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Photometric Investigations of Lunar Landing Sites and Silicic Regions using LRO Narrow Angle Camera Images

Ryan Nicole Watkins
Washington University in St. Louis

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Department of Earth and Planetary Sciences

Dissertation Examination Committee:
  Bradley L. Jolliff, Chair
  Raymond Arvidson
  Randy L. Korotev
  William B. McKinnon
  David A. Peters

Photometric Investigations of Lunar Landing Sites and Silicic Regions using LRO Narrow Angle Camera Images

by

Ryan Nicole Watkins

A dissertation presented to the
Graduate School of Arts & Sciences
of Washington University in
partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

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Ryan N. Watkins

Washington University in St. Louis

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The reflectance properties of a planetary surface are related to the physical and compositional properties of that body. Photometry is a powerful method for determining differences in composition and regolith structure, and photometric data from orbital images coupled with soil sample data can greatly enhance our understanding of the regolith properties of our nearest neighbor, the Moon. At the time of writing, the United States has no operating missions on the Moon and no future plans to send robots or humans to study our nearest neighbor, so we must rely on remote sensing data to provide us with information about the lunar surface. This dissertation uses photometric studies of high-resolution Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images and Hapke photometric modeling to understand the behavior and composition of lunar soil at spacecraft landing sites and areas of non-mare volcanism on the Moon. This work has implications for future mission planning and implementation, including landing site selection, landing safety, and sampling strategies. Topics include: i) the effects of rocket exhaust on lunar soil reflectance properties at the Apollo, Luna, and Surveyor landing sites, ii) photometric analysis of the recent Chang'e-3 landing site and
comparison of reflectance alterations with those of older landing sites, and iii) compositional variations at regions of non-mare volcanism using NAC photometry and spectral analysis of glassy analog materials.

Rocket exhaust from the Apollo, Luna, and Surveyor descent engines disturbed the regolith at their landing sites, causing the soil to become more reflective. These surface alterations, which we call “blast zones”, are still evident in NAC images, and I use photometry and Hapke modeling to show that the increase in reflectance was caused by smoothing, destruction of fine-scale surface structure (i.e., “fairy-castle” structure), and possibly redistribution of fine particles. The recent Chinese Chang'e-3 spacecraft also disturbed the soil at its landing site in the same fashion, and I show that the reflectance changes and area of disturbance are in family with those of older landing sites, indicating reflectance changes have not changed on the order of decades. I determine the relationship between lander mass and blast zone area and use this to make predictions of the area of soil disturbance for future missions. Finally, using photometric methods optimized from landing site studies, I place compositional constraints on areas of non-mare and intrusive volcanism and confirm that these areas exhibit a range of evolved silicic compositions (dacite, andesite, and rhyolite) and pyroclastic deposits, and should be considered as scientific targets for future landed sample-return missions.
Chapter 1: Introduction to the Dissertation

Understanding the formation and evolution of the Moon, our nearest neighbor, will subsequently answer fundamental questions regarding the formation and evolution of Earth and our Solar System. In order to seek the answers to these questions, we must explore and study the Moon via robotic and manned missions. The United States currently has no lunar exploration program in place, and with the exception of China, no country has landed a spacecraft on the Moon in the last 43 years. The Soviet Luna 24 mission returned the last sample from the Moon in 1976. Because returned lunar samples do not represent the full range of compositions on the Moon, and there are no active U.S. spacecraft on the lunar surface, we must rely on remote sensing to further our understanding of the formation and evolution of the Moon beyond the body of knowledge gained from Apollo and Luna era samples and exploration, and the more recently discovered lunar meteorite sample suite.

The Lunar Reconnaissance Orbiter (LRO) launched in 2009 with the goal of mapping the Moon and identifying sites with high scientific value and favorable terrain for future robotic and human missions. While the U.S. currently has no plans to send any robotic or manned missions to the Moon, LRO is delivering a comprehensive data set with which to broaden our understanding of the lunar surface. Furthering our knowledge of the physical and compositional properties of the lunar surface using LRO data will help pave the way for future robotic and manned missions to our nearest neighbor.

This dissertation explores using photometry of LRO Narrow Angle Camera (NAC) images to better understand the lunar surface, specifically how rocket exhaust from lunar landers interacted with lunar regolith during the early rounds of landed exploration (Surveyor, Apollo, and Luna), how the landing of the recent Chinese Chang'e-3 spacecraft interacted with the
surface at its landing site, and how the compositional diversity of non-mare volcanic regions compares to ground-truth landing sites and other key photometric sites on the Moon. The work presented in this dissertation has implications for improving landing safety, sampling techniques, and identifying locations of high scientific value for future landed missions. Each chapter contains its own introduction, so this introduction to the dissertation includes a brief overview of the topics covered in the following chapters. Each of the main chapters is designed as a peer-reviewed publication. The first chapter, *Effects of rocket exhaust on lunar soil reflectance properties*, has been published (Clegg et al., 2014), the second has been submitted for publication, and the third is intended for submission later in 2015.

1.1 Photometry

Photometry is a powerful tool for studying the physical and compositional properties of planetary surfaces, especially when returned samples are not available or are difficult to access. Photometric analysis of orbital images is becoming a widely utilized method of investigating the cause(s) of reflectance variations on planetary bodies. This dissertation focuses on studying photometric properties of the Moon, which is highly backscattering and has on average a low albedo, and on extracting information about surface properties from reflectance data.

Many different factors affect how a surface scatters light, including composition and mineralogy, glass content, surface roughness, regolith structure, space weathering, and grain size (Carrier, 1973; Hapke, 1981; Carrier et al, 1991; Hapke 2012; Hapke et al., 2012). Photometric models have been developed to test variable parameters that depend on physical and compositional properties to determine which parameters more accurately account for the reflectance characteristics of a planetary surface. For this work, Hapke photometric models are used to fit reflectance data from orbital data and make inferences about the physical and
compositional properties of the lunar surface (see Hapke, 1993; Hapke, 2002; Hapke, 2012; Hapke et al., 2012). Hapke reflectance models are among the most widely used for interpreting regolith properties from spacecraft data (Helfenstein and Shepard, 2011) and they yield very good fits to the photometric data that we observe with LROC images. The LROC team uses Hapke formulations for many purposes, including to correct NAC reflectance values for different viewing and illumination geometries in order to compare reflectance at different latitudes and across broad scenes such as those obtained with the Wide Angle Camera (WAC). Hapke functions are also useful for large image processing tasks, such as correcting for shading gradients and making photometrically seamless mosaics.

Reflectance, as defined by Nicodemus et al. (1977), is the ratio of reflected to incident flux and the magnitude of reflection is controlled by the real and imaginary indices of refraction. The Hapke model uses the bidirectional reflectance, which describes the intrinsic reflectance properties of a surface and is the typical quantity measured when studying planetary surfaces. Hapke (2012) defines the bidirectional reflectance as “the ratio of the radiance scattered from the surface of a medium into a given direction to the power incident per unit area perpendicular to the direction of incidence.” Radiance is defined as the uncollimated power per unit area per unit solid angle, whereas irradiance is the power per unit area of a collimated beam (Hapke, 2012). Other quantities commonly used in the derivation of the Hapke model are the reflectance factor and the radiance factor. The reflectance factor is the ratio of the reflectance of the surface to that of a perfectly diffuse surface under the same illumination conditions. The radiance factor, \( I/F \), is the ratio of the bidirectional reflectance of a surface to that of a perfectly diffuse Lambertian surface illuminated at an incidence angle of 0\(^\circ\), where \( F \) is the irradiance, \( J \), divided by \( \pi \) (Hapke, 2012). A Lambertian surface has the same reflectance regardless of viewing position. The
radiance factor is the quantity measured by the NACs (Robinson et al., 2010) and is the quantity measured and used for comparison in our studies.

1.2 Spacecraft Landing Sites

Presently, there have been 15 soft landings on the Moon by three different countries: the United States, the Soviet Union, and China. Rocket exhaust from each of these spacecraft altered the regolith at their landing sites, creating areas of altered reflectance around the landers called blast zones. Typically the reflectance is lower than background beneath the landers and higher than background in an approximately annular region surrounding the landers. It was unknown how significant the effects of rocket exhaust would be on lunar regolith before the advent of these missions, and little data were taken during the landings to understand how the soil was altered during descent. The Apollo astronauts reported that blowing dust obscured visibility during landing and noted that the surface near the lander appeared somewhat smoothed and more reflective (Armstrong et al., 1969; Conrad et al., 1969; Shepard et al., 1971; McDivitt et al., 1971; McDivitt et al., 1972; McDivitt et al., 1973), but they did not take samples with the intent of studying physical or compositional changes caused by rocket exhaust interaction with the soil. Only a few studies have been undertaken to understand what happened to regolith at the landing sites, and most have been focused on measuring the amount of dust that was blown away during landing and the physics of the rocket plume interaction with the soil (e.g., Lane et al., 2008; Metzger et al., 2009; Immer et al., 2011; Metzger et al., 2011). A few recent photometric studies have suggested that the increase in reflectance could be attributed to fine particles being redistributed within the blast zone (Kreslavsky and Shkuratov; 2003, Metzger et al.; 2011, and Shkuratov et al., 2011) or to surface smoothing (Kaydash et al., 2011; Shkuratov et al., 2012). We also use photometric studies to address whether the cause of increased reflectance is caused
bu redistribution of fine particles, surface smoothing, or some other process(es) in a paper published in 2014 (Clegg et al., 2014) and included here as Chapter 2 of the dissertation.

Understanding the effects of rocket exhaust on the lunar surface is important for the planning of future missions, especially if multiple missions are going to land in the same area. spacecraft and nearby hardware could incur damage from soil being blown by a landing rocket, potentially thwarting the success of the mission. The Mars Science Laboratory, which landed on Mars in 2012 and carried the Curiosity rover, created a large, dark blast zone in the area where the Sky Crane rockets blew away brighter dust during descent. Fragments of rock were delivered to the top of the Curiosity rover as a result of rocket exhaust interaction with the surface. The Chemistry and Camera (ChemCam) instrument onboard the rover took spectral measurements of rocks within the blast zone that appeared darker than similar rock types outside of the blast zone, indicating the surficial coating of dust on these rocks was removed and thus giving different spectral measurements than seen for rock types outside of the blast zone (Johnson et al, 2015). While the spectral measurements may have been more accurate for the blast zone rocks, it can then be difficult to compare these measurements to similar rocks that have not been affected by rocket exhaust. Understanding how regolith has been altered under and near a landed spacecraft is therefore also important for sampling strategies, especially for landers that cannot move to a location where soil is pristine.

1.3 Non-Mare Volcanic Regions

A small number of areas on the Moon, including the Compton-Belkovich Volcanic Complex, Hansteen Alpha, ejecta from Aristarchus Crater, the Lassell Massif, and the Gruithuisen and Mairan Domes, exhibit distinctive reflectance and morphological properties that indicate a non-mare (non-basalt) origin and that they are either silicic volcanics, or in the case of
Aristarchus target rocks, a shallow silicic intrusive body. These areas are indicated to be silicic on the basis of Diviner data (Glotch et al., 2010; Greenhagen et al., 2010; Jolliff et al., 2011; Ashley et al., 2013), but their exact composition is unknown because we lack ground truth in the form of samples known to originate from such sites. Although rare samples of silicic volcanic or intrusive rocks are found in the Apollo sample collections, the provenance of such samples is not known. Using reflectance data from our studies of spacecraft landing sites, we have derived a relationship between composition and reflectance and apply our optimized photometric models to better understand the chemical composition and formation of silicic volcanic areas. Mineralogy is well represented by chemical composition, and throughout the dissertation I use \( \text{Al}_2\text{O}_3 \) as a proxy for plagioclase feldspar and \( \text{FeO+MgO+TiO}_2 \) as a proxy for the sum of the mafic minerals olivine, pyroxene, and ilmenite. Showing further evidence that these areas are products of silicic volcanism through photometric studies can provide a better picture of the extent of volcanic processes that occurred on the Moon (Hagerty et al., 2006).

Lunar Prospector Gamma Ray Spectrometer data revealed a thorium anomaly on the northern farside of the Moon, well away from the locus of Th-rich areas in the Procellarum region, but it wasn’t until high-resolution LRO NAC images of this area were acquired that this area was shown to be a volcanic construct (Jolliff et al., 2011). Known as the Compton-Belkovich Volcanic Complex (CBVC), this unique feature has been of interest to lunar scientists in recent years because there are no other isolated silicic areas quite like it on the Moon. Several instruments onboard recent lunar missions have provided evidence for the presence of pyroclastic deposits at the CBVC (Jolliff et al., 2011; Bhattacharya et al., 2013; Petro et al., 2013; Pieters et al., 2014; Chauhan et al., 2015), and in this dissertation we provide photometric
evidence for pyroclastics, silicic composition, and compositional variability at this volcanic feature.

1.4 Topics of the Dissertation

This dissertation focuses on using photometry to study the physical and compositional properties of various features on the lunar surface, specifically spacecraft landing sites and areas of silicic volcanism. Images from the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) are the primary data set used for these studies. The NACs provide high-resolution (~50 cm/pixel) images of the Moon under a wide variety of illumination conditions, allowing for detailed photometric analysis. Techniques such as photometric modeling, analysis of the mineralogy and composition of lunar samples coupled with reflectance measurements, and laboratory spectral measurements of analog materials are used to understand the physical and compositional properties of spacecraft landing sites and non-mare volcanic regions.

Chapter 2 focuses on the effects of rocket exhaust on soil reflectance properties at the Apollo, Luna, and Surveyor landing sites. As a spacecraft touches down on the surface of the Moon, rocket exhaust from the descent engine interacts with the soil and changes the physical properties, which in turns alters the reflectance. The areas surrounding the landers disturbed by rocket exhaust appear more reflective than surrounding undisturbed areas and are referred to as “blast zones” (BZs). The BZs consist of a high reflectance blast zone (HR-BZ) extending up to hundreds of meters from the lander and a low reflectance blast zone (LR-BZ) directly beneath the lander. We use NAC photometry and Hapke photometric modeling to quantify differences in reflectance between the blast zones (both HR-BZs and LR-BZs) and undisturbed regions and to measure the spatial extent of the disturbed areas. The HR-BZs are less backscattering than undisturbed areas and the LR-BZs are more backscattering than both the background and the
HR-BZs. We include the Apollo, Surveyor, and several Luna sites in this analysis, but do not include Luna 9 and Luna 13 because these spacecraft were small and have been difficult to locate even in high-resolution NAC images. We also exclude Luna 21, which carried the Lunokhod 2 rover, because rover tracks around the lander significantly disrupted the regolith within the HR-BZ. Finally, Surveyor 3 was also excluded because it lies in the blast zone of the Apollo 12 lander.

In addition to photometry, we examine Apollo soil data and exhaust plume dynamics to determine the cause(s) of increased reflectance at the landing sites. We find that the increased reflectance is likely caused by smoothing of the surface, destruction of the fine-scale surface structure (including so-called “fairy-castle” structure), and possibly also in part redistribution of fine particles from the LR-BZ to the HR-BZ. Macroscopic roughening of the surface by the engine exhaust and, in the case of Apollo, by astronaut activity, caused the decreased reflectance seen in the LR-BZs. These findings have implications for planning and safety of future landed missions on the Moon (Clegg et al., 2014).

Chapter 3 builds upon the study of rocket exhaust effects on the Moon by analyzing the recent Chinese Chang’e-3 (CE-3) landing site. Chang'e-3 touched down in Mare Imbrium in December 2013, giving us the opportunity to investigate reflectance changes at a new and fresh landing site and to compare reflectance changes at a recent site to those of the significantly older Surveyor, Apollo, and Luna landing sites. The CE-3 blast zone consists of an outer, diffuse blast zone (DBZ) and an inner, focused blast zone (FBZ). Average reflectance changes normalized to a 30° phase angle for the Apollo, Luna, and Surveyor blast zones are 11±2%, 8±3%, and 10±4%, respectively. We find that the reflectance increase at the CE-3 FBZ is 10±1%, which compares favorably with the older landing sites and suggests that the change in reflectance caused by the
effects of rocket exhaust results from a process that is not reset on the short time scale of decades. We consider several methods of “resetting” reflectance on the Moon and conclude that longer-term processes such as space weathering may eventually reset the reflectance at the blast zones because shorter-term processes such as potential dust movement caused by diurnal thermal cycling and electrostatics do not appear to have significantly changed the reflectance at the BZs of older landing sites. We also determine a relationship between lander dry mass, as a proxy for thrust, and blast zone area for the Apollo, Luna, and Surveyor landing sites, and find that the CE-3 FBZ area falls close to the expected value based on the trend established by the older landing sites. The CE-3 DBZ is much larger and was created when the spacecraft hovered during hazard avoidance prior to final descent and touch down. The relationship between lander dry mass and blast zone area can be used for predicting the likely extents of disturbance resulting from rocket exhaust for future lunar soft landings.

Chapter 4 uses the photometric model optimized from spacecraft landing sites to place compositional constraints on areas of non-mare volcanism on the Moon. Most regions of non-mare volcanism have high albedos and a strong absorption in the ultraviolet and are referred to as “red spots” (Whitaker, 1972; Malin, 1974; Hagerty et al., 2006). Non-mare volcanic areas on the Moon generally correspond to areas with some of the strongest thorium anomalies and have morphological features such as cones and domes that indicate a volcanic origin (Hagerty et al, 2006; Glotch et al., 2011; Jolliff et al., 2011). Data from the Diviner Lunar Radiometer onboard LRO indicate that most of these areas are indeed silicic in composition, based on the position of the “Christiansen feature” (Greenhagen et al., 2010). Returned samples that are highly silicic in composition are rare, so we must rely on remote sensing and measurements of analog materials to place compositional constraints on silicic areas. For this project, we use NAC photometry
coupled with soil compositional data from Apollo, Luna, and Chang'e-3 to show that regions of non-mare volcanism have low (<5-10 wt%) mafic contents (measured as FeO+MgO+TiO$_2$) and high reflectance compared to background non-mare materials. To determine what material(s) need to be added to a highlands-type material to produce the reflectance values we see at the CBVC and other silicic volcanic areas, we mixed varying proportions of rhyolitic pumice, as a glassy analog, with a highlands simulant and compared visible spectral reflectance measurements, convolved to a range consistent with the NAC spectral responsivity. We find that the CBVC has the highest reflectance values measured for the silicic sites, and that the addition of up to ~20 wt% glassy silicic materials (which could be pyroclastic in nature) can account for the highest reflectance values measured within the volcanic complex. We also discuss variations in composition and mineralogy for areas of lower reflectance in the CBVC and at other silicic volcanic sites in terms of related rock types that may be part of the volcanic rocks and key to understanding their petrogenesis. Gathering information on these rare lunar features will help guide site selection and sample collection for future robotic and/or manned missions to these key scientific sites.

1.5 Statement of Labor

The dissertation chair, Dr. Bradley Jolliff, and Dr. Philip Metzger of the Florida Space Institute provided the early motivation for the projects described in this dissertation. The Lunar Reconnaissance Orbiter Camera (LROC) team at Arizona State University made available the NAC images used for all of the projects. Ryan N. Watkins did all of the NAC image processing unless otherwise noted. Members of the LROC team at Arizona State University and the University of Arizona created the digital topographic models (DTMs) used for NAC processing. Ryan N. Watkins carried out all Hapke photometric modeling, with guidance from Bruce Hapke
and Aaron Boyd. All phase-ratio images used for the spacecraft landing site studies were created by Ryan N. Watkins, with the exception of the Chang’e-3 landing site phase ratio image, which was provided by Emerson Speyerer. Glassy analog materials for studies of the silicic volcanic regions were crushed and prepared by Ryan N. Watkins. Spectral measurements were also taken by Ryan N. Watkins, with assistance from Ecaterina Coman and Jie Wei. Brad Jolliff provided the data necessary for calculating the normative mineralogy for Apollo and Luna samples, and all calculations were carried out by Ryan N. Watkins.

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References


Chapter 2: Effects of Rocket Exhaust on Lunar Soil Reflectance Properties

Article link: \url{http://www.sciencedirect.com/science/article/pii/S001910351300393X}

Abstract

High-resolution images of the Surveyor, Luna, and Apollo landing sites obtained by the Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) show regions around the landers where reflectivity of the surface was modified. We interpret the change in reflectance properties of these regions mainly as disturbance of the regolith by rocket exhaust during descent of the spacecraft and we refer to these areas herein as “blast zones” (BZs). The BZs consist of an area of lower reflectance (LR-BZ) compared to the surroundings that extends up to a few meters out from the landers, as well as a broader halo of higher reflectance (HR-BZ) that extends tens to hundreds of meters away from the landers. When approximated as an ellipse, the average Apollo BZ area is \(\sim29,000\ \text{m}^2\) (\(\sim175 \pm 60\ \text{m by } 200 \pm 27\ \text{m}\)) which is 10\times larger than the average Luna BZ, and over 100\times larger than the average Surveyor BZ. The LR-BZs are most evident at the Apollo sites, especially where astronaut activity disturbed the soil, leading to a 15-30\% (relative to background undisturbed areas) reduction in reflectance at \(\sim30^\circ\) phase angle. The LR-BZs at the Surveyor and Luna sites are less evident and are unresolvable with NAC images. The average reflectance in the HR-BZs as determined for 30\(^\circ\) phase angle is 3-12\% higher than in the undisturbed surrounding areas; this magnitude is the same, within uncertainty, for all sites, indicating a common process or combination of processes causing differences in reflectance properties of the regolith. Phase-ratio images and photometric data

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collected over a range of illumination geometries show that a greater separation in reflectance occurs between the HR-BZs and undisturbed areas at phase angles between 0° and 70° and indicates that the HR-BZs are less backscattering than undisturbed areas. The LR-BZs are affected by macroscopic disruption of the surface and astronaut activity (at the Apollo sites). There are two possibilities to account for the HR-BZ. The one we favor is that the HR-BZ reflectance has been affected by scouring from particles entrained by exhaust gases with low-angle trajectories. Regolith particle interactions with surface soil within HR-BZs may destroy fine-scale surface structure (e.g., “fairy-castle”) and decrease macroscopic roughness, contributing to a decrease in backscattering character within the HR-BZs and an increase in backscattering character within the LR-BZs. The second possibility is redistribution of fine particles from the LR-BZ into the HR-BZ. Photometric modeling supports both of these hypotheses.

2.1 Introduction

The descent engine exhaust plumes of the Surveyor, Luna, and Apollo spacecraft significantly affected the regolith surrounding their landing sites, and owing to the lack of rapid weathering processes on the Moon, these surface alterations are still visible as photometric anomalies in Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images. These areas, which we refer to as “blast zones” (BZs), are interpreted as disturbances of the regolith by rocket exhaust during descent of the spacecraft and activity of the astronauts in the area right around the landers. Each BZ consists of an area of lower reflectance (LR-BZ) compared to the surroundings that extends from beneath the lander up to a few meters out from the lander, as well as a broader ‘halo’ of higher reflectance (HR-BZ) that extends tens to hundreds of meters away from the lander (Figure 2.1). Kaydash et al. (2011) first discussed the
basic phenomenon of BZ reflectance changes; here we present an in-depth analysis of several hypotheses to test possible causes of the reflectance changes. We use photometric modeling, phase-ratio images, and analysis of Apollo sample data to analyze reflectance variations at all of the Apollo sites, as well as at the Luna and Surveyor robotic landing sites.

Disturbed lunar regolith has distinctly different photometric properties compared to undisturbed regolith (Carrier, 1973; Hapke, 1981; Carrier, 1991; Kaydash et al., 2011). Properties such as grain size, grain shapes, composition and mineralogy, regolith structure, surface roughness, and glass and Fe$^0$ contents determine how the surface reflects light. Lunar regolith properties can be inferred by analyzing the reflectance of the HR-BZ and LR-BZ over a range of incidence, emission, and phase angles from the NAC images. These results can then be compared with the known properties of lunar soils from sample analysis in order to infer the behavior of lunar soil during human and robotic missions (Carrier et al., 1991; Goguen et al., 2010).

The LROC NACs provide high-resolution (50 cm/pixel) images of all the Apollo, Surveyor, and Luna landing sites under a wide variety of illumination conditions (see Appendix A), allowing for a detailed photometric analysis of the landing sites. We use photometric analysis of the NAC images to measure the spatial extent of the disturbed areas, as well as to quantify differences in reflectance between the blast zones (both HR-BZs and LR-BZs) and nearby undisturbed regions. This work focuses mainly on the Apollo landing sites because extensive data exist regarding the descent of the lunar modules and the soil behavior around the landing sites. However, we also compare the spatial extent of the BZs and reflectance variations with those seen at the Luna and Surveyor landing sites.
Hypotheses that we consider to explain the reflectance differences between the HR-BZ and background regions include: 1) change in macroscopic roughness (cm to m scale); 2) redistribution of fine particles (excavation from LR-BZ and deposition to HR-BZ); 3) removal of a more mature surface layer in the HR-BZ and exposure of less mature soil beneath; 4) microscopic (μm scale) modification of fine-scale structure in the HR-BZ (e.g., “fairy castle” structure, see Hapke and van Horn, 1963); 5) compaction of the regolith within the more reflective area; 6) Chemical changes due to contamination by the rocket exhaust, and (7) some combination of these effects. We also compare our conclusions with those of recent work by Shkuratov et al. (2012).

