SEASONAL ILLUMINATION AT THE LUNAR POLES: PARTIAL DOUBLE SHADOWS AND SUPER-VOLATILE STABILITY.
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Introduction: Topographic depressions near the poles of low obliquity bodies can be perennially shielded from the Sun's rays. Without direct insolation, permanently shadowed regions (PSRs) reach temperatures of < 110 K, cold enough to sequester water ice [1]. However, illumination conditions, and consequently temperatures, are not constant between PSRs or even within individual shadows [2,3].

Shadows are heated by scattered sunlight and thermal emission from nearby warm, sunlit surfaces and the fluxes from these secondary sources are the dominant control on temperature within permanent shadows. A location is doubly shadowed if it is shielded from both direct insolation and secondary illumination. Thermal modeling predicts that temperatures within lunar double shadows could be as low as 25 K [4], cold enough to sequester super-volatiles like Ar, CO, CO_2, and organics found in comets [5-7].

Double permanent shadows (DPSRs) were previously mapped using laser altimetry-derived topography. [8] found that DPSRs are both rare and small, with only ~0.04% of lunar PSR area doubly shadowed at the scale of 30 m/pxl. The largest DPSRs are comparable in size to the footprint of the Diviner radiometer instrument [9], rendering it challenging to directly measure the temperature of these extreme illumination environments. Some far-infrared emissivity features in Diviner temperature measurements (channels 7,8,9) are consistent with surface anisothermality from unresolved double shadows [10], leading us to investigate whether the DPSRs can be resolved in these data.

Super-volatile cold traps: Although unable to resolve most permanent double shadows, Diviner measurements reveal the presence of spatially contiguous regions where maximum and average surface temperature are conducive to the long-term stability of super-volatile ices [6,7]. The total area of super-volatile cold traps is significantly larger than the area of permanent double shadows, raising the question: what illumination conditions are necessary for the existence of a super-volatile cold trap? Where/when do these conditions occur on the Moon?

We address these questions by mapping instantaneous double shadows at the lunar poles throughout the Draconic year. We then estimate the fraction of double shadowing down to sub-Diviner FOV scales to constrain the degree of anisothermality in surface temperature measurements. Probing illumination conditions at the smallest spatial scales [11] is necessary for understanding the thermal environments and potential volatiles that will be encountered by upcoming orbital and in situ missions [12-14], including NASA's Artemis program.

Data and Methods: We use high resolution topography data from the Lunar Orbiter Laser Altimeter instrument. Resolution ranges from 240 m/pxl to 30 m/pxl, with coverage down to 75° latitude. We assess geometric shadowing with a modified version of the method pioneered by [15] for mapping single shadows. As described in [8], a point is shadowed if the Sun does not rise above the horizon. Here we add a time-dependent solar position to investigate seasonal shadowing. In the resulting time-dependent single shadow map, a raycasting algorithm determines double shadowing states. A point is doubly shadowed if it has no direct line of sight to any non-shadowed surface facets.

Partial double shadows: Although permanent double shadows (areas that only "see" PSR terrain) will be the very coldest regions of a shadow, other locations may see only a few non-PSR facets or see non-PSR facets that are only illuminated for a short period throughout the year. Such locations are termed *partial double shadows*. Since average, rather than maximum, temperature is a more nuanced predictor of ice stability as it accounts for the general temperature of a region, rather than potential transient extremes [7], partial double shadows could significantly increase the total area of super-volatile stability zones, compared to the estimate from DPSR area alone. If partially double shadowed features only see briefly illuminated terrain, ultra-cold temperatures could persist very near the surface, i.e., a fraction of the ~7 cm thermal skin depth for lunar regolith [16]).

To quantify the extent of partial double shadowing, we determined the number of non-PSR surface facets visible from permanent shadows at the lunar poles. Figure 1 shows the total area of periodically illuminated terrain visible from PSRs poleward of 85° S. To first order, this quantity is a proxy for the flux of secondary illumination and highlights the range of illumination conditions intermediate between single and double permanent shadowing. Ongoing work includes refining the secondary illumination proxy to factor in solid angles subtended by each visible terrain facet and time illuminated throughout the year.

Points within smaller PSRs generally see fewer non-PSR facets than those on the flat floors of large permanently shadowed craters. This is consistent with past work demonstrating that smaller, shallower craters host colder PSRs [17,18]. The interiors of craters embedded within large PSR craters offer the potential geometric conditions for double shadowing [7]. These areas see fewer non-PSR facets than the surrounding crater floor because of the shielding effect of the embedded crater's rim and are expected to be colder than the surrounding singly shadowed floor.

