# UNDERSTANDING THE CONTEMPORARY LUNAR VOLATILE SYSTEM AS A KEY TO THE PAST.

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**Introduction:** While the central paradigm for the existence of lunar ice deposits is the concept of polar cold traps, cold traps are barren without supply. The chief supply mechanism, ballistic transport of water molecules across the lunar surface, may not operate effectively [1]. Direct evidence for ballistic transport is scant and ambiguous, while direct measurements of the lunar exosphere suggest that ballistic transport may not operate effectively. If ballistic transport is ineffective, the supply of water to the lunar poles is choked off and the efficiency of transport would be lower by factor of 10 or more relative to commonly assumed estimates. This would force estimates of polar ice volumes delivered by impact and volcanic sources to be revised downward by a factor of ten or more. The efficacy of ballistic transport is an existential knowledge gap in the understanding of the lunar polar deposits.

**Evidence for ballistic transport:**

*UV and IR measurements:* The first direct evidence for ballistic transport of water was reported by Sunshine et al. [2] who discovered that the observed strength of the lunar surface 3µm hydration band--ubiquitous in water bearing material--showed strong temperature dependence. They suggested this indicated migration of water along temperature gradients. The observed effect is not subtle; no detectable 3µm band is present at high lunar surface temperatures indicating all water present departs the surface as temperatures rise. This effect is also seen in M3, Cassini and ground-based observations [3,4,5]. