Lunar Data Analysis Program
Abstracts of Selected Proposals
(NNH18ZDA001N-LDAP)

Below are the abstracts of proposals selected for funding for the LDAP program. Principal Investigator (PI) name, institution, and proposal title are also included. 37 proposals were received in response to this opportunity. On September 28, 2019, 9 proposals were selected for funding.

Mustafa Aksoy/University at Albany, SUNY
Characterization of Lunar Regolith and Bedrock Using Wideband Microwave Radiometry

The lunar surface consists of a regolith layer which covers the underlying bedrock. Understanding thermal, physical, and chemical properties of lunar regolith and bedrock is very important to reveal geologic features of the Moon, discover potential natural resources that humans can exploit through future lunar missions, and obtain information regarding the history of the solar system. Because of the high cost, logistical challenges and extreme environmental conditions associated with lunar exploration, remote sensing is the most suitable approach for surveying such properties. More specifically, microwave radiometers, due to high sensitivity of their measurements to thermal, physical and chemical properties of lunar regolith and bedrock (such as subsurface temperature and heat flux, density, and FeO and TiO2 abundance), can be utilized to accurately estimate important regolith and bedrock parameters.

Remote sensing of Lunar regolith and bedrock through microwave radiometry, however, requires development of an accurate forward microwave emission model. Several models for microwave emissions from the lunar surface have been developed and are available in the literature. However, many important factors such as volume scatterings, roughness of bedrock and regolith layers, density fluctuations within the regolith, and coherent wave interferences have been ignored in these models. This research, therefore, aims to develop a new forward microwave emission model based on the Dense Media Radiative Transfer theory which takes many of the aforementioned factors into account by leveraging extensive studies conducted for Earth remote sensing applications. The model will be tuned using measurements performed by Chinese Chang'E-1 and Chang'E-2 microwave radiometers, in-situ data collected during Apollo missions, and auxiliary data provided by other Lunar remote sensing instruments such as Lunar Reconnaissance Orbiter and Clementine. Finally, the developed model will be coded as a software tool and released for public use.
In this two year proposal we will investigate the explosive volcanic deposits that are located near the Montes Apenninus. Our study area includes 10 known pyroclastic deposits, as well as parts of Mare Imbrium, Serenitatis, and Vaporum, the Apollo 15 landing site, and the irregular mare patch called Ina. We propose to create band parameter maps of this region using Moon Mineralogy Mapper (M3) near-infrared images. This study will address three objectives:

Science Objective 1: Characterize pyroclastic deposit mineralogy and assess the relationship between surface features and the subsurface magma plumbing system for explosive volcanic deposits.
Science Objective 2: Determine the relationship between explosive volcanic deposits and nearby effusive features (including rilles) to assess whether both effusive and explosive activity occurred at the same vent.
Resource Objective: Identify potential resources (glass-rich pyroclastic material) located near the equator.

Task 1: Create the M3 mosaic and band parameter maps
This involves mosaicking ~30 M3 images and deriving band parameter maps. We will produce an 83-band mosaic that spans ~5 to 30 degrees latitude and -10 to 15 degrees longitude, and we will create parameter maps for low calcium pyroxene, high calcium pyroxene, a glass/olivine index, and 1 and 2 micron band depths and asymmetries (Horgan et al., 2014).

Task 2: Investigating Explosive Volcanism
The Montes Apenninus area is located at the edge of multiple mare basins, suggesting that the underlying crustal rock is weak and heavily fractured. This is an area where magma can more easily reach the surface, providing many occurrences of volcanic deposits for us to identify and characterize. There are 10 previously known pyroclastic deposits within our study area (i.e. Gaddis et al., 2003). We will use our glass parameter map to identify potential previously unrecognized pyroclastic deposits (Task 2.1). We will characterize the mineralogy and eruption style of the pyroclastic deposits in our study area (Task 2.2). We will test a hypothesis that pyroclastic deposits erupt from sinuous rilles (Task 2.3). Finally, we will analyze our results and the regional mosaic to constrain the subsurface magma plumbing system in this region, potentially identify a vent that sourced both effusive and explosive volcanic activity, and constrain the distribution of a high priority lunar resource (pyroclastic glass) within our study area.

