Ground Truth: Testing Theories for the Distribution of Lunar Volatiles
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Mathew A. Siegler, Planetary Science Institute & Southern Methodist University
Norbert Schorghofer, Planetary Science Institute

Introduction: A key goal of the Artemis polar missions is the search for volatiles, most importantly water ice deposits. As of yet, the potential water ice distribution detected at the lunar poles is not easily explained by a simple origin theory. The one widely accepted constant is that ice will only exist where it is cold enough to be stable. While other processes can add or remove ice, in locations where warm enough, sublimation will rapidly deplete the ice. Processes such as space weathering, impact gardening, and vapor pumping also affect the distribution of ice. Through the Artemis mission, these theories (Figure 1) can be put to a test.

Predictive Models and Theories:

The Diviner Lunar Radiometer Experiment, on the Lunar Reconnaissance Orbiter (LRO), measures surface temperature at high spatial resolution (Paige et al. 2010a,b) that can be used to map cold traps (Figure 2).

For areas where thermal data does not exist, illumination models can be used to simulate surface and subsurface ice stability. This technique has been used in Paige (2010a, 2013), Siegler et al. (2016) and others to produce maps of past and present ice stability on the Moon and Mercury. The models use ray tracing of illumination by a solar model and exchange of visible and infrared light between triangulated surface facets.

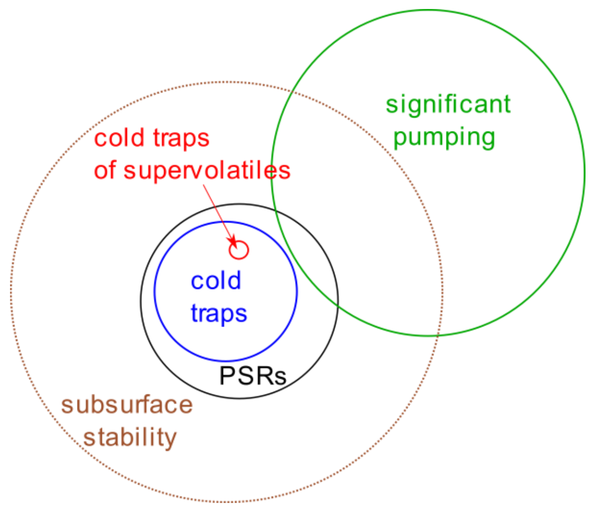

Figure 1: Illustration of the overlap between various ice storage processes and Permanently Shadowed Regions (PSRs). The area enclosed by each circle is roughly proportional to the total area covered in the south polar region of the Moon.

Given high resolution topography, these types of models can predict temperatures and ice stability at higher resolution than thermal data exists. Figure 3 shows such an example of two models run at 480m resolution (3a, similar to Diviner full-seasonal resolution) and a second at 20m resolution (3b, near the limit of LOLA topography). While the low resolution captures the general presence of stable regions in this area, errors in model insolation due to low resolution topography cause errors in temperatures and predicted stability. Such model illumination errors are not present in the data-based ice prediction approach.

Due to the low thermal conductivity of lunar regolith, lateral heat flow is generally negligible. At length scales of 10's of cm, lateral heat flux will become important (Hayne et al., 2020). The LCIRIS infrared imaging instrument on the Prime-1 south polar mission is designed to aid in understanding the stability and temperatures of these small "micro-cold traps". Similar instruments may be critical for Artemis detection and prediction of small scale cold traps.

Providing high resolution topographic data of the Artemis sites prior to, or during the mission will prove invaluable to providing proper guidance for planned traverses aimed at locating surface and subsurface ice. Local high-resolution thermal data could provide similar information and verify thermal models.

Models have so far not been able to predict the abundance and vertical distribution of the ice. The ice could be vapor-deposited in the form of interstitial ice deposits; it could be in form of ice fragments created during impacts, or in form of a more deeply buried ice sheet. Each of these situations will create very different ice distributions, even if stable. In Situ drilling or coring of potential ice rich layers could allow theories and predictions to be improved.

Determining Ground Truth:
A future landed mission can determine the ground truths:

1) To what extent does the predicted geographic distribution of ice, through cold trapping or pumping, correspond to the actual distribution?
2) What is the vertical distribution and concentration of the ice?

These questions can be answered by drilling and sampling to depths as small as 20-50 cm at a few, well-chosen locations in the south polar region. Both questions could potentially be answered with a single landed mission near a cold trap. Shallow drilling could be performed at two or more locations that are predicted to be water ice cold traps (of different ages), and one or more locations that are predicted to have accumulated thermally pumped H_2O molecules. The sample cores would then be analyzed for their ice content.

These ground measurements would make it possible to predict the geographic distribution and abundance of water ice with far more confidence than is currently possible.

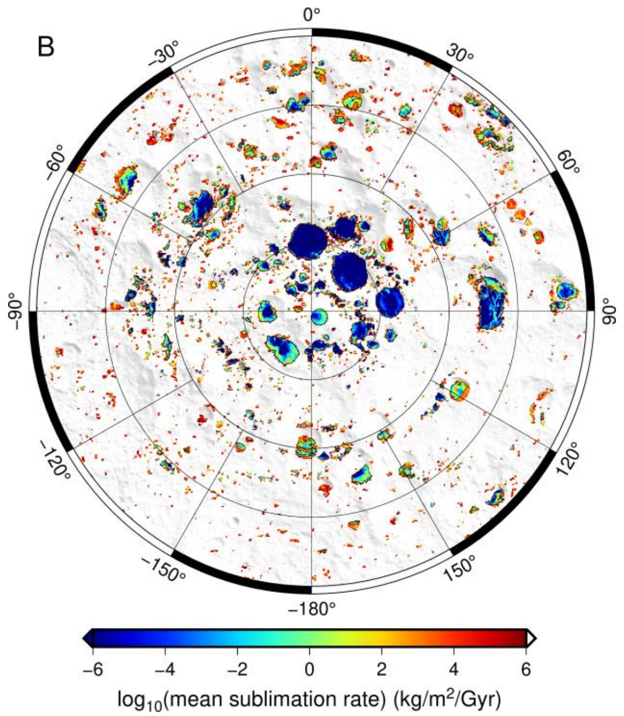

Figure 2: Potential sublimation rates poleward of 80°S. Black contours correspond to 100 kg $m^{-2}Gyr^{-1}$. From Schorghofer and Williams (2020).

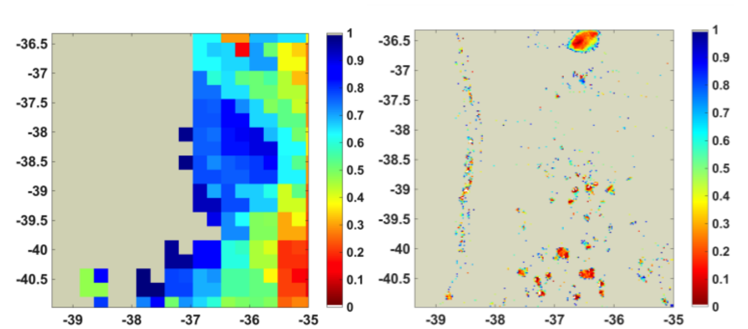

Figure 3: (a) A 480m resolution ice stability model of a near polar region near Haworth Crater and (b) that same area now run with a 20m resolution topographic model.

References

Hayne et al. (2020). *Nat. Astr.*, in press.
Paige et al. (2010a). *Science 330*, 479.
Paige et al. (2019b). *Space Sci. Rev. 150*, 125.
Schorghofer & Williams (2020). *Planet. Sci. J.*, in review
Siegler et al. (2016)