and viscosity measures (η_t, η_p), of the target (t) and projectile (p). All other material properties of the target and projectile are collapsed into the Π groups. Physically, the velocity of the ejecta is dependent on the initial conditions of the impact (e.g., the energy and momentum coupled into the target), the time after impact, spatial location, and the properties of the target and projectile that affect the flow pattern. This full dependence is presented for completeness; however, because this study is focused solely on the effect of impact angle, many of the terms are constant here.

By taking the ratio of like terms and converting the bulk modulus to a sound speed in the target and projectile (by $c = \sqrt{K/\rho}$), a material set Π_m for a given impact is given by:

$$\Pi_m = \left[\frac{K_p}{K_t}, \frac{\delta}{\rho}, \frac{\eta_p}{\eta_t}, \Pi_t, \Pi_p \right] \quad (3.3)$$

leaving:

$$v = F(\theta, \phi, V_i, a, \delta, t_l, g, r, c, \eta_t, \Pi_m) \quad (3.4)$$

The velocity is then defined by eight dimensional variables and three dimensionless parameters utilizing three fundamental units. According to the Buckingham Pi theorem [Buckingham, 1914], this set yields, at most, $8-3=5$ additional dimensionless Π -groups:

$$\frac{v}{V_i} = F\left(\theta, \phi, \frac{r}{a}, t\frac{V_i}{a}, g\frac{a}{V_i^2}, \frac{c}{V_i}, \frac{\eta_t}{\rho a V_i}, \Pi_m\right) \quad (3.5)$$

It is recognized that the Π_m group contains density terms previously found to affect early-stage scaling in vertical impacts [Hermalyn and Schultz, 2010]. As these terms are constant in this study (the same projectile/target materials are used throughout), they are left in the Π_m group; future work will examine the effects of these terms.

Finally, omitting viscous terms and late-stage effects (gravity or strength), we find:

$$\frac{v}{V_i} = F\left(\theta, \phi, \frac{r}{a}, t\frac{V_i}{a}, \frac{c}{V_i}, \Pi_m\right) \quad (3.6)$$

The θ term is related to the energy and momentum coupling of the impact, and therefore is inexorably linked to V_i . The r/a term includes a radial dependance on ϕ ; the tV_i/a term does not. Moreover, the crater radius R is ill-defined without a dependence on the other Π groups (due to migration and asymmetric transient crater dimensions). Since the two terms are related, we adopt the use of time as the independent variable, and define τ as:

$$\tau = \frac{tV_i}{a} \quad (3.7)$$

Thus, we use τ as our temporal scale.

The velocity measure in a vertical impact provides a starting point for extrapolation to obliquity. The ejection velocity as a function of time is given (ignoring density terms) as:

$$\frac{v}{V_i} = k_1 \tau^\gamma \quad (3.8)$$

where k_1 a non-dimensional constant and γ is the dimensional exponent; there is no dependence on ϕ for vertical impacts. This relationship is dimensionally predicted, and is expected to hold for either absolute magnitude of velocity (as it is commonly invoked) or for any component thereof (e.g., upward or radial), with adjustment to the k_1 term.

At any particular point in time, as presented in Fig. 3.8, the velocity dependence simplifies to

$$\left. \frac{v}{V_i} \right|_{t=t_{launch}} = k_1 * k_2 \quad (3.9)$$

where $k_2 = \tau^\gamma|_{t=t_{launch}}$; i.e., a constant line without slope for all azimuths for a given launch time. This is consistent with the measured upward velocity components for all impact angles, as presented in Fig. 3.9, and the in-plane component for vertical impacts. Returning to oblique impacts, we find that the radial component, however, exhibits a dependence on azimuth that is reliant on both impact angle and time. For any given discrete condition in Fig. 3.10, this can be expressed by superimposing the constant line with a sinusoidal dependence on azimuth:

$$\left. \frac{v}{V_i} \right|_{t=t_{launch}} = A + B \cos \phi \quad (3.10)$$

This formulation is still self-consistent for vertical impacts, as the azimuthal term $B \cos \phi = F(\theta) \rightarrow 0$ as $\theta \rightarrow 90$. The choice of a cosine dependence is physically motivated from the dot product of the impact momentum vector and the ejection azimuth in the $x - y$ plane.

Comparison with the upward component of the 30° impact experiment using the 2D method discussed above matches measurements from the 3D-PTV method. This experiment also exhibits no difference in the upward component between the down-range and uprange components. As an additional check of validity, ejection angle and velocity data from Anderson and Schultz [2006] for a 30° impact at 1km/s were reprojected to the cylindrical coordinate system presented here. The upward component at discrete times after impact was also found to lack azimuthal dependence (within the errors discussed in the paper).

3.4 Discussion

Scaling relationships for crater size have been found to follow vertical impact laws (in gravity-controlled craters) by simply replacing the impact velocity with the downward component ($V_i \sin \theta$) down to incident angles of $< 5^\circ$ [Gault and Wedekind, 1978, Chapman and McKinnon, 1986, Dahl and Schultz, 2001]. This equivalence suggests that it is the downward-directed energy and momentum coupled to the target that controls most of the cratering event (as in vertical impacts), and is evidence for the concept of superposition of flow-fields [Anderson and Schultz, 2006]. The absence of azimuthal dependence on the upward velocity component suggests that it is this initial downward-directed shock that controls the upward release of material. In vertical impacts, the kinetic energy of the target is divided into radial and upward components; these components must be approximately equal to result in 45° ejection angles. It is also noted that the lateral component of all impacts reflects behavior for a vertical impact. This implies that the radial enhancement orthogonal to the impact vector is constant for a given material.

Recent experiments have demonstrated that observed ejection angles do not match the assumed 45° [Housen et al., 1983] for sand throughout crater growth [Anderson et al., 2003, 2004, Hermalyn and Schultz, 2010], and are characteristically different

from the nominal 45° in different target materials (such as air-fall pumice dust, e.g., [Hermalyn and Schultz, 2011], and underdense perlite [Schultz et al., 2005, 2007]). Thus, individual scaling of the velocity components is desirable as $v_{radial} \neq v_{upward}$ in a general cratering problem. In the present study, the intercept a is found to be the same for both radial and upward components; that is, the radial component fit line intersects the upward component fit line at 90° . This might be a function of the $\sim 45^\circ$ ejection angle for (vertical) impacts into sand, which distribute the initial energy and momentum from the impact equally into radial and upward components in the far-field. At early times, however, the radial component is greater in magnitude than the upward component even for vertical impacts [Hermalyn and Schultz, 2010], which leads to lower ejection angles that progress upward toward the expected 45° ; thus, this simplification is not expected to hold for all of growth.

The fit coefficients described above and displayed in Figs. 3.12a and 3.12b can provide insight into the cratering evolution, as well as a first step toward analytical scaling of the ejecta velocity distribution for oblique impacts. The form of Eq. 3.1 provides some clues to the physical underpinnings. Both A and B are functionally required to be non-dimensional. Because A is independent of ϕ , it can be expected that this is a constant for a given impact event of form $F(V_i, \theta)$ (ignoring density terms). Since the velocity is still required to follow Eq. 3.6, B should be composed of a function of the impactor energy or momentum, related to V_i and θ .

By examining the coefficients temporally, we can construct a scaling relationship for the velocity as a function of azimuth and τ . Both $A(\tau)$ and $B(\tau)$ appear to follow power-law relationships (as expected for ejecta velocity). Under this assumption, A and B can be represented by

$$A(\tau) = k_A \tau^\alpha \quad (3.11)$$

and

$$B(\tau) = k_B \tau^\beta \quad (3.12)$$

where multiplicative factors k_A , k_B and exponents α , β are constants for a given material and impact angle (although only B terms appear to rely on impact angle in these data). The scaling of velocities for a given impact angle can then be formulated by

$$\frac{v}{V_i}(\tau, \phi) = k_A \tau^\alpha + k_B \tau^\beta \cos \phi \quad (3.13)$$

Thus, by plugging in only four constants, the ejecta velocity at a given time and azimuth can be determined.

The in-plane component of impactor momentum (with the exception of extremely low incident angles) does not significantly affect the final crater dimensions (which are controlled by the vertical component of projectile kinetic energy), but plays an important and highly visible role in ejecta. For example, at the earliest stages of contact, the radial component of the initial vapor plume scales according to the momentum of the impactor [Schultz, 1996, Schultz et al., 2007]. The form of Eq. 3.1 (and the lateral-component equivalence to vertical impacts) indicates an enhancement of energy/momentum downrange. Uprange ejection angles demonstrate a reduction in energy/momentum partitioning compared to a vertical impact, thereby resulting in higher ejection angles. The shape of the transient cavity also affects the ejection angle, since launch vectors have been shown to be related to the surface tangent.

3.5 Conclusions

The high temporal resolution of this study allows a physically based description of the ejecta velocity distribution for oblique impacts for the first time. In the downrange direction, the initial momentum of the projectile is retained in the target, visible in an

enhancement of high speed material early in the process (e.g., [Schultz, 1999, Schultz and Mustard, 2004]). Incomplete coupling at early times uprange results in the “zone of avoidance.” The radial component exhibits a cosine dependence on azimuth, expressed by a velocity enhancement in the downrange direction and a reduction in the uprange side, related to the momentum partitioning. The lateral azimuth largely follows velocity and ejection angle trends commensurate with vertical impacts. The vertical component of ejecta velocity, however, is found to be independent of azimuth.

The value in the point-source ejecta models developed by Housen et al. [1983] is that they provided a simple metric for the ejecta. The model developed here delivers a similar tool for oblique impacts, based on the initial conditions of the event. The temporal nature of these data allow this description in time, and removes the dependence on the spatial domain. It also allows objective characterization of the time-varying spatial evolution. The convolution of the decreasing ejection velocities and early-stage coupling contributes to the appearance of “curved” rays in the uprange direction [Schultz et al., 2009]. Further study of the effect of different impact variables will constrain the early-time component and ultimately allow scaling to planetary events. With increasing crater size, early-time processes encompass a greater percentage of crater growth [Schultz, 1992, Schultz et al., 2005]. Understanding the evolution of the ejecta distribution is essential for interpretation of impact mission results (such as the Deep Impact mission) and can be used to map out the ejecta distribution on planetary bodies.

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Figure Captions

Figure 3.1. Jackson, a crater on the lunar far side that exhibits asymmetries consistent with an oblique impact. (Clementine composite image).

Figure 3.2. Experimental setup and schematic for studies at the AVGR (side view). A pulsed laser is optically spread into a horizontal light sheet (i.e., parallel to surface), and is projected a few centimeters above the target, serving as the sole light source for the experiments. As ejecta reach the laser plane, light pulses stroboscopically illuminate the discrete particles in cross-section; these slices are recorded in stereo by multiple high-speed cameras.

Figure 3.3. Example 3D-PTV Data. Four cameras record instantaneous cross sections of the ejecta curtain at 12,000 fps (6000Hz data rate for image pairs). By imaging the same particles from multiple locations, the location of each particle can be determined photogrammetrically (as described in the text). A single time step (~ 2.5 msec after impact) of the 30° impact at 5.5 km/s is displayed here for each camera (A-D). The approximate orientation of the down-range vector is displayed in blue. One example particle (inscribed by a red square) is identified in each image to illustrate the perspective projection provided by the image data. Images are inverted for clarity.

Figure 4.3. Visual comparison of the impact experiments. Rows correspond to the 30° and 90° experiments; images are selected at approximately equal τ . Downrange is to the left; uprange is to the right (vector directions shown in blue). Images display only one half of the curtain. The 30° impact demonstrates the delay in uprange ejecta and maintains asymmetry for much of crater growth. Early-time ejecta is characterized by sparse, crushed material that evolves into main-stage behavior.

Figure 3.5. Description of the spatial definitions used in this study (perspective view from above and slightly uprange). The projectile impacts at an angle of θ_i with respect to the target surface plane along the red arrow vector. The azimuth (ϕ) is defined to be 0° in the vector direction of the impact (“Downrange”) and 180° opposite the impact direction (“Uprange”). The ejecta velocity distribution is similarly presented in cylindrical coordinates, where the upward component (W) is defined by the vector orthogonal to the target surface (black arrow), and the “in-plane” or radial velocities are defined by azimuth.

Figure 3.6. Ejection angles for 30° , 45° , 60° , and 90° impact experiments (a-d) for 20° bins of downrange, lateral, and uprange azimuths (as defined in text). A 45° reference line (dashed black) is overplotted. The largest deviation from symmetry occurs at early times, where the downrange component of ejecta is $10\text{-}15^\circ$ lower than lateral; uprange ejecta are launched at $50\text{-}60^\circ$. As time progresses, the asymmetry reduces as the ejection angles converge near the expected 45° for sand; slight deviations remain thorough measurement. Comparison to the two-dimensional validation experiments (presented here as “2D” data) is included in (a) and (d).

Figure 3.7. Ejection angles for 30° , 45° , and 60° impact experiments (a-c) for all azimuths. 45° reference line (dashed black) is overplotted. Color bar indicates azimuth in degrees, where 0° is defined to be downrange and 180° is uprange.