Task 3: Publication
We will publish our results in a manuscript, share our results at two conferences, and archive our regional M3 mosaic with the PDS.
Relevance: The proposed investigation is relevant to the Lunar Data Analysis Program because we will be conducting data analysis tasks by processing, mosaicking and analyzing M3 data. Our science goals fall within the high priority area of lunar research identified in the LDAP call of “Identification/characterization of lunar mineralogy as a function of location and depth” because we will constrain the mineralogy of the area surrounding the Montes Apenninus. Additionally, our science task of characterizing several pyroclastic deposits will address landing site science because pyroclastic materials are potential resources for future exploration.

Catherine Elder/Jet Propulsion Laboratory
The Lunar Rock Size-Frequency Distribution and Implications for Rock Breakdown

We propose to address two main objectives: 1) identify and understand global variations in the present day lunar rock population; and 2) quantify the breakdown rate of rocks on the Moon.

Methodology:
Objective 1: Produce maps of the lunar rock abundance, rock size-frequency distribution (SFD), and regolith thermal inertia and provide a geologic interpretation of the global variation of these parameters across the lunar surface.

We will use data from the Lunar Reconnaissance Orbiter (LRO) Diviner Lunar Radiometer Experiment (Diviner) to produce maps of the lunar rock abundance, rock SFD, and regolith thermal inertia and provide a geologic interpretation of the global variation of these parameters across the lunar surface. Regolith has a low thermal inertia, so it cools quickly after sunset, whereas rock remains warm. This results in multiple temperatures within a single pixel. Warm temperatures have a stronger effect on radiance at shorter wavelengths, so observing the lunar surface at multiple wavelengths enables the detection of sub-pixel rocks. Bandfield et al. (2011) used Diviner observations and rock temperatures from a one-dimensional (1D) thermal model to map the lunar rock abundance. However, a 1D rock temperature represents that of an infinite slab of rock, whereas real rocks vary in size and thus cool at different rates. Therefore, the 1D approach is only sensitive to large rocks (>1 m).

We propose to model the nighttime temperatures of rocks of a range of sizes (from 1 mm – 100 m) by using a 3D thermal model and to model the nighttime regolith temperatures for different regolith densities using a 1D thermal model. We will then calculate a model radiance and solve for the regolith thermal inertia and rock SFD that best fit Diviner nighttime observations. In addition to improving our understanding of the geologic variability across the Moon, these maps will be valuable for future landing site selection.

Objective 2: Compare the rock abundance and rock SFD at craters of different ages to quantify the rate of disappearance of rocks of different sizes and the overall decrease in rock abundance as rocky ejecta is broken into regolith or buried.
We will then use variations in the rock abundance and rock SFD in the ejecta of craters of known ages to infer rock disappearance rates. Ghent et al. (2014) used rock abundance maps produced from Diviner data to show a correlation between crater age and Diviner rock abundance in crater ejecta. Existing Diviner derived rock abundance maps (Bandfield et al., 2011) did not include small rocks or determine the size of the rocks detected, so the method could not be used for old craters (> 1 Gyr) where large rocks have already disappeared or to investigate how rock size affects the breakdown/burial rate. We will determine the relationship between rock SFD and age, use that relationship to determine the size-dependent disappearance rate of rocks on the lunar surface. These results will enable the application of the Ghent et al. (2014) crater dating method to older craters than is currently possible.

Catherine Elder/ Jet Propulsion Laboratory
Mapping the Thickness of the Lunar Regolith Using a New Class of Young Craters

Previous work has used the ‘blockiness’ of the ejecta of fresh lunar craters and the estimated excavation depths to detect variations in the thickness of the lunar regolith. However, more recent studies have shown that rocks on the lunar surface breakdown faster than previously thought. Thus variability in blockiness of crater ejecta varies with both regolith thickness and crater age. We propose to address this problem by identifying very young craters through thermal inertia anomalies known as a ‘cold-spots’.

One of the unexpected discoveries by the Lunar Reconnaissance Orbiter (LRO) Diviner Lunar Radiometer Experiment (Diviner) is a previously unrecognized class of lunar impact craters, ‘cold-spot’ craters. These craters are surrounded by low thermal inertia material extending ~10-100 crater radii. This ‘cold-spot’ fades within ~0.5-1 Myr after impact; thus providing a new method for identifying very young craters on the Moon. The blockiness in the proximal ejecta of these craters varies only with regolith thickness since they all have essentially the same age.

Objectives
1. Constrain variations in the thickness of the lunar regolith using the presence or absence of rocks in the proximal ejecta of ‘cold-spot’ craters.
2. Compare the estimated regolith thickness in maria units with different ages based on crater counting.