2.2 Methods

NAC images were photometrically corrected and projected to map format using the USGS’s Integrated Software for Imagers and Spectrometers (ISIS) (Anderson et al., 2004). We use ISIS to create phase-ratio images, and use both ENVI (Environment for Visualizing Images) and ISIS to analyze NAC images to quantify reflectance properties. In ISIS, the processing step ironaccal was used to remove camera artifacts by applying a radiometric calibration to each NAC image. The images were corrected to \( I/F \) (Minnaert, 1961), the ratio of the radiance \( I \) received at the detector to the radiance from a normally illuminated Lambertian surface \( F \) (defined as the source radiance divided by \( \pi \)). The spectral responsivity of each NAC was measured using a monochromater before flight. Once the spectral responsivity was characterized, the DN values could be converted to radiance values. For any given observation, the image count rate (measured in DN/ms) constitutes the spectral radiance of the lunar scene weighted by the NAC responsivity. The weighted mean radiance for the NACs is calculated using the image count rate and spectral responsivity. Using the solar irradiance at a distance of 1
AU, the Sun-Moon distance, spectral responsivity of the NACs, and the image count rate, the weighted radiance $I/F$ for the NACs can be calculated for each pixel. For more details, see Robinson et al. (2010). Higher $I/F$ values correspond to areas of higher reflectance, or to areas where local slopes combined with solar incidence are more reflective.

### 2.2.1 Measuring the Blast Zone Spatial Extents

Phase-ratio images were created for each landing site to delimit the spatial extent of the disturbed areas and to quantify differences in reflectance and backscattering characteristics within the BZs compared to undisturbed areas. A phase-ratio image is made from two images of the same site with similar incidence angles ($i$) but with significantly different ($>20^\circ$ for most pairs) emission angles ($e$), and thus different phase angles ($g$), and then dividing the higher phase image by the lower (see Kaydash et al., 2011; Table 2.1). Figure 2.2 shows a schematic of a forward scattering viewing geometry ($i$ and $e$ are on opposite sides of the surface normal; $g \sim i + e$) and a backward scattering viewing geometries ($i$ and $e$ are on the same side of the surface normal; $g \sim |i - e|$); these terms will be used throughout the remainder of the paper. Creating a phase-ratio image using two images of each landing site with different viewing geometries enhances variations associated with disturbance from the landing and astronaut activity, and minimizes influences from small-scale surface topography that existed before and after the landings (Kaydash et al., 2011; Shkuratov et al., 2011). By contrast, images taken at zero phase angle emphasize albedo changes that might be caused by chemical changes or particle size effects (Hapke, 1972). We used images taken in subsequent orbits where the incidence angle was approximately the same but emission angle was varied by slewing the spacecraft, resulting in different phase angles. Our phase-ratio images were made using sets with phase angle differences greater than $10^\circ$. 


Figure 2.3 shows an example of a phase-ratio image created for the Apollo 12 landing site. The phase-ratio image provides enhanced contrast between the blast zone and surrounding regolith, thus distinctly revealing the perimeters of the blast zone. This enhanced contrast allows the spatial distribution to be measured more accurately than from the original, individual images. The phase-ratio image also reveals differences in backscattering characteristics of the disturbed region compared to the background undisturbed region. The phase function slope is dominated by light scattering characteristics of the regolith; in this case a darker region in a phase-ratio image corresponds to a lower phase slope and therefore a region that is less backscattering. Shadowed crater walls in the NAC images appear bright in the phase-ratio image, reflecting changes in illumination geometry (phase angle) interacting with large-scale topography, and changes in regolith physical properties associated with different parts of the impact craters such as interiors vs. rims vs. ejecta (Kaydash et al., 2011).

2.2.2 Reflectance Profiles

Reflectance profiles taken across each landing site are used to quantify changes in reflectance between the LR-BZs, HR-BZs, and undisturbed areas, as well as to cross-check the boundaries of the BZs with those determined using phase-ratio images. However, Sun-facing crater walls and local topography with Sun-facing slopes are more reflective, so in addition to taking horizontal profiles across each landing site, profiles were carefully drawn across the landing site so as to avoid Sun-facing facets, although some topographic effects are inevitably included in the profiles.

The shapes of the profiles indicate areas where reflectance ($I/F$) is highest and show how $I/F$ decreases toward the perimeter of the HR-BZ and transitions gradually to the undisturbed background beyond the blast zone. $I/F$ within the blast zone is highest closer to the landers, and
dips in the center immediately adjacent to and presumably beneath the lander (LR-BZ). We use these datasets to determine average $I/F$ values for the area inside the blast zone (both HR-BZ and LR-BZ) and at the landers. The local background can also be determined on the basis of the profiles. Although the effects of local, small-scale topography on reflectance tend to average out, we used larger areas and averaged the $I/F$ values. To determine average background values, we selected two large rectangular areas nearby, but well outside the blast zone, and recorded the average $I/F$ value in these regions using ISIS measuring tools. This average was checked for agreement with averages given by the profiles and was later used for comparing BZ reflectance to the background. Figure 2.4 shows an example of how areas outside the blast zone were selected, as well as a histogram indicating the spread of $I/F$ values found in one rectangular region. The reflectance measurements are given in Table 2.2.

2.2.3 Soil Data

Soil samples were taken from various locations around each Apollo landing site, so we used data from the Lunar Soils Grain Size Catalog (Graf, 1993) and the Handbook of Lunar Soils (Morris, 1983) to evaluate whether trends can be seen in grain size and maturity differences for soil samples collected within and outside the blast zones. First, any samples that were taken near the rim of fresh craters were excluded because these naturally represent deeper, less mature regolith. Core samples were also excluded because they include soil taken at depths that would not have been affected by the rocket exhaust (greater than ~5-10 cm) and that exhibit different maturity and grain size properties than the surface regolith. The material at the top of the core samples was also slightly disturbed during sampling and therefore not useful for comparison. We compared maps of sample locations at each landing site to the landing site images to determine which samples were within the blast zones and which were collected at greater distances from
the LM. Samples from outside the blast zone were selected on the basis of descriptions of the
type of sample that was taken – samples near crater rims were excluded, and surface scoops were
the most desired type of sample for comparison because they best represent the upper,
undisturbed regolith. The sample locations are given in Table 2.3.

Next, we calculated the mean grain size for each sample based on published sieve fraction
weights for the \(< 250 \mu m\) size range; considering only the \(< 250 \mu m\) size range because there is
sufficient data in this size fraction to use for comparing across samples. The mean grain size was
calculated using statistical methods developed by Folk and Ward (1957). We also recorded the
maturity value, $I_s/FeO$, for each sample. Finally, the average grain size and average $I_s/FeO$ for
the samples within the blast zone and outside the blast zone were calculated and the results are
given in Table 2.3.

2.2.4 Photometry

We have numerous NAC images of the same site taken under different illumination
conditions, mostly with different incidence angles, but also different emission angles, the effects
of which will be discussed later. For the Surveyor, Luna, and Apollo landing sites, we used
images spanning a range of phase angles from ~0-90 degrees. On the whole, reflectance values
vary systematically over this range (see Section 2.3.4). We report reflectance values at a
common 30° phase angle on the basis of our photometric fits to NAC images.

Photometric functions are useful for constraining composition, mineralogy, and particle
size from the reflectance of the regolith and are used for our studies (Hapke, 1981; Helfenstein
and Veverka, 1987; Carrier et al., 1991; Quinn et al., 2010). The simplified bidirectional
reflectance function (Hapke, 199; Hapke, 2001; Hapke, 2012; Hapke et al., 2012), which is the
ratio of the radiance $I$ received at the detector viewing the surface from angle $e$ to the radiance $F$ from the source at angle $i$, and then divided by the Lommel-Seeliger Function (LS), is:

$$\frac{IoF}{LS} = \frac{\mu_{0e}}{\mu_{0e} + \mu_e} \frac{\mu_0 + \mu_w}{\mu_0} \frac{1}{4} \left[ p(g) + H(\mu_{0e}, w)H(\mu_e, w) - 1 \right] \left[ 1 + B_{C0}B_C(g, h_C) \right] S(i, e, \theta) \tag{1}$$

where $\mu = \cos(e)$, $\mu_0 = \cos(i)$, $\mu_{0e}$ and $\mu_e$ are effective cosines (Hapke, 1993; Hapke, 2012), and the quantity $IoF = I/F$ is the “radiance factor” as defined by Hapke (1993; 2012) and is equivalent to the pixel DN value in each processed NAC image (see Section 2.2.2). The single scattering albedo, $w$, is the probability that a photon will be scattered by a particle and $p(g)$ is the probability that a photon will be scattered in the direction $g$ (phase angle), and is defined by the double Henyey-Greenstein Function (Carrier et al., 1991; Hapke, 1993; Goguen et al., 2010):

$$p(g) = \frac{1+c}{2} \frac{1-b^2}{(1-2b \cos g + b^2)^{3/2}} + \frac{1-c}{2} \frac{1-b^2}{(1+2b \cos g + b^2)^{3/2}} \tag{2}$$

where $b$ is the angular width of the backward (first term) or forward (second term) scattering lobe and $c$ is the magnitude of the lobe. Hapke approximates the Ambartsumian-Chandrasekhar $H$ functions by

$$H(x, w) = \frac{(1 + 2x)/(1 + 2x\sqrt{(1 - w))}} \tag{3}$$

(Hapke, 2012). The terms $B_{C0}$ and $B_C$ are the amplitude of an effective coherent backscatter opposition effect (CBOE) and the angular shape function of the CBOE, respectively. These terms are important only at small phase angles and are described in detail in Hapke (2001). The CBOE angular width parameter, $h_C$, depends on grain size, as does the single scattering albedo. The term $S(i, e, \theta)$ is the shadowing function and depends on the roughness of the surface and mean slope angle $\theta$. Derivations for the shadowing function can be found in Hapke (2012).

For each landing site, we chose an area that encloses the HR-BZ, an area directly beside the lander but avoiding the lander shadow (the LR-BZ), and two areas well outside the blast.
zone, and then recorded the average $i$, $e$, $g$, and $I/F$ for each region (see previous section). For the initial photometric analysis, we obtain $I/F$ values from the pixel DN values in each calibrated image. We then use the $I/F$ values to report the reduced reflectance and the normalized reflectance. The reduced reflectance (Equation 1) is the reflectance ($I/F$) divided by the Lommel-Seeliger Function (Hapke, 1993; Hapke, 2012). We calculate this value by using the average $i$ and $e$ values for the image and then dividing the $I/F$ values by the LS Function. The normalized reflectance is $I/F$ for the blast zone divided by the background $I/F$ values. We then explore Equation 1 to fit the data by varying parameters that depend on physical properties of the regolith. This process is explained in detail in Section 2.4.3.

### 2.3 Results

#### 2.3.1 Blast Zone Characteristics and Spatial Extents

NAC images and Apollo surface photographs provide information about the size of the areas that were disturbed by rocket exhaust. Figure 2.5 shows cropped NAC images for each of the Apollo landing sites, with the HR-BZs highlighted. Figures 2.6 and 2.7 show the Surveyor and Luna landing sites, respectively. We will detail the results photometric analysis of these blast zones in the following sections and discuss implications for this study in Section 2.4.

Figure 2.8 shows two images of the Apollo 12 landing site taken under similar illumination conditions – one from Lunar Orbiter 3 (LO-3), taken before the Apollo missions, and one from LROC. In the LROC NAC image, both the Apollo 12 lunar module (LM) and Surveyor III spacecraft are visible, and Surveyor Crater is more reflective than in the LO-3 image. This difference indicates that the Apollo 12 rocket exhaust had an appreciable effect on the regolith, and that Surveyor Crater likely acted as a mechanism to contain the rocket exhaust and allow the entire crater to experience disturbance. Surface photographs taken during the Apollo missions
also show photometric differences around the landing sites. Figure 2.9a shows a photograph taken beside the lunar module at the Apollo 11 landing site. Close to the lander, the regolith has lower reflectivity. A high reflectance streak possibly due to rocket plume effects is visible directly beside the LM. Figure 2.9b also shows another view under the nozzle of the LM and the regolith appears to be less reflective than the surroundings. This area is roughened-up, and appears to be disrupted and pitted beneath the nozzle (see also Figs. 7-9 in Metzger et al., 2011). In addition, a region farther from the nozzle appears to be smoother than the disrupted region, and has been brightened, likely due to interaction with the exhaust plume. The region of decreased reflectance beneath the engine nozzle is part of the lower reflectance blast zone (LR-BZ) for the landing sites. At the Apollo sites, the area of astronaut bioturbation around the LM is indistinguishable from the LR-BZ and thus included in the measurements of the LR-BZ.

The average values of BZ elliptical areas, calculated from the measured diameters, are reported in Table 2.2. The Apollo BZ diameters range from approximately 130 m to 280 m. When approximated as an ellipse, the average area of increased reflectance for the Apollo missions is ~29,000 m² (~175 ± 60 m by 200 ± 27 m), with values ranging from as low as ~18,800 m² for Apollo 15 to as high as ~54,000 m² for Apollo 12, which has an enlarged disturbed region extending in the direction of Surveyor Crater.

The average BZ area for the Luna missions is 2100 m² (~56 ± 12 m by 47 ± 13 m), about 10 times smaller than Apollo, and the average area for the Surveyor missions is 215 m² (~19 ± 3 m by 14 ± 3 m), about 100 times smaller than Apollo. Shkuratov et al. (2012) used phase-ratio images to investigate the HR-BZs at the Luna 23 and Luna 24 landing sites and found that the Luna 24 HR-BZ appears to be offset by approximately 150 m. They suggested that perhaps the Luna 23 and 24 sites, which are only 2 km apart, have been misidentified and that the HR-BZ we
attribute to Luna 24 actually belongs to Luna 23. However, Dolgopolov et al. (2013) analyzed LROC images and virtual models of Luna 23 and Luna 24 and concluded that the landing sites were correctly identified (Robinson et al., 2012). The blast zone may not be evident in the immediate vicinity of Luna 24 owing to immature soil at the rim of the fresh crater next to its landing site. However, the offset photometric anomaly could have been caused by Luna 24 if it translated horizontally 150 m after transitioning to small engines to decelerate (Dolgopolov et al., 2013). For this study, we report the size of the photometric anomaly in the direct vicinity of the Luna 24 spacecraft (Table 2.2).

Most of the blast zones are elliptical in shape, but some are irregular – Apollo 12’s HR-BZ was significantly expanded by Surveyor Crater, and Apollo 17 has a lobe that may indicate the path of descent of the LM. Table 2.4 lists observations made by the Apollo astronauts during each mission regarding the blowing dust during landing. Dust was reported as first blowing from altitudes ranging from ~80-300 ft (~25-90 m). Most of the astronauts reported that visibility was greatly obscured, and in some cases features such as small craters and boulders disappeared completely from view. On only two missions (14 and 17) did the astronauts report that the blowing dust did not hamper their ability to land safely. Apollo 11 moved sideways to avoid landing in a crater, and both Apollo 12 and Apollo 16 hovered over the surface while looking for safe landing spots (Conrad et al., 1969; McDivitt et al., 1972; Harland, 2008).

2.3.2 Apollo Soil Data

Table 2.3 lists the samples that were chosen for examination of grain size and maturity trends within and outside the blast zones, as well as a description of the type of sample (surface scoop, trench sample, etc.) and its location. For Apollo 11, grain size data exists only for 10084, which came from within the area of the blast zone (Graf, 1993). Some samples have grain-size
distribution data for several subsamples, so the mean grain sizes for the subsamples were averaged together. The mean grain size for soil samples at all Apollo sites ranges from 35-85 µm for samples collected within the blast zones and 33-80 µm for samples collected outside the blast zones. $I_{S}/FeO$ values range from 45-94 for samples collected in the blast zone and 36-85 for samples collected outside the blast zone. The mean grain size for soils at all Apollo sites for the blast zones and background regions is $49 \pm 13$ µm and $50 \pm 14$ µm, respectively. The mean $I_{S}/FeO$ value for samples from the blast zones is $62 \pm 16$ and $63 \pm 17$ for samples from regions outside the blast zone. In summary, there appears to be little difference in soil properties inside and outside the blast zones.

2.3.3 Reflectance Profiles

Profiles for the Apollo landing sites, shown in Figure 2.10, indicate that, outside of the LR-BZ, reflectance is greatest close to the LM, within ~20-40 meters, then tapers off with distance from the LM, reaching background levels typically at ~70-140 meters distance from the landers. The reflectance is lowest directly at the LM in the LR-BZ, where the astronauts disturbed the regolith, and perhaps directly beneath the landers where disruption of regolith by descent engines was chaotic.

Figure 2.10a shows the horizontal profile taken across the landing site and Figure 2.10b shows the $I/F$ profile data, with reflectance effects from local topography and from the LM and its shadow appearing as anomalous values. Figure 2.10c shows the profile that was drawn to carefully avoid craters and going directly over the LM or through its shadow. Dashed lines in Figure 2.10d indicate the average reflectance value for the region outside the HR-BZ, and solid lines indicate averages inside the HR-BZ and LR-BZ. The dip in $I/F$ towards the center of the plot is the region of the profile taken across the LR-BZ. Multiple reflectance profiles were
constructed for each Apollo landing site and all show similar trends in reflectance changes across the blast zone, at the LM, and in the undisturbed background regions. Profiles for each of the landing sites are shown in Appendix B.

Surveyor and Luna landing-site profiles show similar trends to Apollo but the LR-BZs are less obvious. Reflectance is greatest within the first 5-10 meters away from the Surveyor and Luna landers. Figure 2.11 shows profiles for Surveyor and Luna examples; in these profiles, the parameters of the HR-BZ are evident, but it is more difficult to determine if LR-BZs exist for these sites. A slight dip occurs beside the lander, but the I/F values never dip below those of the background as they do at the Apollo landing sites. The LR-BZs likely exist but are typically too small to be unambiguously resolved in the NAC images.

2.3.4 Photometry

The average reflectance values for the entire HR-BZ region at a phase angle of 30° for each site are listed in Table 2.2. The value of 30° was arbitrarily chosen because the reflectance values vary according to phase angle, and because there are NAC images for each landing site at or near 30° phase that can be used for comparison. The systematic variations in reflectance for the BZs as a function of phase angles ranging from 0°-90° for each landing site are shown in Figure 2.12. The BZ values were also normalized to the background values and plotted against phase angle, showing that normalized reflectance (HR-BZ/background) increases with increasing phase angle (Figure 2.12b; note that the normalized reflectance values in Table 2.2 are for a phase angle of 30°, whereas the normalized reflectance values in Figure 2.12b span all phase angles). Plotting the reduced reflectance versus phase angle (Figure 2.12a) shows that reflectance decreases with increasing phase angle for each landing site and shows that compositional variations between landing sites affect the overall reflectance (Figure 2.12c).
At low (less than ~30°) incidence angles, the effects of viewing geometry are clearly seen. Images with a backward scattering viewing geometry such that \( g < i \) (see Figure 2.2) tend to have higher reflectance \((I/F)\) values than images with a forward scattering viewing geometry such that \( g > i \) (Figure 2.13a). When plotting \( I/F \) as a function of phase angle, some scatter is seen in the data and fitting a smooth curve is difficult (Figure 2.13b). However, when plotting reduced reflectance as a function of phase angle, the effects of viewing geometry are minimized and a much smoother trend is seen (Figure 2.13c). The Lommel-Seeliger function takes the cosine of incidence and emission angles, so the spread caused by having images with varying viewing geometries is smoothed when dividing by this function.

2.4 Discussion

2.4.1 Blast Zone Spatial Extents

Using LROC NAC images to measure the spatial extent of the blast zones and perform photometric analysis and modeling, paired with plume effects modeling and analysis of soil data, allows us to limit the causes of increased reflectance within the HR-BZs and the decreased reflectance within the LR-BZs. In this section, we consider the implications of the blast zone spatial extents, and in subsequent sections, we consider how each of the other kinds of information bear upon the various hypotheses for the origin of changes in reflectance within the areas affected by lander exhaust.

Most Apollo mission reports state that dust began blowing around 150 feet (~45 m) altitude (Table 2.4) on approach, disturbing the surface for moderately long periods of time (Armstrong et al., 1969; Conrad et al., 1969; McDivitt et al., 1971; Shepard et al., 1971; Hinners and El-Baz, 1972; McDivitt et al., 1972; Cernan et al., 1973; McDivitt et al., 1973). The LMs approached their landing sites at different angles and therefore the length of time that soil was
disturbed and the size of the disturbed regions varied. The disturbed areas around the lunar modules are all approximately elliptical in shape but they vary in size.

The largest measured blast zone is that of Apollo 12; it is evident in NAC images as well as when comparing LROC images with LO images that the regolith in Surveyor Crater was also disturbed during descent of the LM. According to Conrad et al. (1969), the LM flew beside the crater and tilted back and forth during descent while the astronauts were searching for a safe landing spot. It is likely that the crater acted as a mechanism for containing the rocket exhaust and allowed the entire crater to experience disturbance during the LM’s descent.

The Apollo 16 BZ also has relatively large dimensions, again likely owing to the fact that the LM hovered at an altitude of around 40-60 feet (12-18 m) before landing (McDivitt et al., 1972). The measured dimensions for the Apollo 15 blast zone are consistently smaller than the other landing sites. At Apollo 15, the lunar module landed on the edge of a small crater and tilted back approximately 11° (McDivitt et al., 1971), causing the area of disturbance to be less than for the other Apollo missions.

As discussed in Section 2.3.1, the average Luna BZ is 10 times smaller than the average Apollo BZ, and the average Surveyor BZ is 100 times smaller. The variation appears to be proportional to the thrust associated with the different spacecraft (see Table 2.2). The average Apollo thrust was around 45 kN, the average Luna thrust was between 15-20 kN, and the average Surveyor thrust was 0.133-0.472 kN. The LR-BZs at Surveyor and Luna are much smaller because of the smaller thrusts and lack of astronaut activity around the spacecraft. They likely exist because of pitting of soil beneath the nozzle, but are too small to be resolved with NAC images.
Immer et al. (2008) used photogrammetric techniques to calculate the angle of blowing soil for each Apollo mission (except for Apollo 12, because the sun angle was too low), and found that the average angle of trajectory for the blowing particles was 3° relative to horizontal. However, the dust ejection angle for Apollo 15 was reported to be closer to 8° because of the 11° tilt of the LM and the fact that the exhaust likely interacted with the rim of a small crater at the landing site during descent. This angled orientation could cause the disturbed area around the landing site to be smaller, which is confirmed in our measurements.

The shape of each blast zone depends on the final descent trajectory of the lunar modules, and varies depending on whether they hovered above the surface or took a steeper approach to the surface. Other variations in the final descent trajectories may explain variations such as the extra lobe that is evident in images of the Apollo 17 landing site. The implication of exhaust flow experiments and modeling (Lane et al., 2008; Lane et al., 2010; Metzger et al., 2010) is that particles picked up and entrained in the exhaust plume would travel much farther than the observed spatial extents of the BZs, unless turbulence within the plume caused particles to re-settle near the landers, i.e., within the HR-BZs. We consider this possibility further in section 2.4.5.

2.4.2 Soil Data

The data in Table 2.3 show no obvious differences in grain size or maturity between soil collected within the Apollo BZs and undisturbed soil collected beyond the BZs. However, none of the soil samples taken within the HR-BZs were surface skim samples, which would be best for a meaningful comparison of grain size differences between the HR-BZs and background. The surface scoops and trench samples that were collected are too few and not ideal for this comparison.
Chemical effects can be eliminated for two reasons: First, no chemical differences between Apollo samples collected in the BZ and undisturbed regions have been reported. Second, it is unlikely that the chemicals in the rocket exhaust would simultaneously darken some areas and lighten others on the same surface.

### 2.4.3 Reflectance Profiles and Possible Causes of Increased Reflectance

Reflectance profiles and photometry plots show several key characteristics of blast zones. Profiles for all landing sites show that reflectance values are highest in the blast zone annular regions (HR-BZ) closer to the lander, and then taper off as distance from the lander increases, with average \( I/F \) values around 7 to 33% higher in the HR-BZs than outside, for a 30° phase angle. In a general sense, the dust that was blown away from beneath the lander would have settled at some distance away from the lander and the surface would presumably be made more reflective owing to one or more of the previously stated mechanisms, either smoothing or redistribution of fine material.

One possibility is that regolith fines were deposited from the exhaust plume onto the annular region (the HR-BZ) surrounding the lander, creating a thin layer of fine particles that caused an increase in reflectance. Redistribution of fine particles would increase reflectance because light can pass through fine particles more easily than through coarse particles, so fines tend to be more reflective. Kreslavsky and Shkuratov (2003), Metzger et al. (2011), and Shkuratov et al. (2011) suggested that the increased reflectance in the HR-BZs is due to finer particles having been transported from beneath the rocket nozzle (i.e., the LR-BZ) and then redistributed in a region close to the LM (e.g., ~50-150 m, cited specifically for Apollo 15 by Kreslavsky and Shkuratov [2003]). Finer particles would effectively create a more reflective surface than coarser particles owing to their greater transparency.
Another possibility is that the exhaust plume destroyed “fairy-castle structure” and made the surface more forward scattering (Shkuratov et al., 2011; Kaydash and Shkuratov, 2012). “Fairy-castle structure” refers to the stacking of grains when particles are small enough that adhesive forces overcome gravitational forces, allowing a small particle to be supported by one contact rather than the three points required for a large particle. This stacking configuration creates a very cohesive and highly porous structure that when viewed with a stereoscopic microscope appears to consist of towers leaning at random angles and connected by bridges – hence the term “fairy castle” (Hapke and van Horn, 1963). The Moon is highly backscattering because of the high porosity of the soil at the surface where light interacts with it, so a decrease in porosity owing to the destruction of the fairy-castle structure would increase reflectance of the surface and, in particular, would make it more forward scattering (Hapke, 2012).

Destruction of the fairy-castle structure would be part of the process of surface smoothing at a microscopic scale; however, smoothing involves compaction and shearing mechanisms that may also occur on a larger (cm to m) scale. Astronauts reported that surfaces near the LM were swept clean of the top, loose layer of soil, and that this area was smoother than areas further away from the lander (NASA Manned Space Center, 1969). The bright streak visible in Figure 2.9 appears to be smoother than the surroundings and to be coming from the direction of the rocket nozzle. We discuss the possibility of surface smoothing further in Section 2.4.4.

