CONSTRAINING THE INVENTORY OF WATER ICE IN MICRO COLD-TRAPS ON THE MOON

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Introduction: In addition to large-scale, thermally resolved cold traps that have been identified on the Moon and Mercury in the recent decade [1-3], models show approximately 10-20% of the total cold trap area is contained within "micro cold traps" on scales < 1 km [4-5]. Compared to large cold traps, which typically reside within craters that can be up to a few km deep, micro cold traps offer greater accessibility for in-situ investigation missions of lunar volatiles. To first order, the maximum amount of ice that can be trapped within a cold trap depends on the permanently shadow volume (PSV) that harbors it. Other effects, such as emission and scattering from nearby topography, should further decrease the amount of cold-trapped ice.

Here we provide an upper limit for the volatile inventory that can be potentially trapped within lunar micro cold traps by modeling the PSV cast by small-scale lunar topography. We find that the small size of micro cold traps, which enhances their accessibility, also limits the amount of ice that can be potentially trapped within them. On scales < 10-100 m, micro cold traps cast PSVs whose depth competes with the ice loss rate, and are thus less likely to preserve lunar ice for geologic timescales.

Methods: *Illumination model:* to simulate the PSV cast by small-scale topography on the Moon, we use an illumination model based on the ray-casting technique [4,6]. The model computes the intersection points between virtual light rays cast from a finite-disc Sun and the topography, and returns the instantaneous shadow depth d at a point of interest z, calculated as,

$$d = z' - z - x \cot\theta$$

where θ is the incidence angle and z' is the height of the topography casting the shadow relative to the reference plane [4]. To compute the depth of the permanent shadow at that point, we find the temporal minimum of the instantaneous shadow depth at every point on the surface (Fig. 1a, 1b).

Model input parameters: the model takes two parameters as inputs: the position of the center of the solar disc and the surface topography. To calculate the position of the center of the solar disc, we set the solar declination equal to the lunar obliquity to the ecliptic. To model the shape of lunar small-scale topography at varying lateral scales, we calibrate the elevation of an example realistic lunar surface (1 km across) measured by the Lunar Orbiter Laser Altimeter (LOLA, [8]; Fig. 1a), so that its root mean square (RMS) slope at the pixel scale matched the RMS slope of the lunar surface, which increases on the Moon with decreasing lateral scale [4,7].

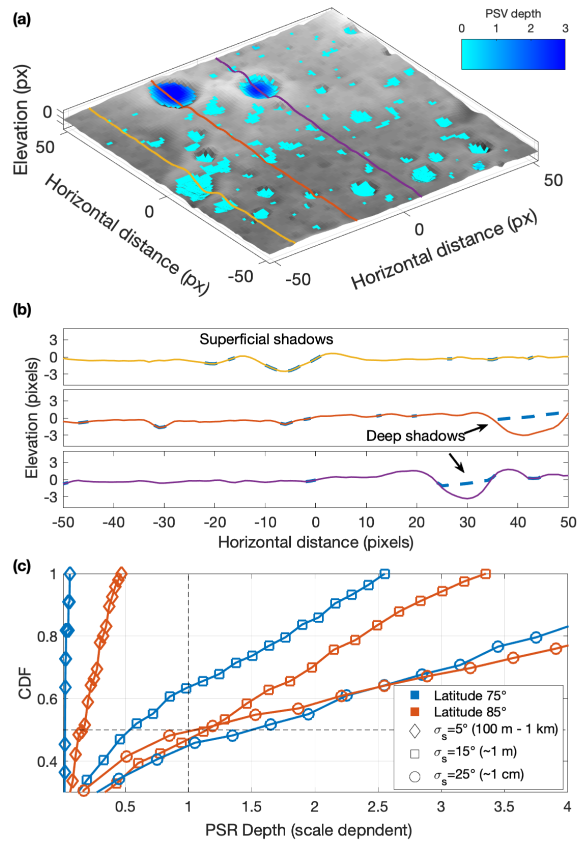

Figure 1: the volume of permanent shadows serves as an upper limit for their potential volatile inventory. (a) we use a realistic lunar surface to model the volume cast by the lunar topography on different lateral scales. The example surface shown here has $\sigma_s = 15°$, which approximately corresponds to lateral scales ~1 m (b) three cross-sections through the realistic topography, showing the depth of the PSV (c) cumulative distributions of PSV depth for various latitudes and σ_s. Values in parentheses in the panel legend indicate approximate lateral size at the pixel scale. For example, the median PSV depth (dashed horizontal line) cast by a surface with $\sigma_s = 15°$ at latitude 75° is ~0.5 m.

Results: we model PSVs cast by three realistic lunar surfaces scaled to have an RMS slope of $\sigma_s = 5°$ (roughly corresponding to a lateral scale 100 m - 1 km), $\sigma_s = 15°$ (1-10 m) and $\sigma_s = 25°$ (1-10 cm). For each surface, we calculate the cumulative distribution (CDF) PSV depth at two latitudes: 75° and 85° (Fig. 3c). For

Fig. 3c, we note that since each value of σ_s corresponds to a different lateral scale, the physical units of PSV depth depend on the value of σ_s. For example, the median PSV depth (black dashed line in Fig. 3c) for latitude 75° and $\sigma_s = 5°$ is ~5-50 m (lateral scale of 100 m - 1 km), but for $\sigma_s = 25°$ it is ~1 cm (lateral scale of 1 cm). Therefore, while the PSV depth increases with the topographic roughness, it also decreases with the lateral scale of the surface.

Discussion: the depth of the PSV provides an upper limit for the amount of ice cold-trapped within it, as scattering and thermal emissions from nearby slopes are expected to increase the temperature of the permanent shadow and induce sublimation. According to recent studies [5], roughly 10% of the lunar permanently shadowed surface is distributed in patches < 100 m. Our simulations show that on those lateral scales, the median PSV depth is ~1 m (*i.e.*, the PSV depth of 50% of the micro cold traps on those scales is < 1 m), equivalent to the expected erosion depth of surface water ice on the Moon, which – for sublimation rates < 1 m/Ga [9] – is dominated by non-thermal destruction mechanisms such as micrometeorites bombardment and photodissociation [9-11]. Unlike surface water ice, subsurface ice is protected from these destruction mechanisms [9]. However, recent models [11] show that the thickness of the in-situ reworking zone, in which the regolith is relatively ice-free, increases with time to ~1 m after 1 Ga. Therefore, due to the depth of the PSV cast by micro cold traps < 100 m, it is unlikely they harbor surface or subsurface ice older than 1 Ga.

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