

TARGETED REGOLITH AND IMPACT STUDIES IN THE NEXT LRO EXTENDED MISSION. H. M. Meyer¹, P. O. Hayne², R. R. Ghent^{3,4}, B. W. Denevi⁵, J. T. S. Cahill⁵, E. J. Speyerer⁶, M. K. Barker⁷, N. E. Petro⁷, J. W. Keller⁷, and the LRO Science Team, ¹Lunar and Planetary Institute, USRA, Houston, TX (meyer@lpi.usra.edu), ²University of Colorado Boulder, Boulder, CO, ³Dept of Earth Sciences, University of Toronto, Toronto, Canada, ⁴Planetary Science Institute, Tucson, AZ, ⁵Johns Hopkins University Applied Physics Laboratory, Laurel, MD, ⁶Arizona State University, Tempe, AZ, ⁷NASA Goddard Space Flight Center, Greenbelt, MD.

Introduction: Lunar regolith represents the product of billions of years of impact bombardment, resulting in a meters-thick layer of fragmented and overturned debris. This is a continuous process driven by individual impact cratering events. Therefore, in order to gain insight into regolith formation on the Moon, the details of the impact cratering process must also be fully understood. The impact flux on the Moon forms the basis of all Solar System chronologies, and hence it is critical to understand impact processes contributing to the observed cratering record. Further, the lunar surface is constantly reworked and chemically altered by micrometeorite bombardment and space weathering, whose effects are poorly understood. The Lunar Reconnaissance Orbiter's (LRO) fourth extended mission (ESM4) will pursue the following targeted, complementary investigations to determine the extent, effects, and origins of impact products and processes from the microscopic to basin-scale and their contribution (in conjunction with solar wind) to the development and evolution of the lunar regolith.

Extent and Distribution of Impact Melt: Among the many insights into the cratering process emerging from LRO is the importance of impact melt in partitioning energy to heating and fundamentally altering surface materials. LRO has shown that melt deposits are more extensive and abundant and stay molten longer than previously thought [e.g., 1-2]. For example, observations of pervasive melt veneers at Copernican craters [e.g., 1-4], putative basin interior melt deposits at the Nectaris [5], Crisium [6], and Imbrium basins, basin-related light plains [7], and antipodal deposits [8-9] suggest that melt is widespread and, therefore, a significant contributor to the regolith. These studies revealed the need for additional high-resolution data and a concentrated multi-instrument approach to the study of impact melt. The key questions for ESM4 are (1) What is the abundance of impact melt in proximal and distal ejecta deposits of impact craters at all scales? (2) What is the nature of putative basin melt? (3) How are antipodal deposits formed?

Variations in the Recent Impact Flux: Recent work [10] from LRO shows strong statistical evidence for a jump in the flux of large impactors (forming $D > 10$ km craters) at some point in the past billion years, most likely at ~290 Myr (Fig. 1). This result requires that the flux of large impactors is decoupled from the flux of sub-km crater-forming impactors [10], the latter

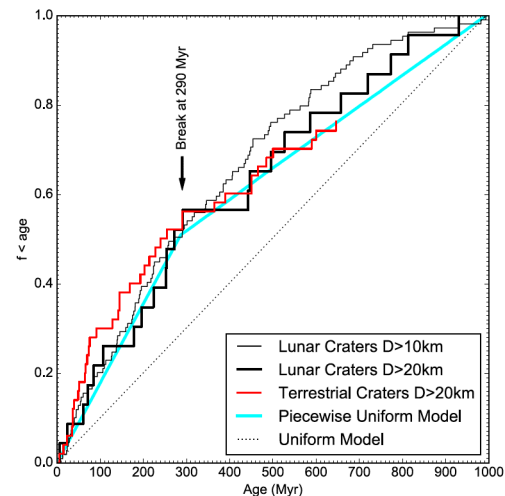


Fig. 1. Plot from [10] showing evidence from Diviner-based age estimates for lunar craters for non-uniform cratering rate. Terrestrial craters with $D > 20$ km show evidence for the same break.

of which are used for conventional chronologies [e.g., 11]. This result has far-reaching implications for the lunar chronology and those extrapolated from the lunar case, as well as for the breakup and delivery of fragments of different sizes into Earth-crossing orbits.