Another process that can increase reflectance is the exposure of fresh, immature soil, such as is in the ejecta of young craters. This characteristic results from the lack of exposure to space weathering, which causes a change in reflectance owing mainly to the production of nanophase iron in agglutinates and on grain edges in more mature soil (see Pieters et al., 2000). However, core samples (Figure 2.14) show that maturity does not change significantly within the first tens
of centimeters of regolith depth. On average, within the first 10 cm of regolith, the mean $I_{\alpha}/FeO$ value only changes by about 10% and is still within the mature range. To expose soil that is at least 50% less mature, the top 60 cm of regolith, on average, would have to be stripped away (Lucey et al., 2006), therefore exposure of less mature soil is unlikely because the rocket exhaust gases clearly did not excavate this much material across the HR-BZs (see also Kaydash and Shkuratov, 2012).

A decrease in reflectance is observed in the area directly beside the Apollo Lunar Modules (Figs. 2.2, 2.3, 2.9b, and 2.9d). This decrease corresponds to areas of astronaut activity, as well as the area where the largest volume of particulate material was likely removed, especially the areas directly beneath the landers. The decreased reflectance beneath the lander may be explained by exposure of coarser particles, because the average particle size increases with depth in lunar regolith and coarser particles are less transparent and have lower albedos. The remainder of the LR-BZ is clearly caused by roughening of the surface by astronaut activities. Although a single bootprint compacts and smooths the regolith and make it more reflective owing to the decrease in porosity (Hapke, 2012), multiple bootprints mutually interfere and darken the surface due to increased shadowing by the loose particles and aggregates of particles (Hapke, 1972; Kaydash et al., 2011; and see the astronaut tracks in the NAC images and in Figure 2.15). Figure 2.15 shows how single bootprints increase reflectance (with the bootprints in Figure 2.15b being more reflective owing to the higher phase angle of the image). The darkening that results from mutual interference of bootprints can be seen in the area beside the LM landing pad in Figure 2.9a. Also, as can be seen in video documentation of astronaut activity on the lunar surface, the walking/shuffling action kicked up and sprayed regolith in the areas where astronauts were moving, contributing to the roughness generated by their movements.
Directly beneath the engine nozzles, clumps of regolith were lofted and increased the roughness. This pitting occurred during the “terrain modification stage”, as defined by Metzger et al. (2011). During this stage, the gas flow was perturbed by the LM’s legs and footpads, as well as the contact probes gouging the surface. Gas was driven into the soil, followed by expansion of the gas and release of pressure, causing soil to become disrupted and regolith to be lofted into the exhaust flow. The soil beneath the nozzle eroded in clods and discrete layers – thus creating a rougher area partly under the LM and extending outward a few meters (see Metzger et al., 2011). The lifting of clumps of regolith would also attribute to the increased roughness and decreased reflectance in the LR-BZs at the Apollo landing sites and this process is probably the dominant mechanism for creating LR-BZs at the Luna and Surveyor landing sites.

Further dispersal of materials caused by the Apollo and Luna (16, 20, and 24) ascent engines is generally taken to be negligible compared to the effects during descent because the descent stage essentially served as a launch pad to disrupt the flow of the ascending rocket exhaust and thus protected the soil beneath the ascent stage. This assumption is supported by preservation of disturbed areas such as astronaut tracks in the direct vicinity of the lunar module (Kaydash et al., 2011).

2.4.4 Photometry and Photometric Modeling

We use Hapke photometric modeling to fit reflectance data by varying different parameters (w, b, c, and θ) in Equation (1). Using this method, we can assess how the regolith has changed in terms of backscattering characteristics and infer what physical and chemical changes might have occurred at the surface during landing. The single scattering albedo (w) depends on properties such as composition and grain size, and varies for each landing site. We first hold w constant across the HR-BZ and background at each site, but vary the mean slope angle, θ, and b
and $c$ in order to fit the observed reflectance data. The mean slope angle is related to roughness, so varying this parameter reveals differences in roughness between the HR-BZ and background. We vary $b$ and $c$ (see Section 2.2.4) between the HR-BZ and background, because these parameters are sensitive to changes in backscattering characteristics and grain shape.

When $I/F$ values are normalized to the Lommel-Seeliger function (reduced reflectance) and viewing geometry is partially accounted for, reflectance decreases with increasing phase angle – a trend commonly seen for planetary surfaces and a trend we expect to see with the NAC images (Figure 2.12; Goguen et al., 2010). Figure 2.16 shows preliminary attempts to fit the blast zone and background reflectance data for Apollo 12 and Apollo 16 by varying parameters in Equation (1). The single scattering albedo $w$ will vary for each site since composition and grain size differences exist across the different landing sites. For Apollo 12, a $w$ of 0.305 was used. For the HR-BZ, the mean slope angle that provided the best fit was $2^\circ$, whereas for the background a value of $23^\circ$ provided the best fit. The values of $b$ and $c$ within the double Henyey-Greenstein function (Equation 3) also varied between the HR-BZ and background for Apollo 12. All parameter values are listed in Table 2.5. No LROC reflectance values are plotted for high phase angles at Apollo 12 because the effects of local topography (especially within Surveyor Crater) begin to dominate the reflectance values as phase angle reaches values of $80^\circ$ and higher.

Apollo 16, Luna 20, and Surveyor 7 consistently have higher $I/F$ values than the other landing sites because they landed in the feldspathic highlands, which have an increased proportion of plagioclase grains that are naturally more reflective than Fe-bearing silicates and oxides that dominate the mare regolith. Consequently, a higher $w$ is used for the Apollo 16 model fits. We use a $w$ value of 0.48 and hold this value constant for the HR-BZ and background. The
mean slope angle for the best fit is 15° for the HR-BZ and 25° for the background. The values of $b$ and $c$ are also varied because these parameters depend on backscattering characteristics and grain shape (see Table 2.5), specifically the shape ($b$) and amplitude ($c$) of the forward- and backscattered lobes (Hapke, 2012).

For this model, changing the mean slope angle (and therefore the shadowing function) has the largest effect on the shape of the fitting curve. A higher mean slope angle corresponds to a rougher surface, and because smaller $\theta$ values are used for the HR-BZ for both model fits, we infer that macroscopic smoothing occurred within the HR-BZs, causing them to be more reflective. Changing $b$ and $c$ between the HR-BZ and background also gave better fits. The value of $b$ is lower in the HR-BZs compared to the background, indicating that particles there are scattering light more isotropically (Hapke, 2012); i.e. the HR-BZs are less backscattering than the background areas, consistent with inferences from the phase ratio images that the HR-BZs and background areas have different light scattering characteristics.

It is also possible to obtain good model fits by holding $\theta$ constant across the HR-BZ and background and instead varying $w$, $b$, and $c$. We used least squares fit regression and found that the fits for the two modeling methods were nearly identical, so we can not rule out the possibility of redistribution of fines based on modeling alone. It is possible that a combination of redistribution of fines and surface smoothing occurred within the HR-BZs.

The effects of viewing geometry are clearly seen in the Apollo 12 reflectance plots in Figure 2.13. Images with a backward scattering viewing geometry ($g < i$) tend to have higher $I/F$ values at lower incidence angles than those with a forward scattering viewing geometry ($g > i$) at the same incidence angle (Figure 2.12a). The reflectance values converge at higher incidence angles; i.e. approaching 90°. When plotting $I/F$ as a function of phase angle (Figure 2.13b),
variations still occur in the data owing to the effects of viewing geometry. To eliminate the scatter, we plot instead the reduced reflectance, which partially corrects for the emission and incidence angles, and minimizes the effects of variable viewing geometry. Figure 2.13c shows the smoother curve that results when plotting reduced reflectance as a function of phase angle. Figure 2.17 shows reflectance data for images taken in subsequent orbits, where the spacecraft was slewed to obtain images with differing emission angles at a relatively constant incidence angle. Images taken with a backward scattering viewing geometry (i.e., $g \sim |i-e|$) yield higher $I/F$ values for the HR-BZs. Each set of images had similar incidence angles (~40° for the first set of observations, DOY 2013-032, and ~13° for the second set, DOY 2013-059), but the variation in $I/F$ values results from changing emission angles (and, consequently, changes in phase angle) and backscattering characteristics between HR-BZ and background areas.

Using photometry data that cover a range of illumination conditions, including conditions where $g \sim i+e$ and where $g \sim |i-e|$, we observe that the increase in HR-BZ reflectance relative to background for each site is greater as $g$ increases from low values (near $g=0^\circ$) to about $g=70^\circ$ (Figure 2.13c). In what follows we will consider several hypotheses to account for the HR-BZ increased reflectivity. We will interpret our observations in terms of surface roughness, particle size, and backscattering character. We interpret the increase in reflectance within the HR-BZs as consistent with a reduction of the backscattering character of the regolith within the HR-BZ as would occur by smoothing and perhaps also destruction of fine-scale roughness. Photometric modeling supports this conclusion; discussed above. Photometric modeling is also consistent with removal of fine particles from the LR-BZ and deposition on the surface of the HR-BZ. Small particles have a higher single scattering albedo and are less backscattering than large particles. Thus the photometric relations alone are not sufficient to eliminate either of these two
hypotheses. For rougher terrain, larger shadows would be cast at higher incidence angles, and therefore we would expect to see a larger separation between the HR-BZ and background with increasing phase angle if the HR-BZ has been smoothed. Plotting HR-BZ reflectance normalized to the background reflectance as a function of phase angle, as seen in Figure 2.18, also shows this trend. As phase angle increases, there is a systematic increase in normalized reflectance owing to the increase in separation between HR-BZ and background values. The correlation for Figure 2.18, which shows Apollo 12 data, is very high (0.93). Table 2.6 shows the least squares best fit slope and intercept for the HR-BZ reflectance data normalized to the background as a function of phase angle for each Apollo site. The same trend is seen for all of the Apollo sites, with correlations ranging between 0.51 and 0.93 (see Appendix C).

2.4.5 Blast Effects Simulations

The process of exhaust plume impingement has been modeled using computational fluid dynamics (CFD) and direct simulation Monte Carlo (DSMC) numerical modeling for the Apollo landings (Lane et al., 2008; Lane et al., 2010; Metzger et al., 2010). Although it is known that regolith was disturbed in some fashion during descent, it has proven difficult to determine what physical properties of the regolith changed as a result of interaction with the exhaust plume. Experiments and fluid dynamics modeling provide some insights.

Beneath the rocket exhaust nozzle, a bowl-shaped shockwave forms. Directly under this shockwave is a stagnation region where the gas is hot, dense, and subsonic. In this region, the kinetic energy of the exhaust is converted into thermal energy and the gas diffuses into the regolith. As the landers descended and more gas flowed into the regolith, pressure built up in the regolith and clumps of soil erupted and were caught up in the exhaust flow, leading to stripping of material from the surface in the region below the engine nozzles (as mentioned in Section
2.4.3), as well as pitting and clumping. Beneath the nozzle, as well as in the stagnation region below the shockwave that forms, the gas flow is nonturbulent. Radially away from the nozzle, the gas cools and rarefies, allowing its horizontal velocity to increase and become supersonic. The turbulent gas flow develops a boundary layer over the surface of the soil, and soil is lifted up into this boundary layer, where the gas velocity and density are high. Turbulence in the gas likely contributes to the lift of the particles. The smallest particles that were close to the nozzle and lifted into the exhaust plume are blown at velocities reaching up to 3 km/s, in some cases exceeding the 2.4 km/s escape velocity of the Moon (Lane et al., 2008; Metzger et al., 2009; Metzger et al., 2011).

The highest turbulence and shear stress would have been located in an annular region away from the LM, on the order of a few meters (Metzger et al., 2011). The shear stress on the soil would be at a maximum at some finite horizontal distance from the rocket nozzle, with the location of the maximum depending on the height of the lander above the surface. This boundary would have been the region of maximum viscous erosion and probably became smaller in diameter and intensified as the landers approached the surface. As the plume encounters local topography, eddies and turbulent boundary layers form and smoothing of small-scale (cm to m) topography occurs. Figure 2.19 shows a schematic diagram of plume exhaust effects and particle entrainment based on descriptions and results of blast-effect simulations.

Digitized Apollo Lunar Module descent videos show large quantities of dust – sheets about 3° in angular thickness and containing $10^8$-$10^{13}$ particles/m$^3$ - being blown radially away from the descent engines, and many researchers (Immer et al., 2008; Metzger et al., 2010) have assumed that the majority of loose, fine particles (dust to sand-sized) in the upper few cm of regolith in the area surrounding the LM were blown several kilometers away, leaving the coarser,
presumably more compact, underlying soil exposed (Immer et al., 2008). Blast-effect simulations and analysis of damage to Surveyor 3 argue against the redistribution of fine particles within distances as small as what we measure for the bright annuli of the blast zones (see Metzger et al., 2010; Immer et al., 2011; Metzger et al., 2011; LaMarche et al., 2012).

The dynamic pressure of the gas upon the surface was likely enough to destroy the fairy-castle structure of the regolith, but may not have been enough to compact the surface because the static pressure was very small at only a meter or two away from the rocket nozzle (Metzger et al., 2011). Hinners and El-Baz (1972) reported that the dynamic pressure of the gas (for Apollo) would have been around 6890 N/m² and large enough to decrease the porosity, but no analysis has been done to show that this effect would have been effective at distances away from the landers as great as those seen for the blast zones (Metzger et al., 2011). Metzger et al. (2011) suggested that the rocket exhaust may have destroyed the fine fairy-castle structure in the blast zone area, which would cause the surface to become more reflective and less backscattering because of decreased porosity.

Frequent particle-particle collisions within the gas plume may allow for some particles to resettle at much shorter distances than indicated by laminar flow modeling (Metzger et al., 2011; Berger et al., 2013). Within the plume, lift and drag dominate over gravity in the region near the lander, so particles do not fall back to the surface apart from fallback after interparticle collisions. Recent modeling has shown that as many as 20% of the particles within the exhaust plume are involved in collisions at a given time, and that these collisions affect the erosion rate (rate at which particles are lifted off the surface by the plume) of the soil (Berger et al., 2013). Soil erosion experiments done at Mauna Kea in Hawaii by Metzger et al. (2011) showed preferential redeposition of fine particles near the nozzle, as well as increased brightening due to
an added layer of fine dust. Particles less than 10 µm are more difficult to lift from the surface into the boundary layer flow because of cohesion, therefore fine particles remain closer to the surface and are more easily redistributed (Lane et al., 2008, 2010; Metzger et al., 2011). Metzger et al. (2011) suggest that the impact and deposition of dust beneath the main sheet of spray is probably the main cause of increased brightness around the landing sites. As dust is being redeposited a thin coating is created, and the surface becomes aerodynamically smoothed, allowing for a smoother gas flow and lower shear stress in the region of exhaust flow. The effects of particle-particle collisions need to be investigated further before any definitive conclusions can be made regarding their role in the redeposition of fine particles within the HR-BZs, but it is likely that they play an important role in the dynamics of dust interaction within the exhaust plume and with the surface.

The physics of the process of erosion by rocket exhaust is poorly understood even on Earth, and becomes even more complicated in extreme environments such as the high vacuum of the lunar surface. The effects of poor sorting of lunar soil and high cohesion of the particles have not been adequately explored in simulations, and a better understanding of how these characteristics affect the interactions between the exhaust plume and particulates may lead to a better understanding of surface erosion and particle distribution during powered descents on the Moon.

2.5 Conclusions

Both LROC NAC images and photometric analysis reveal that there are regions of changed reflectance around the Apollo, Surveyor, and Luna landers, created by disturbance resulting from rocket exhaust. Most notable are areas of increased reflectance that are readily visible in many NAC images and enhanced in phase-ratio images. Table 2.7 lists a truth table for the hypotheses
we have considered. The table indicates whether a test has classified the hypothesis as a likely or unlikely cause for the increased reflectance. Surface smoothing, destruction of the fairy-castle structure, redistribution of fine particles within the HR-BZ, or a combination of these processes are likely causes of increased reflectance visible around the landers.

The largest blast zones, those of Apollo, were measured to be only ~150 – 260 m in diameter, but modeling and analysis of dust particle velocities and trajectories indicate that most particles probably traveled kilometers and some may even have reached the escape velocity of the Moon. However, observations at Earth-bound test sites indicate that some mechanism of particle interactions in the exhaust-driven dust plumes leads to redeposition of fines near the landers. Such turbulent interactions are not yet well understood. Moreover, photometric modeling does not exclude the possibility that redistribution of fines within the HR-BZ contributes to the increased reflectance. Exposure of less mature soil is also not likely since the rocket exhaust only excavated the first few centimeters of regolith and did not excavate regolith to depths that would be needed to expose significant changes in maturity (>20 cm) (Lucey et al, 2006; Shkuratov et al, 2012), especially more than a few meters away from the landers.

Smoothing of the surface (macroscopic roughness) and destruction of the fine-scale roughness of the regolith (including fairy-castle structure, which is commonly thought to be key in the highly backscattering character of lunar regolith) are supported by the photometric characteristics and modeling, by lunar surface photographs, and by exhaust-flow modeling. Smoothing of the surface as the main cause of the HR-BZ was also supported by the considerations of Kaydash et al. (2011) and by Shkuratov et al. (2012).
References


NASA Manned Space Center, 1969. Apollo 12 technical air-to-ground voice transcription, pp. 348, 409, 436, Houston, TX.


Figure 2.1: Apollo 11 landing site, with LR-BZ and HR-BZ outlined. NAC Image M150361817R.
Figure 2.2: Schematic illustrating incidence (i), emission (e), and phase (g) angles. (a) Forward scattering viewing geometry where i and e are on opposite sides of the surface normal; g~i+e. (b) Backward scattering viewing geometry where i and e are on the same side of the surface normal; g~|i-e|. Both schematics are the projection of solid angle onto a plane.
Figure 2.3: Phase-ratio image for the Apollo 12 landing site compared with the original NAC image. (a) Original NAC image, M114319742R \((i = 39.8^\circ, g = 51.3^\circ)\). Inset shows viewing geometry for the image. (b) M111433947R \((i = 41.8^\circ, g = 17.0^\circ)\) divided by M114319742R.
Figure 2.4: (a) Example of background I/F determination for NAC images – two large rectangular regions are selected far outside the BZ using ISIS and the average I/F value is returned. Apollo 17, NAC image M190394800R. (b) Histogram showing frequency of I/F values within the lower rectangular background region.

- Mean: 0.034
- St. Dev: 0.0017
Figure 2.5: Original NAC images of each Apollo landing site, cropped to the region around the LM and with important features labeled. Dashed lines outline the outer extent of each blast zone (HR-BZ). a) Apollo 11, image M150361817R. b) Apollo 12 and Surveyor 3, image M120005333L. c) Apollo 14, image M11406206L. d) Apollo 15, image M119822622L. e) Apollo 16, image M152770233R. f) Apollo 17, image M113758461R.
Figure 2.6: NAC images of the Surveyor landing sites (excluding Surveyor 3, which is grouped with Apollo 12), with blast zones highlighted. a) Surveyor 1, image M122495769L. b) Surveyor 5, image M106726943L. c) Surveyor 6, image M117501284L. d) Surveyor 7, image M17355093L.
Figure 2.7: NAC images of the Luna landing sites, with blast zones highlighted. a) Luna 16, image M159582808L. b) Luna 17, image M114185541R. c) Luna 20, image M119482862R. d) Luna 23, image M174868307R. e) Luna 24, image M174868307L.
Figure 2.8: Images of Surveyor Crater before and after the Surveyor III and Apollo 12 landings. Arrows indicate the Intrepid lander and the Surveyor III spacecraft. (a) Lunar Reconnaissance Orbiter Camera image M1108432631R, $i = 68.8^\circ$, $g = 67.6^\circ$. Note that Surveyor Crater is more reflective in the LROC image, especially in the shadowed region. (b) Lunar Orbiter 3 image LO3-154-H2, $i = 67.21^\circ$, $g = 68.76^\circ$. 
Figure 2.9: (a) Apollo 11 surface photograph showing Buzz Aldrin, footpad, and disturbed areas close to the lander and an area of increased reflectance, indicated by the arrows, behind Aldrin. NASA Photo AS11-40-5902. Image Credit: NASA, scan by Kipp Teague and Ed Hengeveld. (b) Apollo 11 surface photograph showing region below the LM rocket nozzle, indicating areas that have been roughed up and/or possibly smoothed by the exhaust plume.
Figure 2.10: Reflectance profiles for the Apollo 11 landing site, NAC image M150361817R.  
a) Horizontal reflectance profile path taken across the Apollo 11 landing site.  b) Plot of reflectance values across the horizontal profile, with important features highlighted.  c) Profile across the Apollo 11 landing site, drawn so as to avoid craters and local topography.  d) Plot of reflectance values across the carefully drawn profile path.
Figure 2.11: Reflectance profiles for Surveyor and Luna. a) Linear profile taken across the Luna 23 landing site. NAC image M106468527R (i = 33°, g = 32°).  b) Plot of reflectance values across the Luna 23 profile. Solid lines indicate average I/F within the blast zone, dashed lines indicate average I/F for the background. c) Linear profile taken across the Surveyor 1 landing site. NAC image M122495769L (i = 23°, g = 27°). d) Plot of reflectance values across the Surveyor 1 profile.
Figure 2.12: a) Systematic variation in reflectance ($I/F$) as function of phase angle for the blast zones. b) Normalized reflectance as a function of phase angle. Values greater than 1 indicate that the blast zone is more reflective than the background undisturbed regions measured at the
same phase angle. Normalized reflectance values exhibit a linear increase as phase angle increases with the sole exception of the Surveyor 7 landing site, which shows the opposite trend. The reason for this opposite behavior is unclear, but this landing site probably exhibits the thinnest regolith owing to the fact that it is located in the impact-melt flow deposits north of Tycho Crater. c) Reduced reflectance as a function of phase angle, showing compositional differences between landing sites. Apollo 16, Luna 20, and Surveyor 7 regolith is significantly richer in plagioclase and thus have higher I/F values than the other sites.
Figure 2.13: Effects of viewing geometry on reflectance values, shown for the Apollo 12 landing site. a) Apollo 12 reflectance versus incidence angle, showing the separation between images with a forward scattering viewing geometry (g~i+e) and those with a backward scattering
viewing geometry (g~i-e). b) Apollo 12 reflectance versus phase angle, again showing the lack of a smooth curve due to viewing geometry differences. c) Apollo 12 reduced reflectance as a function of phase angle, which masks the effects of viewing geometry and creates a smoother curve. Also note the increased separation between blast zone and background reflectance values at higher phase.
Figure 2.14: Variation in regolith maturity with depth in Apollo cores. Modified from Lucey et al. (2006).

Figure 2.15: Images showing that single bootprints compact and smooth regolith and increase the reflectance inside the bootprint. (a) NASA Photo AS11-40-5877HR. Image Credit: NASA, image scan by Kipp Teague. (b) NASA Photo AS17-134-20492HR. Image Credit: NASA, image scan by Kipp Teague.
Figure 2.16: Preliminary photometric modeling done to fit reflectance data for Apollo 12 and Apollo 16.  

a) Apollo 12 blast zone and background data fitted using Hapke photometric functions. Mean slope angle ($\theta$) is $2^\circ$ for BZ and $23^\circ$ for background. 

c) Apollo 16 blast zone and background data fitted using Hapke photometric functions, $\theta=15^\circ$ for BZ and $25^\circ$ for background.
Figure 2.17: Apollo 12 reflectance data for two sets of observations in which the spacecraft was slewed in subsequent orbits to obtain images with varying emission angles. The spread in reflectance at similar incidence angles is due to changing emission and phase angles, with the higher I/F values occurring for images with a greater backscattering viewing geometry where $i$ and $e$ are on the same side of the surface normal; $g \sim |i-e|$. Images taken on DOY 2013-032 ($i \sim 40^\circ$) and 2013-059 ($i \sim 13^\circ$).
Figure 2.18: Apollo 12 normalized reflectance (HR-BZ values normalized to the background) as a function of phase angle. The increasing trend is due to separation between HR-BZ and background values increasing at increasing phase angle.
Figure 2.19: Schematic drawing representing different regimes of exhaust flow and interaction with surface. Beneath the nozzle, a bowl-shape shock wave forms. Point A represents the impingement point below the shock wave, along the plume centerline. Beneath the shock wave is a stagnation region where the gas is dense and subsonic. In this region, pitting, clump lifting, and shear failure may occur before and during engine shutoff as gas diffuses into the regolith and then erupts. The gas cools radially away from the nozzle and its horizontal velocity increases and becomes supersonic (Metzger et al., 2011). The region of maximum viscous erosion, where particles are swept away by the tangential gas velocity, occurs at some finite distance from the lander (on the order of a few meters). This region is also where the maximum shear stress (B) occurs. Local scouring occurs along the surface (C) and particles are lofted into a boundary layer over the surface and into the high velocity gas above the surface. Particles are entrained in the plume (D), and some experience collisions. As the plume encounters local topography, turbulent boundary layers and eddies form (E). Smoothing of small-scale topography (F) occurs in these regions as the gas flows across the surface. Some particles that undergo collisions are subsequently redep osited within the HR-BZ (G), while others remain entrained and may be transported kilometers away (H), or may even reach escape velocity (Lane et al., 2008).
Tables

Table 2.1: List of images used to create phase-ratio images for each Apollo landing site

<table>
<thead>
<tr>
<th>Image #</th>
<th>Orbit</th>
<th>Day of Year (DOY)</th>
<th>Center Latitude</th>
<th>Center Longitude</th>
<th>i (degrees)</th>
<th>e (degrees)</th>
<th>g (degrees)</th>
<th>Resolution (m/pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Apollo 11</strong></td>
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<td></td>
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<tr>
<td>M150361817R</td>
<td>7293</td>
<td>2011-022</td>
<td>0.79</td>
<td>23.49</td>
<td>62.61</td>
<td>9.39</td>
<td>71.99</td>
<td>0.47</td>
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<td>M150368601R</td>
<td>7294</td>
<td>2011-022</td>
<td>0.76</td>
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<td>63.51</td>
<td>31.88</td>
<td>31.64</td>
<td>0.54</td>
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<tr>
<td><strong>Apollo 12</strong></td>
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</tr>
<tr>
<td>M120012135R</td>
<td>2819</td>
<td>2010-036</td>
<td>-2.58</td>
<td>336.55</td>
<td>53.05</td>
<td>21.24</td>
<td>31.87</td>
<td>0.52</td>
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<td>M120005333L</td>
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<td>2010-036</td>
<td>-3.44</td>
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<td>52.11</td>
<td>21.33</td>
<td>73.40</td>
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<td>M109386083R</td>
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<td>-3.02</td>
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<td>-2.57</td>
<td>336.58</td>
<td>3.90</td>
<td>27.13</td>
<td>30.92</td>
<td>0.54</td>
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<td>M114064206L</td>
<td>1943</td>
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<td>57.86</td>
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<td>1944</td>
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<td>M111708164L</td>
<td>1596</td>
<td>2009-305</td>
<td>-3.80</td>
<td>342.53</td>
<td>29.87</td>
<td>3.74</td>
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<td>M127049821R</td>
<td>3856</td>
<td>2010-117</td>
<td>-4.10</td>
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<td>29.12</td>
<td>14.53</td>
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<td>-3.56</td>
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<td>5.29</td>
<td>1.16</td>
<td>4.28</td>
<td>0.50</td>
</tr>
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<td>M124687860R</td>
<td>3508</td>
<td>2010-090</td>
<td>-4.08</td>
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<td>5.98</td>
<td>1.95</td>
<td>5.52</td>
<td>0.48</td>
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<tr>
<td>M119829425L</td>
<td>2793</td>
<td>2010-034</td>
<td>26.56</td>
<td>3.60</td>
<td>58.21</td>
<td>17.75</td>
<td>41.45</td>
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<td>M119822622L</td>
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<td>57.18</td>
<td>18.71</td>
<td>75.24</td>
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<td></td>
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<tr>
<td>M152777016R</td>
<td>7648</td>
<td>2011-050</td>
<td>-9.10</td>
<td>15.52</td>
<td>36.10</td>
<td>20.47</td>
<td>17.13</td>
<td>0.50</td>
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<tr>
<td>M152770233R</td>
<td>7647</td>
<td>2011-050</td>
<td>-9.09</td>
<td>15.51</td>
<td>35.19</td>
<td>22.89</td>
<td>57.55</td>
<td>0.51</td>
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<tr>
<td><strong>Apollo 17</strong></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>M113751661L</td>
<td>1897</td>
<td>2009-329</td>
<td>20.61</td>
<td>30.85</td>
<td>56.73</td>
<td>18.86</td>
<td>38.80</td>
<td>0.53</td>
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<tr>
<td>M113758461R</td>
<td>1898</td>
<td>2009-329</td>
<td>19.78</td>
<td>30.76</td>
<td>55.72</td>
<td>14.88</td>
<td>70.17</td>
<td>0.51</td>
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</table>
Table 2.2: Average blast zone measurements and reflectance values for each landing site.