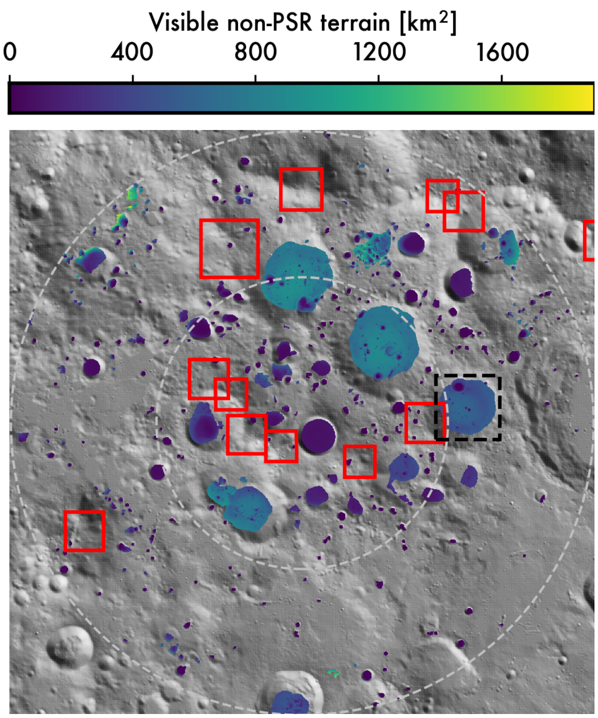

Figure 1. Area of periodically illuminated surface facets visible from southern PSRs. Circles indicate intervals of 2.5° latitude and solid red boxes denote the Artemis III landing region candidates.

Temperatures within PSRs: We examined Diviner surface temperatures covering the lunar polar regions over multiple years. Average nighttime temperatures within PSRs correlate with the area of visible non-PSR terrain (Figure 2). Embedded craters that see relatively few illuminated surface facets correspond to locations where average nighttime temperatures are < 50 K. Channel 9 observations, sensitive to wavelengths of 100-400 μm and most representative of temperatures < 43 K [19], show significant variation across the large south polar PSRs in Haworth, Shoemaker, and Faustini.

Conclusions: Permanent double shadows are predicted to be significantly colder than singly shadowed terrain but are rare at the lunar poles. However, the total area where temperatures are low enough for super-volatile stability is significantly higher than that of ultra-cold DPSRs. Our preliminary results demonstrate how partial double shadowing corresponds to variations in temperature within PSRs. We will present high-resolution maps of seasonal double shadowing and discuss how the instantaneous area fraction of double shadows within PSRs influences surface temperatures at the scale of the Diviner dataset.

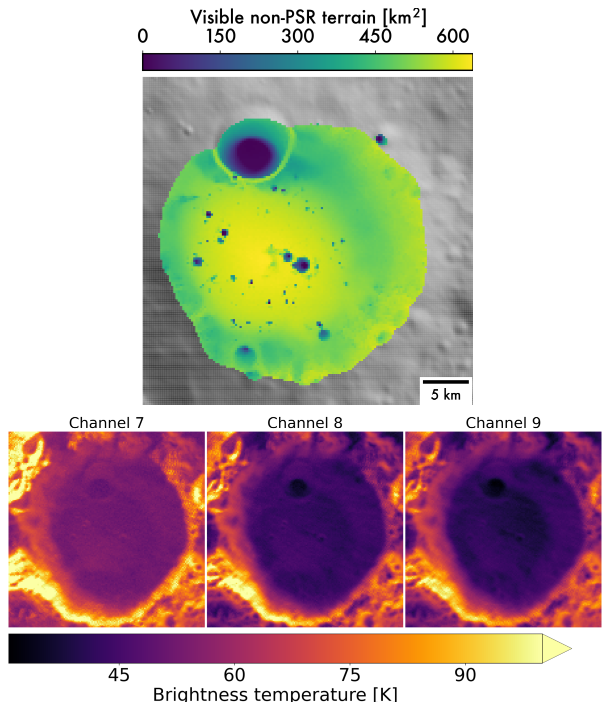

Figure 2. (top) Area of non-PSR terrain visible from within Faustini crater (region indicated by dashed box in Figure 1). (bottom) Diviner average nighttime temperatures. The large embedded crater near the top of each inset is partially double shadowed.

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