Figure 3.8. Radial velocity measurements for 30° , 45° , 60° , and 90° impact experiments (a-d) as a function of τ . Bins of 20° are downrange (blue), lateral (green), and uprange (red) azimuths (as defined in text). The radial component of the dimensionally-predicted late-stage power law line from Housen et al. [1983] (fit to

temporal data from Hermalyn and Schultz [2010]) is overplotted in black. Comparison to the two-dimensional experiments (as discussed in the text) is included here as “2D” data; “3D” data is from the primary 3D-PTV technique. As a result of laser settings, the 45° experiment has less measurable early-time ejecta immediately uprange and downrange (and hence has fewer points), although other azimuths are affected much less.

Figure 3.9. Upward (W) velocity measurements for 30°, 45°, 60°, and 90° impact experiments (a-d) as a function of time. Bins of 20° are downrange (blue), lateral (green), and uprange (red) azimuths (as above and as defined in text). The dimensionally-predicted late-stage power law line from Housen et al. [1983] (fit to temporal data from Hermalyn and Schultz [2010]) is overplotted in black. As above, two-dimensional experiments are presented for comparison as “2D” data.

Figure 3.10. Upward (W) velocity measurements for 30°, 45°, 60°, and 90° impact experiments (a-d) as a function of azimuth at selected times after impact. The fit line of $v/V_i|_{t=t_{launch}} = A + B(\cos \phi)$ for the data (solid black) is superimposed by slope confidence intervals of 80% (blue and red dashed lines), which bracket $B = 0$. At late times (lower velocities) the shadowing effect of the optically thick curtain (as described in the text) causes obscuration in the uprange and downrange directions, limiting the number of illuminated, measurable particles. The ordinate axis is presented logarithmically to allow display of the large differences in velocities for different times. As a result, the sinusoidal variance of azimuth visually appears to have only a small effect even though it actually represents a $\sim 50\%$ difference in radial velocity between downrange and uprange components for early-time ejecta from the 30° impact.

Figure 3.11. Radial (*in - plane*) velocity measurements for 30° , 45° , 60° , and 90° impact experiments (a-d) as a function of azimuth at selected times after impact (matching W times in Fig. 3.10). The fit line for the data (black), and confidence intervals (blue and red dashed lines, as described in the text) are overlaid.

Figure 3.12. Velocity regression analysis for the model. The intercept coefficient “ A ” is non-dimensionalized by V_i as a function of τ in part (a). The radial regression coefficient “ B ” is non-dimensionalized by V_i as a function of τ , presented in (b). Slight gap in data is due to the difference between the timing of the laser pulses and data rate (as discussed in the text).

