THERMOPHYSICAL BEHAVIOR OF THE UPPERMOST LUNAR SURFACE FROM DIVINER HIGH TIME-RESOLUTION, POST-SUNSET OBSERVATIONS.

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Introduction: Lunar "Cold Spots" are areas around small fresh craters that are colder than their surroundings in nighttime regolith temperature [e.g., 1, 2] (Fig. 1). The size of the cold spots in Diviner data typically extend several crater radii beyond the visible crater ejecta. However, recent findings based on LROC photometry suggest subtle surface modification extends still further beyond the thermal cold spot [3]. The differences observed by Diviner and LROC suggest that cold spot formation is a complex process that may affect shallow but varying depths to different degrees. While it may not correlate with the extent of visible alteration, Diviner data illustrates that the thermophysical properties of the surface in the cold spot region have somehow been altered by the impact process. Intriguingly, this cold anomaly does not appear in Diviner observations during eclipses when the sun has been blocked for only a short period of time [4]. Likewise, in the half hour just after sunset, it appears that the cold spot area may in fact be warmer than the surroundings (Fig. 2). While these observations add a wrinkle of complexity they also lead to an opportunity.

Methods: Here, we extend the investigation of the immediate reaction of cold spots to the cessation of solar heating by specifically targeting and analyzing observations in the post-sunset, or "twilight", period (i.e., ~18:00-19:00 local time). Analysis of this time period focuses specifically on variability in the thermophysical structure of the upper ~1 cm of lunar surface, whereas previous analyses of nighttime temperatures (well after sunset) typically speak to the upper 10s of cm. Importantly, it is the uppermost portion of the surface that largely influences what is detected by a host of other remote-sensing techniques. Constraining the thermal intertia of the very surface would also benefit thermal models of the near- and sub-surface. Unlike eclipses, which are rare and very narrowly limited geographically, a large fraction of the moon (roughly half) will be observable at least once within the 18:00-19:00 twilight period every ~6-8 months. Over 2016-2018, there are six opportunities for twilight observation, each lasting about 4 weeks; the cumulative number of times that a surface location is observable during twilight is illustrated in Fig. 3. Many locations may be observed multiple times at moderate emission angle (<40°) during this period, every ~7 lunar minutes on 4-5 sequential orbits, or more depending on latitude. By observing targeted locations over successive orbits over multiple twilight opportunities, we are building up a high-resolution time series of post-sunset thermal evolution of the uppermost surface. Prior to this campaign, Diviner measurements within this time period for most locations were few, scarce, or absent; constructing a time series to even half-hour resolution could require inclusion of non-colocated data from adjacent similar terrain.

As observation during the local-twilight time period is a general method of obtaining specifically focused information on the uppermost surface, we have expanded the scope of our investigation from cold spots to include a host of other lunar features, for which the high-frequency thermal response to sunset is unknown. These features include: Irregular Mare Patches (IMPs), impact rays, swirls, pyroclastics, impact melts, landing sites, and a few others. Roughly 100 locations have been identified for sequential targeted Diviner observations during twilight periods. An example of the local-time coverage over our surface targets during the most recent twilight period (Oct-Nov, 2016) is given in Fig. 4.

Results: The first two twilight campaigns (the first of which was a trial) collected 46 and 171 individual observations over 16 and 46 targets, respectively, during the local times 17:45-19:00. This is already 160% more than existed for our 100 targets previously.

As mentioned, initial observations of the twilight time period at cold spots suggest that twilight temperatures mimic the behavior of eclipse temperatures, in that the cold spot does not become colder until ~half hour after sunset. In fact, it is warmer than surroundings in the first ~30 min. This suggests that the thermal inertia of the upper ~1 cm is higher than surroundings, while the thermal inertia of the upper 10s of cm may be lower. Initial thermal modeling [5] bears this out in that high-resolution twilight measurements are best fit with a thermal model containing a higher surface density than the surroundings with a greater rate of decrease in density with depth than surroundings. This provides a contrast to the previous interpretation of cold spots (which didn't use twilight data) of areas at which the surface density had been drastically reduced, or fluffed up [1]. Here we compare temperature curves of four additional cold spots to the one modeled by [5], also examining radial variation within the cold spots. In addition, we take a first look at the post-sunset thermal behavior of the range of feature types listed above and in Fig. 4. As demonstrated by the cold spots, it may be unexpected how the relative thermal behavior of different surfaces extrapolates from nighttime behavior back to the period of higher-frequency forcing post-sunset.

References: [1] Bandfield J. L. et al. (2014) *Icarus, 231,* 221–231. [2] Williams J.-P. et al. (2017) *Icarus, 283*, 300-325. [3] Speyerer E. J. et al. (2016) *Nature, 538,* 215–218. [4] Hayne P. O. et al., (2015) *LPSC XLVI,* Abstract

#1997. [5] Powell T. M. et al., (2016) *AGU Fall*, Abstract #P21A-2079.