Average $I/F$ values for each region are for phase angles of 30°.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Average $I/F$ for HR-BZ</th>
<th>Average $I/F$ for LR-BZ</th>
<th>Average background $I/F$</th>
<th>Average normalized $I/F^a$</th>
<th>Elliptical Area (m$^2$)</th>
<th>Lander Mass (kg)</th>
<th>Average Thrust$^b$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap11</td>
<td>0.028</td>
<td>0.009</td>
<td>0.027</td>
<td>1.151</td>
<td>25403</td>
<td>15095</td>
<td>42.5</td>
</tr>
<tr>
<td>Ap12$^c$</td>
<td>0.054</td>
<td>0.053</td>
<td>0.050</td>
<td>1.123</td>
<td>53872</td>
<td>15235</td>
<td>42.8</td>
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<tr>
<td>Ap14</td>
<td>0.062</td>
<td>0.061</td>
<td>0.056</td>
<td>1.134</td>
<td>21339</td>
<td>15264</td>
<td>42.9</td>
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<tr>
<td>Ap15</td>
<td>0.041</td>
<td>0.031</td>
<td>0.036</td>
<td>1.185</td>
<td>18725</td>
<td>16600</td>
<td>46.7</td>
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<tr>
<td>Ap16</td>
<td>0.099</td>
<td>0.073</td>
<td>0.095</td>
<td>1.110</td>
<td>34483</td>
<td>16660</td>
<td>46.8</td>
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<tr>
<td>Ap17</td>
<td>0.032</td>
<td>0.023</td>
<td>0.029</td>
<td>1.153</td>
<td>18888</td>
<td>16658</td>
<td>42.5</td>
</tr>
<tr>
<td><strong>Apollo</strong> avg</td>
<td><strong>0.053</strong></td>
<td><strong>0.042</strong></td>
<td><strong>0.042</strong></td>
<td><strong>1.085</strong></td>
<td><strong>28785</strong></td>
<td><strong>15919</strong></td>
<td><strong>45.0</strong></td>
</tr>
<tr>
<td>L16</td>
<td>0.041</td>
<td>–</td>
<td>0.037</td>
<td>1.108</td>
<td>3355</td>
<td>5600</td>
<td>15.9</td>
</tr>
<tr>
<td>L17</td>
<td>0.038</td>
<td>–</td>
<td>0.036</td>
<td>1.056</td>
<td>1889</td>
<td>5700</td>
<td>16.2</td>
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<tr>
<td>L20</td>
<td>0.076</td>
<td>–</td>
<td>0.070</td>
<td>1.086</td>
<td>2166</td>
<td>5600</td>
<td>15.9</td>
</tr>
<tr>
<td>L23</td>
<td>0.041</td>
<td>–</td>
<td>0.037</td>
<td>1.108</td>
<td>2105</td>
<td>5800</td>
<td>16.4</td>
</tr>
<tr>
<td>L24</td>
<td>0.038</td>
<td>–</td>
<td>0.033</td>
<td>1.152</td>
<td>987</td>
<td>5800</td>
<td>16.4</td>
</tr>
<tr>
<td><strong>Luna</strong> avg</td>
<td><strong>0.047</strong></td>
<td>–</td>
<td><strong>0.043</strong></td>
<td><strong>1.102</strong></td>
<td><strong>2100</strong></td>
<td><strong>5700</strong></td>
<td><strong>16.2</strong></td>
</tr>
<tr>
<td>S1</td>
<td>0.039</td>
<td>–</td>
<td>0.036</td>
<td>1.083</td>
<td>197</td>
<td>292</td>
<td>–</td>
</tr>
<tr>
<td>S5</td>
<td>0.044</td>
<td>–</td>
<td>0.040</td>
<td>1.100</td>
<td>131</td>
<td>303</td>
<td>–</td>
</tr>
<tr>
<td>S6</td>
<td>0.044</td>
<td>–</td>
<td>0.040</td>
<td>1.100</td>
<td>252</td>
<td>299.6</td>
<td>–</td>
</tr>
<tr>
<td>S7</td>
<td>0.070</td>
<td>–</td>
<td>0.068</td>
<td>1.029</td>
<td>279</td>
<td>305.7</td>
<td>–</td>
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<tr>
<td><strong>Surv.</strong> avg</td>
<td><strong>0.049</strong></td>
<td>–</td>
<td><strong>0.046</strong></td>
<td><strong>1.078</strong></td>
<td><strong>215</strong></td>
<td><strong>300.1</strong></td>
<td><strong>0.133-0.472</strong></td>
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</tbody>
</table>

$^a$Normalized $I/F = IoF_{bz}/IoF_{background}$ (for HR-BZs)

$^b$Calculated from average Apollo, Luna, and Surveyor thrust values

$^c$Apollo 12 measurements include Surveyor Crater (and therefore Surveyor 3 BZ)
Table 2.3: Soil sample data from inside and outside the blast zone for the Apollo landing sites.

<table>
<thead>
<tr>
<th>Apollo Mission</th>
<th>Sample Number</th>
<th>Sample Type</th>
<th>Mean Grain Size&lt;sup&gt;a&lt;/sup&gt; (µm)</th>
<th>I&lt;sub&gt;s&lt;/sub&gt;/FeO&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inside Blast Zone</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>10084,79</td>
<td>surface soil, 5m north of LM</td>
<td>85.38</td>
<td>48</td>
</tr>
<tr>
<td>12</td>
<td>12001,7</td>
<td>surface soil, 30m NW of LM</td>
<td>63.62</td>
<td>56</td>
</tr>
<tr>
<td>12</td>
<td>12001,62</td>
<td>surface soil, 30m NW of LM</td>
<td>48.14</td>
<td>56</td>
</tr>
<tr>
<td>12</td>
<td>12070,104</td>
<td>surface sample 15m NW of LM</td>
<td>44.57</td>
<td>47</td>
</tr>
<tr>
<td>14</td>
<td>14259,(52,64,88)</td>
<td>surface sample 100m WNW of LM</td>
<td>52.77</td>
<td>85</td>
</tr>
<tr>
<td>14</td>
<td>14163,(76,120)</td>
<td>surface sample 15m NW of LM</td>
<td>44.75</td>
<td>57</td>
</tr>
<tr>
<td>14</td>
<td>14003,23</td>
<td>contingency sample collected NW of LM</td>
<td>38.27</td>
<td>66</td>
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<tr>
<td>15</td>
<td>15041,(34,78)</td>
<td>top of trench, near surface</td>
<td>37.79</td>
<td>94</td>
</tr>
<tr>
<td>15</td>
<td>15013,94</td>
<td>Under bell of LM descent engine, top soil&lt;sup&gt;c&lt;/sup&gt;</td>
<td>35.22</td>
<td>77</td>
</tr>
<tr>
<td>15</td>
<td>15021,38</td>
<td>12m from LM, surface</td>
<td>37.07</td>
<td>70</td>
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<tr>
<td>16</td>
<td>60051,2</td>
<td>surface sample, 170m S-SW of LM</td>
<td>52.93</td>
<td>45</td>
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<tr>
<td>16</td>
<td>60501,1</td>
<td>surface sample, 100m SW of LM</td>
<td>40.39</td>
<td>80</td>
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<tr>
<td>17</td>
<td>70161,1</td>
<td>180m W of LM, very edge of BZ</td>
<td>56.69</td>
<td>46</td>
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<tr>
<td>17</td>
<td>70181,1</td>
<td>surface soil at ALSEP</td>
<td>52.42</td>
<td>47</td>
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<tr>
<td><strong>average</strong></td>
<td></td>
<td></td>
<td><strong>49.29</strong></td>
<td><strong>62.43</strong></td>
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<tr>
<td><strong>Outside Blast Zone</strong></td>
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<tr>
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<td>surface sample 50m E of Bench crater</td>
<td>44.78</td>
<td>63</td>
</tr>
<tr>
<td>14</td>
<td>14148,(22,23)</td>
<td>from top of trench, 30m NE of N Triplet Crater</td>
<td>50.70</td>
<td>74</td>
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<tr>
<td>15</td>
<td>15091,(1,34)</td>
<td>surface soil at station 2</td>
<td>35.53</td>
<td>74</td>
</tr>
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<td>15</td>
<td>15071,19</td>
<td>surface sample</td>
<td>58.26</td>
<td>52</td>
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<td>15</td>
<td>15012,136</td>
<td>bottom of trench</td>
<td>37.55</td>
<td>66</td>
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<tr>
<td>16</td>
<td>63321,14</td>
<td>from shadowed region of a rock, station 13</td>
<td>65.41</td>
<td>47</td>
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<td>16</td>
<td>68501,33</td>
<td>surface sample between two 15m craters</td>
<td>62.55</td>
<td>85</td>
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<tr>
<td>16</td>
<td>63501,30</td>
<td>reference soil at station 13, no craters</td>
<td>80.42</td>
<td>46</td>
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<td>16</td>
<td>69941,15</td>
<td>in shadow of boulder, station 9</td>
<td>49.64</td>
<td>85</td>
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<tr>
<td>17</td>
<td>76261,26</td>
<td>surface soil at station 6, 2cm depth</td>
<td>49.02</td>
<td>58</td>
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<td>17</td>
<td>78501,25</td>
<td>surface soil at station 8</td>
<td>37.95</td>
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<td>17</td>
<td>78261,6</td>
<td>surface soil at station 6, 5cm scoop</td>
<td>33.32</td>
<td>45</td>
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<td>17</td>
<td>78481,27</td>
<td>upper 1cm of trench at station 8</td>
<td>41.09</td>
<td>82</td>
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<tr>
<td><strong>average</strong></td>
<td></td>
<td></td>
<td><strong>49.71</strong></td>
<td><strong>62.54</strong></td>
</tr>
</tbody>
</table>

<sup>a</sup>For <250µm size range

<sup>b</sup>I<sub>s</sub>/FeO = concentration of nanophase iron (Is) normalized to the total iron content (FeO). Higher values indicate more mature soils.

<sup>c</sup>Location comments: “Contaminated”
Table 2.4: Descent observations of blowing dust reported by astronauts during each Apollo landing.

<table>
<thead>
<tr>
<th>Apollo Mission</th>
<th>Descent Observations</th>
<th>References</th>
</tr>
</thead>
</table>
| 11             | 1. Dust began blowing at an altitude of 100 ft  
                2. Blowing dust obscured visibility and the astronauts could not determine lateral velocities  
                3. Dust sheet was moving at a fast rate and masked the ability to detect motions | Armstrong et al. (1969); Harland (2008) |
| 12             | 1. “Tremendous amount” of dust picked up at 300 ft altitude – higher than reported for Apollo 11  
                2. LM hovered over Surveyor Crater at 100m altitude and tilted back and forth. Astronauts couldn’t obtain attitude references.  
| 14             | 1. Dust was obvious around 100 ft altitude  
                2. Less of a problem with dust than previous two missions | Shepard et al. (1971) |
| 15             | 1. Dust began blowing around 120 ft altitude  
                2. Surface was completely obscured and no rocks were visible through dust sheet | Harland (2008) |
| 16             | 1. Dust began blowing at 80 ft altitude  
                2. A 15 m crater in the distance “disappeared” under the dust cloud  
                3. LM hovered around 40 ft altitude, “well into the dust”  
                4. “There’s plenty of dust down there to blow” – John Young | McDivitt et al. (1972); Harland (2008) |
| 17             | 1. Thin layer of dust around 60-70 ft altitude  
                2. Didn’t hamper operations  
                3. Could see through dust layer all the way down, visibility was excellent | McDivitt et al. (1973); Cernan et al. (1973) |
Table 2.5: Parameters used in Equations (3) and (5) to obtain fits for the Apollo 12 and Apollo 16 reflectance data.

<table>
<thead>
<tr>
<th></th>
<th>$w$</th>
<th>$\theta$</th>
<th>$b$</th>
<th>$c$</th>
<th>$B_{co}$</th>
<th>$h_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Apollo 12</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR-BZ</td>
<td>0.305</td>
<td>2°</td>
<td>0.35</td>
<td>-0.20</td>
<td>0.77</td>
<td>0.107</td>
</tr>
<tr>
<td>Background</td>
<td>0.305</td>
<td>23°</td>
<td>0.40</td>
<td>-0.25</td>
<td>0.77</td>
<td>0.107</td>
</tr>
<tr>
<td><strong>Apollo 16</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR-BZ</td>
<td>0.48</td>
<td>15°</td>
<td>0.40</td>
<td>-0.20</td>
<td>0.58</td>
<td>0.107</td>
</tr>
<tr>
<td>Background</td>
<td>0.48</td>
<td>25°</td>
<td>0.43</td>
<td>-0.22</td>
<td>0.58</td>
<td>0.107</td>
</tr>
</tbody>
</table>

Table 2.6: Least squares best-fit slope, intercept, and correlation for HR-BZ reflectance data normalized to background reflectance as a function of phase angle

<table>
<thead>
<tr>
<th>Mission</th>
<th>Slope</th>
<th>Y-Intercept</th>
<th>$R^2$</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap11</td>
<td>0.0025</td>
<td>1.035</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Ap12</td>
<td>0.0027</td>
<td>1.025</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>Ap14</td>
<td>0.0021</td>
<td>1.056</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Ap15</td>
<td>0.0041</td>
<td>0.961</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Ap16</td>
<td>0.0032</td>
<td>0.985</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Ap17</td>
<td>0.0021</td>
<td>1.042</td>
<td>0.73</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.7: Truth table indicating the current views on each hypothesis that is being tested to explain the increased reflectance seen around the Apollo landing sites.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Exhaust Plume Modeling</th>
<th>Core Sample Characteristics</th>
<th>Soil Data (grain size, I$_s$/FeO)</th>
<th>Surface Photography</th>
<th>Photometric Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Smoothing</td>
<td>Likely</td>
<td>—</td>
<td>—</td>
<td>Likely</td>
<td>Likely</td>
</tr>
<tr>
<td>Redistribution of Fines</td>
<td>Not Likely</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Likely</td>
</tr>
<tr>
<td>Compaction</td>
<td>Not Likely</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Not Likely</td>
</tr>
<tr>
<td>Exposure of less mature soil</td>
<td>Not Likely</td>
<td>Not Likely</td>
<td>Not Likely</td>
<td>Not Likely</td>
<td>Not Likely</td>
</tr>
<tr>
<td>Destruction of small-scale structure</td>
<td>Likely</td>
<td>—</td>
<td>—</td>
<td>Likely</td>
<td>Likely</td>
</tr>
</tbody>
</table>
Chapter 3: Photometric Characterization of the Chang'e-3 Landing Site using LROC NAC Images


Abstract

China’s robotic Chang'e-3 spacecraft, carrying the Yutu rover, touched down in Mare Imbrium on the lunar surface on 14 December 2013. The Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) imaged the site both before and after landing. Multi-temporal NAC images taken before and after the landing, phase-ratio images made from NAC images taken after the landing, and Hapke photometric techniques were used to evaluate surface changes caused by the disturbance of regolith at the landing site (blast zone) by the descent engines of the Chang'e-3 spacecraft. The reflectance of the landing site increased by 10% as a result of the landing, a value similar to reflectance increases estimated for the Apollo, Luna, and Surveyor landing sites. The spatial extent of the disturbed area at the Chang'e-3 landing site, 2530 m², also falls close to what is predicted on the basis of correlations between lander mass, thrust, and blast zone areas for the historic missions. A multi-temporal ratio image of the Chang'e-3 landing site reveals a main blast zone (slightly elongate in the N-S direction; ~75 m across N-S and ~43 m across in the E-W direction) and a diffuse, irregular halo of increased reflectance slightly larger and less reflective than the main blast zone (extending ~55–60 m in the N-S direction and ~10–15 m in the E-W direction). The N-S elongation of the blast zone likely results from maneuvering during hazard avoidance just prior to landing. The phase-ratio image reveals that the blast zone is less backscattering than surrounding undisturbed areas. The similarities in

² Author’s name changed after marriage, so publication submitted under Ryan Clegg-Watkins
magnitude of increased reflectance between the Chang'e-3 landing site and the Surveyor, Apollo, and Luna landing sites suggest that lunar soil reflectance changes caused by interaction with rocket exhaust are not significantly altered over a period of 40 to 50 years and are independent of regolith composition, indicating that the reflectance change is caused by a change in the physical properties of the regolith, likely microscopic to macroscopic smoothing of the surface, and possibly a change in surface maturity by removal of highly mature very fine-grained regolith components.

3.1 Introduction

On 14 December 2013, the Chinese Chang'e-3 (CE-3) spacecraft made the first soft landing on the Moon (44.121°N, 340.488°E; LROC derived coordinates) since the Soviet Luna 24 lander in 1976. The Chinese spacecraft landed 60 m east of the rim of a 450 m diameter impact crater (Li et al., 2014; Robinson et al., 2014). The vehicle consisted of a 1200 kg robotic lander and a 120 kg rover, Yutu, and is part of China’s Lunar Exploration Program (Ip et al., 2014). Both the lander and rover were equipped with eight scientific payload elements to image the surface, analyze compositional properties of the regolith, and investigate the subsurface structure of the regolith (Zhao et al., 2014).

On 24 December 2013, the Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) first captured images of the Chang'e-3 landing site that showed both the lander and the rover (Robinson et al., 2014; Wagner et al., 2014; Zhao et al., 2014). LRO passes over the Chang'e-3 landing site once a month and has acquired ~thirty-five (as of 10 March 2015) high-resolution NAC images over a range of viewing geometries. These images reveal an area of increased reflectance around the lander (Figure 3.1), which are interpreted as disturbances caused by interaction of rocket exhaust with the regolith, based on previous studies of spacecraft landing.
sites, which exhibit similar increased reflectance areas (Kaydash et al., 2011; Kaydash and Shkuratov, 2012; Clegg et al., 2014a). NAC photometric imaging observations provide the means to quantitatively investigate changes caused by the impingement of rocket exhaust on the regolith (“blast zones”) around the Apollo, Luna, and Surveyor landers (Hinners and El-Baz, 1972; Kreslavsky and Shkuratov 2001; Kreslavsky and Shkuratov, 2003; Kaydash et al., 2011; Kaydash and Shkuratov, 2012; Clegg et al. 2014a). Here we examine before and after images of the Chang'e-3 landing site (see Figure 3.2) to quantify changes in reflectance around the lander, and then we compare reflectance changes with those seen at the older landing sites.

3.2 Methods

NAC images acquired over a range of incidence angles (between surface normal and sub-solar vector, \( i \)) and emission angles (between surface normal and camera boresight, \( e \)) provide a record of reflectance both before and after the Chang'e-3 landing over a range of phase angles (the angle between \( i \) and \( e \) as viewed from the surface, \( g \)). Multi-temporal NAC ratio images taken before and after the landing and phase-ratio images made from NAC images taken after the landing were used to evaluate changes caused by the disturbance of regolith at the landing site by the descent engines of the CE-3 spacecraft. Images were processed and radiometrically calibrated using the USGS Integrated Software for Imagers and Spectrometers (ISIS) (Anderson et al., 2004). The images were corrected to radiance factor \( I/F \) (Robinson et al., 2010), the ratio of the radiance, \( I \), received at the detector viewing the surface (at angle, \( e \)) to the irradiance from a normally illuminated Lambertian surface, \( F \) (at an angle, \( i \) (source radiance divided by \( \pi \)) (Minnaert, 1961)).

In order to compare reflectance at the site before and after the Chang'e-3 landing, we used the same Hapke photometric function (see below) that was used to fit reflectance data for
the Apollo, Surveyor, and Luna landing sites (Clegg et al., 2014a), but with different best-fit parameters for \( w, b, c, \) and \( \theta \). From the fitted Chang'e-3 site NAC observations we computed reflectance values at a common phase angle (30°) for key units. Reflectance (\( I/F \)) was normalized with the Lommel-Seeliger function (LS), which describes single scattering as a function of \( i \) and \( e \) (e.g., Hapke, 2012). Normalizing to the LS function minimizes the effects of varying \( i \) and \( e \) and is useful because variations in the reflectance of the Moon are strongly controlled by phase angle (Hapke et al., 2012). Hapke (2012) defines the reflectance normalized to the LS function as the “reduced reflectance” (\( IoF/LS \)), as follows:

\[
IoF/LS = \frac{w}{4} [p(g) + H(\mu_0, w)H(\mu, w) - 1][1 + B_{co}B_c(g, h_c)]S(i, e, \theta)
\]

where \( \mu = \cos(e) \) and \( \mu_0 = \cos(i) \). The single scattering albedo, \( w \), is the ratio of the power scattered to the power removed by scattering and absorption for a single scattering event (Hapke, 2012) and depends on composition, grain size, and optical constants (indices of refraction). The quantities \( w \) and \( p(g) \), where \( g \) is the phase angle, describe the scattering by a single particle, where \( p(g) \) is the single particle phase function, and the term \( B_{co}B_c(g, h_c) \) describes the Coherent Backscattering Opposition Effect. The probability that a photon will be scattered in the direction \( g \) is given by \( p(g) \) and is defined by the double Henyey-Greenstein Function (Carrier et al., 1991; Goguen et al., 2010; Hapke, 2012),

\[
p(g) = \frac{1+c}{2} \left( \frac{1-b^2}{(1-2b \cos g+b^2)^{3/2}} \right) + \frac{1-c}{2} \left( \frac{1-b^2}{(1+2b \cos g+b^2)^{3/2}} \right)
\]

where \( b \) is the angular width of the backward (first term) or forward (second term) scattering lobe and \( c \) is the magnitude of the lobe. Chandrasekhar’s H functions, expressed as \( [H(\mu_0, w)H(\mu, w) - 1] \), describe multiple scattering and are approximated by

\[
H(x, w) = \frac{(1 + 2x)/(1 + 2x\sqrt{(1-w)})}{(1 + 2\sqrt{(1-w)})}
\]
The term $S(i,e,\theta)$ is the shadowing function and corrects for macroscopic roughness of the surface and depends on mean slope angle $\theta$. For more details and derivations, see Hapke (2012) and Hapke et al. (2012). For details on how we fit other photometric parameters ($w$, $b$, $c$, and $\theta$) to determine changes in physical properties within the blast zones, see Clegg et al. (2014a).

The use of NAC observations acquired over a broad range of acquisition geometries ($i$, $e$, $g$) allowed us to determine reflectance at a common $g$ by fitting the site-specific, zone-specific (blast zone, background) IoF/LS-phase curves and retrieving the reduced reflectance at a specific desired phase angle (e.g., Fig. 16 in Clegg et al., 2014a). We then use the values determined by phase-curve fitting to compute $I/F$ at a phase angle of 30° (incidence 30°, emission 0°), henceforth referred to as the normalized reflectance, $I/F(g)$, allowing site-to-site comparisons (Clegg et al., 2014a). For this study we compare normalized reflectance values at the Chang’e-3 site from before and after the landing with values from historic (1966-1976) landing sites.