Methodology
Previous work has identified over 2000 lunar craters with prominent ‘cold-spot’ anomalies. We have conducted a preliminary study using Diviner rock abundance maps, which shows that cold-spot craters excavate more rocks in the lunar maria than the highlands suggesting that the regolith is thinner in the maria than the highlands, as expected. However, the cold-spot size significantly exceeds the crater size and only ~300 of the over 2000 cold-spot craters are large enough to analyze the proximal ejecta using
Diviner rock abundance maps. For the other ~1800 cold-spot craters, we propose to use LROC NAC images to determine which cold-spot craters excavated rocks and which did not. Craters that do excavate rocks will provide an estimate of the maximum thickness of the regolith and craters that do not excavate rocks will provide an estimate of the minimum thickness of the regolith.

Hiesinger et al. (2011) defined distinct flow units in the lunar maria based on spectral data and used crater counting to estimate the age of each of those units. We expect that older units, should have thicker regolith. We will determine the blockiness of cold-spot crater ejecta and look at the percent of craters in a given size range that excavate rocks. To ensure that we consider a statistically significant number of craters, we will bin units of similar ages. We will determine the relationship between surface age and regolith thickness.

Determining the variability in the thickness of the lunar regolith and quantifying how it changes with time will help us to understand the surface evolution of the Moon. This will help to constrain surface evolution models and provide context for detailed regional geologic studies.

Alexander Evans/Brown University
Quantitative Assessment of the Distribution of Lunar KREEP Material

The evolution of lunar KREEP material is poorly understood and remains a significant obstacle in understanding the early thermochemical development of the Moon. KREEP – material with a high abundance of potassium, rare Earth elements, and phosphorus – is hypothesized to be the residuum from an early, extensive magma ocean that crystallized beneath the less dense, feldspathic crust.

Although the magma ocean is expected to have occurred globally, the observed regional concentration of KREEP-rich material on the nearside surface requires that some localization process operated asymmetrically during or subsequent to magma ocean crystallization. Partial overturn or lateral migration of late stage mantle cumulates (e.g., KREEP) have been invoked to explain the observed asymmetry, but satisfactory evaluation of these theories has been hindered by the unknown initial and present subsurface distribution of the late stage cumulates, such as KREEP.

Previous work conducted by Haskin (1998) indicates that the distribution of surface thorium abundance, a proxy for KREEP, is correlated with the projected pattern of Imbrium impact ejecta. Thus, either primary emplacement of surface KREEP may have been due to the excavation of KREEP-rich material during the Imbrium impact or, alternatively, the ejecta from the Imbrium impact event may have substantially altered the primary distribution of surface KREEP.

We propose to use GRAIL, LRO, and LP data to constrain the distribution of surface and subsurface KREEP in the following manner:
We will use recent topographic and reflectance data from LRO to identify those craters that have impacted into non-mare regions of the PKT. In conjunction with thorium data from LP and established depth-diameter crater relationships, identified craters will be used to quantify the present depth and extent of KREEP. Additionally, the craters will be used to re-evaluate (with recent, high resolution data) the influence of Imbrium ejecta on the observed regional concentration of KREEP within the PKT.

We will use GRAIL gravity data to constrain the excavation diameter and depth of major basins capable of exhuming subsurface KREEP material. By applying established depth-diameter and ejecta volume relationships for basins, we will constrain the volume of KREEP that could have been excavated by each lunar basin. The thorium abundance associated with the ejecta area of each respective basin will be used as a primary constraint. The aggregated result from the basin analyses will provide a regional distribution of subsurface KREEP.

Based on the above, we will determine plausible scenarios for the distribution of subsurface KREEP that are consistent with the above analyses and past findings. Additionally, we will identify regions that may have large subsurface reservoirs of KREEP material.

The distribution of surface and subsurface KREEP has profound implications for the thermochemical evolution of the Moon. The work proposed herein will use recent measurements to significantly improve our understanding of the distribution of KREEP and will produce a standard set of areal maps for the distribution of KREEP that may be used in future studies. Understanding of the distribution of KREEP will contribute to our understanding of the influence of KREEP on the following: (1) the nearside concentration of lunar maria; (2) relatively low crustal thickness associated with the PKT; (3) lunar interior thermochemical evolution; (4) the final stages of the lunar magma ocean crystallization process; (5) the basin formation process; and (6) the present structure of the Moon.

This work is relevant to the goals of NASA’s Lunar Data Analyses program (LDAP), as it uses publicly available data from LRO, GRAIL, and LP missions and will enhance their scientific return. This proposal is responsive to LDAP as it will include “data analysis tasks” and “non-data-analysis tasks that require the use of lunar mission data.”

