

# LUNAR SURFACE AND SUBSURFACE COLD-TRAPPING IN TIME-VARIABLE ENVIRONMENTS.

Norbert Schorghofer, Planetary Science Institute, Tucson, AZ (resident in Honolulu, HI) ([norbert@psi.edu](mailto:norbert@psi.edu))

**Cold traps update:** Cold traps are thought accumulate volatiles from episodic or continuous sources, and are defined by sublimation losses lower than the amount received [1, 2]. Cold traps experience diurnal temperature variations over the solar day as well as seasonal temperature variations over the draconic year [3, 4, Fig. 1]. Peak sublimation rates can be far above time-averaged sublimation rates, and taking the full time dependence (known from 12 years of Diviner temperature measurements [5]) into account, results in more accurate maps [4].

The difference between time-averaged and peak sublimation rates is especially large for supervolatiles, like  $\text{CO}_2$ , and the new method of evaluating the extent of cold traps more firmly establishes the existence of  $\text{CO}_2$  cold traps in the lunar polar regions, including the LCROSS impact site [6], where  $\text{CO}_2$  has been observed [7].

Recent work on the evolution of the Moon-Earth distance [8] pins the lunar spin axis excursion that occurred at 34.2 Earth radii [9] at 4 Gyr ago, and the lunar obliquity was not much higher than today's over the last 3.4 Gyr, which places a maximum age on the PSRs.

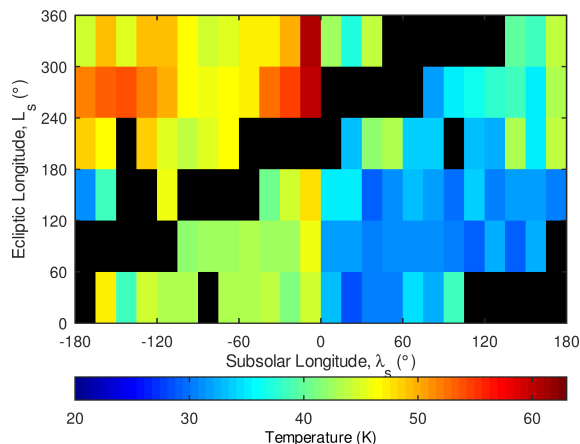


Figure 1: Diviner surface temperatures at the LCROSS impact site in Cabeus as a function of time of day (horizontal axis) and season (vertical axis). Most sublimation takes place during a small fraction of the draconic year. Figure from Ref. [6].

**Subsurface cold traps:** Water molecules can be cold-trapped not only on the surface, but also in the subsurface, after they undergo a sequence of short hops (Fig. 2). For example, when the interior of a lunar cave is cold enough, the number of water molecules leaving will be smaller than the number of water molecules that arrive over time [10]. The same process is expected to take place in the porous lunar soil, if the subsurface is sufficiently cold.

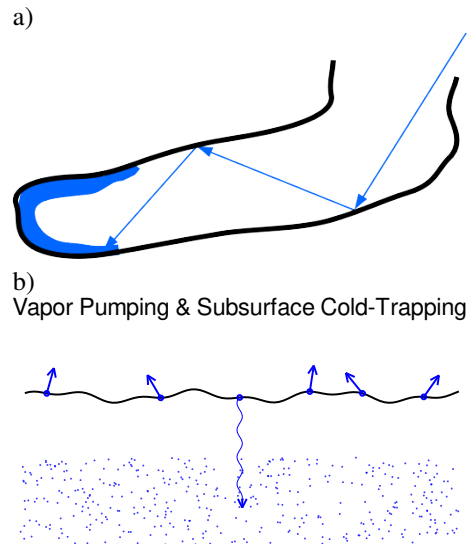


Figure 2: Examples of subsurface cold traps. a) A sufficiently cold cave interior emits fewer water molecules than it receives. b) Adsorbed water molecules migrate into the porous subsurface until they reach depths, beyond the influence of diurnal temperature cycles, that are sufficiently cold so the molecules remain indefinitely.

