A POSSIBLE SOLAR WIND ORIGIN OF SURFACE EXPOSED WATER ICE IN THE LUNAR PERMANENTLY SHADED REGIONS. S. Li[1], A. N. Deutsch[2], and J. R. Szalay[3]. [1]Hawai'i Institute of Geophysics and Planetology, University of Hawai'i. [2]Ames Research Center, NASA. [3]Department of Astrophysical Sciences, Princeton University. shuaili@hawaii.edu

Introduction: Origins of the surface exposed water ice in the lunar permanently shaded regions (PSRs) still remain unclear [1]. The asymmetric distribution of H-bearing species in the lunar polar regions seen in the Lunar Prospector (LP) epithermal neutron data (**Fig. 1a**) was interpreted to be due to the lunar true polar wander (TPW), occurring > ~3.5Ga ago [3]. Strong neutron suppression (i.e., high abundance of H-bearing species) is found in both present-day and ancient PSRs (those present when the Moon was on its paleo-axis) [3]. The distribution of surface water ice seen by the Moon Mineralogy Mapper (M^3) data seems broadly spatially consistent with that of H-bearing species shown in the epithermal neutron data (**Fig. 1a**) [1]. Thus, the currently observed H-rich species may be ancient, delivered before the TPW (> ~3.5 Ga [3]). However, age dating results of PSRs that host water ice suggest that some of those PSRs are younger than the TPW, which raises a question about the origins of water ice seen in those younger PSRs. If these younger water ice exposures were from uniform sources in the polar regions, such as a transient atmosphere induced by the interior degassing [6] and/or randomly distributed water-rich impacts, why do not all PSRs < ~3.5 Ga show ice exposures? If the lunar PSRs received asymmetric supplies of water after the TPW, what are the asymmetric water sources? Understanding the origins of surface exposed water ice on the Moon is critical to reveal processes on the surface and in the exosphere that are associated with the formation, destruction, and deposition of water ice. It may also provide clues about origins of water on Earth.

We examine the mapped surface water (H_2O/OH) from M^3 data to understand whether the surface water at illuminated regions may have been contributing water to the PSRs. We also assess the topographical features (e.g., the surface slope) near PSRs to understand whether it plays any role on shielding or facilitating water delivery to PSRs.

Data & Methods: In this study, we use maps of surface exposed water ice mapped from M^3 in [1], the LP epithermal neutron data [2], the surface water map derived from the M^3 data [4], and the surface slope map in [5]. Since the distribution of surface water ice is dominantly controlled by the location and size of PSRs, we also use the map of PSRs derived from the data acquired by the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO) [7]. We show the south pole as an example.

Results: **Fig. 1a** shows that the surface exposed water ice exhibits great correlation with regions showing strong neutron suppression (i.e., high content of H-bearing species) at ~85° – 90° S. However, at lower latitudes, the strong neutron suppression is only seen in the ~300° – 330° longitude direction. Surface water ice is relatively randomly distributed everywhere but exhibits less distribution within the ~60° – 180° longitude range. There is no clear spatial correlation between surface water ice in PSRs and water mapped in the illuminated regions (**Fig. 1b**). Interestingly, we observed much fewer rough terrains with surface slope greater than 20° in the 60° – 180° longitude range where fewer water ice exposures are detected (**Fig. 1c**).

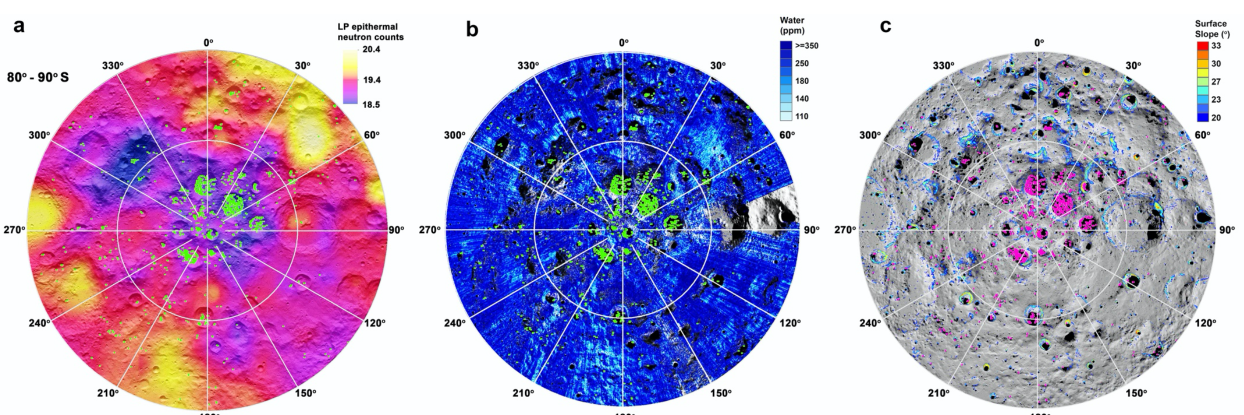

Fig. 1. a. Water ice exposures (green dots) seen in M^3 data [1] overlain on the LP epithermal neutron data [2]; b. water ice exposures (green dots) overlain on the surface water content mapped from M^3 data at illuminated regions [4]; c. the same water ice exposures (pink dots) as in a, b overlain on the surface slope map derived from the LRO LOLA data [5]. Maps a-c are the lunar south pole from 80° to 90°.