Jasper Halekas/University of Iowa
A Reexamination of the Composition, Structure, and Variability of the Lunar Exosphere

Despite a recent dedicated mission to study the lunar exosphere, fundamental questions about the exosphere still remain unanswered, and the seminal LADEE results have led us to ask new questions.
LADEE and LRO have confirmed the importance of noble gases such as argon, neon, and helium at the Moon, and also revealed the presence of other species, including metallic elements, water and hydroxyl, and methane and other carbon-bearing molecules. However, despite these groundbreaking findings, major questions still remain as to the bulk composition of the exosphere, its structure, and its variability. Even a seemingly simple question such as “What are the most common elements in the lunar exosphere?” remains surprisingly challenging to answer unequivocally, in part due to the difficulty of measuring molecular gases in situ.

The limited temporal duration of the LADEE observations (~6 months) complicates our quest to understand how the exosphere responds to external drivers such as micrometeoroid impact, charged-particle irradiation, and solar photon flux, which vary over annual and decadal time-scales. Thus, a long-baseline set of supporting observations is required to complement the LADEE neutral composition measurements and place them in a broader context.

The measurement of ions derived from the exosphere has proven a powerful technique to reveal exospheric composition and structure, thanks to the high sensitivity and low background of ion measurements. However, reported observations of ions at the Moon differ widely in their characteristics, with little agreement as to even the majority species. This likely reflects the differences in observation geometry and the limited duration of most reported measurements. A long-duration set of observations with consistent observation geometry and a consistent analysis technique could reconcile discrepancies in the literature.

The two-probe ARTEMIS mission provides a long-duration (>7 years) data set suitable for placing LADEE results in context and resolving long-standing questions about the lunar exosphere and its ionized constituents. ARTEMIS measures lunar ions, but does not directly discriminate between different lunar species. However, the proposers have developed techniques capable of fitting the energy/angle/time characteristics of the ion observations to multi-species exospheric models in order to retrieve exospheric composition and structure for each ion observation. These techniques have so far been tested and validated on only a limited set of observations, yet have already yielded valuable insight into the lunar exosphere.

Given the non-collisional nature of the lunar exosphere, each species behaves independently, making it challenging to untangle the overall structure and variability of the exosphere. To understand the exosphere, we have to understand the sources and sinks of each individual species, requiring sophisticated models. The proposers have developed the framework for a multi-species exospheric model that accounts for the wide range of sources and sinks of the various constituents of the exosphere. This model must be validated against observations, and tuned and/or extended in order to accurately represent the lunar exosphere.

We therefore propose to conduct a comprehensive reexamination of lunar ion observations from ARTEMIS, applying well-tested techniques to the entire data set in
order to constrain the average composition and structure of the exosphere and its variability over a broad range of time scales, and to validate and improve multi-species exospheric models.

This proposed scientific investigation of the Moon is relevant to the LDAP call since it will enhance the scientific return of the ARTEMIS mission through the use of publicly available mission data. This proposal addresses the high-priority goal of “characterization of the global variability and structure of the lunar exosphere”.

Jennifer Heldmann/NASA Ames Research Center
Understanding the LCROSS Impact Event and Characterizing the Physical State and Distribution of Water Ice in the Permanently Shadowed Region on the Moon

The LCROSS (Lunar Crater Observation and Sensing Satellite) mission impacted Cabeus crater on 9 October 2009 to explore a permanently shadowed region near the lunar south pole. Through the combination of spacecraft data analysis and numerical modeling, we will characterize the physical state and distribution of water ice within the permanently shadowed region (PSR) of Cabeus crater. Specifically, we will determine the thermal evolution of the impact site as a function of time through analysis of multiple lunar mission datasets: 1) LCROSS mid-infrared (MIR) camera thermal images of the impact site, 2) LCROSS near-infrared (NIR) spectrometer flash observations to determine the initial thermal pulse temperature, 3) LCROSS NIR camera images of the ejecta and impact site to constrain temperature, and 4) the single LRO Diviner temperature measurement of the crater late after impact. We will also use our knowledge of the ice grain characteristics within the plume post-impact to constrain the ice release in the numerical model, specifically using the results of Heldmann et al. (2015) coupled with new analysis conducted here of the sun-looking NIR spectrometer on LCROSS which measured water ice and vapor at lower altitudes and later times post-impact than reported in previous published works.