LRO has also provided new information about the formation rate of smaller craters. Speyerer et al. (2016) [12] detailed evidence from repeat LRO Camera (LROC) imaging for rapid resurfacing by small impacts based on a catalog of small impacts formed during the duration of the LRO mission. Consistent with this, Diviner data have revealed the presence of ubiquitous negative temperature anomalies associated with small impacts ["cold spots":13] whose signatures faded in ~200 kyr [14]. Both datasets provide the opportunity to investigate the properties and formation rates of sub-km craters, probing temporal and spatial variations in their formation and degradation. The key questions for ESM4 are (1) How has the impact flux varied over the past billion years? (2) What are the implications for the lunar chronology and solar system dynamics?

Regolith Evolution and Space Weathering: LRO has provided a new view of how regolith gardening, micrometeoroid impacts, and the solar wind work individually and in concert to mature the lunar surface. For example, the discovery of surface changes related to primary and secondary impact cratering yielded strong

evidence that impact gardening of the upper few cm of regolith is over 100x faster than estimated [12]. This regolith gardening could be responsible for the short (<0.5 Myr) lifetimes of cold spots by the destruction of their anomalous textural properties [13-14]. In terms of solar wind, reflectance trends with latitude and on crater walls have been attributed to systematic variations in solar wind fluence due to the curvature of the Moon and the Moon's passage through the Earth's magnetotail [15-16]. Laboratory simulations suggest that maturation due to solar wind irradiation may occur over timescales of ~0.1 My, but confirmation has been complicated by regolith gardening and micrometeoroid bombardment, and a lack of independent estimates of surface ages. The key questions for addressing these issues in ESM4 are (1) *How are the albedo and texture of newly exposed materials altered?* (2) *What is the rate of this alteration?*

Reconciling Photometric and Thermophysical Properties of the Lunar Regolith: Numerous enigmatic features on the Moon have emerged since LRO entered orbit in 2009. In ESM4, we will investigate the most prominent classes of anomalies to better understand their origins. These anomalies fall within two categories, (1) optical and (2) thermophysical. The most widely discussed (1) optically anomalous regions include lunar swirls which have a high visible and a low far-ultraviolet albedo, sinuous surface morphology, and association with magnetic anomalies, as well as curious photometric and hydration characteristics [17-21]. Recent Lyman Alpha Mapping Project (LAMP) and LROC Wide Angle Camera (WAC) observations have also identified additional unusual optical features, not associated with magnetic anomalies [22-24]. Another prominent class are (2) non-cold spot thermal anomalies revealed by Diviner, which are similar to cold-spots, but lacking an obvious impact crater and extending over dramatically different spatial scales. The Atlas thermophysical anomaly (Fig. 2) is the largest of this class of anomaly, with very low thermal inertia [25], suggesting finer materials with higher porosities. In Mini-RF and Earth-based radar observations (12.6 and 70 cm) this region also shows distinctive low backscatter characteristics similar to radar-dark halo craters [26-27] and consistent with regolith devoid of scatterers to at least ~10 m depths. However, there are unusually significant differences in detectability from one radar wavelength to another suggesting significant depth to the deposit despite its thermophysical signature. For example, the Atlas region displays much lower thermal inertia in the upper few cm, compared to most other radar-dark halo craters. Each type of anomaly provides additional context and contrast with lunar swirls and cold-spots, respectively. The key questions for ESM4 are (1) *How does*

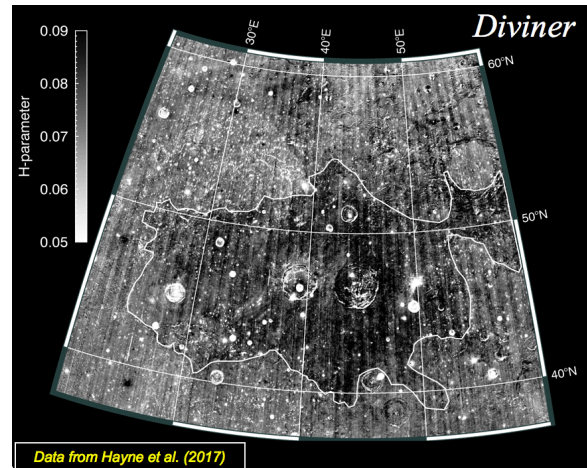


Fig. 2. The Atlas thermophysical anomaly, revealed in Diviner H-parameter data [25], outlined in white.

the small-scale structure of the lunar surface affect the photometric and thermal properties we observe? (2) *What processes are responsible for creating variations in surface texture and thermophysical properties leading to anomalies with differing depth signatures?*

Conclusions: New observations from LRO collected in ESM4 will improve our understanding of impact processes, regolith development, space weathering, and the chronology of inner solar system bombardment.

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