DISTRIBUTION OF SURFACE WATER ICE ON THE MOON: AN ANALYSIS OF HOST CRATER AGES PROVIDES INSIGHTS INTO THE AGES AND SOURCES OF ICE AT THE LUNAR SOUTH POLE.

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Introduction: Over the last several decades, ground- and spacecraft-based observations have provided data to support the presence of water ice at the poles of the Moon [e.g., 1–5]. The polar ice appears to be spatially heterogeneous in distribution. For example, mapping of UV albedo spectra and surface temperature measurements reveal a highly spatially heterogeneous distribution of water frost within PSRs [3]. Enhanced surface albedo suggestive of water frost [4] and detections of exposed water ice [5] also indicate a patchy distribution of surface water ice.

Impact gardening can produce spatial heterogeneities in ice distribution because these processes cause loss and redistribution of volatiles [6,7]. Impacts remove volatiles via vaporization and also preserve volatiles through the emplacement of ejecta, with a net effect of breaking up and burying the ice [6,7]. Because these processes take time, the spatial heterogeneity is highly likely to be related to the exposure age of the ice.

Objective: Here we assess the distribution of surface water ice [5] at the south polar region of the Moon (80°S–90°S). We estimate ages for host craters to provide upper limits for any ice contained within the craters, and examine the relationship between the patchiness of the ice within each crater and the age of each host crater. Finally, we discuss possible sources for the ice, given the results of our age analyses.

Methods: *Age estimates for lunar cold traps.* From crater-counting statistics, we estimate ages of 20 south polar lunar craters that are located between 80°S and 90°S. In combination with previous estimates of south polar crater ages [8,9], our catalogue represents 24 large polar craters, capturing all permanently shadowed craters in this region that have at least 100 km^2 of flat-floored regions (<10°) for counting statistics. The count areas are in permanent shadow, so we create artificially illuminated hillshade maps (pixel resolution of 20 m) at various azimuth angles from a gridded digital elevation model that was derived from Lunar Orbiter Laser Altimeter data. For each host crater, superposed craters with diameters >200 m are catalogued. Obvious secondary craters (those that appear elongated in form, or in chains or clusters) are systematically excluded from the counts. CSFDs are produced and fit to models of the production function [10] in order to estimate ages using CraterStatsII [11]. The ages of the host craters provide a maximum age of any surface ice contained within each crater.

For age analyses, we require count areas to be ≥100 km^2 and have slopes <10°, and thus not all south polar impact craters (particularly impact craters <20 km) are analyzed. Some smaller impact craters also host surface water ice, and here we identify all simple craters that have crisp-looking rims, but are too small in size to accurately date with from crater counting statistics. From this dataset, we determine what population of small (<100 km^2) craters with morphologically fresh characteristics host surface ice.

Patchiness of lunar surface ice. The patchiness of surface water ice within each of the 24 south polar craters analyzed here is quantified as the percent of the current cold trap surface area that is occupied by surface water ice. Cold traps are defined as surface areas with maximum surface temperatures ≤110 K, as measured by the Diviner Lunar Radiometer Experiment [12], representing temperatures at which surface water ice is stable. Direct detections of exposed surface water ice [5] are used as surface ice detections. These surface water ice detections were made using NIR data acquired by the Moon Mineralogy Mapper (M^3) instrument, specifically from diagnostic overtone and combination mode vibrations of water ice that occur near 1.3, 1.5, and 2.0 μm [5].

Results: The majority of surface water ice at the lunar south pole [5] is found in large, old (~3.5 Gyr) craters, which comprise the majority of the cold-trapping area available. We also identify 301 small (<15 km in diameter) impact craters that are likely to be relatively young, given sharp crater rim morphologies. We find that ~5% of these craters, which are too small for crater counting analyses, have at least one pixel with a positive ice detection [5]. Thus, while surface ice is predominantly located in ancient craters (Fig. 1), it is found in relatively young craters as well. Furthermore, given that the footprint size of the M^3-derived surface ice detections [5] is ~280 m x 280 m, it is possible that many additional surface ice deposits are cold-trapped below this resolution [13,14], both in ancient and young craters.