Figures

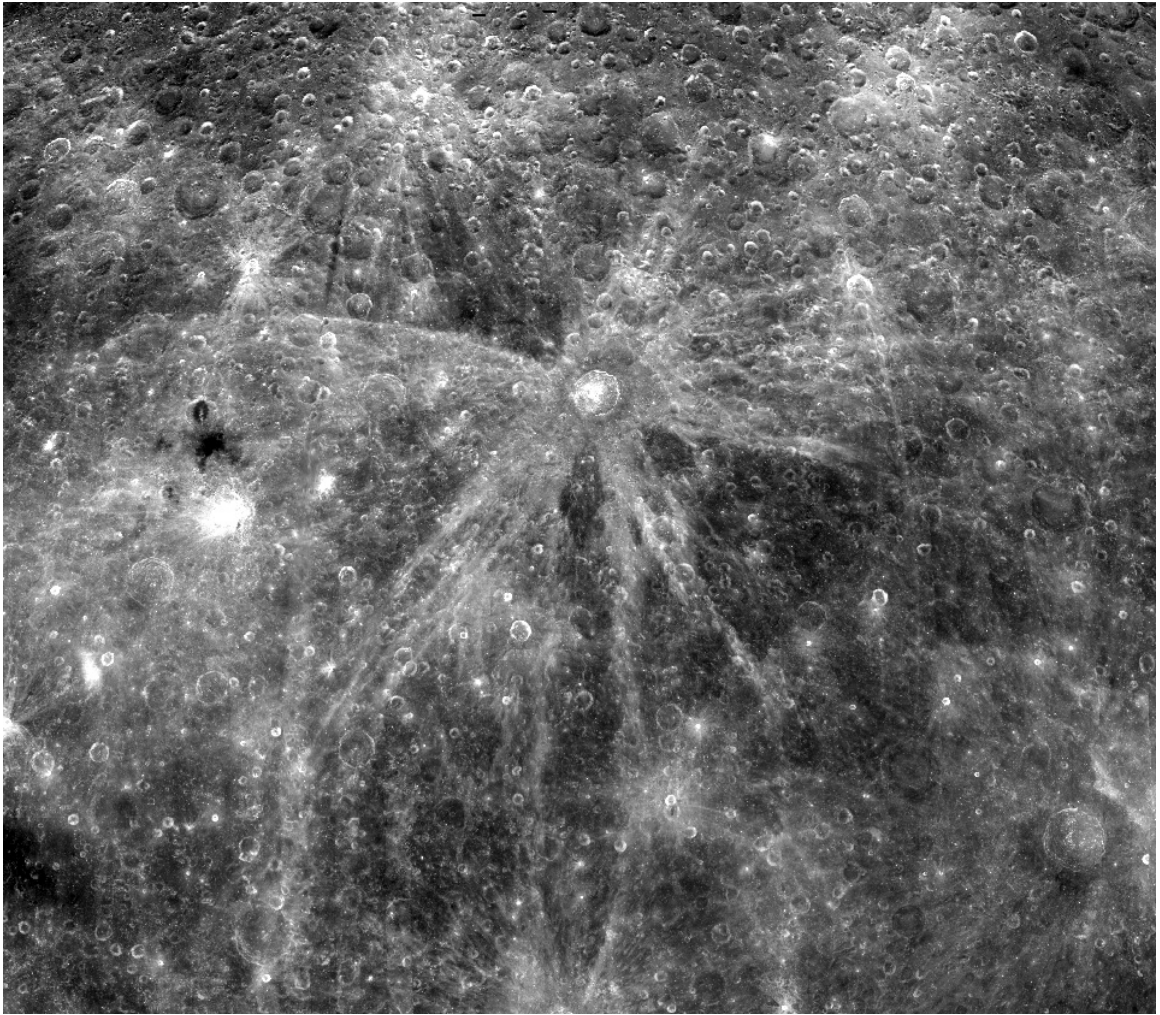


Figure 3.1

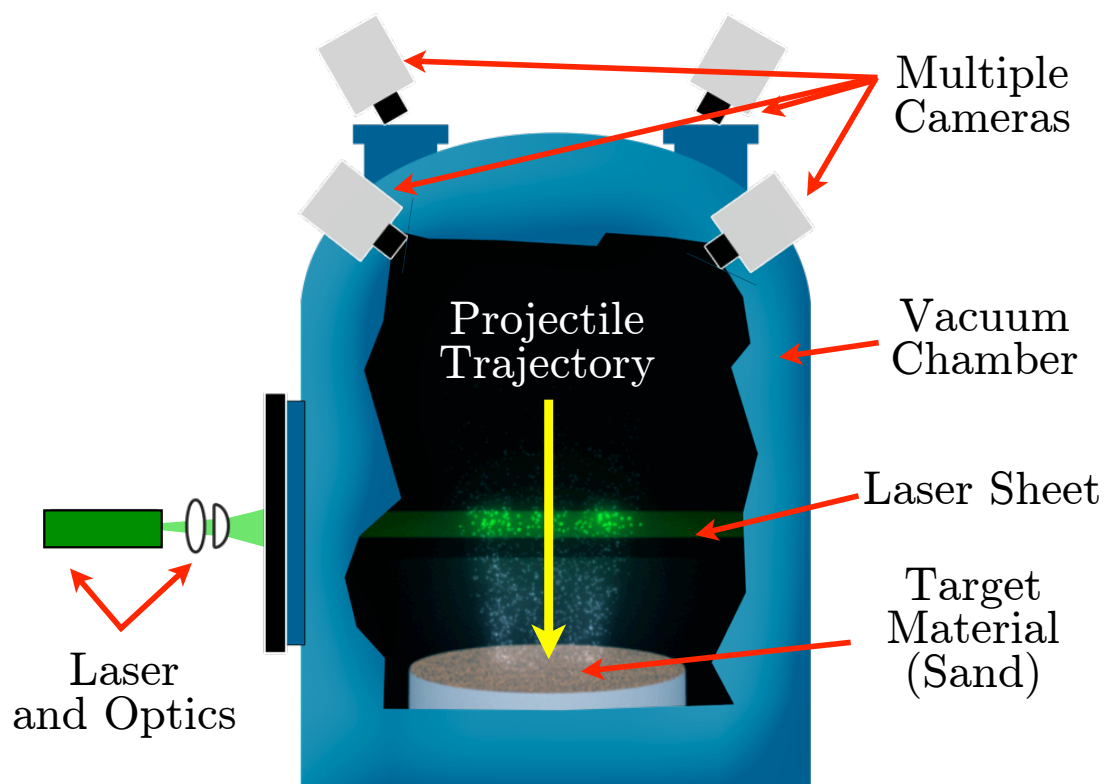


Figure 3.2

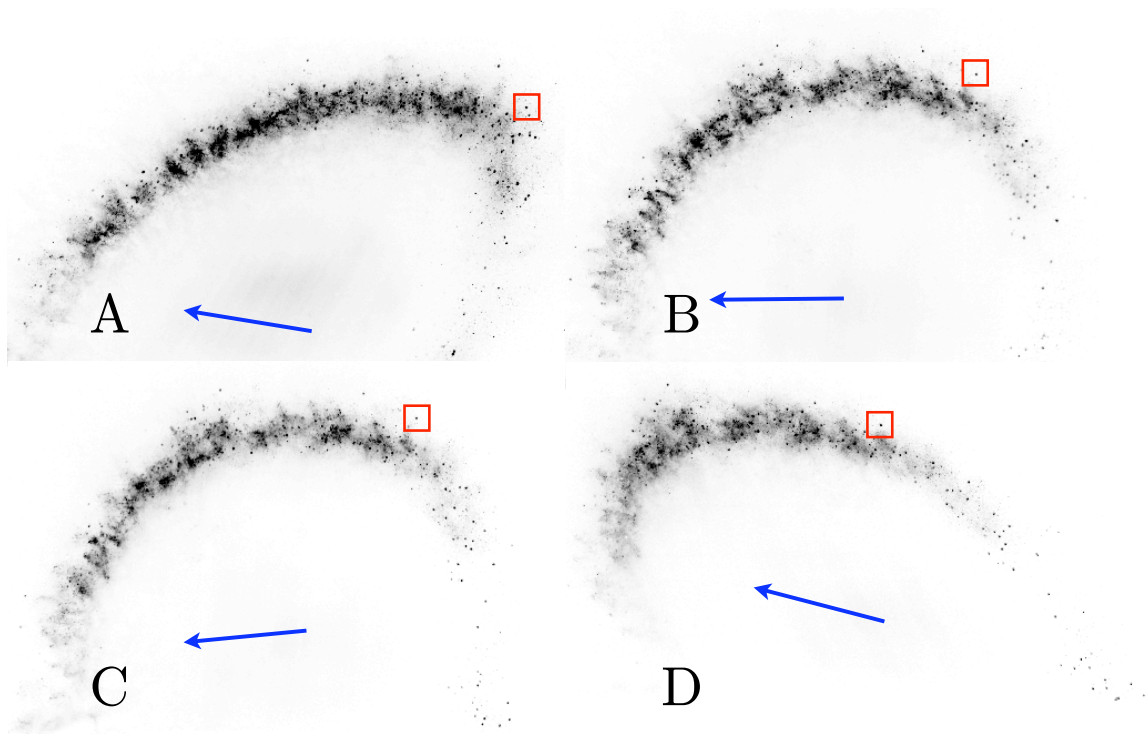


Figure 3.3

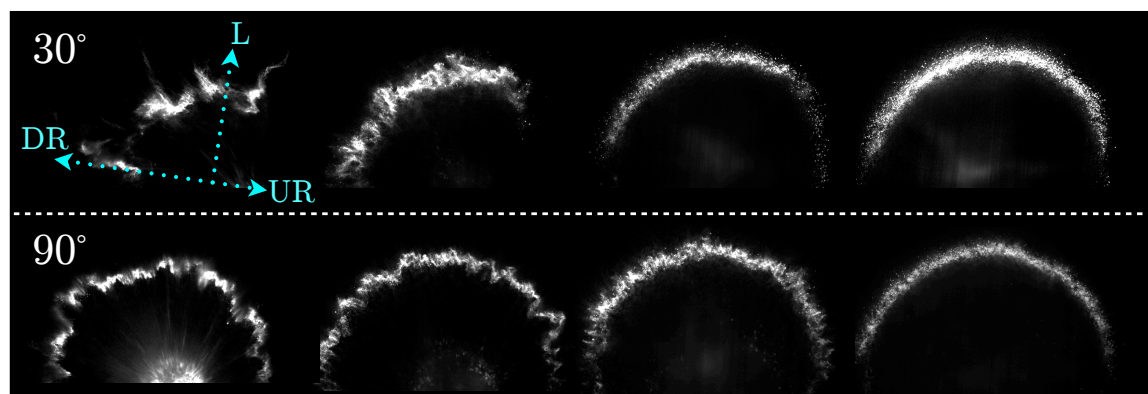


Figure 3.4

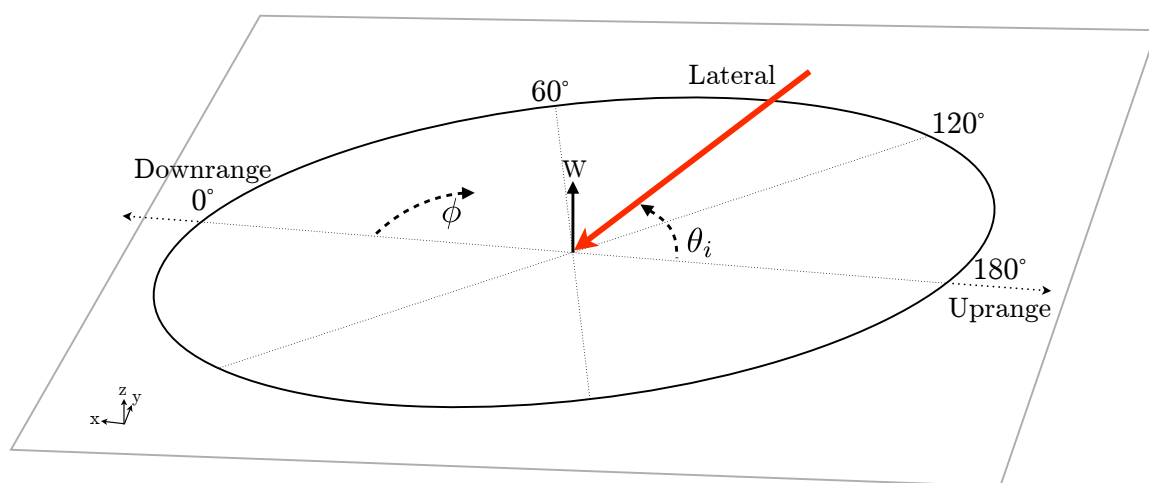


Figure 3.5

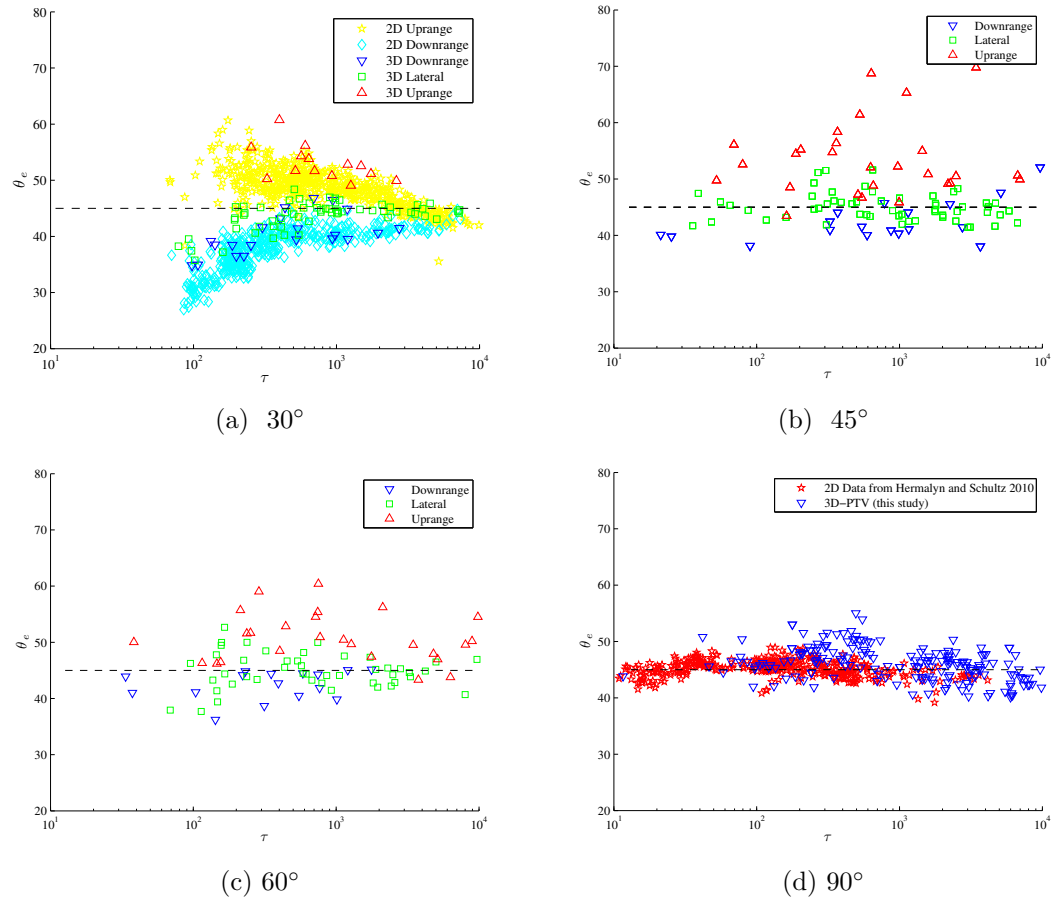
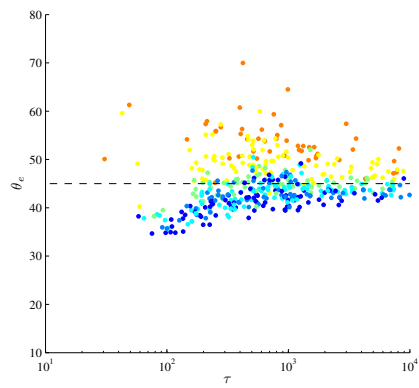
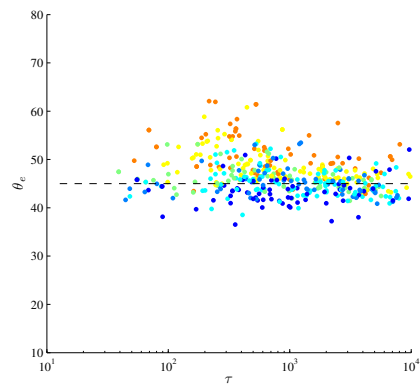


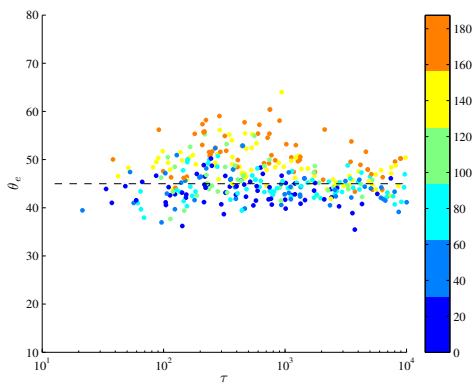
Figure 3.6



(a) 30°



(b) 45°



(c) 60°

Figure 3.7

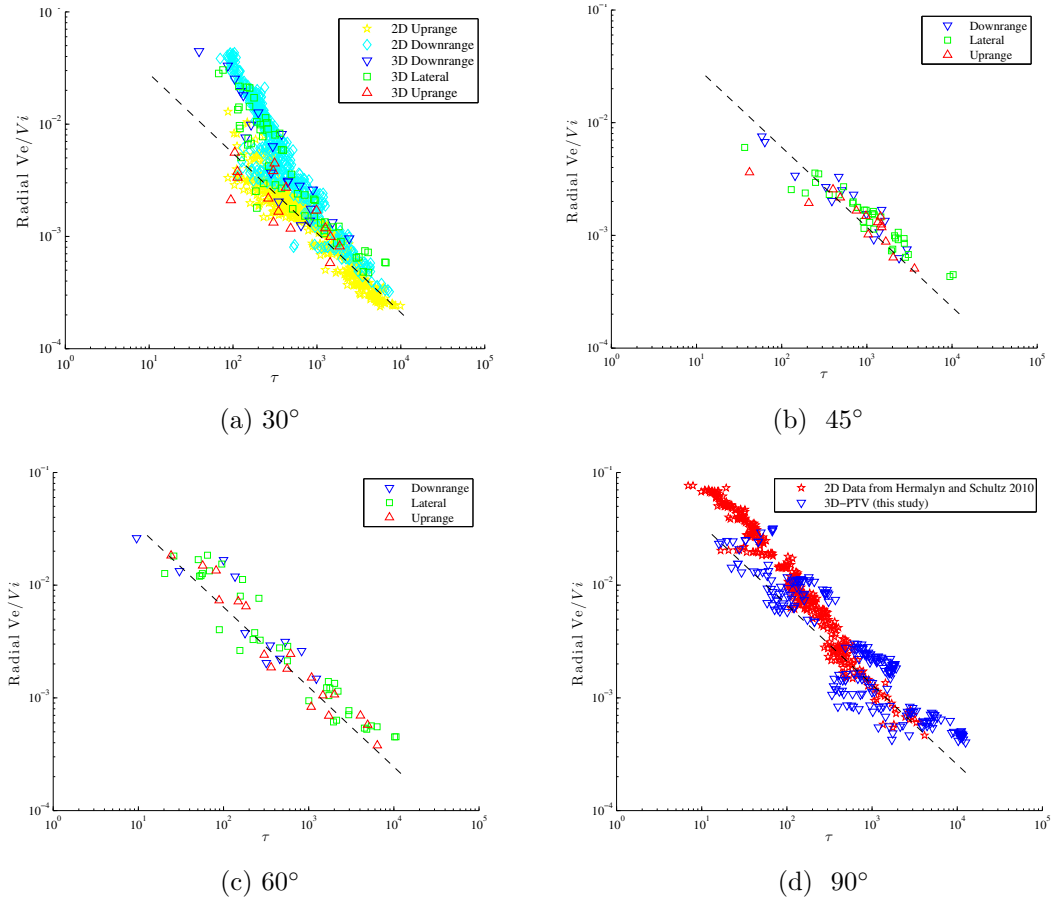


Figure 3.8

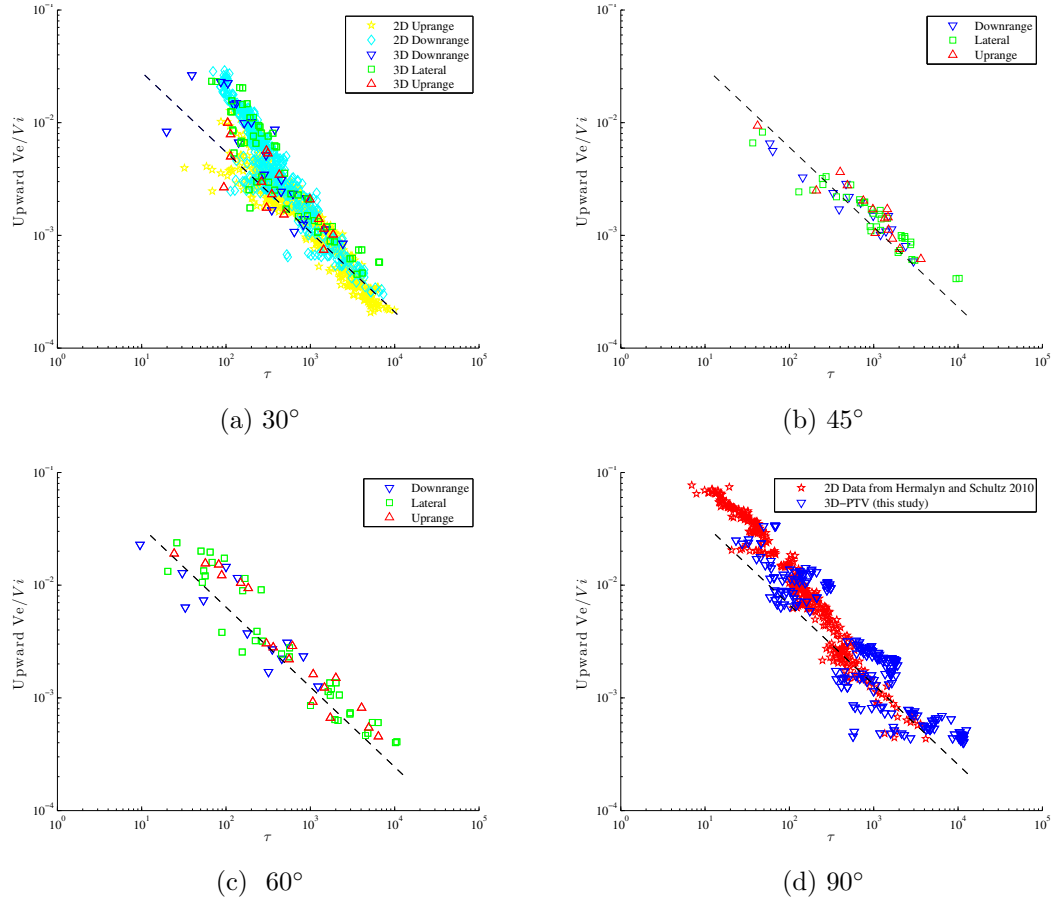
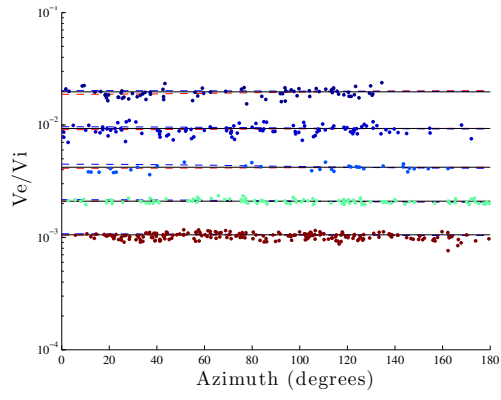
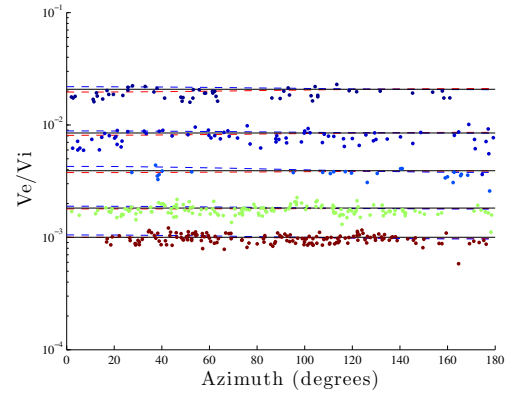