Discussion: The lack of water ice exposures in PSRs in the ~60º – 180º longitude range near the south pole may reflect either asymmetric supplies or destructions of water ice in PSRs or both. The lunar interior degassing and water rich impacts in the early history of the Moon (i.e., > ~3.5 Ga) may be major contributors of water ice in the lunar PSRs. However, these two processes may contribute water randomly and evenly to all PSRs in the lunar polar regions. The asymmetric distribution of water ice in PSRs near the south pole can be explained by the lunar TPW hypothesis that PSRs in the ~60º – 180º longitude range were under solar illumination when the Moon was on its paleo-axis (> ~3.5 Ga) [3], and thus they could not provide cold environment to accumulate water ice. It is also indicated that the supplies of water to PSRs were substantially declined and thus no significant water ice could be accumulated in new casted PSRs after TPW. However, some ice-hosting PSRs are younger than the TPW (~3.5 Ga) [8], and they may have different water sources other than the interior degassing and impact delivery that may have contributed evenly to PSRs in the lunar polar regions.

Solar wind induced hydration (OH, H_2O) could be another major and continuous source of surface water ice in PSRs. However, solar wind is a collimated source on the lunar surface and cannot directly cause asymmetric distribution of water ice in PSRs. It is suggested that the lunar surface water is not subjected to thermal desorption and thus migrates to PSRs at latitudes > ~70º when the temperatures is lower than ~280 K [4, 9, 10].

The asymmetric distribution of surface water ice in PSRs (**Fig. 1**) also indicates that water migration (if any) from much lower latitudes (< 70º) cannot reach the PSRs near the poles, unless there exist(s) asymmetric destruction mechanism(s) of exposed water ice. Otherwise, a relatively homogeneous distribution of surface exposed water ice in PSRs across the polar regions would have been observed.

Impacts could be one of the major destruction processes of water ice in PSRs. However, studies of the impact environment in the lunar polar regions suggest that micrometeoroid bombardments exhibit no spatial asymmetry [11]. Additionally, water-rich impacts can randomly contribute water into PSRs. Thus, the lack of water ice exposures in the ~60º – 180º longitude range near the lunar south pole should not be associated with impacts.

Sputtering of ions and electrons from the sun and galaxy could be another major destruction process of PSR water. Those high energy ions and electrons are from relatively collimated sources and no observations show that they have weaker effects at the ~60º – 180º longitude range near the south pole. Additionally, a recent study suggests that high energy electrons from the plasma sheet in Earth's magnetotail and cosmic rays may induce new water formation and contribute water ice into PSRs across the polar regions [12]. However, it is suggested that localized magnetic anomalies may have shielded the sputtering by ions and electrons to protect water ice in PSRs [13], which may explain the asymmetric distribution of surface water ice on the Moon [13].

Interestingly, there seems a spatial correlation between the distribution of rough terrains with a surface slope > 20º and PSRs that host water ice (**Fig. 1c**). The surface temperatures at these slopes >20º can be equivalent to those of flat surfaces at < 60º latitudes near the local noon. Molecular water can be released through re-combinative desorption of solar wind induced OH under such high temperatures [10]. It is possible that the desorbed molecular water can hop to and accumulate in nearby PSRs. Orbital observations suggest that the diurnal variation of the lunar surface water content reaches 30 – 50 ppm at ~ 60º latitude [4]. In an extreme endmember case where all desorbed water is sequestered and accumulated in nearby PSRs, it may take only ~100 years to reach 3 – 5 wt.% water ice on the surface that is similar to orbital and *in situ* observations [1, 14, 15].

Conclusion and Future work: We found that PSRs within the longitude range of ~60º – 180º near the lunar south pole show substantially fewer water ice exposures than those out of this longitude range. We hypothesize that this distribution pattern may be associated with cold-trapping of molecular water that is released through recombinative desorption of solar wind induced OH at high temperatures. Future isotope measurements of water ice exposures in the lunar PSRs will help to test our hypothesis (e.g., they should mimic the solar wind H isotope signature with extremely low D/H). In future studies, we will perform a thorough analysis of the distribution of water ice exposures to examine their relationship with surface slopes. Major contribution and destruction processes of water ice in lunar PSRs will be quantitatively constrained to further refine this hypothesis.

References: [1]. Li, S., et al. *PNAS*, 2018. [2]. Lawrence, D., et al. *JGR*, 2011. [3]. Siegler, M., et al. *Nature*, 2016. [4]. Li, S. and R.E. Milliken. *Sci. Adv*, 2017. [5]. Rosenburg, M., et al. *JGR*, 2011. [6]. Wilcoski, A.X., et al. *PSJ*, 2022. [7]. Mazarico, E., et al. *Icarus*, 2011. [8]. Deutsch, A.N., et al. *Icarus*, 2020. [9]. Tucker, O., et al. *JGR*, 2019. [10]. Jones, B.M., et al. *GRL*, 2018. [11]. Szalay, J.R., et al. *JGR*, 2019. [12]. Li, S., et al. *Nat. Astro.*, In revision. [13]. Hood, L.L., et al. *GRL*, 2022. [14]. Hayne, P.O., et al. *ICARUS*, 2015. [15]. Colaprete, A., et al. *Science*, 2010.