Phase-ratio images, multi-temporal ratio images, and reflectance profiles allowed us to characterize the reflectance changes at the landing site and to precisely determine the boundaries of the area disturbed by the Chang’e-3 descent plume. Phase-ratio images minimize influences from small-scale topography and reveal subtle differences in backscattering characteristics between disturbed areas and undisturbed areas (Kaydash et al., 2011; Shkuratov et al., 2011; Clegg et al., 2014a). We created a phase-ratio image by taking two images with similar incidence angles but different emission angles and therefore different phase angles ($>\sim 10^\circ$ difference for each pair) and dividing the lower-phase image by the higher-phase image (see Kaydash et al. (2011) for details on creating phase-ratio images). We used images taken in subsequent orbits, where the incidence angles are approximately the same but emission angles varied owing to slewing of the spacecraft, resulting in different phase angles. The phase-ratio image for the
Chang'e-3 landing site was created by dividing NAC frame M1144950543L \( (i=59^\circ, g=46^\circ) \) by NAC frame M1144929211L \( (i=57^\circ, g=66^\circ) \) (Figure 3.3). We compare the phase-ratio image to a multi-temporal ratio image made by dividing an image of the site after landing (M1144936321L; \( i=58^\circ, g=59^\circ \); Figure 3.4a) by an image from before landing (M183661683L; \( i=54^\circ, g=56^\circ \)) (Figure 3.4b).

Profiles taken across the landing site from the multi-temporal image ratio (Figure 3.5) reveal changes in reflectance and delimit the spatial extent of the disturbed area. The shape of each profile indicates changes in reflectance across the landing site and each profile was taken using pixel row averages across the N-S track. Reflectance values are reported as the ratio of \( I/F \) after landing to \( I/F \) before landing \( (I/F\text{(ratio)}) \); note that the phase angles are \( 56^\circ \) and \( 59^\circ \) for these images and, because they are so similar, we have not normalized the reflectance values to a common phase angle. We use the profiles to calculate the average percent increase in reflectance.

A NAC Digital Terrain Model (DTM; Tran et al., 2010; Burns et al., 2012; Henriksen et al., 2014) was created using NAC stereo observations composed of images acquired on sequential orbits with convergence angle of ~18° that allowed us to assess topography at the Chang'e-3 landing site at the 5-meter scale (see Figure 3.6). The stereo images were radiometrically calibrated and then exported to SOCET SET, where they were tied to ground coordinates by controlling the terrain model to elevation profiles derived from Lunar Orbiter Laser Altimeter (LOLA) measurements (Zuber et al., 2010). Changes in local slopes contribute to changes in reflectance, so we “correct” the reflectance, taking into account slopes at a baseline of ~14 m, by determining the \( i \) and \( e \) value at each pixel and using our Hapke model to determine the corresponding normalized reflectance, \( I/F(30^\circ) \).
3.3 Results

The dashed line in Figure 3.1b outlines the area of increased reflectance (blast zone or BZ), defined visually and using reflectance profiles (see below). The area of the BZ, so defined, is about 2530 m² as determined from measurements using the "qview" measuring tool in ISIS (Anderson et al., 2004). The BZ is elongated in the N-S direction, ~75 m, accentuated by a 15 m crater about 15 m to the north of the lander. As outlined in Figure 3.1b, the BZ is some ~43 m E-W at maximum width, with an irregular shape in part dictated by topography and descent maneuvers (explained in Section 3.4.1).

Reflectance profiles at the Chang'e-3 landing site show similar trends to those seen at the Apollo, Luna, and Surveyor landing sites, with higher reflectance values close to the lander and decreasing with distance from the lander, and leveling off in surrounding undisturbed areas (Figure 3.5). At the Apollo and Luna sites, there is also an area of lower reflectance extending up to a few meters away from, and presumably directly beneath, the landing vehicle. If present at the Chang'e-3 site, this low reflectance blast zone is too small to be resolved, especially since the landing site does not have as favorable a pixel scale as the historic sites.

The multi-temporal ratio image in Figure 3.4b shows the area that was disturbed by rocket exhaust during landing as a bright feature. This image illustrates the increased reflectance within the BZ and a diffuse area of reflectance slightly larger than the primary BZ feature (extended ~55 – 60 m from the edge of the BZ in the N-S direction, and ~10 – 15 m in the E-W direction; measuring ~5400 – 5800 m² in area). We refer to the diffuse area as the diffuse blast zone (DBZ) and the more highly reflective blast zone as the focused blast zone (FBZ). The DBZ has an average 4% increase in reflectance relative to the background, which is slightly lower than the 10% increase (see below) seen within the FBZ, allowing us to distinguish between the two. The
two blast zone areas are outlined in white (DBZ) and yellow (FBZ) in Figure 3.4c, and we discuss the possible causes of each in Section 4.1. The DBZ is also seen in the c-c’ (N-S) profile (indicated by arrows in Figure 3.5d), helping us to determine the boundaries of each portion of the overall BZ. The FBZ appears as a darker region in the phase-ratio image (Figure 3.3), but the DBZ is only apparent in the multi-temporal ratio image.

Three profiles were taken across the BZ in the multi-temporal ratio image (Figure 3.5a), two east-west and one north-south. These profiles were made using 3-pixel averages along the N-S and E-W tracks. Multiple profiles were acquired to assess reflectance changes: one across the northern half of the BZ (a-a’; Figure 3.5b), one across the southern half of the BZ (b-b’; Figure 3.5c), and one north-south across the BZ and intersecting the lander (c-c’; Figure 3.5d). The effects of local, small-scale topography such as crater walls and local slopes appear as small-scale signals in the profiles. The solid red lines in Figure 3.5b-d indicate average reflectance values for the background areas.

The background ratio values of the profiles should be close to 1 because they have not been altered by rocket exhaust; however, the before and after images used to create the phase-ratio image have phase angles of 56° (before, NAC image M183661683L) and 59° (after, NAC image M1144936321L), causing the background values to be slightly lower than 1.0. Taking this offset into account, we extract \( I/F(ratio) \) values from the phase-ratio profiles, and use the Hapke function to normalize the data to 30° phase angle for comparison across landing sites. This method gives a 10±1% increase in reflectance within the FBZ. Table 3.1 lists the mass, thrust, BZ area, and normalized reflectance measurements at 30° phase angle for each landing site.
3.4 Discussion

Previous studies into the effects of rocket exhaust on lunar soil have attempted to measure the spatial extent of the disturbed area as well as determine what physical changes occurred in the regolith to contribute to changes in reflectance (see Kreslavsky and Shkuratov, 2001; Kreslavsky and Shkuratov, 2003; Kaydash et al., 2011; Kaydash and Shkuratov, 2012; Clegg et al., 2014a. In the following sections we compare the Chang'e-3 blast zone with those of historic sites and discuss similarities and differences in reflectance changes and the processes that led to these changes.

3.4.1 Reflectance at the Landing Site

NAC images of the Chang'e-3 landing site record an area of increased reflectance around the lander that was not previously present, which we interpret as disturbance of the regolith by rocket exhaust. Using the Hapke photometric model to calculate reflectance values at a common 30° phase angle for each landing site, we found that the 10±1% increase in normalized reflectance at the Chang'e-3 landing site is comparable (within uncertainties) to the change at older landing sites, which average ~11±2% for Apollo (ranging from 7.5-12.5%), ~8±3% for Luna (ranging from 5.1-10.6%), and ~10±4% for Surveyor (ranging from 3.4-13.2%), where the “±” value indicates variations of measurements among the different sites.

One might consider the effects topography and local slopes have on the increased reflectance of the BZ. We used a NAC DTM to assess local topography and slopes at the Chang'e-3 landing site (Figure 3.6). The landing site lies on the ejecta blanket of a 450 m diameter crater and the surface slopes ~6° gently to the east with about a constant 2° change across the landing site, resulting in an elevation change of only ~2 m. When testing the variations in slope change with the Hapke model, we found little difference in the normalized reflectance
values (differences of $I/F(30^\circ)$ on the order of 0.001-0.002) for such small changes in slope. However, local slopes seem to have affected the shape of the FBZ, as evidenced in Figure 3.6b. The FBZ is wider to the east of the lander and seems to coincide with a small ($\sim 2^\circ$) slope. Similarly, the BZ extends slightly farther in the southwest direction than in the southeast direction, again coinciding with a small slope.

The blast zone (specifically, the focused blast zone) appears as a dark region in the phase-ratio image (Figure 3.3). The phase-ratio measures the slope of the phase function $p(g)$ (the probability that a photon will be scattered in an angle $g$; see Section 3.2 and Hapke, 2012) for two phase angles, i.e., $p(g_1)/p(g_2)$ when $g_1 < g_2$ (see Kaydash et al., 2011; 2012). The phase-function slope is dominated by light-scattering characteristics and roughness of the regolith, and lower phase slopes create darker regions in phase-ratio images (described in more detail in Kaydash et al., 2011). This phenomenon can be interpreted as a decrease in backscattering character within the BZ caused by smoothing of small-scale topography, including possible destruction of the microscopic fairy-castle structure, which is consistent with what we see at the historic landing sites (Clegg et al., 2014).

Reflectance profile shapes are similar across all landing sites, with the highest reflectance values close to the lander, tapering off with increasing distance away from the lander, and leveling off in surrounding undisturbed areas (Clegg et al., 2014a). Previous work on the effects of rocket exhaust on lunar soil has shown that the surface around the landers was made more reflective and less backscattering owing to smoothing of small-scale (cm-mm) roughness and possibly redistribution of fine materials (Kreslavsky and Shkuratov, 2003; Kaydash et al., 2011; Kaydash and Shkuratov, 2012; Clegg et al., 2014a). The inferred smoothing of the BZs implies that high-velocity particulates especially affected these areas when they were entrained in the
boundary layer gas flow above the surface (Metzger et al., 2011; Clegg et al., 2014a). Experimental and computer modeling work on the entrainment of particles in high-velocity gases suggests that smaller particles are quickly entrained within the rocket exhaust gas flow as it impinges upon the surface and are accelerated to high velocities (~ 1000 m/s for 2 µm particles and up to 2000 m/s for particles ~ 200 nm in size) (Morris et al., 2015) and thus redistribution of fines would be expected to be well beyond the limits of the observed BZ. However, turbulence and particle-particle collisions within the entrainment plume should cause the gas plume to become more diffuse and some of the particles slowed (Berger et al., 2013; Morris et al., 2015), allowing them potentially to be redistributed within a few 10s to 100s of meters of the lander.

Exhaust plume modeling has also shown that at altitudes below 2.5 m, the shock of the plume upon the surface begins to have normal and oblique components, creating vorticity within the plume, creating a “recirculation vortex” that intensifies the erosion and entrainment of dust (Morris et al., 2015). The area of reduced reflectance under and closely surrounding the larger Apollo landers is likely the result of increased roughness owing to pitting of the soil, in part as a function of pressurization and subsequent release as described by Metzger et al. (2011), and possibly enhanced by turbulence associated with the recirculation vortex. Around the close perimeter of the Apollo landers, disturbance and roughening of the surface also occurred as a result of astronaut activity, and possibly also by removal of fine particles from this area (Clegg et al., 2014a). Such areas of reduced reflectance are not observable with the smaller landers, including Chang'e-3, at NAC resolution, but likely exist at these sites.

The diffuse blast zone (DBZ) is not seen at other spacecraft landing sites and the cause of the diffuse increase of reflectance is not initially obvious. Chang'e-3 approached from the south to within 100 m above the surface before hovering over the landing site while executing obstacle
avoidance maneuvers (Liu et al., 2014) and moving several meters first in the N-S and then in
the E-W directions (up to 6 m in each direction, as reported by Liu et al., 2014). The entire BZ
area is elongated in the N-S direction, so it is likely that while the spacecraft hovered it induced
the diffuse disturbance by redistribution of fine particles from particle-particle collisions within
the exhaust plume (supported by exhaust plume modeling; discussed above) of regolith primarily
in the N-S direction. Several of the Apollo lunar modules also hovered prior to final descent (see
Section 3.4.2) and may have generated a DBZ at their landing sites, but we have not seen DBZs
in the NAC images of Apollo sites. The CE-3 DBZ is not seen in NAC images or in the phase-
ratio image; it is only seen in the multi-temporal ratio image. It is possible that these DBZs once
existed at the Apollo sites but have already been “reset”, or we may simply not be able discern
them because we do not have both before and after NAC-quality multi-temporal, equal-
illumination images of those sites.

3.4.2 Effects of Composition of the Landing Site

Elemental concentrations derived from APXS data onboard the Yutu indicate that the
regolith is predominately basaltic (Ban et al., 2015; Neal et al., 2015; Ling et al., submitted),
with fresh basalt delivered to the site as ejecta from the 450 m diameter crater situated just to the
west of the landing site; in fact, the Chang'e-3 landing site sits within 60 m of the rim of this
crater. Using data from Kaguya’s Multispectral Imager (pixel scale 20 m for the visible bands
and 62 m for the near-IR bands at a 100 km orbit (Ohtake et al., 2012)), Zhao et al. (2014)
derived FeO and TiO$_2$ abundances of ~18 wt% and 5-10 wt%, respectively, for the landing site.
Also using APXS data, Neal et al. (2015) estimated values of 4.7 wt% TiO$_2$, 21.3-22.1 wt% FeO,
and 8.3-9.1 wt% MgO for the regolith at the landing site. We previously determined a
relationship between normalized reflectance and mafic mineral contents (using FeO+MgO+TiO$_2$
as a measure) for the Apollo and Luna landing sites (Clegg et al. 2014b) and found that reflectance is strongly anti-correlated with mafic content. The normalized reflectance near the Chang'e-3 landing site, but outside (east) of the BZ, is 0.034. This value is less than a similarly measured background area at all of the Apollo and Luna sites (Clegg et al., 2014b; Table 3.1), consistent with the high concentration of FeO+TiO$_2$+MgO of the CE-3 site.

FeO and TiO$_2$ abundances vary among the mare sample return sites (Apollo 11, 12, 14, 15, 17, and Luna 16 and 24), but percentage reflectance changes, before and after landing, are approximately the same regardless of composition, indicating that composition does not play a significant role in the magnitude of reflectance changes caused by rocket exhaust.

3.4.3 Surface Processes and the Persistence of Blast Zone Reflectance Anomalies

One of the key motivations for comparing the Chang'e-3 landing site blast zone effects to those of the older landers (Apollo, Luna, and Surveyor) is to assess whether changes have occurred since the earlier landings and to then consider various mechanisms that might be responsible for re-establishing or “re-maturing” the increased BZ reflectance in terms of their time dependence. In this section, we consider processes and corresponding timescales that might act to change or “reset” the reflectance at the blast zones. What we do know is that the increase in reflectance associated with the Chang'e-3 FBZ is of the same degree as the increase in reflectance in the BZs of Apollo, Luna, and Surveyor, as observed today, and that the blast zones at all landing sites are less backscattering than the surrounding undisturbed areas. These reflectance and backscattering character similarities suggest that reflectance changes resulting from rocket exhaust interacting with regolith during spacecraft landing have not significantly changed on the order of 40-50 years.
Diurnal temperature variations that drive electrostatic forces may cause local movement of dust very close to the surface (3-30 cm above the surface), which might, over a span of decades, cause soil to become less reflective and more backscattering (Rennilson and Criswell, 1974; Stubbs et al., 2005; Poppe and Horányi, 2010). Movement of dust on a diurnal timescale is, in theory, a short-lived process, possibly taking as little as 30-300 seconds for grains to be lofted and move across the surface (Stubbs et al., 2005). Dust particles are positively charged by solar radiation during the lunar day and negatively charged during the lunar night, and as the night-to-day terminator crosses the surface, the surface temperatures rise rapidly and strong electric fields are created due to photoelectric emission from the unevenly illuminated surfaces, causing charged grains to be lofted owing to their induced positive charge from the incoming solar radiation (Colwell et al., 2009). However, the longevity of the high-reflectance blast zones indicates that the process that would alter or erase the effects of increased reflectance caused by rocket exhaust must occur over a much longer time scale than a few hundred diurnal cycles.

Longer-term space weathering processes such as micrometeorite impacts, solar wind irradiation, and production of fine-grained materials and agglutinates are, in general, mainly responsible for producing differences in reflectance properties over time (Hapke 2001; Pieters et al., 2000; Noble et al., 2001; Loeffler et al., 2009) and result in maturation of the regolith in BZs. In general, mature soils are finer grained, less reflective, and have a higher percentage of agglutinates and nanophase iron (McKay et al., 1991; Pieters et al, 2000; Noble et al., 2001) than their immature counterparts. The rate at which a soil accumulates nanophase iron (npFe⁰) and matures is not well constrained, but maturity in the optical range is thought to take on order of ~50 My (Denevi et al., 2014). Micrometeorite impacts alter the particle size distribution, which in turn changes the path of light in the particles and has a direct influence on the reflectance
characteristics (Loeffler et al., 2009). Micrometeorite gardening may also re-establish small-scale roughness of the surface on a time scale similar to re-maturation (npFe$^0$ production), which could eliminate the increased reflectance and return the surface to a more backscattering character.

The presence of npFe$^0$ particles contributes to darkening of lunar soil (Fischer and Pieters, 1994; Taylor et al., 2000). Vapor deposits from micrometeorite impacts and ion-particle sputtering from the solar wind cause a preferential loss of oxygen and reduction of Fe$^{2+}$ in regolith grains, producing nanophase iron on the rims of lunar soil grains (Tsay et al., 1971; Hapke, 2001). The relative amount of npFe$^0$ increases with decreasing particle size, and the finest fraction (<10 micron) of lunar soils comprises about two-thirds of the surface area (Pieters et al., 2000; Morris et al., 1974). Previously, Clegg et al. (2014a) correlated Apollo and Luna sample grain sizes (considering soil fractions <250 microns) and I$_S$/FeO properties to compare samples collected within and outside of blast zones. That study did not find evidence for grain size differences between the blast zone and undisturbed areas. However, the best BZ samples for comparison would be very carefully excavated surface skim samples, but the astronauts did not take such samples (with the exception of the Apollo 16 Clam Shell Samples, which did not collect much material and were only collected well outside the blast zone; see Noble et al., 2011). Therefore the Apollo samples collected within the BZs may not be adequate for a meaningful comparison of surface texture within and outside blast zones. Apollo core samples also show that maturity does not change significantly for the first tens of centimeters of regolith, and it is not likely that the landers excavated to a depth significant enough to excavate immature material (Kaydash and Shkuratov, 2012; Clegg et al., 2014a). The historic blast zones likely have not been exposed to space weathering long enough to experience new production of nanophase
iron and to have the reflectance values significantly affected. Therefore, the most likely way to produce differences measureable by one of the common maturity indicators, if any exist, within the BZ is by preferential removal of fine particles, which might also increase surface porosity. Fine particles dominate the optical properties of the surface and are generally more affected by space weathering owing to their larger surface area (Morris et al., 1978; Pieters et al., 2000; Hapke 2001), so the removal of these particles during landing could potentially contribute to the decrease in backscattering character within the BZs. The $<10 \, \mu m$ fraction constitutes about 2/3 of the total surface area of the Moon and this “finest fraction” is generally considered more mature because the individual small particles are more likely significantly affected by weathering than larger particles owing to their large surface:volume ratio and the fact that they tend to cling to and thus “protect” larger particles (McKay et al., 1974; Noble et al., 2001). McKay et al. (1974) showed that increasingly more mature soils become gradually finer-grained. In addition, the Morris (1976) determination of $I_s/FeO$ for fine fractions revealed higher values, e.g., ~80-100 (see Fig. 5 of Morris, 1976).

Changes in roughness also play an important role in the reflectance differences seen at spacecraft landing sites. Because the landers did not excavate to depths significant enough to reveal natural immature material, we attribute the increase of reflectance to smoothing of microscopic (nm scale) to macroscopic (mm to cm scale) surface roughness. Smoothing may possibly be coupled with removal of fine particles around the lander, as discussed above. To “reset” the maturity or return the surface reflectance around the landers to pre-landing or background levels thus could take on the order of millions of years, e.g., on a time scale needed to develop a micro- to macroscopically mature surface, most likely caused by micro-scale to
small micrometeorite impacts. The reflectance would not be reset on a time scale as short as a few decades of surface exposure or diurnal variations.

3.4.4 Relationship between Lander Mass and Blast Zone Area

In this section, we explore the relationship between lander mass, thrust, and BZ area, and how this relationship could be used to make predictions for future landed missions. Data for Apollo, Surveyor, and Luna landers show that lander thrust is related to lander mass approximately linearly (for these spacecraft, thrust was vectored approximately normal to the surface). Therefore it follows that blast zone areas likely correlate to lander mass and thrust, even though the Apollo, Luna, and Chang'e-3 landers had a one-engine configuration and Surveyor had three-engine configurations.

We tested for a relationship by plotting the lander dry mass versus blast zone area for the Apollo, Luna, and Surveyor sites and found that the blast zone areas for these sites scale quadratically with lander dry mass (see Figure 3.7 and Clegg and Jolliff, 2014). We plot dry mass because we have more confidence in the dry mass values than the reported thrust values at the time of landing. We know the maximum thrust capability of each spacecraft engine, but the engines were also capable of throttling to different thrust values during landing, and most missions only report these maximum values and not the actual thrust immediately before touch down. However, most spacecraft were almost completely out of fuel in the moments before touchdown, during which they were able to alter surface properties and therefore the dry mass values may be better for comparison with blast zone area.

The area of increased reflectance at the Chang'e-3 site (FBZ) is ~2530 m² (~75 m × 43 m), compared with an average of 23,770 ± 2100 m² for the Apollo sites (excluding Apollo 12, areas range from 18,725-34,480 m²), 2100 ± 530 m² (ranging from 990-3360 m²) for the Luna sites,
and 215 ± 50 m² (ranging from 130-280 m²) for the Surveyor sites (Clegg et al., 2014a). The ± values indicate variations for the different landing sites, based on variations in landing strategies and lander masses.

To assess whether the Chang'e-3 FBZ falls along the same trend, we plotted a 95% confidence envelope based on the Apollo-Luna-Surveyor correlation (Figure 3.7). Variations in descent trajectory, engine configuration, velocity, and thrust contribute to varying blast zone sizes. However, despite these variations there is a consistent relationship between lander mass and BZ area. We found that the Chang'e-3 FBZ area value falls within the 95% confidence envelope and close to the expected value on the basis of comparison to the other spacecraft. When plotting thrust vs. FBZ area, we found that the Chang'e-3 value actually falls off (above) the line, suggesting that the reported thrust value might be too high or the reported values for one or more of the other missions (which are used to determine the best-fit curve) are inaccurate. The consistent correlation of BZ area with lander dry mass indicates that the majority of surface alterations likely occur within the final meters of descent where the exhaust plume interacts with the surface; the Apollo astronauts reported first seeing blowing dust at altitudes ranging from 25-90 m above the surface, and in most cases the dust greatly obscured landing visibility (with the exception of Apollo 14 and 17). Both Apollo 12 (at 30 m) and Apollo 16 (at 12 m) hovered above the surface in order to find a safe landing spot because blowing dust obscured the surface (Armstrong et al., 1969; Conrad et al., 1969; Shepard et al., 1971; McDivitt et al., 1972; McDivitt et al., 1973; Cernan et al., 1973; Harland, 2008).

The relationship between BZ area and mass can be used to predict the size of disturbed areas for future lunar missions. For example, the descent propulsion system designed for the Altair lander (Constellation Program) would have provided ~83.0 kN of thrust. Estimating a dry
mass of ~13,000 kg and using our BZ area vs. lander dry mass relationship, Altair would create a BZ with an area of ~682,400 m$^2$ compared with only about 24,000 m$^2$ for Apollo. SpaceX’s new SuperDraco thrusters, which are designed for entry, descent, and landing on Mars and likely would not be used for a lunar landing but are included here as an example of predicting BZ area for varying spacecraft specifications, provide 71.2 kN of thrust. Assuming a spacecraft has just one of these thrusters and estimating a dry mass of ~11,200 kg, then the approximate BZ area would be ~489,400 m$^2$. Whereas many factors affect the actual size of the disturbed area at the surface, these estimates show that lander mass is an accurate predictor of blast zone, which is an important observation that is important for the planning of future lunar missions.

3.5 Conclusions

The Chang'e-3 landing site exhibits an area of increased reflectance around the lander that, measured using multi-temporal ratio images and Hapke modeling for normalization to 30° phase for comparison to historical landing sites, is 10±1% more reflective than surrounding undisturbed areas. This reflectance change is in family with similarly disturbed areas observed at the Surveyor, Luna, and Apollo landing sites when comparing the higher-reflectance blast zones with nearby background surface reflectance. The CE-3 FBZ is darker in phase-ratio images of the landing site (see Section 3.4.1), indicating a decrease in backscattering character and smoothing of the surface, which is also consistent with observations of the historic sites. The reflectance and light-scattering similarities indicate that a similar process or set of processes affected all of these landing sites, as rocket exhaust interacted with the regolith. Furthermore, these similarities suggest that ongoing processes at the older landing sites have not significantly changed the reflectance of the high-reflectance blast zones on the order of four to five decades. We infer from these observations that the change in reflectance caused by the effects of rocket
exhaust results from a process or combination of processes that is/are not reset on the short time scale of decades. Rocket exhaust from all of the landed spacecraft did not excavate deeply enough to excavate immature material according to the normal variation of maturity with depth observed in Apollo cores (Lucey et al., 2006; Clegg et al., 2014a). However, preferential scouring of very fine regolith, e.g., <10 µm, which is the most mature fraction of a given regolith sample, could effectively lower the maturity of the very top-most regolith (e.g., upper few mm) in the BZ, thus we keep open the possibility that redistribution of fines – essentially a removal from the HR-BZ – could be a contributing factor. Nonetheless, the change (decrease) in backscattering that characterizes the HR-BZ and that is evident in phase-ratio images suggests that the increase of reflectance results primarily from smoothing of microscopic to macroscopic surface roughness, possibly including destruction of the fine-scale surface structure (e.g., “fairy-castle” structures), and smoothing of small-scale surface topography on mm to cm scales, (see also Kaydash et al., 2011; Kaydash and Shkuratov, 2012; Clegg et al., 2014a). Longer-term space weathering processes such as micrometeorite gardening, re-establishment of fairy-castle structure, and production of npFe⁰ will eventually alter the reflectance characteristics of the soils within the BZs. Destruction of fairy-castle structure alone may not account for the longevity of the increased reflectance within the BZs, because fairy-castle structures are governed by electrostatics and surface particles may be re-established during the Moon’s diurnal cycle (Gold 1955; Hapke and van Horn, 1963; Rennilson and Criswell, 1974; Stubbs et al., 2005; Colwell et al., 2009).