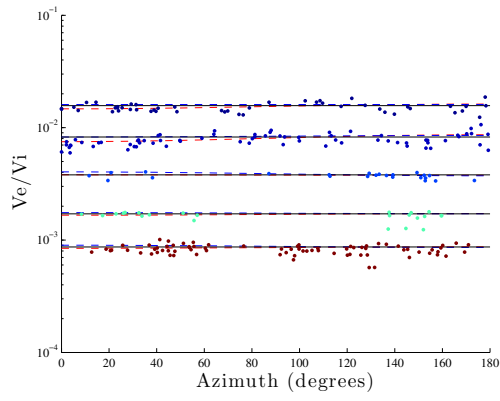
Figure 3.9



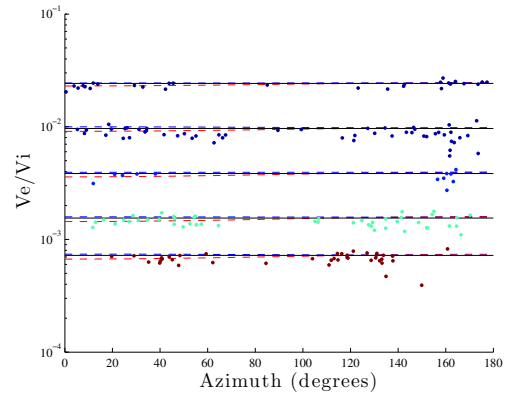
(a) 30°



(b) 45°



(c) 60°



(d) 90°

Figure 3.10

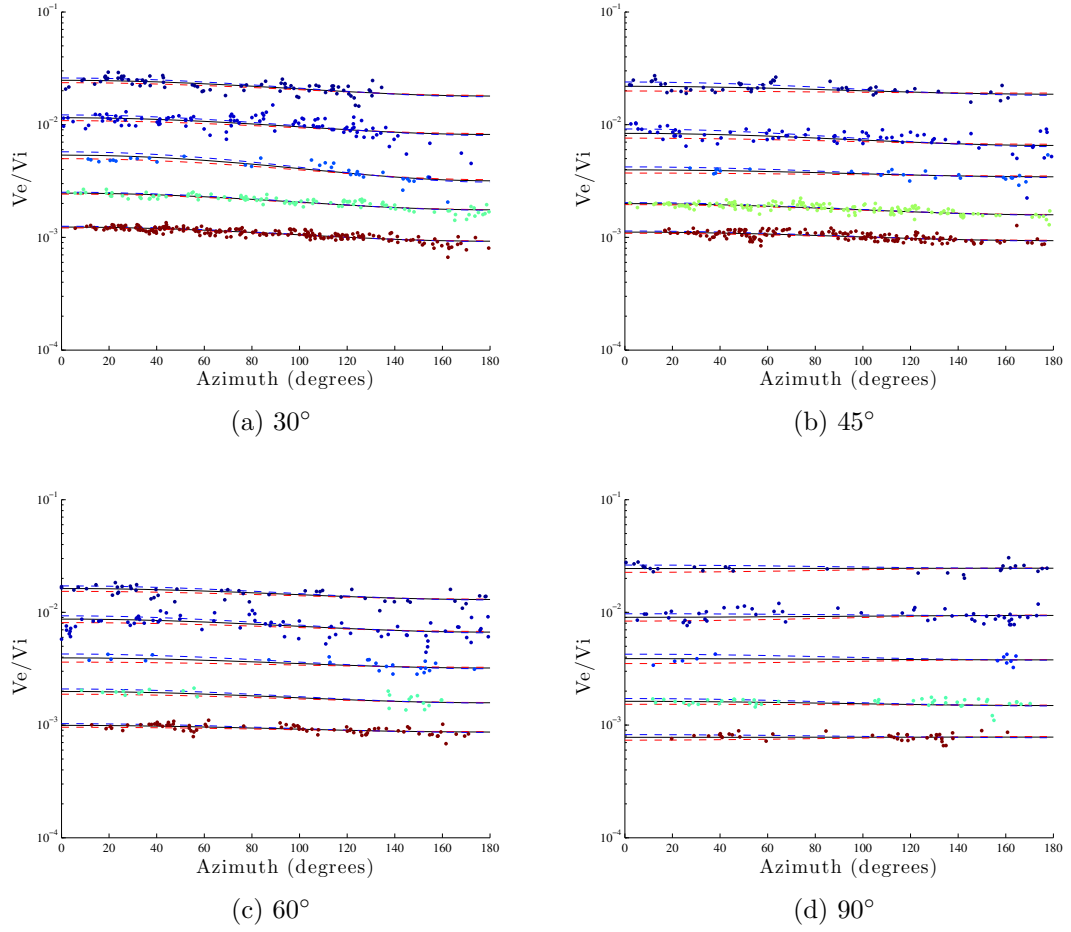
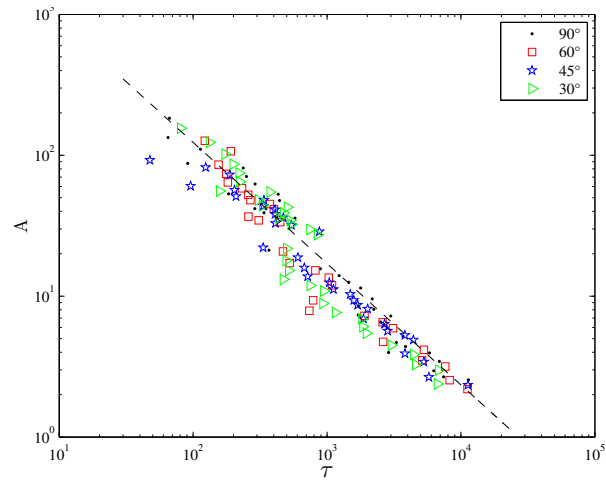
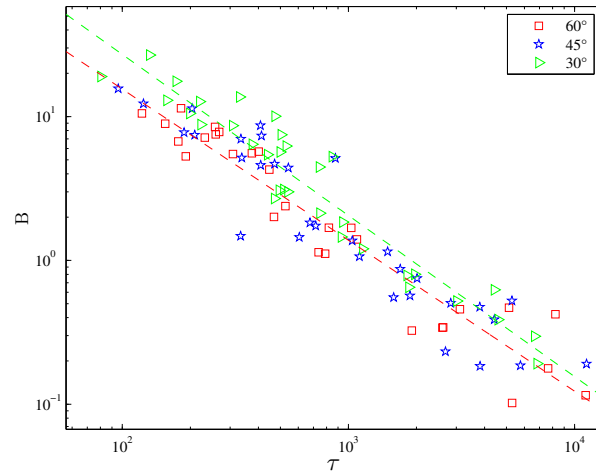


Figure 3.11



(a)



(b)

Figure 3.12

**Chapter 4. Ejecta Patterns from Oblique Impacts:
Experimental Insights for Forward Modeling of
Emplacement**

Brendan Hermalyn and Peter H. Schultz

Department of Geological Sciences, Brown University

Providence, RI 02912

Abstract

The asymmetries of ejecta deposits on solid-surface planets expose the oblique nature of impacts even when crater shapes remains circular. Patterns such as the uprange “zone of avoidance” (ZoA) and non-radial ejecta emplacement provide clues to the initial conditions of the event. In this chapter, we present time-resolved measurements of the extent and evolution of the uprange ZoA and flow-field center migration in a series of hypervelocity impact experiments over a range of impact angles. In order to examine the ramifications of these early-time effects on the emplaced patterns, an experimentally based ejecta model is developed to allow ballistic propagation and return to the surface. A parametric study of the ejecta curtain closure rate and flow-field center migration establishes a physical rationale for the formation of the morphology of these uprange patterns. This model is then applied to the Deep Impact mission to permit a reconstruction of the event based on experimental data.

4.1 Introduction and Background

Asymmetric ejecta deposits exist on all cratered solid-surface planets (see Fig. 4.1 for a series of selected lunar craters over a wide range of sizes). These are interpreted to be a manifestation of obliquity in the impact event (e.g., [Gault and Wedekind, 1978, Schultz and Lutz-Garihan, 1982, Schultz, 1992, Herrick and Forsberg-Taylor, 2003, Herrick and Hessen, 2006, Herrick et al., 2008, Schultz et al., 2009]). In a seminal experimental study of oblique impacts into granular materials, Gault and Wedekind [1978] reported trends for many of the morphological features exhibited on planetary surfaces, the most characteristic being the emergence of an uprange Zone of Avoidance (ZoA) for low impact angles ($<45^\circ$ from horizontal). At extremely low angles ($<10^\circ$ from horizontal), both downrange and uprange ZoAs appear, creating a “butterfly wing” ejecta pattern. The usefulness of the uprange component as a diagnostic of the initial conditions of the impact has been demonstrated by the ballistic flight of ejecta from the Deep Impact mission, which struck comet 9P/Tempel-1 at $\sim 30^\circ$ [Schultz et al., 2007, 2005], and for interpretation of early-time coupling from the emplaced deposits [Schultz et al., 2009]. The bilateral symmetry of these blankets is commonly used as a metric for the direction of impact.

While the emplaced ejecta patterns reflect the impact conditions, Gault and Wedekind [1978] found that the crater rims retain circularity until the impact angle reaches $<5^\circ$ for hypervelocity impacts into granular materials. Until that point, the crater dimensions were found to scale with the vertical component of the impact velocity ($V_i \sin \theta$). Crater size is thus not a unique metric for determining impact parameters. For example, a 30° impact of a given body at 20 km/s will make the same size crater as a vertical impact of that same body at 10 km/s. Most studies of planetary craters do not take the effect of impact angle on crater size into account and instead use scaling laws developed for vertical impacts (e.g., Housen et al. [1983]).

Under the point-source approximation, however, asymmetries in the ejecta curtain are not permitted, and no craters would exhibit the uprange ZoA. Characterization of the ZoA has generally been limited to morphologic assessments from planetary surfaces (e.g., Herrick and Forsberg-Taylor [2003], Herrick and Hessen [2006]). These studies have not addressed the physical processes controlling the effect. Low-velocity impacts, at or near the sound speed in the material, produce uprange patterns similar to those observed on planets [Herrick et al., 2008]. It is difficult to approach the ejecta distribution for hypervelocity impacts into sand from the ballistically emplaced patterns after the event, since the curtain closes quickly after impact and early-time, high-speed target material interacts with the vacuum chamber walls within ~ 10 crater radii at the NASA Ames Vertical Gun Range. Oblique hypervelocity impacts into compressible or low-density targets, such as pumice dust or perlite, exhibit extension of the ZoA to the edge of the final crater (Fig. 4.2) [Schultz et al., 2005, 2007]).

Previous studies of the in-flight ejecta [Anderson et al., 2003, Anderson and Schultz, 2006] explored realistic scaling of experimental data. Extrapolations from these data, which adjusted the early to late time transition using scaling formulations, produced curved ejecta patterns for lunar craters [Anderson, 2004] and Deep Impact [Schultz et al., 2005, 2007, Schultz et al., 2009]. While this direct scaling method qualitatively effected the expected pattern, these discrete data (usually 4-5 data points per impact condition) did not allow assessment of the temporal or spatial development of the ZoA (since in general, only one or two data points included this early stage).

In this study, we build on the results of Chapter 3 to examine the time-resolved evolution of two parameters relating to the ballistic return of the ejecta over a range of impact angles: in-flight measurement of the ZoA, and the migration of the flow-field center during excavation. While this study is not designed to comprehensively address the scaling relations (e.g., the effect of projectile and target densities, velocity, etc.), it

provides a physical basis and first order assessment for comparison to planetary-scale events. The goal of this study is to control the appearance of emplaced ejecta patterns by parametrically approaching the rate of curtain closure and flow-field migration from a physical standpoint, with the aim of recreating the morphologies produced on the planets and in low-density materials.

We develop this work in four parts. First, analysis of experimental data provides the motivation for this study through measurement of the time-resolved evolution of the uprange ZoA and the flow-field center. Next, a forward model is developed to permit reconstruction of the ejecta pattern by ballistically propagating the in-flight velocity measurements of individual particles. Third, a parametric study of the separate and cumulative effects of these parameters on the resulting distribution is explored. Lastly, these results are applied to the Deep Impact mission.

4.2 Methodology

4.2 Experimental Data

A full description of the experiments is outside the scope of this study; for a more complete description see [Hermalyn et al., 2011a,b]. Briefly, a series of impact experiments into non-cohesive quartz sand was performed at the NASA Ames Vertical Gun Range (AVGR) and recorded by a novel 3-Dimensional Particle Tracking Velocimetry (3D-PTV) system. This technique captures stereoscopic images of thin horizontal cross-sections of the ejecta curtain at high framing rates, allowing measurement of the velocity and positions of the ejecta at high temporal resolution. To address the effects of obliquity on the ballistic emplacement of ejecta, we utilize the scaling relations and data described in Chapter 3 for 6.35mm diameter Aluminum projectiles impacting the Ottawa sand at $\sim 5.5\text{km/s}$ for a range of impact angles: 30° , 45° , 60° , 90° . These angles cover the majority of the probable impact angles [Gilbert, 1893, Shoemaker, 1962]; however, extremely oblique impacts ($<30^\circ$) which can form both

uprange and downrange avoidance zones (“butterfly” shaped ejecta patterns) are not treated in this study.

The ZoA is usually expressed as a “forbidden zone” uprange of the crater where ejecta have not been emplaced. Generally, the initially asymmetric ejecta curtain, including a downrange enhancement of material and uprange zone of avoidance, evolves into a relatively symmetric “closed” curtain at late times (Fig. 4.3). In this study, we can resolve the individual particles forming the curtain in a time-resolved fashion, and can therefore measure the instantaneous azimuth corresponding to the particles furthest uprange (see Fig. 4.4a). This azimuth is defined as the “curtain closure angle.” A closure angle of 180° denotes a fully-closed curtain (e.g., no azimuthal avoidance zone).

In order to find the instantaneous flow-field center as a function of time, a 2-dimensional grid search in the $x - y$ plane is performed for each discrete image pair (see Fig. 4.5 for a graphical depiction of the minimization performed at each time step). At each grid point, the difference between the radial (in-plane) velocity vector angle and the angle between the grid point and the particles is computed for all of the measured ejecta. The sum of the squares of these errors is minimized to locate the flow-field center. This grid search is repeated for each time step, allowing temporal description of the flow-field center location and migration.

4.2 Forward Model

Prior studies of ejecta dynamics have used randomly placed tracer particles [Geissler et al., 1996, Durda, 2004] or polygonal meshes [Richardson et al., 2007] that assume a canonical ejection model (such as the dimensionally predicted power laws presented in Housen et al. [1983]), to map out the location of ejected materials spatially and temporally. Although these models qualitatively match 90° impacts (due to their reliance on the point-source assumption), they do not capture the full complexity of

the ejecta flow field. For example, a constant ejection angle is assumed in vertical impacts instead of temporally varying ejection angles, and the asymmetries present in the ejecta distribution of oblique impacts, including azimuthal velocity dependence and the uprange ZoA, are ignored.

In this study, we employ a matrix of tracer points consisting of layers of equally spaced particles in azimuth. Each tracer point is initialized with a velocity as a function of time and azimuth (e.g., Fig. 4.6a, 4.6b, which are constructed from the velocity data presented in the preceding chapter) and launch position. The particles are then ejected by time step. In this manner, the asymmetries measured in the ejecta from oblique impacts can be directly input into the model, including velocity, flow field center migration, and uprange ZoA. A polygonal surface mesh is created by drawing triangular faces between adjoining layers and azimuths for visualization of the ejecta curtain. Although qualitatively similar to the ejecta model employed by Richardson et al. [2007], this approach is instead developed entirely in the temporal domain (rather than from launch position metrics). It also includes the additional effects measured in our studies (instead of extrapolation from point-source laws) including the ZoA and flow-field center migration. The ejecta mass distribution is not yet constrained for oblique impacts (except for discrete bins, e.g., Schultz [1999], Schultz and Mustard [2004]). Consequently, no attempt at incorporating a mass-velocity relationship is made in this work, and the tracers employed here are of unit mass.

The motion of each particle is numerically integrated using a 4th order Runge-Kutta method to account for forces acting on the points (e.g., gravity). This approach is preferred over analytic ballistics because it allows propagation over non-uniform gravitational fields (e.g., small bodies or actual gravity fields) as well as the inclusion of other forces (such as solar radiation pressure). Additionally, propagation over discrete time steps allows for an “in-flight” reconstruction of an impact event (as required for interpretation of the Deep Impact mission data and the LCROSS event)

rather than the emplacement location alone.

4.3 Analysis and Results

All oblique experiments (even at 60°) display asymmetry in their early-time ejecta velocity distribution and exhibit the uprange ZoA in Fig. 4.3. This observation contrasts with the usual assumption that only impacts occurring at angles $<45^\circ$ exhibit asymmetries. Obliquity plays a strong role in the evolution of the curtain closure angle (Fig. 4.7), and while this effect has been noted previously (e.g., [Anderson, 2004, Schultz et al., 2005]) these are the first hypervelocity studies for these higher angles. The 30° experiment exhibits the greatest downrange focusing of material, initially displaying a ZoA that encompasses the uprange half of the ejecta curtain before evolving to full closure. The 45° impact displays a similar avoidance zone at early times but never as great in extent as the 30° experiment, thereafter closing more quickly. The curtain closure angle appears to follow a power-law with respect to time (shown in Fig. 4.7) of form $\phi(\tau) = a\tau^b$ where ϕ is the azimuth, τ is the non-dimensional early-stage time parameter (defined as time after launch divided by the ratio of the projectile radius to impact velocity), and a, b are constants. A power-law form is physically relevant since ejection is considered a function of the azimuthally-dependent peak pressures resulting from the oblique impact. Peak pressures decay with distance following a power law relationship in vertical impacts.

The curtain from the 60° experiment is clearly asymmetric at early-times in Fig. 4.3, yet no uprange void is exhibited in Fig. 4.7. This discrepancy demonstrates the fleeting duration of the ZoA in this experiment. While the ZoA is apparent in the first few images after impact, high-speed ejecta are only captured in one frame before moving out of the illumination volume; thus, the velocity of these particles cannot be measured. Future studies will examine this high-speed regime in more depth.

The migration of the flow-field center can now be shown as a function of time in

Fig. 4.8. In these experiments, the impact vector is aligned with the x axis; thus, the motion is in the downrange x direction. Deviations in the y direction are over an order of magnitude smaller, as the system is well-aligned with the impact vector. For each oblique experiment, the flow field center appears to migrate downrange until it ceases motion at a critical distance away from the impact point. The relative amount of motion is greatest for the 30° impact, and diminishes as the impact angle is increased toward 90° .

Fig. 4.9 presents the in-flight forward models of 90° and 30° lab-scale impacts under a uniform gravitational field (downward). These models use the experimental data directly (e.g., without rescaling), and track the evolution throughout growth. Since the effects of the 45° experiment are limited in this data set (encompassing only a few data points), we focus on the 30° impact. Direct scaling of the the ejecta measurements results in a curved uprange ejecta pattern with the characteristic ZoA (Fig. 4.10b). The ZoA closes hundreds of crater diameters away from the crater center. This result is consistent with the approximately symmetric ejecta curtain seen throughout much of growth in Fig. 4.3, but indicates that closure occurs significantly farther out than exhibited by craters in Figs. 4.1 or 4.2.

The power-law relationship can be adjusted in order to parametrically approach the effect of the rate of curtain closure on the eventual ejecta deposit (Fig. 4.11). This strategy allows matching observations from the pumice and perlite experiments. The time of closure (and thus the distance from the crater) is set by the multiplicative factor, a ; these were matched to the pumice and perlite closures respectively. The curvature of the ZoA is controlled by the exponent b , where smaller values decrease the radius of curvature and higher values straighten the boundaries of the ZoA. By altering this metric, both the exaggerated curvature and the straight-ray (little to no apparent curvature) patterns were reproduced in the reconstructed ejecta deposits (Fig. 4.12).

The effects of flow-field center migration are more subtle (Fig. 4.10). This migration is geometrically limited to no more than half of the crater diameter (D) in the direction of the impact vector. For example, the flow-field for oblique impacts into perlite migrate from the impact point just inside the final crater rim to the center of the crater [Schultz et al., 2005, 2007]. For a 30° impact into sand, this migration (based on these experiments) is $<D/3$. In the absence of any migration (e.g., a constant launch position), the ejecta still produce the characteristic curved uprange pattern (Fig. 4.10a). In this case, the ejecta particles are deposited radially from the constant flow-field center. When migration is included in the model (Fig. 4.10b), the ejecta continues to form the curved zones uprange, but the particles are no longer emplaced radially from the final crater center. Instead, the convolution of the uprange closure and source migration cause the vectors of the ballistically emplaced curtain (i.e., tertiary streaks) to point uprange of the crater center [Schultz et al., 2009, Schultz et al., 2005]. With this new model, the evolution and curvature of the uprange ZoA on planetary surfaces can be reconstructed after adjustments for gravity, crater size, and target properties.

4.4 Application to Deep Impact

The Deep Impact probe impacted comet 9P/Tempel 1 at an angle of $\sim 30^\circ$ from local horizontal with a velocity of 10.2 km/s. After the initial ejection of a high speed “eyebrow” of vaporized material that decoupled from later excavation stages, the resulting ballistic (e.g., non-vapor driven) ejecta revealed phenomena that largely followed expectations from laboratory investigations of oblique impacts into low-density, porous material, and included a downrange bias, uprange zone of avoidance, and cardioid (curved) rays [Schultz et al., 2005, 2007].

Modeling of the impact based on canonical models and scaling laws [Richardson et al., 2007] presented a first-order reconstruction of the event, but did not fully

represent the three-dimensional nature of the ejecta flow-field in an oblique impact essential for interpretation of the DI data. In order to match the ejecta patterns recorded by the DI spacecraft, canonical vertical ejecta laws required the local surface around the impact point to be drastically tilted. In addition, the uprange ZoA and downrange focusing of material cannot be accounted for with the simplified vertical laws. By instead applying the experimentally determined ejecta model developed above, we can reconstruct the DI event by scaling the ejecta distribution. Matching trajectory and view conditions of the DI spacecraft instruments permits comparison to the event.

Using the 30° impact model described above, the data are scaled to the DI event, placed and oriented on the comet, and compared to the DI data at two different phases of the encounter (Fig. 4.13). The minute gravity force of Tempel-1 can be included (computed according to the polyhedral method presented in Werner [1994] and applied to the shape model of Tempel-1 from Thomas et al. [2007]). Solar radiation pressure is ignored since it is substantially weaker than gravity and will have minimal effect on the ejecta motion due to the relatively short duration of this comparison.

First, early-time downrange-directed ejecta (top) match the initial high-speed component that trails behind the leading edge of the self-luminous vapor plume (shown in Fig. 4.13). Although there is only a small amount of mass in this component, it is comprised of ballistic (e.g., not the earlier vapor driven) ejecta traveling hundreds of meters per second downrange, and may be the source of the material derived from the upper surface of the comet reported in Sugita et al. [2005]. The lower row of images in Fig. 4.13 represents a slightly later phase when the ejecta curtain is more fully developed. While several elements of the morphology match the DI data, particularly the extreme foreshortening of the uprange azimuth due to perspective, the sand model of ejecta does not fully capture the angles and extent of the ZoA. This disparity requires that the surface of Tempel-1 is quite porous and compressible

[Schultz et al., 2007]. Effects of gravity ($\sim 0.04\text{cm/s}^2$) are minimal at these times and only become significant during the look back phase.

4.5 Discussion

The migration of the flow-field center effects only a small overall change in the eventual emplacement. Absolute distance, on the other hand, can be significant, as even a shift $1/10$ the radius of a Jackson-sized crater yields $\sim 3.5\text{km}$ in motion. Nevertheless, migration and ZoA closure may provide a powerful metric for inverting the cratering event when coupled to the velocity bounds provided by crater size [Schultz et al., 2009]. Physically, this migration is a manifestation of the horizontal coupling length. While coupling is very rapid and close to the surface in the sand target, the projectile takes a much greater distance and time to fully couple in underdense and compressible targets [Schultz et al., 2005, 2007].