The amount of ice that is cold-trapped in the subsurface depends not only on the rate of water delivery to the surface, but also on the diffusion barrier that has to be overcome. This diffusion can be accelerated by the diurnal temperature wave, a process known as “vapor pumping” [11]. A hallmark of ice sequestration by vapor pumping and subsequent subsurface cold-trapping, is that the top layer ( $\sim 10\text{cm}$ ) remains ice-free. Three sets of model calculations [12, 13, 14], using different adsorption and diffusion models, have predicted comparable  $\text{H}_2\text{O}$  sequestration rates.

*Discussion: Observational evidence.* Subsurface cold-trapping in lunar soil might result in local concentrations on the order of 1wt% of  $\text{H}_2\text{O}$ , which far exceeds the trace amounts of non-volatile hydrogenous species found in lunar soils [15]. Neutron spectroscopy from lunar orbit suggests the hydrated layer is buried [16, 17, 18, 19] perhaps by 10 cm. This is consistent with the predicted thickness of the desiccated layer [14]. Moreover, regions of neutron suppression (enhanced hydrogen) outside of polar regions appear to be in areas favorable to vapor pumping [20, 21]. And observations by LADEE suggest cm-sized impactors release water but mm-sized impactors do not [22]. All of these perplexing observations would be naturally explained by a reservoir of  $\text{H}_2\text{O}$  that formed by subsurface cold-trapping.

**Molecular residence times of H<sub>2</sub>O on lunar grains:** Subsurface diffusion of water vapor, in the long-term such as for subsurface cold-trapping and in the short-term such as for drilling in ice-rich regolith, depends on the residence times of volatile water molecules on lunar grains.

*High adsorbate concentrations ( $\gtrsim 1/2$  monolayer).* In environments where grains are covered by  $\sim 1/2$  to many monolayers of H<sub>2</sub>O, an adsorption isotherm measured on a lunar sample [23] can be used to estimate desorption rates (Fig. 3a). For polar molecules, the Brunauer-Emmett-Teller (BET) isotherm is appropriate. Figure 3b shows the adsorbate concentration as a function of vapor pressure for four adsorption models that have been used for modeling diffusion of water molecules in lunar soil. Additional isotherm measurements on lunar samples, combined with measurements of the specific surface area (as in Ref. [23]), would provide a more comprehensive quantitative understanding of desorption rates as a function of areal H<sub>2</sub>O concentration.

*Low adsorbate concentrations ( $\ll 1$  monolayer).* For most of the lunar surface, the areal concentration of H<sub>2</sub>O on grain surfaces is very low. A small fraction of the surface of a lunar grain has strong binding sites (up to 1.7eV) whereas most of a grain's surface has binding energies around 0.6eV [24], close to that of ice (about 0.5eV).

Above a temperature threshold (perhaps 0.1eV [25]), water molecules are expected to migrate laterally on a grain surface, and could thus move from low-energy binding sites to high-energy binding sites. A water molecule will ultimately be either desorbed or the high-binding sites will be permanently filled with H<sub>2</sub>O molecules. This site-to-site diffusion into deep defects could delay migration of water molecules, but is not expected to inhibit it entirely.

I am currently working on combining existing Temperature-Programmed-Desorption and adsorption isotherm measurements to build a thermostistical model for the H<sub>2</sub>O residence time on the surfaces of lunar grains.

