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Lunar cold spots: Granular flow features and extensive insulating materials surrounding young craters

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ABSTRACT

Systematic temperature mapping and high resolution images reveal a previously unrecognized class of small, fresh lunar craters. These craters are distinguished by near-crater deposits with evidence for lateral, ground-hugging transport. More distal, highly insulating surfaces surround these craters and do not show evidence of either significant deposition of new material or erosion of the substrate. The near-crater deposits can be explained by a laterally propagating granular flow created by impact in the lunar vacuum environment. Further from the source crater, at distances of ~10–100 crater radii, the upper few to 10s of centimeters of regolith appear to have been "fluffed-up" without the accumulation of significant ejecta material. These properties appear to be common to all impacts, but quickly degrade in the lunar space weathering environment. Cratering in the vacuum environment involves a previously unrecognized set of processes that leave prominent, but ephemeral, features on the lunar surface.

1. Introduction

Impact cratering is the dominant geologic process currently shaping the lunar surface. Both large and small scale impacts leave their imprint on the surface morphology and materials. Any observations from orbit or the surface must be viewed through the lens of impact cratering and take into account the physical and chemical changes caused by impact events. Terrestrial and laboratory studies have provided us with much of what we know about impact processes (e.g., Braslau, 1970; Melosh, 1989; Osinski et al., 2011; Housen and Holsapple, 2011). However, the extreme velocities and energies involved make it difficult to recreate impact conditions in the laboratory, especially at larger scales in a vacuum (Braslau, 1970; Housen and Holsapple, 2011). In addition, impact craters accessible for study on Earth are quickly degraded and modified, erasing many of the finer scale and more delicate properties that could reveal details about the conditions present at the time of impact (e.g., Osinski et al., 2011). These properties include loose, fine particulates and thin, discontinuous surface modifications at large distances from the impact site.

In situ and orbital studies of the lunar surface itself present an opportunity to characterize the details of well preserved impact craters. The recent resurgence in lunar observations from orbiting spacecraft such as Kaguya, Chang'e 1 and 2, Chandrayaan-1, and the Lunar Reconnaissance Orbiter (LRO) has provided a series of systematic, high quality observations showing details that have given rise to new perspectives on the development of the Moon. These new observations build on decades of lunar cratering studies based on the wealth of information returned from the Apollo and Luna programs of the 1960s and 1970s (e.g., Heiken et al., 1991).

In particular, thermal infrared mapping of the lunar surface can be used to determine near-surface thermophysical and compositional properties. Initial telescopic and Apollo 17 Infrared Scanning radiometer measurements were used to show that most lunar surfaces are covered by a fine particulate regolith (Shorthill, 1970; Mendell and Low, 1974). Isolated surfaces with warm nighttime temperatures were identified as rocky ejecta from relatively young craters that had not yet degraded in the lunar space weathering environment (Mendell and Low, 1974).

More recently, the Diviner Lunar Radiometer Experiment aboard the LRO spacecraft has acquired systematic global diurnal temperature measurements (Paige et al., 2010). These data have been used to characterize the near surface thermophysical environment, including polar temperatures, global rock abundances,

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and typical lunar regolith fines layering and thermophysical properties (e.g., Paige et al., 2010; Bandfield et al., 2011; Vasavada et al., 2012). These and other studies have revealed that lunar surface temperatures are highly sensitive to properties such as density and particle size distribution of the upper 10s of cm of the lunar regolith. These properties are a result of a delicate balance of impact and other processes that produce a highly structured regolith over time (e.g., Keihm and Langseth, 1973; Vasavada et al., 2012; Hayne et al., 2011; Ghent et al., 2012). For example, seismic events and overburden act to compress and increase the bulk density of the regolith, while micrometeorite impacts have a tendency to disrupt the regolith, lowering its bulk density. Even slight changes in the packing or rock concentration cause a temperature contrast relative to typical lunar regolith that can be readily detected in Diviner temperature measurements (e.g., Vasavada et al., 2012; Hayne et al., 2011; Bandfield et al., 2011).

In addition, recent high-resolution images returned from the LRO Camera (LROC; Robinson et al., 2010) have allowed for the characterization of lunar surface textures and morphology at meter scales. These images show detailed properties of recent impact craters at a finer scale than previously possible (e.g., Stopar et al., 2010). Because most impacts are small and their fine-scale features are quickly degraded, these new high resolution images of recent impact craters can show properties that provide new clues to details of impact processes.