The factors controlling the slope and intercept of the curtain closure are less constrained, but we can attempt to resolve their physical significance. For identical 30° impact experiments (e.g., equivalent velocity and projectile), the curtain closes at different times and rates depending on the target material (Fig. 4.2). Additionally, planetary impacts exhibit a variety of different ZoA morphologies, from extremely curved and closing at large distances from the crater to straight patterns that extend to the crater rim or, in some cases, inside the crater [Schultz et al., 2009]. A similar coupling argument can be made for these effects: impacts that couple quickly relative to crater formation time (e.g., small projectiles, high speeds, relatively dense target compared to projectile, and high impact angles) should behave more like the sand target in the experiments and rapidly evolve toward main-stage point-source behavior. Events that take longer to couple (larger projectiles, lower speeds or impact angles, low density targets) should resemble the ejecta distribution of impacts into perlite.

Alternately, this can be phrased from a cratering efficiency standpoint (i.e., ejected

mass relative to projectile mass). Efficient impacts will reach the late-stage equivalence rapidly, whereas lower efficiencies cause the early-time coupling component to eat into main- and late-stage growth, extending the ZoA to later times and altering the slope of the curtain closure angle power-law [Schultz et al., 2007]. Low-density projectiles impacting obliquely at near (or below) the sound speed into a sand target will not result in a closure of the ZoA before crater growth is ceased [Schultz et al., 2007, Herrick et al., 2008]. Since low-density, low-speed impacts are less efficient, the ZoA is more prominent. At very low speeds for cluster impacts (e.g., extremely low cratering efficiency), the ZoA can exceed 90° [Schultz and Gault, 1985].

Although the full contribution of the different impact parameters requires additional experiments, we attempt to address the effects of impact speed and target strength through 3D simulations designed to match the experimental impact conditions at 30° using the CTH hydrocode from Sandia National Laboratories [McGlaun et al., 1989] as a preliminary step. Direct comparison to experimental data is a goal for future work. Three initial studies were performed, all of which utilized the SESAME tabular equation of state (EOS) package and employed Mohr-Coulomb pressure dependent yield strength, available in CTH as the “geo yield” option and Steinberg constitutive models for the target and projectile, respectively.

A grid of Eulerian tracer particles was placed over one half of the bilaterally symmetric event to record the position and velocity of the ejecta, analogous to the laser plane in the 3D PTV studies. The grid also provides visualization of the expanding ring of ejecta and the degree of curtain closure at any time step; top view images of the studies are presented in Fig. 4.14. These initial studies were limited in scope due to computational requirements, but were continued through the end of curtain closure (when possible). The three numerical experiments presented are: a direct comparison to the 30° impact using a low yield strength for the sand of $10e5$ Pa; the same experiment at 15km/s ; and an additional experiment at 5.5km/s but with a greater

amount of strength (yield set to 10^9 Pa) added to the target. All experiments used a Poisson's ratio for sand of 0.25 and a tensile fracture strength of 10^6 Pa. Sand should ideally exhibit zero strength under extension following the results of chapter one.

In absolute time, the 15km/s impact couples sooner and the curtain closes slightly ahead of the 5.5km/s impact, again consistent with the efficiency argument above. The ejecta curtain in the simulated experiment with a slight amount of target strength, however, never closes, even when run out a factor of 10 later. Instead, the curtain reaches and maintains a maximum curtain closure angle throughout growth. The obliquity of the impact diminishes the energy and momentum of the shock that is partitioned to the uprange direction, thereby reducing the peak pressure sufficiently to keep ejecta from launching (in this continuum fashion). This result has implications for oblique impacts into targets with a slight amount of sheer strength (such as regolith). At high velocities, though, peak pressures should increase to overcome this effect near the impact point.

4.6 Conclusions

The time-resolved nature of the in-flight ejecta measurements permits temporal study of the evolution of the flow-field center and uprange zone of avoidance. Coupling these parameters with the ejecta velocity distribution from oblique impacts allows the development of an experimentally based ejecta model. By ballistically propagating this model in a gravity field, we can reconstruct the emplaced pattern for the “distal” high-speed ejecta, similar to the ejecta motion on planetary bodies. A parametric study of these early-time oblique effects reveals the following: 1) non-radial ejecta patterns (or rays) can be caused by the flow-field center migration, 2) the curved uprange zone of avoidance can be directly exhibited by using the ejecta velocity distribution from an oblique impact, and 3) the curvature and closure distance from

the crater can be related to the efficiency of the impact event.

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Figure Captions

Figure 4.1. Comparison of lunar craters exhibiting the uprange zone of avoidance. Clockwise from top left: Jackson crater (Clementine composite), small ($\sim 1\text{km}$ diameter) unnamed crater in Serenitatis (AS15-9337), Proclus (LROC WAC), and an oblique view of an additional small unnamed crater exhibiting uprange rim collapse (AS16-4511).

Figure 4.2. Uprange curved ejecta patterns for 30° impacts into airfall pumice dust and perlite. The ZoA extends considerably closer to the crater (to the rim for the case of perlite) than for identical impacts into sand (where the ejecta pattern closes uprange hundreds of crater radii away). From Schultz et al. [2005].

Figure 4.3. Cross-sectional ejecta comparison for different impact angles. Each row corresponds to an experiment; images are dewarped and selected for approximately equal τ . Downrange is to the left; uprange is to the right. Images display only one half of the curtain. The oblique impacts show the delay in arrival of the uprange ejecta; the 30° case maintains asymmetry for much further into crater growth than the other impacts. Early-time ejecta is characterized by sparse, crushed material that evolves into main-stage behavior.

Figure 4.4. Nomenclature description and experimental data for a top view (a; inverted for clarity) and a perspective view (b). Downrange (D.R.) and uprange (U.R.) are denoted in each figure; 0° is defined to be downrange (i.e., the vector where the dot-product with the impact vector is zero). In (a), the edge of the curtain is circled in red. The curtain closure angle θ_c is denoted with a dashed blue (a) or black (b) line. Fig. 4.4b is from a color camera located at a 45° port in the vacuum chamber;

the green coloring is due to the laser illumination. Impact vector is shown as a red dotted line.

Figure 4.5. Flow-field center regression example for a discrete time step. A 2D grid search is employed (visualized as the surface) to minimize the sum of the squares of the errors between the direction of the instantaneous velocities of the measured particles (magenta vector arrows) and the vector between each grid node and the particle location (represented by green dots). The color map for the surface is RGB, where blue represents low values, and red indicates high error. The calculated center is shown as a green circle.

Figure 4.6. Ejecta component velocities as a function of time and azimuth. The ejection velocity v_e (vertical axis) is scaled to the impact velocity V_i , and is presented as function of both time τ and azimuth. The velocity vector is decomposed into radial and upward components (as in Chapter. 3). Fit surfaces are presented for both 30° and 90° impacts (a and b, respectively). In the 30° case, the uprange zone of avoidance is exhibited by a cutoff in azimuth space.

Figure 4.7. Curtain closure angle vs. τ . The azimuth of the last detected particle is presented as a function of time for 30° (green), 45° (blue), 60° (red) and 90° (black x's). The 30° case takes the longest time to reach full closure. The 60° experiment does not display a zone of avoidance in this plot (identical to the vertical case) because the ZoA closes before the first particles could be measured (although the ZoA is apparent in Fig. 4.3 at early times).

Figure 4.8. Downrange motion of the flow field center, scaled to the final crater radius as a function of τ . x is defined as the absolute magnitude of the distance between the

regressed flow field center and the center of the final crater. Thus $x = 0$ represents that the flow field center is at the crater center. A degree of scatter, particularly later on in measurement, is due to a reduction in the number of measurable particles in the uprange and downrange directions. Trendlines are drawn for clarity.

Figure 4.9. Time series of in-flight ejecta model. Examples of lab-scale reconstructions using the experimental ejecta velocity distribution for vertical (A) and 30° (B) impacts into sand. Perspective is set to approximately match the oblique viewing geometry of the 45° port at the AVGR (as shown in Fig. 4.4b). The particles are launched at discrete times with the velocity distribution in Fig. 4.6a,b and then tracked under the influence of standard earth gravity. The vertical impact largely follows canonical expectations (although the early-time component is traveling considerably faster than prior studies). The oblique impact, however, exhibits a marked velocity enhancement in the downrange direction while incomplete coupling in the uprange direction forms the zone of avoidance (ZoA) at early times. The ejecta curtain eventually closes over all azimuths before the end of crater formation. The early-time asymmetry is expressed in the ejecta pattern that returns to the target surface.

Figure 4.10. Uprange portion of the emplaced ejecta curtain with (bottom) and without (top) flow-field center migration. Impact direction is from the top. Velocity vectors (green) are overplotted on the node points. Without flow-field center migration (which occurs in the downward direction in these plots), all velocity vectors are radial to the crater center (top image). Note that the uprange curvature is apparent even with a stationary flow-field center. When the flow-field center is allowed to migrate as in the 30° laboratory experiments, however, the vectors on the edge of the ejecta blanket are not radial to the crater center and will trace uprange towards the point of impact.

Figure 4.11. ZoA power-law relationships utilized in the parameter study of form $\phi(\tau) = a\tau^b$ where ϕ is the azimuth, τ is the non-dimensional early-stage time, and a, b are constants. The exponent b controls the curvature of the ZoA, as the “straight” ZoA ejecta pattern requires a stronger exponent than the “curved” ZoA. The multiplicative factor a determines the horizontal offset from the experimental data (e.g., the τ corresponding to full closure).

Figure 4.12. Top view of reconstructed ejecta pattern emplacement for experimental (left), strong power-law (middle), and weak power-law (right) studies, according to the curtain closure parameters defined in Fig. 4.11. The impact direction in these images is from the bottom; the views are magnifications of the uprange area. Inset are plan views of the total curtain emplacement. Note that while this displays where particles would land, it does not account for the reduced excavated mass at early times; thus, these displayed blankets represent an idealized case.

Figure 4.13. Ejecta model on Tempel-1. Alignment and scaling of the ejecta and shape models to the impact conditions allow comparison to DI data. Experimental data are scaled to the impact event (left side) and compared to the DI data (right hand column) at two different phases of the encounter.

Figure 4.14. Top views of CTH comparison of three 30° impacts into sand. Top row is at $10\mu\text{sec}$ after impact; bottom at $45\mu\text{sec}$. The left and middle columns are identical 5.5km/s impacts except for the yield strength of the sand. The right column is a 15km/s impact into the same material as the middle column. A horizontal “sheet” of tracers (analogous to the laser plane in the 3D PTV studies) is placed over one half of the forming curtain, allowing measurement of the ejecta as well as visualization

of the curtain closure as the material passes through the plane. Inset in lower left demonstrates that the higher yield strength material does not fully close the curtain even a factor of ten later into growth ($450\mu\text{sec}$ after impact).

Figures

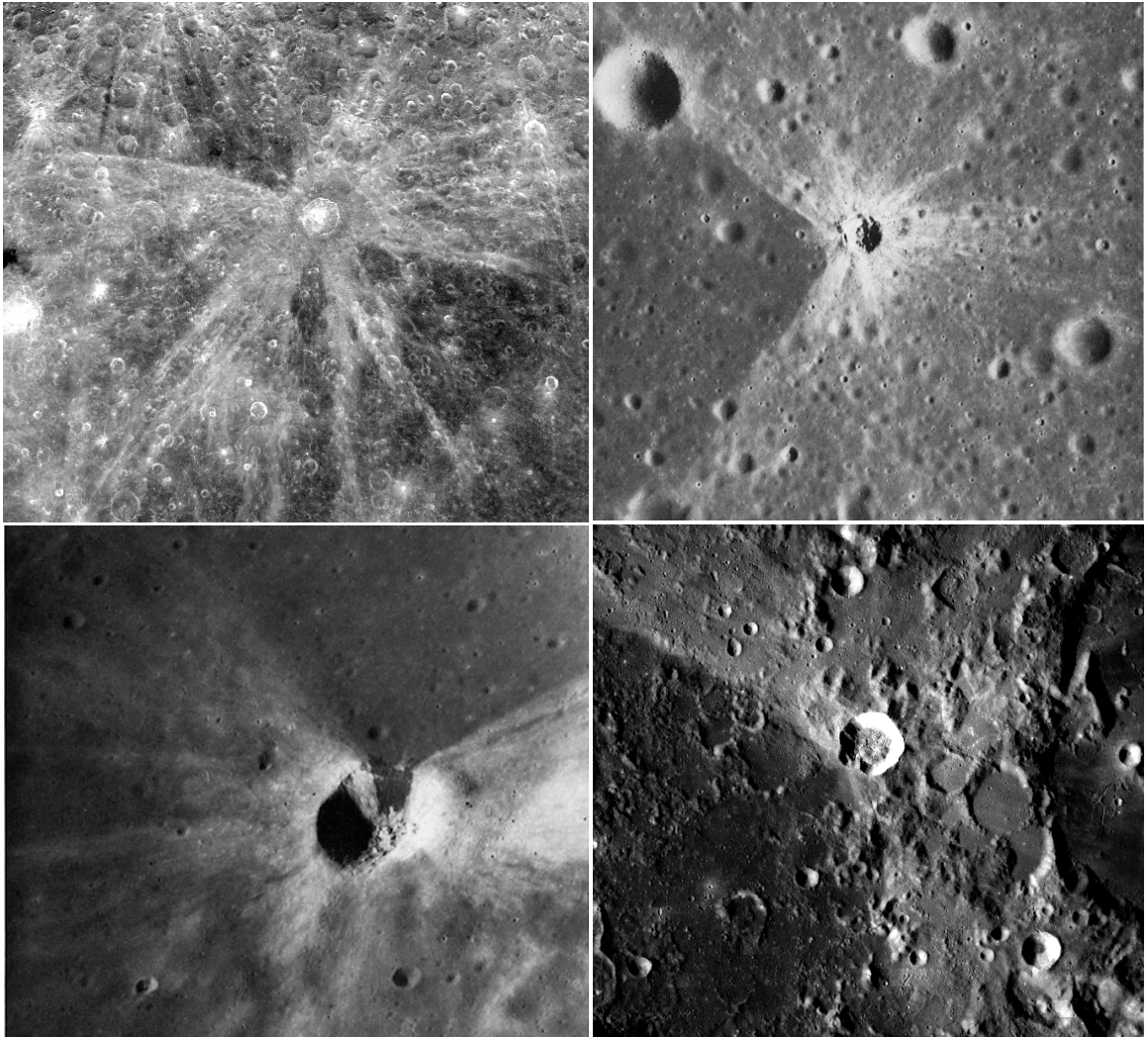


Figure 4.1

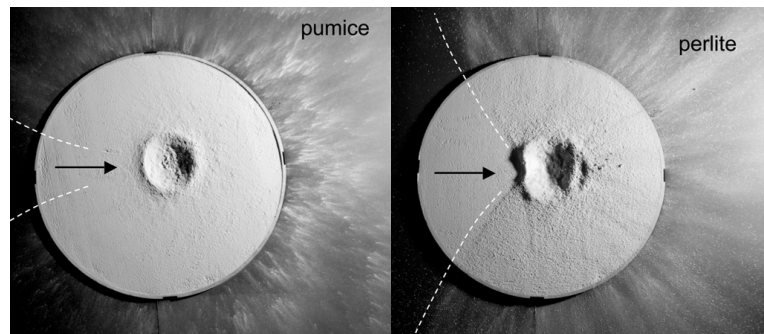


Figure 4.2

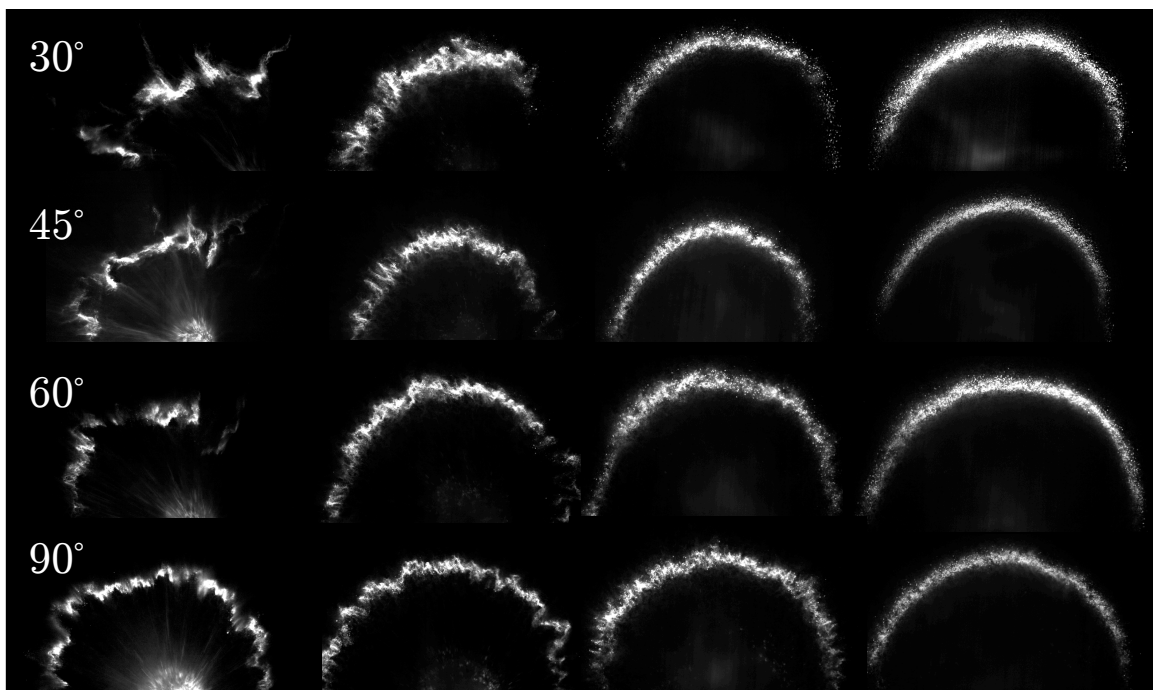
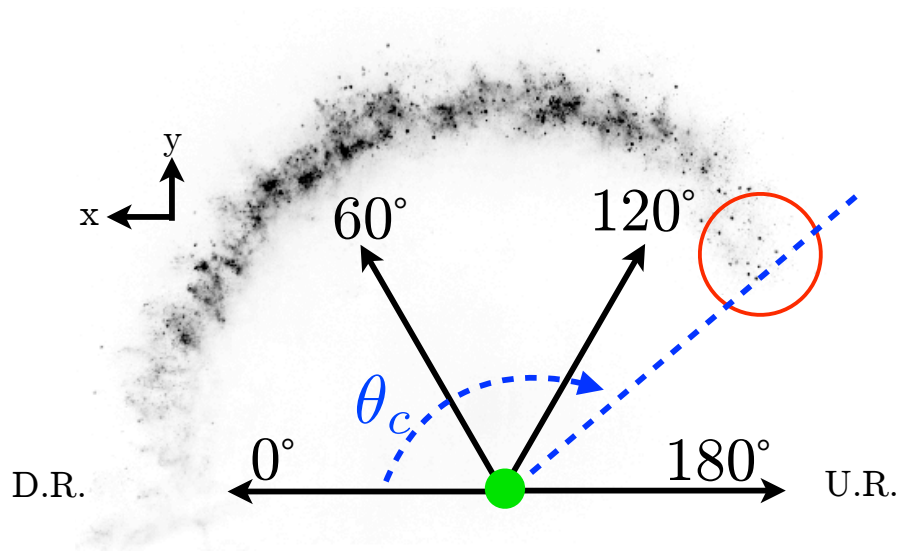
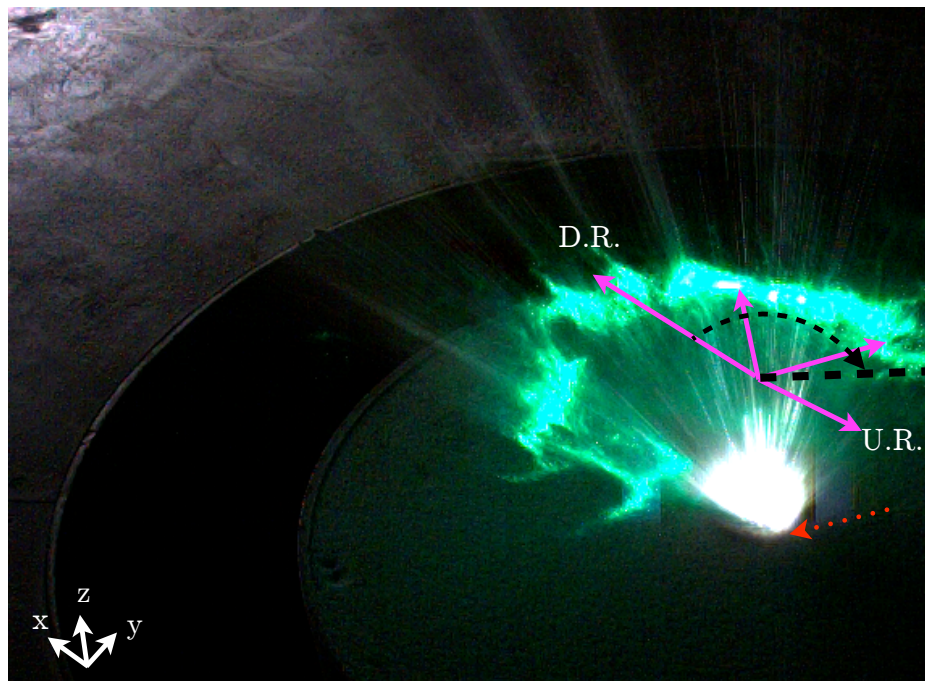


Figure 4.3



(a)



(b)