## References

- [1] J. R. Arnold. *JGR* 84:5659, 1979.
- [2] P. O. Hayne et al. *Nat. Astr.* 5:169, 2021.
- [3] J.-P. Williams et al. *JGR* 124:2505, 2019.
- [4] N. Schorghofer & J.-P. Williams. *PSJ* 1:54, 2020.
- [5] D. A. Paige et al. *SSR* 150:125, 2010.
- [6] N. Schorghofer et al. *GRL* 48:e2021GL095533, 2021.
- [7] A. Colaprete et al. *Science* 330:463, 2010.
- [8] M. Farhat et al. The resonant tidal evolution of the Earth-Moon distance. *arXiv preprint arXiv:2207.00438*, 2022.
- [9] W. R. Ward. *Science* 189:377, 1975.
- [10] N. Schorghofer. *Earth, Moon, and Planets* 126:5, 2022.
- [11] N. Schorghofer & G. J. Taylor. *JGR* 112:E02010, 2007.

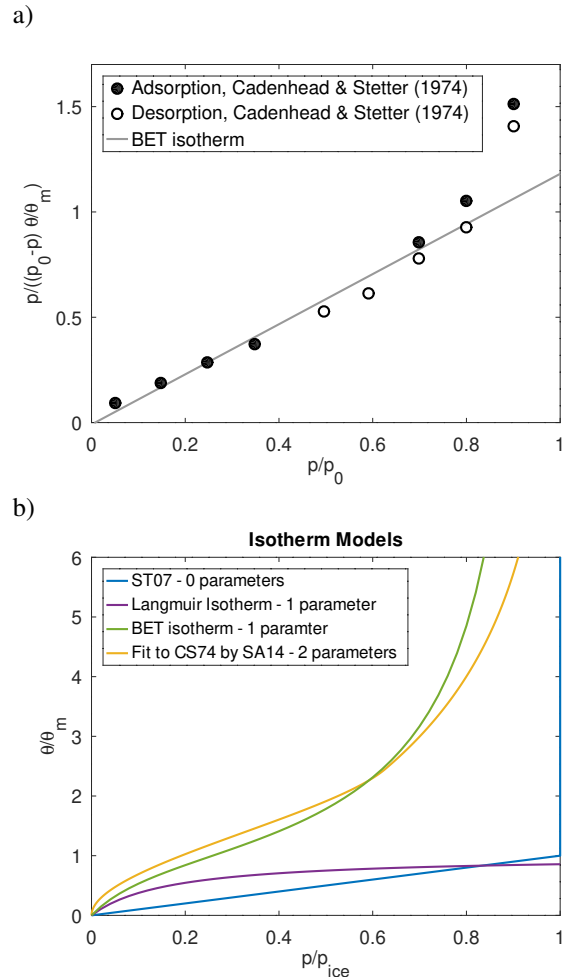


Figure 3: a) Fit of BET isotherm to adsorption isotherm measurements [14, 23]. The vertical axis uses a combination of variables that turns the BET isotherm into a straight line. The BET equation has only one free parameter. b) Various adsorption isotherm models used for modeling diffusion of water molecules in lunar soil [11, 12, 13, 14].

- [12] N. Schorghofer & O. Aharonson. *ApJ* 788:169, 2014.
- [13] P. Reiss et al. *JGR* 126:e2020JE006742, 2021.
- [14] N. Schorghofer. *ApJL*, 927:L34, 2022.
- [15] F. M. McCubbin et al. *Am. Mineral.* 100:1668, 2015.
- [16] W. C. Feldman et al. *Science* 281:1496, 1998.
- [17] W. C. Feldman et al. *JGR* 105:4175, 2000.
- [18] D. J. Lawrence et al. *JGR* 111:E08001, 2006.
- [19] I. G. Mitrofanov et al. *Science* 330:483, 2010.
- [20] W. V. Boynton et al. *JGR* 117:E003979, 2012.
- [21] P. Gläser et al. *JGR* 126:e2020JE006598, 2021.
- [22] M. Benna et al. *Nat. Geosci.* 12:333, 2019.
- [23] D. A. Cadenhead & J. R. Stetter. In *Proc. Fifth Lunar Conf.* pages 2301–2316, 1974.
- [24] B. M. Jones et al. *EPSL* 571:117107, 2021.
- [25] M.-C. He & J. Zhao. *Chin. Phys. Lett.* 29:036801, 2012.