Using these LCROSS and LRO data as constraints, we will feed this information into a numerical model to simulate the thermal signature decay of the impact site and structure and evolution of the plume in order to place constraints on the nature and distribution of water ice within the regolith. The model will nominally include effects such as the percolation of water vapor through regolith while also including the important component of radiative transfer of heat within the warm disturbed regolith. Using the thermal data characterizing the impact site and plume over time as well as the NIR spectrometer measurements of water ice and vapor abundance and characteristics, we will use the model to discriminate among different physical processes contributing to the plume (e.g., #sweating# crater with sustained water release, prompt abrasion emission, ice sublimation/vapor dissociation, and/or direct photodissociation of ice). We will also determine the relative contributions of ice sources within the lunar regolith at Cabeus including interstitial pore ice, ice comingled with regolith, and/or a relatively pure #ice basement# layer at the LCROSS impact site.
Through this work we will improve our understanding of the LCROSS impact event, plume evolution, and the nature of the ice and regolith in the permanently shadowed region of the Cabeus crater at the LCROSS impact site, yielding valuable insights into the nature of permanently shadowed terrain on our Moon.

This work is relevant to LDAP since the proposed work requires new analysis of LCROSS mission data. The proposed work also addresses the LDAP high priority research area to study the identification, distribution, transport, and characterization of volatiles in and on the Moon.

Robert Herrick/University of Alaska Fairbanks
Detailed Examination of Highly Oblique Lunar Impacts

Impacts on the Moon that occur at low angles with respect to horizontal produce asymmetric ejecta patterns, and at the lowest impact angles the crater becomes noncircular, elongated in the downrange direction. Understanding the details of how highly oblique impacts produce these unusual crater forms is important for a variety of planetary topics, including lunar-specific topics like inferring properties of the present-day near-earth asteroid population from the recent small-crater population. Planetary impacts that occur at very low angles are important for understanding cratering mechanics because the craters that they form are not axisymmetric. The nature of the asymmetry provides unique information that helps distinguish between competing hypotheses for various aspects of impact cratering mechanics. Because the Moon has few volatiles in the crust and no appreciable atmosphere, we can learn a great deal about the basic mechanics of oblique impact through detailed examination of lunar craters and comparison to experimental craters formed in a vacuum in a strengthless medium. The flood of new high-resolution imaging and topographic data for the Moon, and improved imaging capabilities for experimental work, mean that we can examine details of the oblique impact process that were not observable in initial studies that were conducted decades ago. We are proposing to examine a sampling of the best preserved craters resulting from low-angle impact on the Moon. For each of these craters, and a companion axisymmetric crater of similar size in a similar setting, we will use the recent high-resolution imaging and topography to infer details of crater formation and ejecta emplacement. We will also conduct a series of low-angle impact experiments at the Johns Hopkins Applied Physics Laboratory's Planetary Impact Laboratory and at the Ames Vertical Gun Range designed to understand how cavity shape and the ejecta curtain evolve with time to generate the final low-impact crater form. Our analysis and interpretation will involve comparing and contrasting the lunar craters with each other and the experimental impacts, and synthesizing these results to provide a broader understanding of crater excavation and modification during oblique impact crater formation. Our research addresses questions in planetary science using data from recent lunar missions and thus is relevant to the Lunar Data Analysis Program.
Since the conclusion of the LADEE mission, our understanding of how the LADEE NMS instrument works with respect to measuring mass 18 (water) has evolved. Many initial studies of water in the lunar exosphere did not account for the accumulation of water in the instrument during the instrument off-time. Our recent work has accounted for the actual operation of the instrument to determine water density. This LDAP proposal will reanalyze LADEE NMS data of water with 3 main tasks. 1) Simulate the expected variations in the exosphere due to meteoroid impacts on the Moon and compare to LADEE data using the time dependent meteoroid flux. Expected outcomes are a better understanding of the role of meteoroids in producing water in the lunar exosphere, including what mass range of meteoroids release water and the ratio of mass of impactor to mass of water released. 2) Map observations by local time with the new knowledge of the accumulating nature of the water measurements to place an upper limit on the background water exosphere as a function of local time. Expected outcome is an upper limit on water migration in the lunar exosphere. 3) Examine the enhancement in water exosphere during the Chang'e 3 landing together with modeling to constrain the propagation of rocket exhaust during a spacecraft landing on the Moon. Expected outcome is determining the interaction of water in rocket exhaust with the surface of the Moon on timescales of <1 day. The work analyzes LADEE data applied to lunar science, and thus is relevant to LDAP.