UPDATE ON THE PROSPECTS FOR FINDING ICE ON THE MOON. Norbert Schörghofer, Planetary Science Institute, Tucson, Arizona (resident in Honolulu, Hawaii) (norbert@psi.edu)

Here, I present an updated assessment of lunar ice in light of the startling observations by ShadowCam [1], advances regarding the spin axis evolution of the Moon [2], and other recent results.

Old and young cold traps: Currently the maximum solar declination on the Moon is small (1.5°), which allows for perennially shadowed regions (PSRs) at the poles, where ice could have accumulated [3–5]. The lunar axis experienced a major reorientation when the Moon transitioned between two Cassini states at $\sim$ 34 Earth-radii [6, 7], which must have resulted in the loss of all prior ice deposits. Thanks to recent results for the evolution of the Moon-Earth distance [8], the history of the lunar obliquity (axis tilt) and the extent of PSRs are now known as a function of time with greater certainty [2].

The solar declination reached twice its current value 2.1 Gyr ago [2]. Ray-tracing has been used to determine the extent of PSRs based on the LOLA (Lunar Orbiter Laser Altimeter) topography (Fig. 1). The cumulative PSR area poleward of 80° latitude was half as large 2.2 Gyr ago (assuming all craters already existed at that time). The PSR area becomes negligible beyond 3.4 Gyr ago. The average age of PSRs is 1.8 Gyr, when assuming present-day topography.

Delivery of comets and hydrated asteroids peaked early in lunar history [9], when the current PSRs did not yet exist. Late-stage outgassing overlapped with early PSRs [10, 11]. Solar-wind generated water [12], identified in Chang'e 5 return samples [13], could be an ongoing and quasi-continuous source of water.

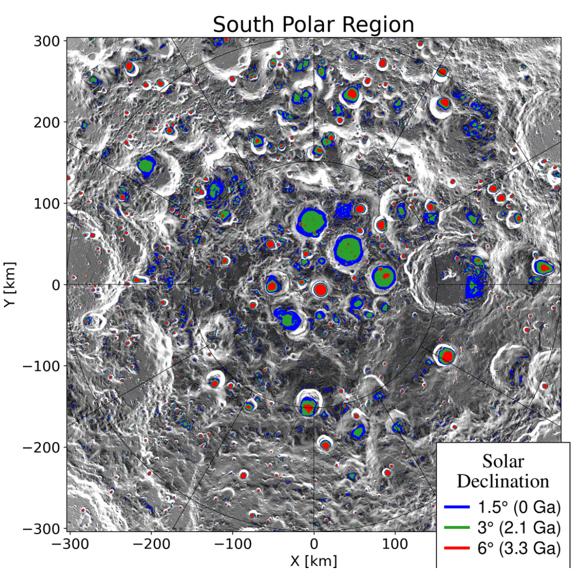

Figure 1: Extent of PSRs for various solar declinations (times in the past) assuming present-day topography [2].

The site of an artificial impact in Cabeus Crater, where various volatiles have been detected [14], became continuously shadowed only about 0.9 Gyr ago, and hence cold-trapping has continued into this relatively recent time period.

The largest amounts of ice are expected in the oldest cold traps (but few missions are planned for such destinations). *All cold traps older than 1 Gyr should contain $\gtrsim$ 6% ice* (as in Cabeus [14]). Younger/smaller cold traps might also contain ice, but that is less definitive.

Ice is beneath the surface: Surface frost is destroyed by space weathering within about 2000 yr, even in areas permanently shadowed from the sun [15]. ShadowCam has not identified any significant areas of bright surface frost in the lunar PSRs [1]. Neutron and gamma ray spectroscopy has long suggested the hydrogenous layer is buried beneath a less hydrogenous layer at least in some parts of lunar polar regions [e.g., 16] by $\sim$10 cm [17].

A remarkable example of extreme contrast between surface and subsurface ice concentration is Ceres. The large asteroid was mapped both with a visible & infrared spectrometer (VIS) and a gamma-ray & neutron spectrometer (GRaND). H_2O was identified on the surface over a total area of 11–20 km^2 [18], whereas GRaND sensed near-surface ice essentially globally [19] on the 470 km radius body. Hence 99.999% of the near-surface ice on Ceres is not exposed on the surface.

Space weathering and thermal devolatization can erase water ice from the surface, but ice can still be present in the subsurface. *To assess the presence of water ice, it is necessary to probe the subsurface.* Measurements of the optical surface cannot provide a definitive answer for the ice concentration, not even for shallow depths.

Ice outside of cold traps: Neutron spectroscopy suggests some hydrogen excess falls outside of the lunar cold traps ("neutron suppression regions") [20, 21]. This hydrogen could arise from relic buried ice or from subsurface cold-trapping (Fig. 2).

Even a thin layer of regolith provides a significant barrier to sublimation, especially once the thickness exceeds the thermal skin depth ($\sim$5 cm) [22]. Relic buried ice can only be expected if the ice was rapidly covered with a protective layer after it was deposited, which stastically could have taken place only at a small fraction of the area cold enough to preserve buried ice outside of cold traps.

Subsurface cold-trapping is a process that can sequester water molecules [23]. It can occur if there is a quasi-continuous supply of water molecules to the polar regions. Small amounts of ice will gradually accumulate below the influence of periodic temperature cycles.

Maps for conditions favorable to the survival of relic buried ice and possible subsurface cold trapping are available online [24]. The areas of “subsurface stability” are far larger than the total area of surface cold traps.

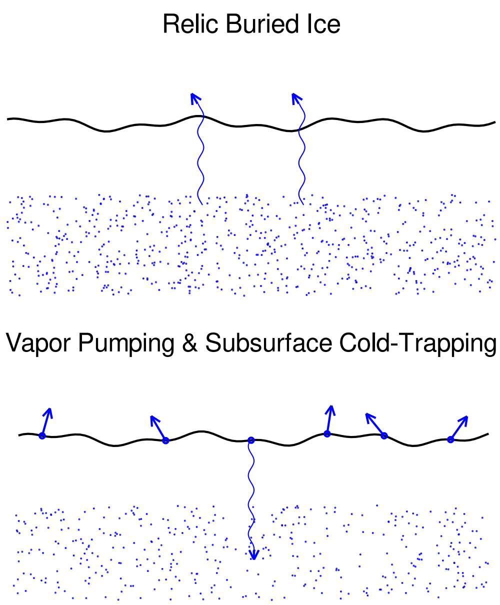

Figure 2: Ice can potentially be stored outside of lunar cold traps in form of relic buried ice or due to sub-surface cold trapping. Figures from Ref. [23].

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