At the Chang'e-3 landing site, an after/before multi-temporal image ratio shows the area of increased reflectance to consist of an inner, focused zone (FBZ) and an outer, diffuse zone (DBZ). The FBZ is elongated in the N-S direction and measures 2530 m² (~75 × 43 m), while
the DBZ measures ~5400-5800 m² and extends an additional 55-60 m to the north and south and 10-15 m to the east and west. The area of increased reflectance of the FBZ is in family with regard to size compared to similarly sized Luna spacecraft, and lies within a 95% confidence envelope for a curve corresponding to the size vs. lander mass fit to Surveyor, Luna, and Apollo landing site data. The DBZ is much larger than what would be expected based on the Apollo, Luna, and Surveyor mass vs. BZ area correlation, and may be related to hovering during hazard avoidance prior to final descent and touch down. However, it is difficult to determine the cause of the DBZ – such diffuse zones might exist now or have existed in the past around the historical landers but simply may not be observable without the high-quality, multi-temporal and similar-illumination images, as for the CE-3 site. Blast zone size variations among landing sites can be attributed to descent trajectories, maneuvering, engine configurations, and spacecraft design; however, despite these variations a consistent relationship exists between lander mass/thrust, and BZ area. This relationship is useful in predicting the scale of rocket exhaust effects for future soft landings on the Moon.

Acknowledgements

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References


National Space Science Data Center (NSSDC), http://nssdc.gsfc.nasa.gov/


Figure 3.1: Chang'e 3 landing site at 44.12°N, 340.488°E in Mare Imbrium. NAC image M1147290066R ($i=45^\circ$, $g=46^\circ$). (b) Same image, labeled with the Yutu rover, rover tracks, and lander. Dashed line outlines the blast zone.
Figure 3.2: Before (left; NAC image M1127248516R) and after (right; NAC image M1142582775R) images of the Chang'e-3 landing site. Long arrow points to the lander, short arrow points to the Yutu rover as it was observed on December 25, 2013.
Figure 3.3: Phase-ratio image for the Chang'e-3 landing site. NAC image M1144950543L ($i=59^\circ$, $g=46^\circ$) divided by NAC frame M1144929211L ($i=57^\circ$, $g=66^\circ$). Area of disturbance appears darker owing to a lower phase-slope and is less backscattering than surrounding undisturbed areas. Dashed line determined from Fig. 1b.
Figure 3.4: Chang'e 3 landing site from (a) NAC image M1144936321L \(i=58^\circ, g=59^\circ\) and (b) multi-temporal ratio image made by dividing the image in (a) by an image from before landing (M183661683L; \(i=54^\circ, g=59^\circ\)). The area disturbed by rocket exhaust after landing is enhanced in the multi-temporal ratio image and (c) outlines the diffuse blast zone (DBZ) and the focused blast zone (FBZ).
Figure 3.5: Reflectance profiles taken across the multi-temporal ratio image for the Chang'e-3 landing site. (a) path of profiles; yellow dashed line outlines focused blast zone (FBZ) and white dashed line outlines diffuse blast zone (DBZ). (b) Profile a-a’ across northern part of FBZ. (c) Profile b-b’ taken across center of FBZ. (d) Profile c-c’ taken N-S across the FBZ and crossing the lander. Solid red lines in plots indicate average reflectance values for the background, with offset from 1 caused by slight photometric differences in illumination geometry between images. Dashed blue lines indicate smoothed slopes for FBZ, dashed green lines are slopes for DBZ.
Figure 3.6: (a) Topography at the Chang'e-3 landing site. There is less than 2m elevation change across the blast zone. (b) Slopes at the Chang'e-3 landing site. There is less than a 2° difference in slope across the landing site. Topography and slope maps are overlain on NAC image M1144922100.
Figure 3.7: Lander dry mass versus blast zone area. Dashed lines are 95% confidence envelope based on Apollo, Luna, and Surveyor correlation (solid line; quadratic fit). Chang'e-3 (CE-3) BZ area fits well within confidence envelope. Variations are largely a function of descent parameters and spacecraft specifications. Figure edited from Clegg and Jolliff (2014).
Tables

Table 3.1: Spacecraft dry mass and thrust, BZ area measurements, and $I/F(30^\circ)$ values\(^a\) at the Apollo, Luna, Surveyor and Chang'e-3 landing sites.

<table>
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<tr>
<th>Spacecraft</th>
<th>dry mass(^b,c,d) (kg)</th>
<th>maximum thrust(^b,c,d) (kN)</th>
<th>BZ area (m(^2))</th>
<th>$I/F(30^\circ)$ BZ</th>
<th>$I/F(30^\circ)$ background</th>
<th>percent increase in $I/F$</th>
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<td>Apollo 11</td>
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<td>21340</td>
<td>0.066</td>
<td>0.059</td>
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<td>Apollo 15</td>
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<td>18725</td>
<td>0.052</td>
<td>0.047</td>
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<tr>
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<td>34480</td>
<td>0.100</td>
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<td>18890</td>
<td>0.047</td>
<td>0.042</td>
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<td><strong>Apollo avg</strong>(^e)</td>
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<td><strong>0.062</strong></td>
<td><strong>0.056</strong></td>
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<tr>
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<td><strong>18.9</strong></td>
<td><strong>2100</strong></td>
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\(^a\) $I/F$ values adjusted from Clegg et al., (2014a) due to improved Hapke photometric modeling

\(^b\) Apollo and Surveyor values from National Space Science Data Center (NSSDC)

\(^c\) Luna values from (Harvey, 2007)


\(^e\) Excluding Apollo 12, because Surveyor Crater effectively enlarged the size of the BZ; adjusted from Clegg et al. (2014a)
Chapter 4: Non-Mare Volcanism on the Moon: Photometric Evidence for the Presence and Characteristics of Evolved Silicic Materials using LROC NAC Imagery

Abstract

Non-mare volcanics are a rare but important part of lunar volcanism on the Moon, and data from the Diviner Lunar Radiometer onboard the Lunar Reconnaissance Orbiter (LRO) show direct evidence that these areas are silicic in composition. Here we focus on the apparent silicic volcanic or intrusive areas associated with the Compton-Belkovich Volcanic Complex (CBVC), Hansteen Alpha, Lassell Massif, the Gruithuisen Domes, and ejecta of Aristarchus Crater. Photometric models developed for spacecraft landing site studies allow us to study the relationship between photometric properties of soils and their mineralogical and chemical compositions. The silicic regions have high reflectance and single scattering albedos that are consistent with different proportions of highly reflective minerals including alkali feldspars and quartz, and low concentrations of mafic minerals. Of the silicic sites studied, the CBVC has the highest reflectance values and single scattering albedos. The CBVC is also likely characterized by silicic pyroclastic deposits, and we present evidence from laboratory spectra that an addition of up to ~20 wt% glassy silicic materials to a highlands-type regolith simulant can account for the increased reflectance of these volcanic regions. Reflectance variations across and within the sites can be explained by mixing of felsic mineral components, evolved to intermediate silicic compositions, and/or silicic pyroclastic deposits.
4.1 Introduction

Remote sensing data indicate localities on the Moon where felsic rocks occur as a result of non-mare (non-basaltic) volcanic or intrusive activity. Many of these areas are classified as “red spots” and are characterized by their high albedo and strong absorption in the UV (first recognized by Whitaker, 1972), which cause them to appear spectrally red. An example of an LRO Wide Angle Camera color composite (RGB) image (Sato et al., 2014) of one of these lunar “red spots”, Hansteen Alpha, is shown in Figure 4.1. Connections have been made between some spectrally “red spots” on the Moon and silicic compositions as reflected by Diviner Christiansen feature data and Lunar Prospector thorium data (Glotch et al., 2010; Greenhagen et al., 2010; Jolliff et al., 2011a; Ashley et al., 2013). Returned samples that may be products of areas of non-mare volcanism are rare and underrepresented, so we rely on remote sensing data to help determine the composition and formation of these regions. Many of the areas indicated to be “red spots” or silicic in composition correspond to high-thorium (Th) anomalies, as detected by the Lunar Prospector Gamma-Ray Spectrometer (LP-GRS), and have low FeO (<5 wt%) contents. They also tend to have relatively high reflectance. High thorium content coupled with high reflectance and low iron content implicates an alkali-suite rock type, i.e., alkali anorthosite or granite/rhyolite, based on correlations observed in Apollo samples (Jolliff et al., 2011a). Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images show morphological features (cones, domes, etc.) that indicate these features are of volcanic origin, and data from the Diviner Lunar Radiometer onboard LRO show evidence for silicic compositions at these sites (Jolliff et al., 2011a; Ashley et al., 2013; Glotch et al., 2010; Greenhagen et al., 2010).

Both the Moon Mineralogy Mapper (M3) and Diviner data indicate that some of the silicic areas, especially the Compton-Belkovich Volcanic Complex, have OH/H2O absorptions that may
be attributed to the presence of pyroclastic deposits (Pieters et al., 2009; Petro et al., 2013; Battacharya et al., 2013). Additional thorium data and radar data from Mini-RF onboard LRO provide evidence for pyroclastics at the CBVC, discussed in Section 4.4.2. Using these robust data sets to better understand non-mare volcanism on the Moon can help piece together the thermal history and crustal evolution of the Moon.

In this chapter, we investigate how NAC photometry (adjusted for topography and varying illumination conditions) can provide information about the composition and physical properties of materials at silicic sites. Our goal is to determine if non-mare regions that show morphological and photometric evidence of volcanic origin are made of materials such as granitic or felsic rocks such as occur in Apollo samples, or if there might be another explanation for their unique features. At least some of the areas of silicic volcanism are more reflective than their surroundings (e.g., Gillis et al., 2002) and we investigate quantitatively how high this reflectance is and compare areas that occur at different latitudes. We use Hapke photometric modeling to test variable parameters to determine which parameters could best account for the reflectance characteristics observed over a range of illumination conditions, as well as determine a relationship between reflectance and soil composition using data from returned Apollo and Luna samples. By coupling soil compositional data with photometric characteristics, we assess variability in reflectance and composition for several highly reflective areas on the Moon (Figure 4.2): the Compton-Belkovich Volcanic Complex (CBVC), the Hansteen Alpha volcanic complex (HA), Gruithuisen Domes, the Lassell Massif (LM), ejecta of unusually silicic composition from Aristarchus crater and a reference area interpreted to be pure anorthosite (PAN) on the basis of hyperspectral data (Figure 4.3) (Ohtake et al., 2009; Cheek et al., 2013; Donaldson Hanna et al., 2014). Finally, we present evidence from laboratory spectra that addition of glassy silicic
4.1.1 Compton-Belkovich Volcanic Complex

Lunar Prospector GRS data detected an isolated thorium anomaly centered broadly at 61°N, 100°E on the lunar farside between the craters Compton and Belkovich (Lawrence et al., 2003). Lawrence et al. (2003) calculated that the Th concentration at this feature might be as high as 40-55 ppm. A small region of elevated topography and high reflectance covering an area ~25×35 km lies approximately at the center of this thorium hotspot and is referred to as the Compton-Belkovich Volcanic Complex (CBVC; 61.1°N, 99.5°E), shown in Figure 4.2a (Jolliff et al., 2011a). The high reflectance of the CBVC was first observed by Gillis et al. (2002) and is apparent in LROC NAC and Wide Angle Camera (WAC) images. The complex is a small, isolated topographic and morphologic feature about 900 km east of the Procellarum KREEP Terrane. It contains a range of volcanic features, including irregular collapse features, small domes, and several large volcanic constructs (cones or cumulo domes) (Jolliff et al, 2011a). The central part of the complex may be an irregularly shaped collapsed caldera. The central part of the elevated topographic feature rises 400-600 m above the surrounding terrain, and the elevated topography corresponds approximately, but not precisely, with the high-reflectance area (Figure 4.4) (Jolliff et al., 2011a). A shallow intrusion of magma of evolved composition (possibly similar to those that form KREEP basalts) likely led to the uplift of topography seen at the CBVC. Diviner Christiansen Feature (CF) data show evidence for silicic composition corresponding to the topographic and albedo feature at the CBVC and Jolliff et al. (2011a) suggested that the CBVC likely contains compositionally evolved rock types such as granite or rhyolite. No other areas on the lunar farside have such a distinct felsic signature and very few
other volcanic constructs on the Moon exhibit such a range of collapse features and domes (Jolliff et al., 2011a), making the CBVC a very interesting and perhaps unique feature on the Moon.

4.1.2 Hansteen Alpha

Hansteen Alpha (HA) is an arrowhead-shaped topographic feature centered at 12.3°S, 50.2°W in southwestern Oceanus Procellarum (Figure 4.2b). It is located close to the rims of two 45 km diameter craters named Hansteen and Billy (Hawke et al., 2003). It has been identified as a lunar red spot (Whitaker 1972; Hawke et al. 2003) and has steep slopes, a high albedo, hackly-textured terrain and domes (McCauley, 1973), and a strong absorption in the ultraviolet (Wagner et al., 2010). Hansteen Alpha is similar in diameter to the Gruithuisen Domes, which are discussed in Section 4.1.4, but the summit region of HA is flat unlike the Gruithuisen Domes. The HA feature is approximately 30 km across, has ~1 km of elevation and is surrounded by mare basalts. Clementine spectral data indicate that the feature has low FeO (~6.9%) and TiO₂ (~0.5%) concentrations, especially compared to the surrounding mare deposits (Hawke et al., 2003; Wagner et al., 2010). The nearby craters Billy and Hansteen are richer in FeO and TiO₂, indicating they formed before Hansteen Alpha because no ejecta deposits with high mafic contents are present on the surface of HA (Wagner et al., 2010). Hagerty et al. (2006) modeled Th abundances between 17-21 ppm for HA, which, combined with morphological evidence, is consistent with a silicic extrusive lithology. The morphology of HA suggests that the feature derives from evolved viscous lava, possibly one similar to KREEP basalt (Hawke et al., 2003), and hereafter we refer to it as the Hansteen Alpha Volcanic Complex.
4.1.3 Lassell Massif

The Lassell Massif (Figure 4.2c) is another lunar red spot, located in the northern region of Mare Nubium at 15°S, 8°W (Whitaker, 1972; Ashley et al., 2013). The massif consists of an uneven, mantled northern portion ~25×46 km (Wood and Head, 1975; Ashley et al., 2013), an eastern plains region, and several nearby craters that may have excavated noritic and gabbroic lithologies (Müller et al., 1986; Hagerty et al., 2006). Remote sensing data indicate FeO values of 6-8 wt% and modeling of the Th signal indicates a concentration perhaps as high as 50 ppm (Hagerty et al., 2006) for the massif. The southern portion of the Lassell Massif has two irregularly shaped negative-relief features, Lassell G and Lassell K, which formed after the massif. These features, along with nearby surrounding craters, have Si-rich signals in Diviner spectral data, indicating they may have excavated and/or collapsed into a Si-rich subsurface (Ashley et al., 2013).

4.1.4 Gruithuisen Domes

The Gruithuisen Domes are located on the western edge of Mare Imbrium, around 36.5°N, 40.2°W (Figure 4.2d). The two largest domes are called Gruithuisen Gamma and Gruithuisen Delta, and the smallest is called Northwest (NW). Gruithuisen Delta is approximately 1600 m high and Gruithuisen Gamma is ~1200 m high. Their unique surface morphologies suggest that the lava flows that produced the domes were highly viscous (Head and McCord, 1978; Hagerty et al., 2006). Similar to Hansteen Alpha, the domes are characterized by their high reflectance and strong UV absorption, and are embayed by mare basalts. In addition, they have steep (15°-30°) slopes and rough surface features (Glotch et al., 2010). Lunar Prospector GRS data and Clementine multispectral data show that these domes are low in FeO (6-8wt%) and high in Th content (43±3 ppm for Gruithuisen Gamma and 17±6 ppm for Gruithuisen Delta), and Diviner
spectral data confirm that these domes have silicic compositions (Hagerty et al., 2006; Glotch et al., 2010). However, the Gruithuisen region contains a combination of mare basalts, highlands materials that were emplaced by impacts, and silica-rich lithologies (Hagerty et al., 2006; Braden, 2013).

4.1.5 Aristarchus Ejecta

The southern rim and ejecta of Aristarchus Crater (Figure 4.2e) have spectral index values (measure of slope and concavity between spectral channels) that are higher than surrounding highlands materials, as detected by Diviner (Glotch et al., 2010). The central peak also exhibits areas of high reflectance, and M3 data indicate a lack of mafic minerals in regions of the central peak, suggesting that the peak was sourced from the “upper anorthositic crust of the Moon” (Mustard et al., 2011). The Aristarchus Plateau does not have a silicic signature in Diviner data (Glotch et al., 2010), and a blanket of TiO2-poor pyroclastic materials covers the Plateau (Mustard et al., 2011). The Th abundance for pyroclastic materials on the Plateau is around 6.6 ppm, which is most similar to Apollo 14 red glasses that may have some KREEP component (Hagerty et al., 2008). It is likely that Aristarchus Crater either exposed an intrusive silicic lithology or exposed an extrusive lithology that was buried by mare lavas (Jolliff, 2004; Glotch et al. 2010; Zanetti and Jolliff, 2012).

4.1.6 Pure Anorthosite

The composition of the highlands crust is important for understanding the lunar magma ocean and evolution of the Moon (Ohtake et al., 2009). Anorthosite, which contains >90 vol% plagioclase (Stöffler et al., 1980), in the Moon’s upper crust provides key information regarding the composition and evolution of the magma ocean (Cheek et al., 2013, and references therein). Lunar regolith has experienced heavy mixing owing to cratering processes, consequently
concealing anorthosite, so the central peaks of craters and rings of large basins are the best places to look for crustal materials that have not been subjected to impact pulverization and mixing, especially during early, heavy impact bombardment (Ohtake et al., 2009). Orbital measurements from the Clementine UV-VIS camera, Kaguya Multiband Imager, and spectral data from M³ show evidence for exposures of pure (> 99% plagioclase) crystalline anorthosite (PAN) along basin rings (Ohtake et. al., 2009; Cheek et al., 2013; Donaldson Hanna et al., 2014). The Moon Mineralogy Mapper hyperspectral imaging spectrometer onboard the Indian Chandraayan-1 spacecraft imaged the Moon in 86 spectral channels from 430-3000 nm (Green et al., 2011) and the Kaguya Multiband Imager imaged the Moon in 9 spectral channels from 415-1550 nm (Ohtake et al., 2009), allowing for detections of diagnostic minerals across the Moon’s surface.

Regions of PAN are characterized by high albedo and a lack of mafic mineral absorptions (Ohtake et al., 2009; Cheek et al., 2013). Anorthosite that is nearly devoid of mafic minerals is dominated by a single mineral, plagioclase, and can be identified with near-infrared spectrometry by a diagnostic absorption at 1250 nm caused by electronic transitions in Fe²⁺ cations substituting for Ca²⁺ within the mineral structure (Cheek et al., 2013). The strong absorption at 1250 nm in M³ and Kaguya spectra for regions in the Orientale Basin suggests that the local rocks never experienced shock pressures high enough to produce maskelynite, which does not have the diagnostic absorption feature at 1250 nm, or that the maskelynite recrystallized to feldspar after the impact.

The Inner Rook Ring (IRR) of the Orientale basin contains massifs that have morphologies similar to those seen at central peaks of complex craters (Cheek et al., 2013). These massifs have a low proportion of mafic minerals and are believed to contain exposures of PAN at their crests (Cheek et al., 2013; Figure 4.3). Since the composition of PAN can be reasonably inferred, we
use reflectance measurements from an area in the IRR to compare with our measurements at areas of silicic volcanism.

4.1.7 Pyroclastic Deposits

Along with morphological features seen in NAC images (collapse features, cones and domes, and large volcanic constructs), evidence from M^3 spectral data, Diviner data, Mini-RF radar data, and LP-GRS thorium data strongly indicate that pyroclastic deposits exist at the Compton-Belkovich Volcanic Complex (discussed further in Section 4.4.2). The CBVC is characterized by a region of elevated topography and high reflectance, but the high-reflectance area extends about 5 km to the east of the area of elevated topography, as seen in Figure 4.4 (Gillis et al., 2002; Jolliff et al., 2011a; Jolliff et al., 2011b). Jolliff et al. (2011a) and Chauhan et al. (2015) identified irregular depressions within the CBVC that appear to be volcanic collapse features and interpreted the large, central feature as a collapse caldera. The collapse of one or more of these features may have been associated with an explosive eruption, creating a blanket of pyroclastic deposits within and extending beyond the topographic manifestation of the complex (Jolliff et al., 2011a; Battacharya et al., 2013; Chauhan et al., 2015; Wilson et al., 2015).

Glassy materials such as silicic pyroclastics in the CBVC could contribute to the increased reflectance seen in this area, but pyroclastics are difficult to detect even with high-resolution NAC images and they have likely been worked into the regolith over the past 3.5 Ga since formation of the CBVC (Shirley et al., 2013). To further investigate the possibility of silicic pyroclastics at this site, we take reflectance measurements of a glassy silicic analog material mixed with a lunar highlands simulant and compare the reflectance with reflectance derived from NAC images of silicic volcanic regions, as discussed in the following sections.
4.2 Methods

For this investigation, we use Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) images acquired over a range of illumination conditions (incidence, emission, and phase angles) for selected sites on the Moon. These data are well suited for determination of phase curves and, thus, for normalization to common viewing geometry, allowing for relative comparisons of reflectance and derived parameters among sites. Photometric studies of areas disturbed by rocket exhaust (blast zones) at the Apollo, Luna, Surveyor, and Chang'e-3 landing sites allowed us to optimize a photometric function that was used to fit reflectance data for silicic volcanic regions (see Chapters 2 and 3; Appendix E; Clegg et al., 2014b). NAC images were photometrically corrected and projected to map format using the USGS’s Integrated Software for Imagers and Spectrometers (ISIS) (Anderson et al., 2004). We use ISIS, ArcGIS, and ENVI (Environment for Visualizing Images) to process and analyze NAC images and quantify reflectance properties. In ISIS, the processing step ironacal was used to remove camera artifacts by applying a radiometric calibration to each NAC image. The images were corrected to $I/F$ (Minnaert, 1961), the ratio of the radiance $I$ received at the detector viewing the surface from angle $e$ to the radiance from a normally illuminated Lambertian surface $F$ (defined as the source radiance divided by $\pi$) at angle $i$. Higher $I/F$ values correspond to areas of higher reflectance. The images were then normalized to the Lommel-Seeliger function ($IoF/LS$, called the reduced reflectance) to masks the effects of viewing geometry. See Hapke et al. (2012) and Clegg et al. (2014a) for derivation of the photometric functions and further explanation of photometric parameters.

Images were processed using NAC DTMs (2 m/pixel horizontal resolution and ~0.5 m/pixel vertical precision) as shape models in order to create backplanes for local incidence,
local emission, and phase angles (Tran et al., 2010; Burns et al., 2012). ArcGIS was used to georeference the NAC images to the DTM, and ENVI was used to create regions of interest from which to extract reflectance values. ISIS is then used to calculate local incidence and local emission angles from the DTM information, allowing us to reduce the effects of topography when we normalize images to the Lommel-Seeliger function ($IoF/LS$). The use of repeat-coverage NAC images of each site permits determination of the photometric parameters $\omega$ (single scattering albedo) and $\theta$ (mean slope angle), and allows us to determine the reflectance $I/F$ and reduced reflectance, $IoF/LS$, at a common phase angle ($g$). We plot $IoF/LS$ vs. $g$ for each NAC image processed at each study area (including Apollo landing sites) and use the Hapke function discussed in Chapter 2 to fit the data and determine best-fit parameters (see Figure 4.5 and Table 4.1). We optimized this parameter determination using the Apollo landing sites and then applied the same method to silicic volcanic areas. Hapke model fits to three regions associated with the CBVC – a highly reflective area, an area of lower reflectance, and an area outside of the complex – are shown in Figure 4.5 as an example of fitting reflectance data with the Hapke function. Fitting a curve to the reflectance data measured over a range of phase angles allows us to determine $IoF/LS$ for the phase angle of interest (or a common phase angle), and we can then convert back to $I/F$ to compare with laboratory spectral data (discussed in the next section). We determine $I/F$ at a common phase angle of 30°, which we refer to as the normalized reflectance ($I/F(30°)$), to use for comparison across silicic sites, which lie at different latitudes, and with the spacecraft landing sites discussed in previous chapters (Clegg et al., 2014a; 2014b).

We chose several regions of interest (ROIs) at the Compton-Belkovich Volcanic Complex, the Lassell Massif, Hansteen Alpha, the Gruithuisen Delta and Gamma domes, and one ROI at the site of possibly silicic Aristarchus ejecta. The study area for the CBVC is shown in Figure
4.6, and the corresponding NAC DTM used for image processing and the ROIs chosen for extracting reflectance values are shown in Figure 4.7. The ROIs for all other silicic sites are shown in Figure 4.8. Coordinates, I/F(30°) values, and associated single scattering albedos for all of the ROIs are listed in Appendix D. We used NAC images with a variety of illumination conditions to obtain reflectance data and then applied a Hapke photometric function to fit the reflectance data, as explained above. We avoided areas near young craters to minimize the effects of fresh, immature materials on the reflectance measurements. To compare how the reflectance measurements at areas of silicic volcanism compare with those of pure anorthosite, we extracted reflectance measurements for a region believed to contain exposures of PAN along the Inner Rook Ring of Orientale (Figure 4.3).

4.2.1 Compositional Analysis

To assess possible mineralogical compositions of the silicic regions, we first correlate soil compositional data from the Apollo, Luna, and Chang'e-3 landing sites with photometric data to assess trends between photometric parameters and composition (and, by inference, mineralogy). We then use spectral measurements of laboratory mixtures and compare these results with reflectance measurements taken at the silicic regions.

To approximate mineralogy at the Apollo and Luna sites, we did a normative mineralogical analysis on soil samples taken from the Apollo and Luna landing sites (outside of the blast zone areas) using data from the Handbook of Lunar Soils (Morris et al., 1983). For approximating mineralogy at the Chang'e-3 landing site, we use elemental concentrations from APXS data obtained by the Yutu rover (Zhao et al., 2014; Neal et al., 2015). We consider mineralogy to be represented well by chemical composition; therefore we use Al₂O₃ as a proxy for plagioclase feldspar and FeO+MgO+TiO₂ as a proxy for the sum of the mafic minerals
olivine, pyroxene, and ilmenite. For most lunar materials, a plot of FeO+MgO+TiO₂ vs. Al₂O₃ makes a very linear (inverse) correlation, as represented by the Apollo data shown in Figure 4.9. We then compare the mafic content (FeO+MgO+TiO₂) and Al₂O₃ content at these landing sites with the corresponding normalized reflectance, \( I/F(30°) \), and with single scattering albedo, \( w \). Both \( I/F \) and \( w \) increase with increasing feldspar content and decrease with increasing FeO-bearing minerals (Helfenstein and Veverka, 1987; Clegg et al., 2014c), so we can use these correlations to infer mineralogical variations from NAC reflectance at sites of silicic volcanism and PAN.

For the analog spectral comparison, we selected NU-LHT-1M (henceforth referred to as NU-LHT), a lunar soil simulant that was created as an analog to highlands materials. NU-LHT has a composition based on the average chemical composition of the Apollo 16 regolith and has 16% glassy material designed to simulate agglutinates (Stoeser et al., 2010). We mixed rhyolitic pumice from Obsidian Dome in Owens Valley, CA, with the NU-LHT simulant as an analog for felsic pyroclastics on the Moon. We measured the pumice using X-Ray diffraction and found it to be completely glassy with no crystalline components, making it a good analog material for a felsic pyroclastic glass. The pumice was crushed and mixed in varying proportions by weight (5, 10, 20, and 50 wt%) with NU-LHT. We took spectral measurements of the mixtures using an Ocean Optics Jaz spectrometer (spectral response range of 190-800 nm) with a pulsed xenon light source. All measurements were taken at an incidence angle of 30°, emission angle of 0°, and phase angle of 30°, allowing us to make comparisons of \( I/F(30°) \) with the silicic volcanic regions. We convolve our spectral data to \( I/F \) values that are consistent with the NAC spectral responsivity in order to make comparisons between our laboratory reflectance measurements and
reflectance measurements taken from NAC images. The LRO NACs have a spectral response from 400-750 nm (Robinson et al., 2010), with the average falling around 650 nm.

Using an average rhyolitic composition for the pumice (Vogel et al., 1989), we also determine the relationship between composition and reflectance for each pumice mixture. Because the pumice was freshly ground in the lab, it likely represents an upper limit to the reflectance we might expect from >3 billion year old glass on the Moon. That said, owing to low FeO content, space weathering would not be expected to have as much of an effect on reflectance as it would on a more Fe-rich material because there would be less Fe available for the production of nanophase Fe metal, which is the main cause of lowered reflectivity of weathered lunar soil (Fischer and Pieters, 1994; Taylor et al., 2000).

4.3 Results

4.3.1 Reflectance Measurements

Extracting reflectance data from NAC images at selected regions of interest at a common 30° phase angle gives \( I/F(30°) \) values that range from 0.14-0.20 for the CBVC, 0.09-0.17 for HA, 0.06-0.08 for LM, and average 0.06-0.07 for the Gruithuisen Domes, and average 0.099 for Aristarchus ejecta (see Table 4.2). These values are most comparable to those seen at the feldspathic Apollo 16 landing site, which, with an \( I/F(30°) \) of 0.093, has the highest reflectance of all the Apollo, Luna, and Surveyor landing sites. We plot the \( IoF/LS \) data and fitted curve for background highlands materials near the CBVC vs. phase angle (\( g \)) alongside the reflectance data for Apollo 16 (Figure 4.10), and it is apparent that the reflectance values for the two sites are very similar. The reflectance data for Apollo 14, which has a higher FeO content than Apollo 16 and is less reflective, is also shown alongside the CBVC background and Apollo 16 reflectance data. The reflectance values for the CBVC fall close to those measured for exposures
of pure anorthosite along the Inner Rook Ring of Orientale, which range from 0.15-0.20 and are the highest values of all the sites studied thus far. The most reflective areas in the CBVC are small bulges or domes that lie in the southern part of the complex, and the least reflective regions are the larger volcanic constructs referred to as the α-dome and β-dome (Figure 4.7).

As discussed in Section 4.2, we use Hapke fits to photometric data of each of the study sites to extract single scattering albedos (w) for each region. Modeled w values for our study regions range from 0.53-0.66 for the CBVC, 0.40-0.62 for HA, 0.35-0.46 for the LM, 0.34-0.38 for the Gruithuisen Domes, and 0.53 for the Aristarchus ejecta ROI. The w values for exposures of PAN range from 0.61-0.66. Single scattering albedo is dependent on composition and mineralogy, and for the Moon, increases with increasing feldspathic composition and with increasing reflectance. Table 4.2 lists the I/F(30°) and w values for the silicic sites, PAN exposure, and, for comparison, the spacecraft landing sites.

4.3.2 Compositional Measurements

Apollo and Luna soil compositions and mineralogy correlate with I/F and w values such that more reflective soils (and therefore soils with a higher w) have higher plagioclase contents and lower mafic mineral contents (shown in Figures 4.11-4.13). Single scattering albedos range from 0.24 to 0.47 for the Apollo and Luna sites, with Apollo 16 and Luna 20 having the highest values because they landed in the feldspathic highlands.

Compositional information for returned Apollo and Luna regolith samples reveal that FeO contents range from ~5 wt% at Apollo 16 to ~20 wt% at Luna 24. MgO contents range from ~6 wt% at Apollo 16 to ~11 wt% at Apollo 15, and TiO₂ contents range from ~0.6 wt% at Apollo 16 to ~8 wt% at Apollo 11. Regolith Al₂O₃ contents vary from ~11 wt% at Luna 24 to ~27 wt% at Apollo 16. The normative plagioclase contents ranges from 34 wt% at Apollo 17 to 78 wt% for
Apollo 16. The average normative ilmenite content ranges from 1.0 wt% at Apollo 16 to 16 wt% at Apollo 17. Zhao et al. (2014) derived FeO and TiO$_2$ abundances of ~18 wt% and ~5 wt%, respectively, for the Chang'e-3 landing site. Neal et al. (2015) report values of 4.7 wt% TiO$_2$, 21.3-22.1 wt% FeO, and 8.3-9.1 wt% MgO for the regolith at the landing site. These concentration values are used to determine the relationship between composition (and derived normative mineralogy) and reflectance.

Plotting Al$_2$O$_3$ versus reflectance (Figure 4.12) shows that an increase in plagioclase content is consistent with an increase in $w$ and $I/F(30^\circ)$. This simple relationship holds for most lunar materials because all are primarily mixtures of plagioclase with pyroxene, olivine, and ilmenite and glass produced therefrom. We also plot mafic components (FeO+MgO+TiO$_2$) versus $I/F(30^\circ)$ for the Apollo, Luna, and Chang'e-3 landing sites (Figure 4.13), and it is evident that there is a strong correlation between increasing mafic content and decreasing reflectance. The CBVC and silicic regions plot along the extrapolation of landing site data to low mafic contents and close to areas of PAN, which have very low mafic contents, consistent with FeO and TiO$_2$ values derived from Clementine UV-VIS data (Blewett et al., 1997; Lucey et al., 2000).

Spectra for the pumice, NU-LHT, and pumice+NU-LHT mixtures show that increasing amounts of pumice added to NU-LHT leads to an increase in reflectance (Figure 4.14). There is a linear correlation between increasing wt% pumice added to NU-LHT and $I/F$ at 30° phase angle (Figure 4.15a). The $I/F(30^\circ)$ values measured for the pumice, NU-LHT, and pumice+NU-LHT mixtures, as well as the percent increase in reflectance from that of pure NU-LHT, are listed in Table 4.3. The addition of 50 wt% pumice to NU-LHT gives a 132% increase in reflectance from that of pure NU-LHT, whereas the addition of 5 wt% pumice gives a 49% increase in reflectance. We calculate $I/F(30^\circ)$ as a function of mafic components (FeO+MgO+TiO$_2$)
estimated for the pumice mixtures (Figure 4.15b), using an average rhyolitic composition for the pumice (see Vogel et al., 1989). The \( I/F(30^\circ) \) values have been convolved to match the peak spectral responsivity for the NACs.

### 4.4 Discussion

#### 4.4.1 Compositional Constraints on Regions of Non-Mare Volcanism

Remote sensing provides strong evidence for the presence of felsic rocks at the Compton-Belkovich Volcanic Complex, Hansteen Alpha Volcanic Complex, Gruithuisen Domes, Lassell Massif, and parts of Aristarchus ejecta. These regions are more reflective than their surroundings and NAC images reveal morphological features that indicate they are compositionally distinct from mare basalts. Steep slopes on volcanic constructs indicate more viscous, and thus, by inference, more silicic lavas. Applying the Hapke model used for our reflectance studies of spacecraft landing sites to areas of silicic volcanism and areas of nearly pure anorthosite on the Moon, we are able to determine accurately the reflectance \( (I/F) \) values at a common phase angle to use for comparison across sites. Our results show that the silicic regions are all, on average, more reflective than the spacecraft landing sites, including Apollo 16 and Luna 20, both of which landed in the feldspathic highlands (see Table 4.2). The Compton-Belkovich Volcanic Complex has the highest reflectance and highest \( w \) of all the silicic sites chosen for comparison, and the highest \( I/F(30^\circ) \) values within the complex are on a par with those of the exposure of PAN at Orientale, which has the highest average reflectance of any of the sites we have studied thus far. Hansteen Alpha has slightly lower values, followed by intermediate values at the Gruithuisen Domes and Lassell Massif.

Reflectance depends on several factors, but we have shown that for the Moon, it is strongly related to composition and, accordingly, mineralogy (see Figure 4.13). There is a strong
correlation between increasing reflectance and decreasing mafic contents using FeO+MgO+TiO$_2$ as a measure of the mafic mineralogical components for the Apollo, Luna, and Chang'e-3 sites. Moreover, the CBVC and silicic regions plot along the extrapolation of Apollo soil mafic contents to as low as $\sim$5 wt% FeO+MgO+TiO$_2$ for CBVC and $\sim$10 wt% for the other silicic regions. The exact mafic content of the silicic regions is unknown, but the extrapolated values are in a range consistent at least with FeO and TiO$_2$ derived from Clementine data. Small fragments of granite/felsite also exist in the lunar sample suite, and we know that these are Si-rich and Fe-poor. The Christiansen Feature data, which characterize an emissivity maximum and have been shown to be related to silicate polymerization (Logan et al, 1973), from Diviner clearly indicate that the CBVC has a silicic composition, therefore we infer that the mineralogy of the CBVC regolith is dominated by SiO$_2$ (quartz) and alkali (K-rich) feldspar, both of which are Si-rich minerals and much richer in SiO$_2$ than plagioclase, and that the volcanic complex likely has similarly low, but not quite as low, contents of Fe- and Ti-bearing minerals to the areas thought to be nearly pure anorthosite. M$^3$ spectral data across the CBVC show very weak mafic silicate bands (Bhattacharya et al., 2013), consistent with very low pyroxene and olivine contents.

The silicic sites all exhibit a range of reflectance values, both within the various regions and among the regions. This is especially evident at the CBVC (see Figure 4.7), where features such as the volcanic cones and domes are less reflective than some of the other regions in the central portion of the complex. The most reflective regions in the CBVC, bright bulges in the central portion of the complex, are 68% more reflective than the background highlands. Comparatively, adding 20 wt% pumice to NU-LHT gives a 70% increase in reflectance (see Table 4.3). Therefore, we infer that the addition of up to $\sim$20 wt% glassy silicic materials could account for
the increased reflectance at the most reflective regions of CBVC (regolith) compared to average Apollo 16 soils.

The least reflective areas that we analyzed in the complex, the α- and β-domes (Jolliff et al., 2011a), are 17% and 28% more reflective, respectively, than the background ROI measured outside and to the north of the CBVC. Comparing to the reflectance of our pumice mixtures, the domes may have less than 5% glassy silicic materials at their surfaces or they may simply be composed of less silicic rock. As these positive-relief features have degraded, any mantling deposits on the top would have been eroded by mass wasting, revealing somewhat higher mafic contents perhaps compositionally similar to KREEP basalts or other intermediate composition materials (e.g., SiO$_2$ $\sim$ 50-60%). An oblique view of the α- and β-domes is shown in Figure 4.16, and it is apparent that the top of the β-dome has been eroded, and is now flanked by a debris apron. The α-dome is actually a cone or dome with a collapse pit on top, indicating that this feature was formed by a viscous lava, consistent with what we might expect at areas that formed KREEP basalts (Neal and Taylor, 1988). On the basis of landing site compositions correlation with $I/F(30^\circ)$, we infer that a soil with KREEP composition would have reflectance values similar to those seen at the Apollo 14 landing site ($I/F(30^\circ) = 0.06$). Since the CBVC α-dome is more reflective than Apollo 14 landing site NAC measurements, it may have a more felsic composition, but it is not as silica-rich as rhyolite. If it indeed has an intermediate silicic composition, then it may be composed of dacite (SiO$_2$ $\sim$63-70 wt%) or andesite (SiO$_2$ $\sim$57-63%). This result is interesting and important because rocks with intermediate compositions with SiO$_2$ contents greater than $\sim$52.5-53 wt% but less than the 70-75% typical of Apollo felsic samples have not been observed among the Apollo samples or lunar meteorites. The Gruithuisen Domes, Hansteen Alpha, and Lassell Massif have lower reflectance values than those seen at the CBVC.
and may contain materials of intermediate silicic compositions or a mixing of felsic components with less silicic materials.

The high Th concentrations at our study areas are consistent with Th concentrations in silica-rich evolved lunar rocks such as granite or its extrusive equivalent, rhyolite (Hagerty et al., 2006; Seddio et al. 2013; Seddio et al. 2014). The evidence for highly viscous lava flows at the Gruithuisen Domes, Hansteen Alpha, Lassell Massif, and CBVC in terms of steep slopes on volcanic constructs is also consistent with what is seen at terrestrial rhyolite flows. However, highly viscous silicic magmas such as those that produce rhyolite would likely not be able to rise through crust as thick as what is seen at the CBVC. The CBVC therefore likely formed after a shallow intrusion of an evolved magma, possibly similar to KREEP basalts, differentiated beneath the surface to produce a silicic residual melt and enrichment in thorium (Jolliff et al., 2011a). The initial intrusion possibly inflated the complex into a broad, low dome, and effusive eruptions along ring fractures created the elevated topography seen on the east and west portions of the complex. The β-dome may reflect effusion along a radial fissure and the α-dome represents a locus of effusive eruption in the north part of the complex. Portions of the interior region collapsed as these elevated features drained lava from the central part of the initial dome, creating a caldera near the center of the CBVC and several satellite collapse features. Pyroclastic activity (see next section) may have occurred early as pressure from degassing volatiles built up in the initial intrusive phase, or it may have occurred late as the magma fractionated and degassed and as the caldera collapse occurred.

4.4.2 Pyroclastic Deposits at the Compton-Belkovich Volcanic Complex

In addition to the presence of silicic materials, multiple lines of evidence support the presence of pyroclastic deposits at the Compton-Belkovich Volcanic Complex. As previously
stated, silicic volcanic areas on the Moon are generally associated with thorium anomalies. The Th data combined with orbital data from Chandrayan-1’s Moon Mineralogy Mapper (M³) and LRO Diviner indicate that there may be an association between OH/H₂O absorptions and silicic volcanism (Petro, 2014). Several small-scale OH/H₂O absorptions have been detected in association with thorium anomalies, including at the CBVC and Hansteen Alpha Volcanic Complex. The M³ experiment had a wavelength range of 430-3000 nm, which includes the feature at 3000 nm that is associated with OH/H₂O (Green et al., 2011). The M³ data for HA shows that the entire feature is enhanced in OH/H₂O relative to the surroundings, and M³ spectra of the CBVC reveal prominent 2800-3000 nm absorptions due to the presence of OH/H₂O, whereas surrounding areas reveal a less prominent absorption (Pieters et al., 2014). Generally, these OH/H₂O absorption features are surface-correlated and do not necessarily indicate OH/H₂O presence deeper than a few millimeters into the regolith (Pieters et al., 2009). Pyroclastics may also be responsible for the hydroxyl signature (Wöhler et al., 2014), although it is unclear whether only silicic pyroclastics would exhibit a hydroxyl signature. The α- and β-domes show no enhancement in OH/H₂O, consistent with a lack of pyroclastics on the surface of these features (Petro et al., 2013), and consistent with the likelihood that the pyroclastic deposits have been removed from these steep-sloped edifices by mass wasting or that they formed prior to the volcanic construction.

Radar data from the Mini-RF instrument onboard LRO (Nozette et al., 2010) has been used to verify the presence of pyroclastics at the CBVC. Mini-RF S-band (12.6 cm) data reveal a radar dark surface within the CBVC, indicating the surface is free of blocks, except for those that occur in association with small bulges and domes, and is likely covered by a uniform layer of fine-grained pyroclastic materials (Bhattacharya et al., 2013; Petro et al., 2013; Chauhan et al.,
Radar is sensitive to the roughness of a surface, and pyroclastic deposits could show up as radar dark because they are both smooth and easily penetrated by radar waves (Chauhan et al., 2015). Chauhan et al. (2015) suggest that the pyroclastics formed during or after the collapse of the caldera and now mantle the floor of the CBVC. Some of the domes within the complex appear as radar-bright, providing further evidence that any pyroclastic deposits that may have been present on the top of these features have eroded away by mass wasting.

As mentioned in Section 4.1.1, there is an offset between the high-reflectance area and the area of elevated topography at the CBVC (shown in Figure 4.4). The high-reflectance materials extend about 5-7 km to the east-southeast of the complex, as observed by Jolliff et al. (2011a). In addition, the thorium anomaly at the CBVC may spread over an area larger than that covered by the high-reflectance area, upward of 300 km eastward of the complex, as suggested by Wilson et al. (2015). The “smeared” thorium anomaly (shown in Figure 4.17) may have been created and distributed by the explosive eruption of silicic magma, resulting in silicic pyroclastic deposits across the complex and the offset between the high-reflectance and the topographic expression of the CBVC (Jolliff et al, 2011a; Wilson et al., 2015). High-Th concentrations (20-65 ppm) are associated with lunar granitic samples (Warren et al., 1983; Jolliff, 1991; Seddio et al. 2013, 2014, and references therein), and silicic materials are intrinsically more reflective than iron-rich basaltic materials, so pyroclastic deposits could explain the extension of both the high-reflectance and the Th anomalies. The great extent of the Th anomaly compared to the area of increased reflectance to the east may be related to “gardening in” of the higher reflectance pyroclastics away from the thicker deposits at the CBVC, whereas the Th signal, sensed by gamma rays, can still be “seen” because the gamma ray signal represents an integration over about a meter of depth (Wilson et al., 2015). As discussed in the previous section, the LRO NAC
reflectance data show that the CBVC is dominated by SiO$_2$–rich materials and that the addition of up to ~20 wt% glassy silicic materials or less can account for the increased reflectance relative to the background highlands, further supporting the case for pyroclastic deposits at this site of apparent extreme and unusual lunar volcanism.

4.5 Conclusions

Regions of non-mare volcanism on the Moon are highly reflective, and we have used photometric analysis of NAC images and spectral measurements of laboratory samples to infer compositional information for these areas. Diviner data reveals that these areas, specifically the Compton-Belkovich Volcanic Complex, Hansteen Alpha Volcanic Complex, the Gruithuisen Domes, the Lassell Massif, and ejecta of Aristarchus Crater, have silicic compositions. NAC photometry coupled with compositional data from Apollo, Luna, and Chang'e-3 shows that the high reflectance at these non-mare volcanic regions is consistent with the presence of silicic materials and low mafic contents. The CBVC has the highest reflectance and single scattering albedos of all the silicic areas we have studied thus far, and the reflectance values we measure approach those of exposures of nearly pure anorthosite that have been shown with spectra to be nearly devoid of mafic minerals (Ohtake et al., 2009; Cheek et al., 2013, Donaldson Hanna et al., 2014). These high reflectance values, coupled with the other data sets further supports the interpretation that the CBVC comprises felsic lithologies – likely extrusive volcanic rocks and pyroclastic glasses, and only minor mafic components.

The variations in reflectance among and within the CBVC, HA, LM, Aristarchus ejecta, and Gruithuisen Domes may be attributed to mixing of felsic components, the presence of KREEPy materials, and/or associated pyroclastic deposits. Reflectance varies within the Compton-Belkovich Volcanic Complex, with all areas having reflectance values higher than that
of the background highlands materials (Clegg et al., 2015). The most reflective regions are small bulges or domes in the central part of the complex, and we have shown with laboratory spectra that the increased reflectance at these features can be accounted for by the addition of up to ~20 wt% glassy silicic/rhyolitic materials. Lower reflectance values correspond to large constructs such as the α- and β-domes, which likely formed by relatively viscous lavas. Intermediate silicic compositions such as andesite or dacite, or lower glass contents (<5 wt% according to our laboratory spectral measurements of glassy silicic materials) may explain the lower reflectance positive-relief features within the complex. The lower reflectance values for Hansteen Alpha, the Lassell Massif, and the Gruithuisen Domes also indicate intermediate felsic compositions. Radar data, the presence of OH/H$_2$O absorptions, eastward extension of the thorium anomaly, and the offset between the high-reflectance and elevated topography at the CBVC indicate pyroclastics are present within and around the complex, which also contribute to the increased reflectance.

The robust data sets discussed in this chapter provide strong evidence for the presence of felsic rock types and pyroclastics at areas of non-mare volcanism on the Moon; however, in-situ analysis methods or, even better, analyzing returned samples are needed to confirm the composition, including possibly indigenous OH/H$_2$O volatile contents, and mineralogy at these locations.

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helpful comments regarding our compositional studies, and Oana Coman and Jie Wei for assistance with UV-VIS spectral measurements. We also thank the late B. Ray Hawke (1946-2015) for his invaluable insight and discussions regarding Hansteen Alpha, as well as for his significant contributions to planetary science and especially his enduring fascination with “red spots” throughout his career.

References


Hansteen Alpha has a strong absorption in the UV and appears spectrally red, classifying it as a lunar “red spot”. WAC color data compiled by Sato et al. (2014).
Figure 4.2: Silicic sites used for this study. a) Compton-Belkovich Volcanic Complex (61.1° N, 99.5° E), WAC mosaic. b) Hansteen Alpha (12.3° S, 50.2° W), WAC context image. c) Lassell Massif (14.7° S, 9.0° W). Figure from Ashley et al. (2013). d) Gruithuisen Domes (36.6° N, 40.1° W), WAC frame 117752970. e) Aristarchus ejecta (23.2° N, 48.2° W), WAC context image.
Figure 4.3: Exposures of pure anorthosite (PAN) along the Inner Rook Ring of Orientale. Figure on left is from Cheek et al. (2013), showing locations of pure anorthosite detections. Red symbols represent areas of 99-100% plagioclase. The NAC image (M1097066114L) on the right was taken over an area of PAN exposures. Reflectance values were extracted from flat areas on the top of the ridge that correspond to these exposures.
Figure 4.4: Offset between elevated topography and area of high reflectance at the Compton-Belkovich Volcanic Complex. Long-dashed outline is the high-reflectance feature and close-dashed line outlines the elevated topography. Figure modified from (Jolliff et al., 2011b).
Figure 4.5: Hapke fits to several areas within the CBVC. The green data points are for a highly reflective area within the complex, the red data points are for an area of lower reflectance within the complex, and the blue data points are the background region outside of the complex. The corresponding curves are the best fit curves based on the Hapke parameters given in Table 4.1.
Figure 4.6: Study area for the Compton-Belkovich Volcanic Complex. Dashed outline on the inset marks the area of increased reflectance at the complex and the rectangular areas are the region of NAC coverage that we use for our reflectance measurements. The study area includes a range of reflectance values that we think are typical for the complex, including more and less reflective surfaces, and an area outside of the complex to the north. The NAC image shown for the study area is image M103852760R. Inset image from Jolliff et al. (2011b).
Figure 4.7: Regions of interest and range in reflectance values at the CBVC. Colored numbers in the NAC image (M103852760R) are the regions of interest where reflectance measurements were extracted. The associated NAC DTM used for processing images is shown on the right. The plot shows the reflectance values (normalized to a 30° phase angle using the Hapke function) for the regions of interest, listed from most reflective to least reflective. This plot shows that the CBVC exhibits a range of reflectance values, with bulges in the central part of the complex having the highest reflectance values and the α- and β-domes having the smallest reflectance values. Coordinates and reflectance values are listed in Appendix D.
Figure 4.8: Regions of interest for the silicic sites (except CBVC). Coordinates and reflectance values for the ROIs are listed in Appendix D. (a) Aristarchus ejecta, NAC image M1121564813R. Reflectance values were taken for one broad area on the ejecta blanket, located at 36.5° N, 40.8° W. (b) Gruithuisen Gamma, NAC image M1096757719L. Like Aristarchus,
only one broad area was studied at the GG dome. (b) Lassell Massif, NAC image M190651433. WAC context image is from (Ashley et al., 2013). (d) Gruithuisen Delta dome, NAC image M1136804003R. Red portion of outline in the WAC context image is the portion of the NAC image used for obtaining ROIs.