The systematic temperature mapping by Diviner and high resolution images from LROC reveal a previously unrecognized class of small, fresh lunar craters with unique thermophysical and morphological properties. These craters are distinguished by near-crater deposits with evidence for lateral, ground-hugging transport. More distal, highly insulating surfaces surround these craters and do not show evidence of either significant deposition of new material or erosion of the pre-existing substrate. The near-crater deposits can be explained by a laterally propagating granular flow created by impact in the lunar vacuum environment. Further from the source crater, at distances of ~10–100 crater radii, regolith surfaces appear to have been "fluffed-up" without the accumulation of significant ejecta material. These properties appear to be common to all recent impacts, but quickly degrade in the lunar space weathering environment.

2. Data and methods

2.1. Instrument description and data

The Diviner Radiometer has 7 thermal infrared spectral channels; 3 spectral filters are near 8 μm wavelengths and separate filters cover ~13–23, 25–41, 50–100, and 100–400 μm wavelengths (Paige et al., 2010). Each channel consists of a 1 by 21 element detector array and separate spectral channels are arranged and data are collected in a pushbroom configuration. The spatial sampling of Diviner is ~160 by 320 m from a 50 km polar orbit and the local time of observations migrated across the full diurnal cycle throughout the primary LRO mission. More complete descriptions of the Diviner instrument characteristics and operations are given in Paige et al. (2010).

The data used for the analysis of individual craters were derived from the level 2 gridded data products available at the Planetary Data System (Paige et al., 2011). These data are constructed from the individual Diviner RDR measurements and resampled to 128 pixels per degree (ppd). We used data collected from Diviner channels 6–8 (with full width half maximum bandpasses of 13–23, 25–41, and 50–100 μm respectively) acquired between July 5, 2009 and September 2, 2012 as well as gridded maps of the local time of each observation. Each of the maps covers a single lunar cycle (~28 days) resulting in 46 separate maps. Each pixel of each map essentially corresponds to a single location and acquisition time though it may represent an areally weighted average of measurements acquired by several detectors.

These data were used to derive rock abundance and rock-free regolith temperatures using the methods described in Bandfield et al. (2011). Briefly, rock temperatures are modeled a priori using the properties for vesicular basalt described by Horai and Simmons (1972) and the 1-dimensional thermal model described by Vasavada et al. (1999). Diviner channel 6–8 radiances are then fit using a non-linear least-squares algorithm with rock fraction and rock-free regolith temperature as free parameters used for the optimization. Data were restricted to local times of 1930 to 0530 to avoid anisothermality effects due to solar heating and shading on sub-pixel local slopes.

2.2. Cold spot identification and diurnal temperatures

The rock-free regolith temperature maps show thermophysically distinct surfaces that we have termed "cold spots" due to their cold nighttime surface temperatures relative to the surrounding terrain. The thermophysical properties of the lunar surface are remarkably uniform and the cold spots are one of the few distinctive surface types. By comparison, the lunar highlands and maria are indistinguishable in night-time temperatures (Vasavada et al., 2012). Cold spots were initially identified by visual inspection of the temperature maps and cataloged using the global 128 ppd rock-free regolith temperature maps (Bandfield et al., 2011). Identifications were limited to surfaces equator-ward of 50°N/S. The number of cold spots that were identified is likely an underestimate due to residual temperature variations present on sloped surfaces, especially at high latitudes and in rough highlands terrain. These surfaces have significant temperature variations on slopes due to variable solar heating that persists through the lunar night. The variable surface temperatures interfere with the identification of cold spots to such a degree that they could not be distinguished and positively identified at latitudes greater than ~50°N/S. The variability of the surrounding terrain prevents a simple identification of cold spots based on quantitative parameters, such as temperature. The criteria for the positive identification of a cold spot is the presence of a coherent pattern of colder temperatures immediately surrounding a fresh crater (identified in the LROC Wide Angle Camera mosaic; Boyd et al., 2012) with no apparent topographic features that could be responsible for the cold temperatures.

We have identified 2060 individual cold spots between 50°S and 50°N using the 128 ppd Diviner night-time rock-free regolith temperature maps (Fig. 1). Cold spots show no obvious distribution pattern and appear randomly distributed, however a test for spatial randomness within 20 degrees of the equator (where cold spot identification is expected to be most accurate and complete) indicates the presence of significant clustering ($P = 0.99$ for a chi-square distribution using a complete spatial randomness test). Observational bias (due to the difficulty of identifying cold spots

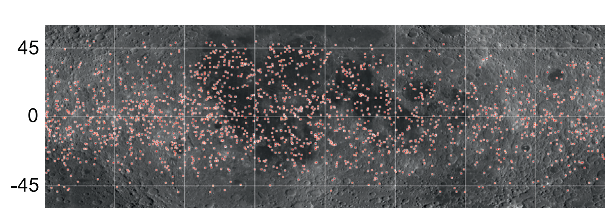

Fig. 1. LROC WAC global mosaic showing the locations of 2060 cold spots. Significant errors of omission are probable, especially at high latitudes.