Figure 4.4

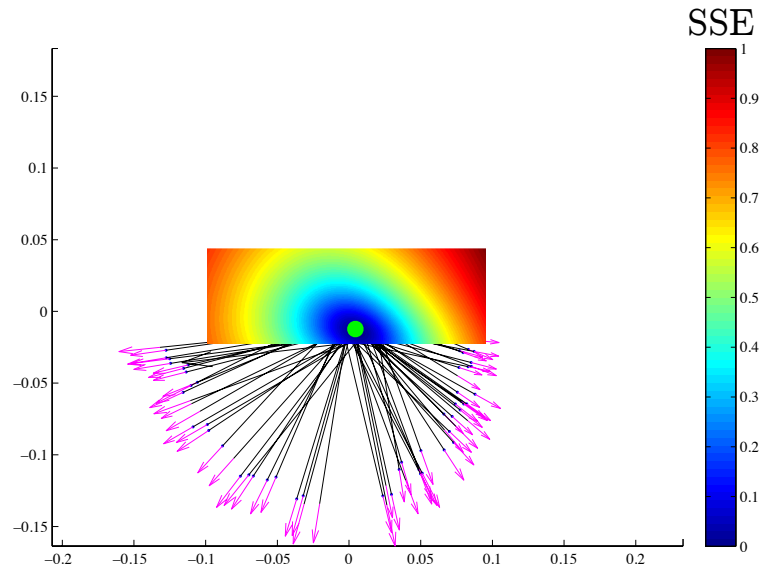


Figure 4.5

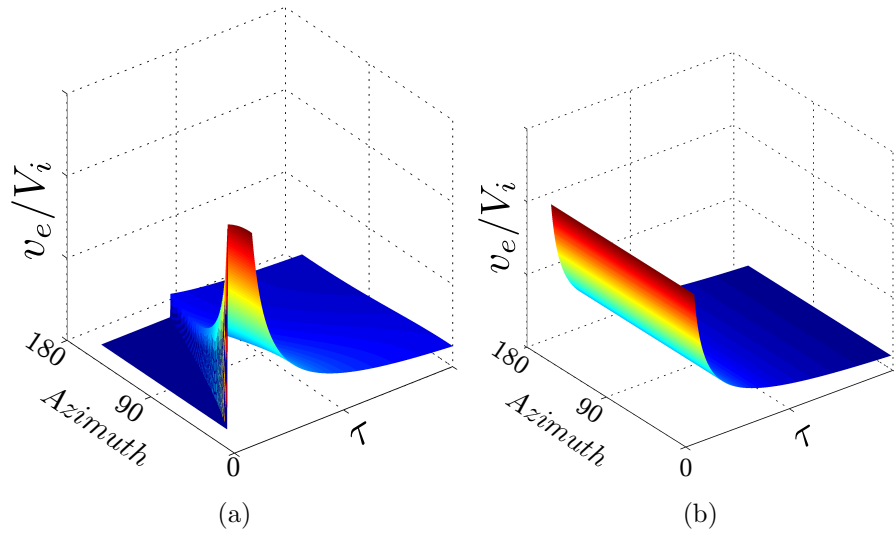


Figure 4.6

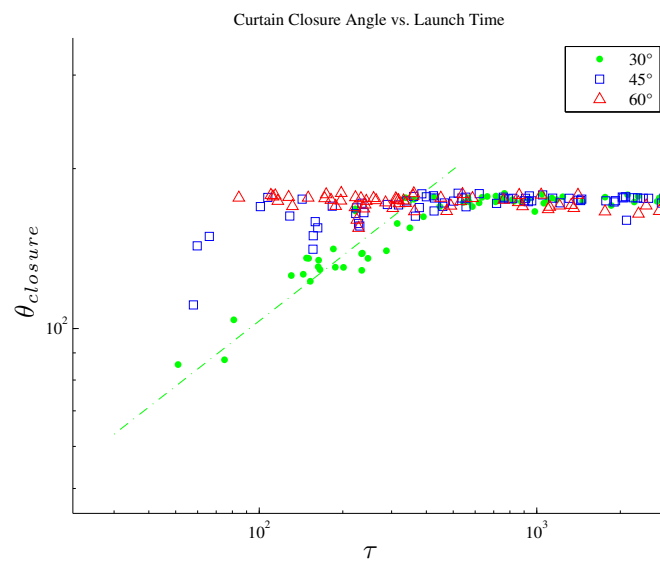


Figure 4.7

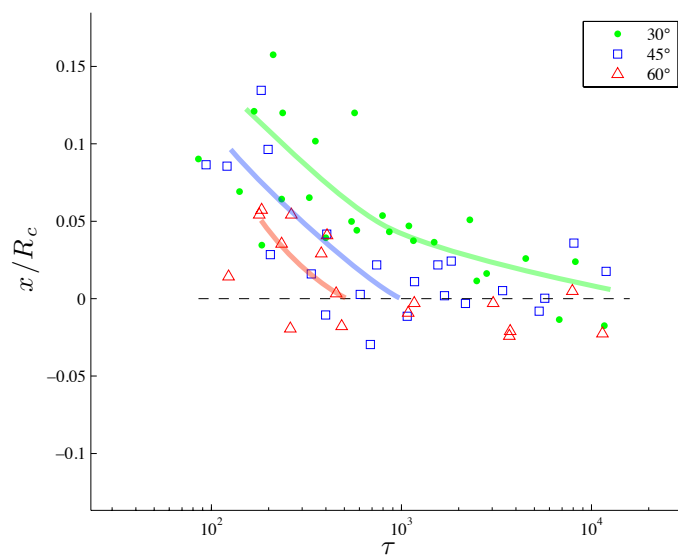


Figure 4.8

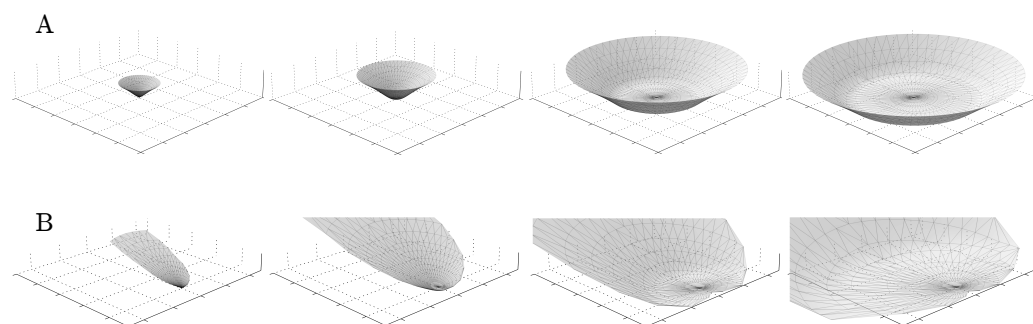


Figure 4.9

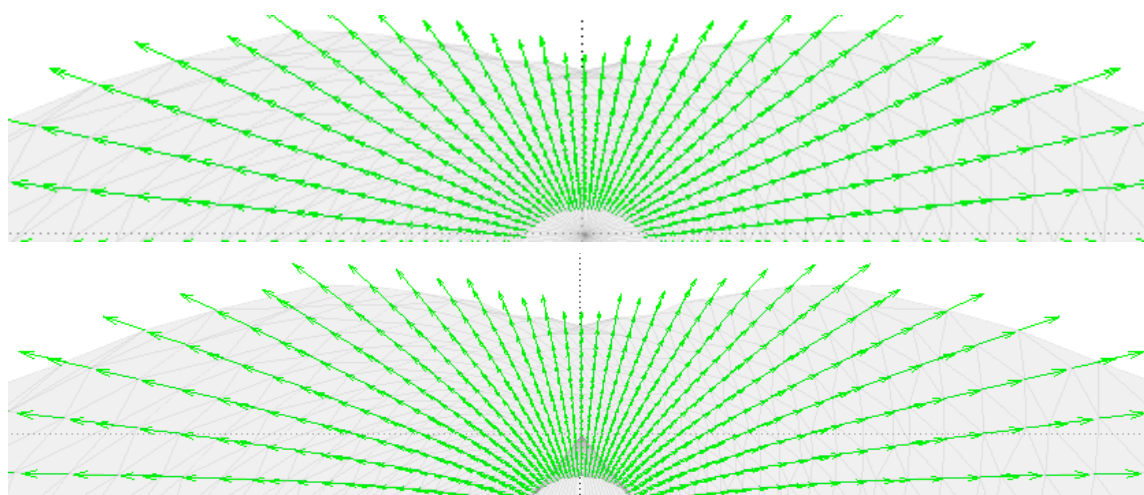


Figure 4.10

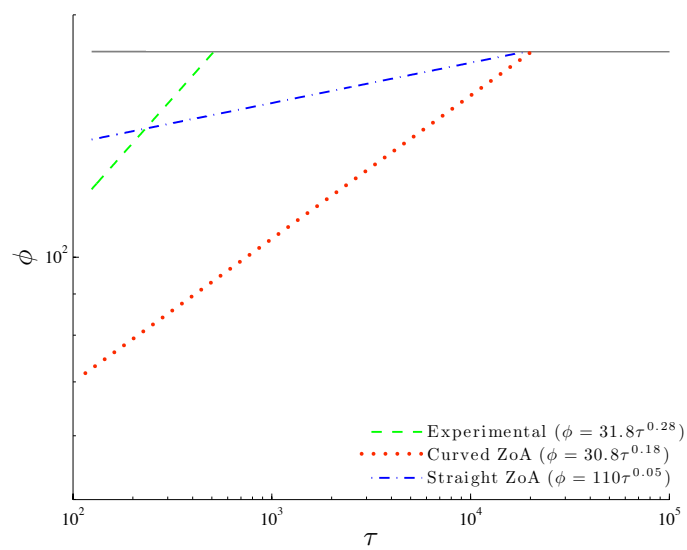


Figure 4.11

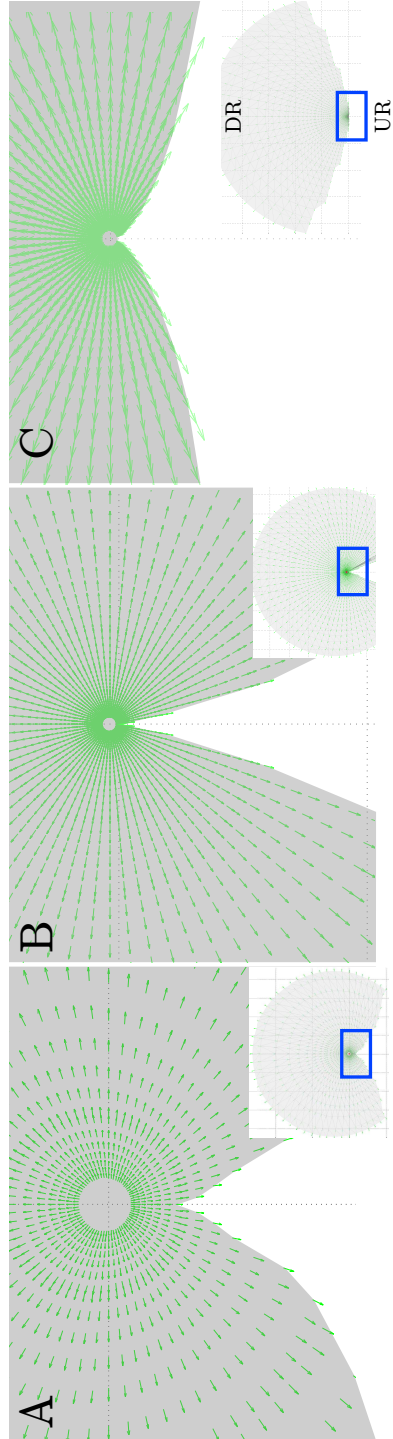


Figure 4.12

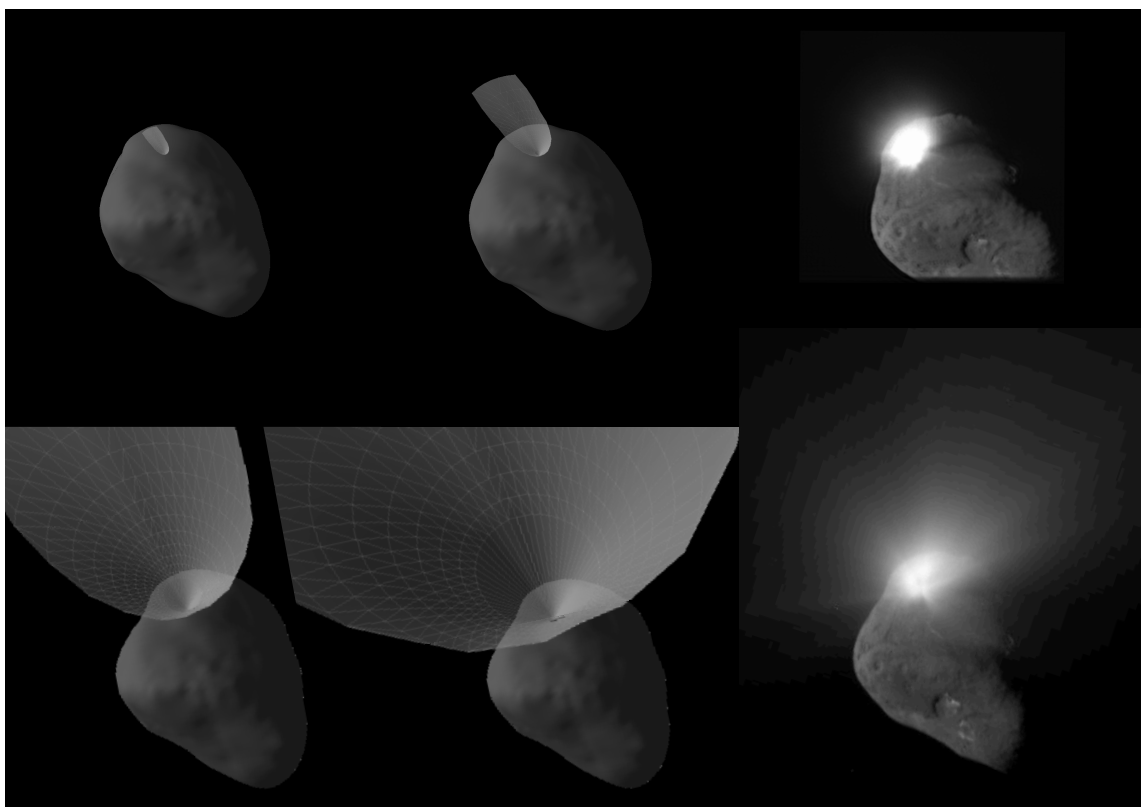


Figure 4.13

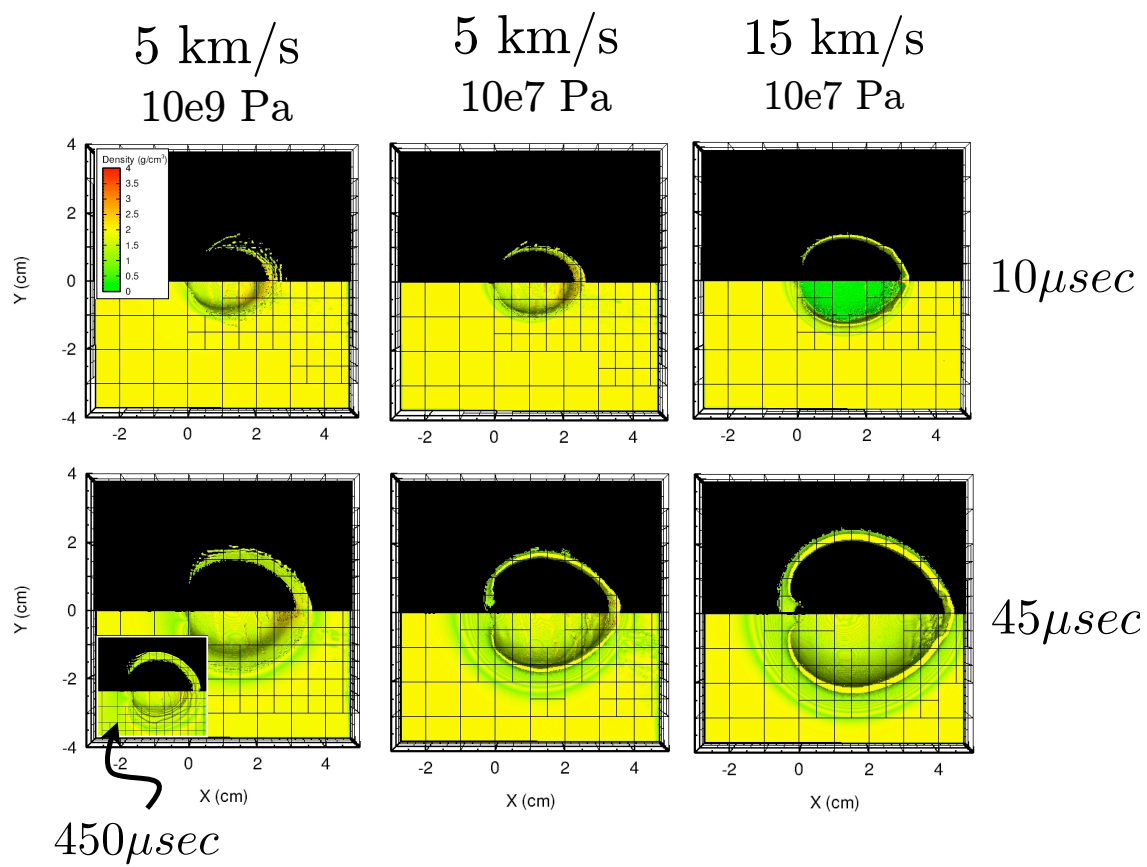


Figure 4.14