Figure 4.9: Plot of mafic (FeO+MgO+TiO$_2$) content vs. Al$_2$O$_3$ for the Apollo landing sites, showing a strong inverse linear correlation. We consider mineralogy well represented by chemical composition, so we use Al$_2$O$_3$ as a proxy for plagioclase feldspar and FeO+MgO+TiO$_2$ as a proxy for the sum of the mafic minerals olivine, pyroxene, and ilmenite for our studies.
Figure 4.10: Hapke fits of Apollo 14, Apollo 16, and CBVC background data. Blue data points are for a background area outside of the CBVC, and the blue line is the Hapke fit for the data. The gray data points and fitted line are for Apollo 16 landing site reflectance data, and the black data points and fitted line are for the Apollo 14 landing site. FeO content for the Apollo 14 site is ~10 wt% and ~5 wt% for Apollo 16. Lunar Prospector data show that the FeO content for the region outside of the CBVC is also ~5 wt%, and this plot shows that the reflectance values for Apollo 16 and the CBVC background area are very similar, as expected.
Figure 4.11: Relationship between mafics (FeO+MgO+TiO$_2$) and single scattering albedo, $w$, for the Apollo, Luna, and Chang'e-3 landing sites. Soils with lower mafic contents have higher $w$ values.
Figure 4.12: Reflectance as a function of alumina content for the Apollo, Luna, and Chang'e-3 landing sites.
Figure 4.13: Plot of mafics versus reflectance for the Apollo, Luna, and Chang’e-3 (CE-3) sites. There is a strong correlation for the Apollo and Luna sites, and the CBVC and silicic regions plot along the extrapolation of Apollo data to low mafic content. The exact mafic content of the silicic regions is unknown, indicated by the question marks, but the extrapolated range is consistent with Clementine data.
Figure 4.14: Spectra of NU-LHT, pumice, and pumice + NU-LHT mixtures. Increasing amounts of pumice mixed with NU-LHT leads to an increase in reflectance. The spectral reflectance measurements of the mixtures were taken at a 30° phase angle and plotted versus wavelength (from 400-750nm to match the NAC spectral responsivity function).
Figure 4.15: Relationship between reflectance ($I/F$) at $30^\circ$ phase angle with (a) increasing amounts of pumice (by weight) mixed with NU-LHT and (b) mafic content for the mixtures listed in Table 4.2.
Figure 4.16: Oblique view of the α- and β-domes at the Compton-Belkovich Volcanic Complex.

These domes exhibit some of the lowest reflectance values measured at the complex and are likely comprised of intermediate silicic materials, such as dacite or andesite.
Figure 4.17: Extension of the thorium anomaly at the Compton-Belkovich Volcanic Complex. The white line outlines the CBVC and the arrows point in the direction of the Th extension. The Th concentrations are from Lunar Prospector, as reported for original LP-GRS global Thorium contents (PDS special products) (Lawrence et al., 2000).
Tables

Table 4.1: Parameters used to obtain Hapke model fits for two areas within the Compton-Belkovich Volcanic Complex and a background region. See Hapke (2012) and Clegg et al. (2014a) for more information about these parameters.

<table>
<thead>
<tr>
<th></th>
<th>$w$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROI A$^a$</td>
<td>0.66</td>
<td>30°</td>
</tr>
<tr>
<td>ROI B$^b$</td>
<td>0.54</td>
<td>35°</td>
</tr>
<tr>
<td>background</td>
<td>0.45</td>
<td>30°</td>
</tr>
</tbody>
</table>

$^a$highly reflective area inside CBVC
$^b$area of lower reflectance inside CBVC
Table 4.2: Table of highly reflective materials and spacecraft landing sites, their reflectance at 30° phase angle, and their associated single scattering albedos (\(w\)). The mafic content (\(\text{FeO} + \text{MgO} + \text{TiO}_2\)) for each spacecraft landing sites is also reported.

<table>
<thead>
<tr>
<th>Site</th>
<th>(I/F(30^\circ))</th>
<th>(w)</th>
<th>(\text{FeO} + \text{MgO} + \text{TiO}_2^a) (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 11</td>
<td>0.040</td>
<td>0.22</td>
<td>31.1</td>
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<tr>
<td>Apollo 12</td>
<td>0.048</td>
<td>0.29</td>
<td>28.6</td>
</tr>
<tr>
<td>Apollo 14</td>
<td>0.059</td>
<td>0.33</td>
<td>22.0</td>
</tr>
<tr>
<td>Apollo 15</td>
<td>0.047</td>
<td>0.31</td>
<td>25.1</td>
</tr>
<tr>
<td>Apollo 16</td>
<td>0.093</td>
<td>0.47</td>
<td>11.9</td>
</tr>
<tr>
<td>Apollo 17</td>
<td>0.042</td>
<td>0.25</td>
<td>26.8</td>
</tr>
<tr>
<td>Luna 16</td>
<td>0.039</td>
<td>0.24</td>
<td>28.9</td>
</tr>
<tr>
<td>Luna 20</td>
<td>0.076</td>
<td>0.42</td>
<td>17.1</td>
</tr>
<tr>
<td>Luna 24</td>
<td>0.047</td>
<td>0.26</td>
<td>30.5</td>
</tr>
<tr>
<td>Chang'e-3</td>
<td>0.034</td>
<td>0.21</td>
<td>33.0</td>
</tr>
<tr>
<td>PAN</td>
<td>0.15 – 0.20</td>
<td>0.61 – 0.66</td>
<td>~0 – 3.0</td>
</tr>
<tr>
<td>CBVC</td>
<td>0.14 – 0.20</td>
<td>0.53 – 0.66</td>
<td>~3.0 – 7.0</td>
</tr>
<tr>
<td>Aristarchus Ejecta</td>
<td>0.099</td>
<td>0.53</td>
<td>~5.0 – 10.0</td>
</tr>
<tr>
<td>Hansteen Alpha</td>
<td>0.09 – 0.17</td>
<td>0.40 – 0.62</td>
<td>~5.0 – 10.0</td>
</tr>
<tr>
<td>Gruithuisen Domes</td>
<td>0.06 – 0.07</td>
<td>0.34 – 0.38</td>
<td>~5.0 – 10.0</td>
</tr>
<tr>
<td>Lassell Massif</td>
<td>0.06 – 0.08</td>
<td>0.35 – 0.46</td>
<td>~5.0 – 10.0</td>
</tr>
</tbody>
</table>

\(^a\) mafic content for silicic sites is only an estimate based on correlation between reflectance and mafic content for spacecraft sites (see Figure 4.13)
Table 4.3: Reflectance of NU-LHT and pumice mixtures. $I/F(30^\circ)$ is reported at a wavelength of 650nm, and all values have been convolved to match the NAC spectral responsivity function.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$I/F(30^\circ)$ for 650nm$^a$</th>
<th>% increase from NU-LHT</th>
</tr>
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<tr>
<td>NU-LHT</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>pumice</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>50 wt% pumice</td>
<td>0.51</td>
<td>132%</td>
</tr>
<tr>
<td>20 wt% pumice</td>
<td>0.38</td>
<td>71%</td>
</tr>
<tr>
<td>10 wt% pumice</td>
<td>0.35</td>
<td>60%</td>
</tr>
<tr>
<td>5 wt% pumice</td>
<td>0.33</td>
<td>49%</td>
</tr>
</tbody>
</table>

$^a$convolved to NAC spectral responsivity function
Appendix A: Table of Images Analyzed for Reflectance Data for Chapter 2

Table A.1: Images used for data analysis for landing sites

<table>
<thead>
<tr>
<th>Landing Site</th>
<th>Image #</th>
<th>Orbit</th>
<th>Day of Year (DOY)</th>
<th>i (degrees)</th>
<th>e (degrees)</th>
<th>g (degrees)</th>
<th>Resolution (m/pixel)</th>
</tr>
</thead>
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<tr>
<td>Ap11</td>
<td>M104362199R</td>
<td>540</td>
<td>2009-220</td>
<td>53.97</td>
<td>6.24</td>
<td>60.21</td>
<td>1.18</td>
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<tr>
<td>Ap11</td>
<td>M106719774L</td>
<td>869</td>
<td>2009-224</td>
<td>27.23</td>
<td>13.49</td>
<td>40.69</td>
<td>1.27</td>
</tr>
<tr>
<td>Ap11</td>
<td>M111443315R</td>
<td>1557</td>
<td>2009-302</td>
<td>26.24</td>
<td>0.90</td>
<td>27.14</td>
<td>0.52</td>
</tr>
<tr>
<td>Ap11</td>
<td>M119693197L</td>
<td>2772</td>
<td>2010-032</td>
<td>55.08</td>
<td>21.03</td>
<td>76.11</td>
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</tr>
<tr>
<td>Ap11</td>
<td>M119699983R</td>
<td>2773</td>
<td>2010-032</td>
<td>55.99</td>
<td>20.07</td>
<td>35.93</td>
<td>0.68</td>
</tr>
<tr>
<td>Ap11</td>
<td>M150361817R</td>
<td>7293</td>
<td>2011-022</td>
<td>62.61</td>
<td>9.39</td>
<td>71.99</td>
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<tr>
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<td>31.88</td>
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<td>43.64</td>
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<tr>
<td>Ap12</td>
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</tr>
<tr>
<td>Ap12</td>
<td>M1116678050R</td>
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<td>2013-059</td>
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<td>17.65</td>
<td>0.90</td>
</tr>
<tr>
<td>Ap12</td>
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<td>23.18</td>
<td>34.34</td>
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| Ap14 | M157709871R | 8375 | 2011-107 | 23.23 | 1.16 | 22.08 | 0.47 |
| Ap14 | M162426054L | 9070 | 2011-162 | 76.07 | 1.68 | 77.74 | 0.48 |
| Ap14 | M170674592L | 10286 | 2011-257 | 10.29 | 2.80 | 13.04 | 0.49 |
| Ap14 | M175388134R | 10981 | 2011-312 | 44.91 | 15.61 | 29.30 | 0.42 |
| Ap14 | M188357066R | 12818 | 2012-097 | 19.10 | 1.20 | 17.92 | 1.05 |
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| Ap15 | M102142784L | 230 | 2009-194 | 80.83 | 9.99 | 70.88 | 1.48 |
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| Ap16 | M152777016R | 7648 | 2011-050 | 36.10 | 20.47 | 17.13 | 0.50 |
| Ap16 | M106777343R | 877 | 2009-248 | 28.38 | 1.20 | 27.24 | 1.10 |
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| Ap17 | M113758461R | 1898 | 2009-329 | 55.72 | 14.88 | 70.17 | 0.51 |
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| L16 | M139538002R | 5697 | 2010-262 | 10.95 | 9.22 | 1.85 | 0.52 |
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| L20 | M106504563L | 839 | 2009-245 | 30.31 | 1.76 | 32.05 | 1.31 |
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| L23 | M139497036L | 5691 | 2010-262 | 17.77 | 2.53 | 16.33 | 0.50 |
| L23 | M141851758R | 6038 | 2010-289 | 21.97 | 16.97 | 14.21 | 0.52 |
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| L23 | M170151523R | 10209 | 2011-251 | 21.23 | 1.16 | 20.29 | 0.49 |
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| L23 | M1116131400R | 16711 | 2013-53 | 23.14 | 21.02 | 11.14 | 1.20 |
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Appendix B: Additional Reflectance Profiles

Figure B.1: Apollo 14, NAC image M150639913L
Figure B.2: Apollo 15, NAC image M119822622L
Figure B.3: Apollo 16, NAC image M122108795L
Figure B.4: Apollo 17, NAC image M113758461R
Figure B.5: Luna 16, NAC image M141899500L

Figure B.6: Luna 17, NAC image M188450826L
Figure B.7: Luna 20, NAC image M106504563L

Figure B.8: Surveyor 5, NAC image M106726943L

Figure B.9: Surveyor 6, NAC image M152885739L
Figure B.10: Surveyor 7, NAC image M157668488R
Appendix C: Normalized Reflectance Plots for Apollo Sites

Figure C.1: Apollo 11 normalized reflectance (HR-BZ values normalized to the background) as a function of phase angle.

Figure C.2: Apollo 14 normalized reflectance (HR-BZ values normalized to the background) as a function of phase angle.
Figure C.3: Apollo 15 normalized reflectance (HR-BZ values normalized to the background) as a function of phase angle.

Figure C.4: Apollo 16 normalized reflectance (HR-BZ values normalized to the background) as a function of phase angle.
Figure C.5: Apollo 17 normalized reflectance (HR-BZ values normalized to the background) as a function of phase angle.
Appendix D: Regions of Interest for Silicic Sites

Table D.1: Regions of interest for the silicic sites, their reflectance values \((I/F)\) at a 30° phase angle, and associated single scattering albedos.

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Appendix E: Optimizing the Fit of Parameters to the Hapke Equation

This appendix includes corrections, clarifications, and further discussion of the Hapke function and its parameters as presented in Chapter 2, as well as information about optimizing the fit of parameters for the models presented in this dissertation. These corrections and the new optimized parameter values are implemented in Chapters 3 and 4.

Corrections and Components of the Hapke Function

Chapter 2 states the single scattering albedo, $w$, as the “probability that a photon will be scattered by a particle,” but a more accurate definition is the ratio of the power scattered to the power removed for a single scattering event. The definition for $I/F$ was stated as “the ratio of the radiance $I$ received at the detector to the radiance from a normally illuminated Lambertian surface $F$ …”, but the correct definition should read “the ratio of the radiance $I$ received at the detector to the irradiance from a normally illuminated Lambertian surface $F$.”

The form of the Hapke function used in this dissertation contains several components: the single scattering component, the single particle scattering phase function, the multiple scattering component, a correction for the Coherent Backscatter Opposition Effect, and the macroscopic roughness correction. The single-scattering contribution is given by

$$r(i, e, g) = w \frac{\mu_0}{4 \mu_0 + \mu} p(g)$$

where $r(i, e, g)$ is the bidirectional reflectance, $\frac{\mu_0}{\mu_0 + \mu}$ is the Lommel-Seeliger function and $\mu = \cos(e)$, $\mu_0 = \cos(i)$. The single particle phase function, $p(g)$, accounts for anisotropic scatterers and is defined by the double Henyey-Greenstein Function, which contains a backward scattering lobe (first term) and a forward scattering lobe (second term):
\[
p(g) = \frac{1 + c}{2} \frac{1 - b^2}{(1 - 2b \cos g + b^2)^{3/2}} + \frac{1 - c}{2} \frac{1 - b^2}{(1 + 2b \cos g + b^2)^{3/2}}
\]

The terms \( b \) and \( c \) are discussed further in the next section.

The brighter the surface, the more times a photon will be scattered before emerging. In order to characterize bright surfaces, multiple scattering must be accounted for; therefore we use the form of the Hapke equation that includes the Ambartsumian-Chandrasekhar H-functions. The directions of the scattered photons are randomized and directional effects average out, so the Hapke distribution for approximating multiple scattering is not too different from the distribution for isotropic scatterers (see Chapter 8 of Hapke, 2012). The H-functions take into account the effects of multiple scattering (Hapke, 2012) and are approximated by

\[
H(x, w) = \frac{(1 + 2x)/(1 + 2x\sqrt{(1 - w)})}{(1 + 2x\sqrt{(1 - w)})}
\]

where \( x = \mu \) or \( \mu_0 \). Hapke’s isotropic multiple-scattering approximation combines single and multiple-scattering and is given by:

\[
r(i, e, g) = \frac{w}{4} \frac{\mu_0}{\mu_0 + \mu} [p(g) + H(\mu_0, w)H(\mu, w) - 1]
\]

When \( w \ll 1 \), the H-function values are approximately 1 and the reflectance is equal to the Lommel-Seeliger Function, but as \( w \) approaches 1, the H function becomes highly nonlinear.

The Coherent Backscatter Opposition Effect (CBOE) is also corrected for in the Hapke formulation that we use. The CBOE occurs when reflected light combines coherently with emitted light at zero phase, creating a surge in brightness. Including a correction for the CBOE where \( B_0 \) is the amplitude of the CBOE, and \( B_C(g, h_C) \) is the angular shape function, and \( h_C \) is the angular width parameter causes the bidirectional reflectance to take the form:

\[
r(i, e, g) = \frac{w}{4} \frac{\mu_0}{\mu_0 + \mu} [p(g) + H(\mu_0, w)H(\mu, w) - 1][1 + B_0 B_C(g, h_C)]
\]
We assume the Shadow Hiding Opposition Effect (SHOE) is negligible for the multiple-scattering term (Hapke, 2012) and do not include a correction for it.

The final component we include is the correction for macroscopic roughness. Reflectance is altered by the scattering of light from one facet to another, unresolved shadows cast on the surface, and preferential tilt of facets toward or away from the detector. The bidirectional reflectance expression assumes that the surface of the medium is smooth on scales large compared to the particle size (Hapke, 2012), which is not a valid assumption for planetary regoliths. Adding a roughness term corrects for large-scale roughness, where “areas of the surface larger than the particle size but smaller than the detector footprint are tilted with an irregular distribution of slopes” (definition from Hapke, 2012). The surface roughness is characterized by the mean slope angle, \( \theta \). The bidirectional reflectance with a roughness correction is expressed as

\[
 r(i, e, g) = \frac{w}{4} \frac{\mu_0}{\mu_0 + \mu} \left[ p(g) + H(\mu_0, w)H(\mu, w) - 1 \right] [1 + B_c B_e(g, h_e)] S(i, e, \theta)
\]

where \( S(i, e, \theta) \) is the shadowing function and depends on the roughness of the surface and mean slope angle \( \theta \). Hapke (2012) should be consulted for all derivations and for more discussion of each of the quantities. Further discussion regarding the form of the bidirectional reflectance used in this dissertation can be found in Chapters 2 and 3.

**Optimizing the Fit of Parameters**

The Hapke parameter values found in Chapter 2 and Clegg et al. (2014) were first-attempts at fitting NAC reflectance data with a Hapke function and were largely determined by trial and error visual fits and minimization of the sum of the squares of deviations of the data from model values. Here we present a more rigorous and systematic method for determining values for the variable parameters.
To minimize the number of free parameters in our model, we hold the parameters $b$ and $c$ constant across all landing sites (with the exception of Apollo 16 and Chang'e-3, as discussed below). The parameters $b$ and $c$ depend on physical characteristics of particles and are found in the double Henyey-Greenstein Function, $p(g)$ (Carrier et al., 1991; Goguen et al., 2010; Hapke, 2012), where $b$ is the angular width of the backward (first term) or forward (second term) scattering lobe and $c$ is the magnitude of the lobe. Experimental measurements have been carried out to determine these values for various types of particles (McGuire and Hapke, 2005; Johnson et al., 2012). These values are plotted against each other, and as particles depart from spherical perfection, values of $b$ decrease and values of $c$ increase, creating an L-shape, also referred to as a “hockey-stick” diagram, such as those seen in Hapke (1993), McGuire and Hapke (2005), and Souchon et al. (2011). The lower-right branch of the L is where values for smooth, transparent particles fall. Such “hockey-stick” diagrams are useful for placing constraints on reasonable values that $b$ and $c$ can take within the Henyey-Greenstein function. A positive value for $c$ indicates a backscattering character and a negative value indicates a forward scattering character (McGuire and Hapke, 2005). Narrow lobes have $b$ values close to 1, wide lobes have values $<<1$, and isotropically scattering particles have $b=0$; in general $0 \leq b < 1$.

Initial estimates of $b$ and $c$ for the Apollo, Luna, and Surveyor landing sites were based on several previous studies, as well as personal correspondence with Bruce Hapke. Souchon et al. (2011) found that materials with $b \leq 0.5$ tended to be more backscattering and had larger modeled surface roughness values, and Johnson et al. (2012) estimated $b$ and $c$ values for Apollo soils and lunar simulants. Our initial estimates for $b$ ranged from 0.32-0.36 for “background” areas at lunar landing sites and $c$ values ranged between 0.18-0.30. These values are similar to those estimated by Johnson et al. (2012) for lunar soils and fall within a narrow range on the
hockey-stick diagram. It is unlikely that \(b\) and \(c\) change drastically between landing sites, based on similarities of regolith samples collected at each of the Apollo sites, so to decrease the number of free parameters and to determine better fits for \(w\) and \(\theta\), we choose constant values to use for all landing sites. We use the averages from the ranges we initially estimated, giving values of \(b=0.34\) and \(c=0.24\) for all sites. The value for \(b\) must be decreased slightly to 0.32 to produce a good fit to Apollo 16 and values for both \(b\) and \(c\) must be decreased to 0.30 and 0.20 to produce a good fit to the Chang'e-3 data.

In order to optimize our model fits, we minimize the sum of the squares of the offsets between the modeled \(\text{IoF/LS}\) values and the NAC measured \(\text{IoF/LS}\) values (a least-squares minimization) using a form of the Simplex Method called the Generalized Reduced Gradient Algorithm. This algorithm is an iterative method that approximates partial derivatives for the sum of the squares of the offsets, based on input parameters and constraints, and continues to vary the input parameters until this partial derivative is close to zero and the sum of the squares is minimized. The parameters being determined for our studies are \(w\) and \(\theta\), and we use the least-squares minimization to determine the values that create the best fit to the NAC reflectance data. We determine a few constraints for our model: \(b\) and \(c\) are set at values of 0.34 and 0.24, respectively, as discussed above and with exceptions only as noted. Values for \(\theta\) must be \(>1^\circ\) and \(0 < w \leq 1\). We also set \(B_{C0}=0.80\) and \(h_C=0.107\) for all landing sites, based on values used by Hapke (personal correspondence). These values were determined by fitting the CBOE function at small phase angles for Wide Angle Camera (WAC) data, and values of 0.80 for \(B_{C0}\) and 0.107 for \(h_C\) would be appropriate for the NAC spectral responsivity (see Fig. 15 of Robinson et al., 2010). The values for \(w\) and \(\theta\) determined using this least-squared minimization method, as well as the corresponding \(\text{IoF/LS}\), and \(I/F(30^\circ)\) values, are reported in Table E.1.
References


Table E.1: Optimized parameter values for landing sites studies. For most sites, \( b = 0.34 \), \( c = 0.24 \), \( B_{c0} = 0.80 \), and \( h_c = 0.107 \).

| Landing Site | \( w \) | \( \theta \) | \( \text{IoF/LS}^b \text{ for blast zone} \) | \( 
\text{I/F(30\textdegree)} \text{ for blast zone} \) | \( \text{IoF/LS}^b \text{ for background} \) | \( 
\text{I/F(30\textdegree)} \text{ for background} \) |
<table>
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<tr>
<td>Apollo 11</td>
<td>0.22</td>
<td>27°</td>
<td>0.097</td>
<td>0.045</td>
<td>0.086</td>
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<td>0.29</td>
<td>40°</td>
<td>0.116</td>
<td>0.540</td>
<td>0.103</td>
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<td>0.066</td>
<td>0.127</td>
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<td>0.31</td>
<td>44°</td>
<td>0.112</td>
<td>0.052</td>
<td>0.101</td>
<td>0.047</td>
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<td>Apollo 16</td>
<td>0.47</td>
<td>31°</td>
<td>0.212</td>
<td>0.100</td>
<td>0.200</td>
<td>0.093</td>
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<td>Luna 16</td>
<td>0.24</td>
<td>38°</td>
<td>0.087</td>
<td>0.041</td>
<td>0.083</td>
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<td>Luna 17</td>
<td>0.23</td>
<td>28°</td>
<td>0.097</td>
<td>0.046</td>
<td>0.090</td>
<td>0.042</td>
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<tr>
<td>Luna 20</td>
<td>0.42</td>
<td>36°</td>
<td>0.171</td>
<td>0.081</td>
<td>0.163</td>
<td>0.076</td>
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<tr>
<td>Luna 23</td>
<td>0.26</td>
<td>29°</td>
<td>0.111</td>
<td>0.052</td>
<td>0.102</td>
<td>0.047</td>
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<tr>
<td>Luna 24</td>
<td>0.26</td>
<td>30°</td>
<td>0.112</td>
<td>0.052</td>
<td>0.100</td>
<td>0.047</td>
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<td>Surveyor 1</td>
<td>0.20</td>
<td>37°</td>
<td>0.077</td>
<td>0.036</td>
<td>0.069</td>
<td>0.032</td>
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<tr>
<td>Surveyor 5</td>
<td>0.23</td>
<td>40°</td>
<td>0.091</td>
<td>0.043</td>
<td>0.082</td>
<td>0.038</td>
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<td>Surveyor 6</td>
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<td>34°</td>
<td>0.1</td>
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<td>0.043</td>
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<td>Surveyor 7</td>
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<td>0.209</td>
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<td>Chang'e-3</td>
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<td>32°</td>
<td>0.080</td>
<td>0.038</td>
<td>0.073</td>
<td>0.034</td>
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\(^a\)To create the best-fit to Apollo 16 and Chang'e-3 data, the values of \( b \) and \( c \) had to be modified. Apollo 16 \( b \) value was set to 0.32 and values of \( b \) and \( c \) for Chang'e-3 were 0.30 and 0.20, respectively.  
\(^b\)for 30° phase angle