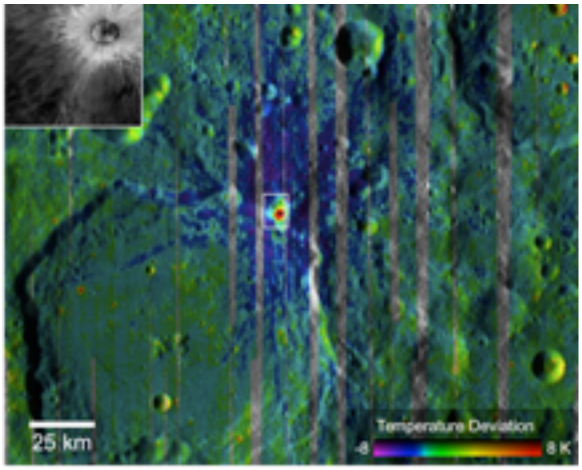
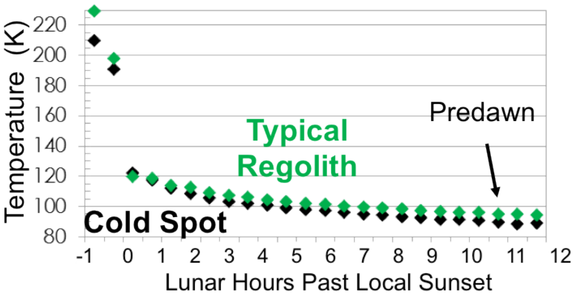


Figure 1. From [1]. Visual image and temperature anomaly at a cold spot.

Figure 2. Coldspot thermal cooling curve from sunset through dawn (black) compared with surroundings (green). Data from ~100 km^2 ROI binned to 30 min intervals. Note that cold spot does not become "cold" reltive to surroundings until ~half hour after sunset, and may actually be warmer immediately after sunset.



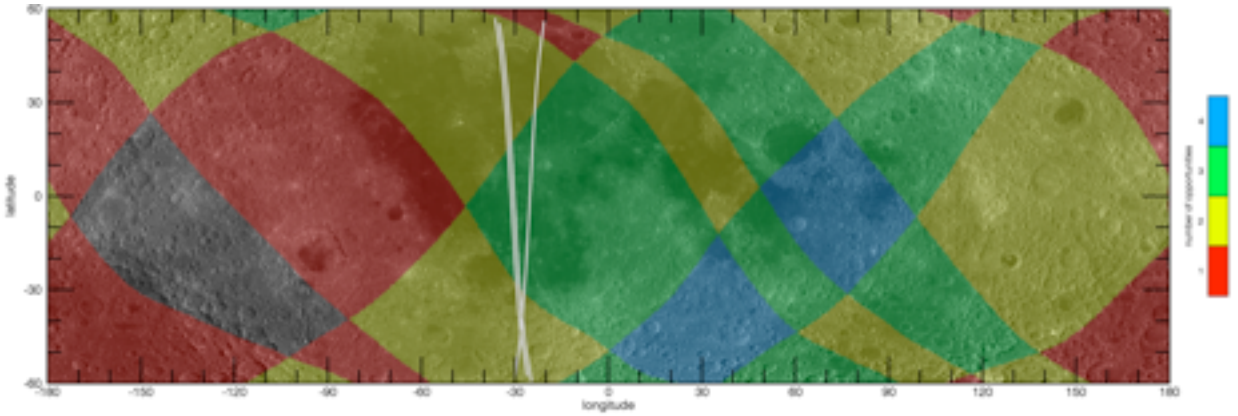


Figure 3. Map of the number of nadir opportunities for observing during the twilight period from 18:00-19:00 between Sep 2016 - Nov 2018. Overplotted in grey are tracks of the 2 total eclipses during this time period (occurring at ~9:30-11:00 local time).

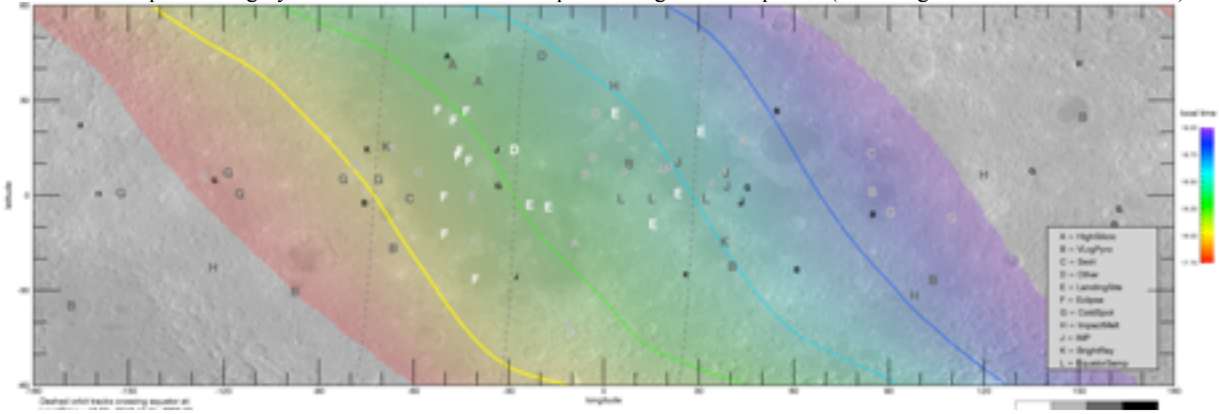


Figure 4. Map of local times at which the nadir LRO groundtrack crosses the local lunar surface, during the Sep 2016 twilight opportunity. Total colored range: 17:45-19:00 local time. Color contours: yellow=18:00, green=18:15, cyan=18:30, blue=18:45. Faint, dashed, grey lines: 3 example LRO nadir groundtracks crossing the equator at 18:00, 18:15, and 18:30 local time. Letters indicate type of targeted feature listed in inset box.