There are also some ancient craters that are present-day cold traps, but do not host surface water ice

(Fig. 1). Our age-dating analysis strengthens the interpretation [5] that the retention of volatiles within cold traps may have been affected by the stability of these cold traps on long timescales, related to true polar wander (TPW). Under predicted paleo-conditions [15], the thermal surface environments of these craters would not have been stable for the survival of surface water ice. Thus, our results suggest that the patchy distribution of surface ice observed at the lunar poles today may be controlled by ice supply rate, impact destruction rate, and an additional factor that affects the long-term stability of volatiles in individual cold traps, such as TPW.

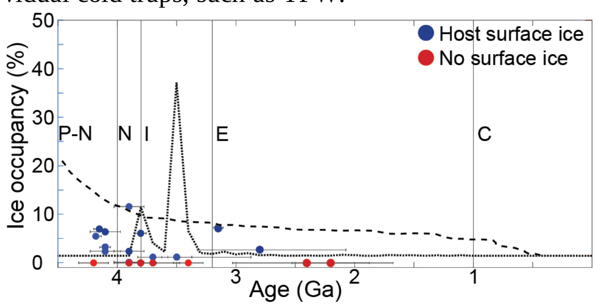

Fig. 1. The percentage of specific cold traps occupied by water ice is plotted with respect to the estimated model ages of the host craters. The modeled impact flux for the Moon [16] is plotted in the thick dashed line, and estimated effusive volcanic flux [17] is plotted in the thin dashed line. Lunar geologic eras are separated by vertical lines.

Discussion: *Patchiness of lunar ice.* No more than ~11.5% of the surface areas of the polar craters in this study are occupied by water ice. The precise surface areas of cold traps occupied by water ice may be even less given that an M^3 spectrum of only ~30% water ice is classified as a positive ice detection, resulting in a single detection at the spatial scale of a M^3 pixel (~280 m x 280 m) in resolution. Overall, the very patchy surface distribution of lunar ice suggests that the rates of destructive processes (regolith gardening) exceed the rates of ice emplacement through time.

Possible sources of ice. The majority of detected surface water ice [5] is confined to large, ancient (>3.5 Gyr) cold traps and appears to be re-worked, given its very patchy spatial distribution within individual cold traps. Ancient ice may have been delivered by impactors [e.g., 16] or volcanically outgassed volatiles [e.g., 17]. Early in the Moon's history, the flux of impactors was much higher than present-day rates [16], and these early impactors were likely to be delivering ice to the lunar poles, in addition to breaking up and covering the ice [6,7], consistent with the patchy surface distribution observed today.

Because we also identify a population of small (<15 km) impact craters that appear to be young, it is possible that some surface water ice has been delivered to the south pole recently. The presence of ice in fresh craters suggests that ice delivery rates to these cold traps are greater than the ongoing destructive and burial processes at these cold traps. Candidates for recent delivery of surface ice include solar wind interactions with the lunar regolith [e.g., 18] as well as micrometeorite delivery.

Differences between ice on the Moon and Mercury. The low percentages of cold trap surface areas that host surface water ice on the Moon are in stark contrast to the host craters on Mercury that are interpreted to be occupied by laterally contiguous ice deposits [19–21]. If ice deposits on Mercury are relatively young [e.g., 14, 19–22], then they have not been exposed to extensive regolith gardening that would break up, destroy, or bury the ice [22]. The same impact bombardment and space weathering processes operate on Mercury and the Moon, and Mercury's regolith may be overturned even more frequently than the lunar regolith due to higher impact rates and speeds [23]. Thus, it is possible that relatively ancient, degraded ice deposits exist below the extensive, pure deposits observed on Mercury's surface today. The lunar polar deposits therefore provide an important opportunity to inform us about the ultimate fate of mercurian polar deposits, as well as ices on other airless bodies.

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