The Depth of Small Craters and the Shadows they Cast: Evidence for Ice on the Moon and Mercury

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Introduction: Topographic depressions near the poles of Mercury and the Moon may trap ice for billions of years inside PSRs [1, 11, 15]. On Mercury, evidence for water ice deposits that are at least a few meters thick was remotely sensed in radar [6]. More recently, data obtained by the MERCURY Surface, Space Environment, Geochromy, and Ranging (MESSENGER) revealed bright and dark deposits in areas cold-enough to trap water ice according to a thermal model [3, 8, 10]. Additional evidence for the presence of ice inside individual small craters (< 1 km) and micro cold-traps (1 – 10 m) was found using data obtained by the Mercury Laser Altimeter (MLA) [4, 12]. In contrast, lunar cold-traps were not observed to contain similar ice quantities. Evidence for a thin layer of ice was found in several lunar craters such as Shackleton [16], but Earth-based radar observations did not detect areas > 1 km² with high backscattering [14], indicating that any existing ice must be thinner than a few decimeters or is in the form of distributed grains [2]. Here we show small (3 – 15 km) craters on both Mercury and the Moon become shallower in latitudes where ice is expected to accumulate according to a thermal model. We estimate the thickness of this infill by comparing the depth to diameter ratios (d/D) of craters with the d/D they would have had if they were filled with ice up to the permanent shadow volume (PSV) limit.

Measuring the Ice Depth Inside Small Craters: We begin by identifying small (3 – 15 km), simple craters on the Mercury Dual Imaging System (MDIS) and the Lunar Reconnaissance Orbiter Camera (LROC) global basemaps. We measure craters’ elevation along a south-north profile on the gridded Mercury Laser Altimeter polar map (MLA, 250 m/px) and gridded Lunar Orbiter Laser Altimeter (LOLA, 120 m/px), as shown in Figure 1, and use it to calculate their d/D. On Mercury we measured 1003 craters between latitudes 75° – 86°, where the most reliable MLA data is found. On the Moon, we measured 1353 craters in latitudes 74° – 90°, and plan to extend this range to lower latitudes. Next, we model the d/D distribution these craters would have had if they were filled with ice up to the permanent shadow limit.

Maximum Possible Infill: Due the exponential dependence of the sublimation rate on temperature, ice can only persist inside permanent shadows. During the day the crater casts transient shadows that add into permanent shadows in high latitudes. We calculate the depth of these transient shadows \( d_s \) modeling the craters as hemispherical (bowl-shaped) cavities,

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\frac{d_s}{d} = 1 - \frac{1}{2\Delta} \cot \theta
\]

where \( d \) is the crater’s depth, \( \theta \) is the incidence angle and \( \Delta \) is the crater d/D ratio. The depth of the permanent shadow volume (PSV) constrains the depth of ice accumulated inside the crater. Therefore, if we subtract the modeled PSV depth from the measured depth in lower latitudes (where only a small amount of ice is expected to persist [11, 13]) we should receive the d/D distribution of craters as if they were filled with ice up to the PSV limit. This assumes the d/D does not significantly change with latitude due to some other geologic property.

Results: Figure 2 shows the d/D distribution for Mercury (a) and the Moon (b). The mean d/D of craters on Mercury decreases from 0.96±0.0036 in latitudes 75° – 78° to 0.075±0.0034 in latitudes 83° – 86°. On the Moon we see a similar but less distinct trend; the mean d/D decreases from 0.123 ± 0.0038 in latitudes 75° – 78° to 0.097 ± 0.0033 in latitudes 87° – 90°. The values above are provided along with the standard error of the mean. As explained above, we model the distribution of craters as if they were filled with ice to the permanent shadow limit (dashed line). We see that on both Mercury and the Moon craters are not filled to the permanent shadow volume limit.

On Mercury, we find craters become shallower with latitude relative to their maximum potential capacity. This can be seen in Figure 3(a), where the markers indicating the measured mean d/D are steeper than the maximum potential capacity lines; in latitude 84°, craters are filled to ~ 20% of their maximum potential capacity, while in latitude 86° craters are filled to ~ 40% of their maximum potential capacity. This effect is much less prominent on the Moon (Figure 3(b)), where the measured mean d/D trend is almost parallel to the ~ 20% maximum infill line. We attribute this difference to the age of the ice as near the poles, the lower sublima-
Figure 2: (a) The d/D distribution on Mercury for two latitude rings. Error bars indicate the square root of the sample size. The mean crater depth decreases as deep (d/D > 0.1) are replaced by shallow (d/D < 0.1) craters. (b) The d/D distribution on the Moon for three latitude rings. On the Moon, craters do not become significantly shallower until near-polar latitudes.

Discussion: Above we have shown small craters near the poles of Mercury become shallower in latitudes where ice is expected to accumulate on their floors. Similar inspection on the Moon showed craters do not become shallower until near-polar latitudes. Additionally, we find craters on both planetary bodies are not filled to their maximum capacity, which is (to first order) constrained by the depth of the permanent shadow volume. Given the dimensions of the craters we measured, we estimate this infill to be 10 – 100 m thick. This result is particularly surprising on the Moon, where radar measurements did not show evidence for thick ice deposits. On Mercury, this implies a net delivery rate of a few meters per Ga, in accord with previous theoretical [7, 9] and observational [5] estimates. Additionally, the difference between the mean measured and modeled filled crater distributions indicates the historic net mean volatile accumulation rate is greater on Mercury compared to the Moon. This is also evident by the different thickness of the deposits relative to the maximum potential infill at every latitude, which is greater for Mercury than for the Moon. We attribute this difference to the age of the ice: on Mercury, polar ice has accumulated for a longer time period filling a larger portion of the craters. On the Moon, the historic mean net accumulation rate is probably much closer to zero and the deposits we measured are probably much younger.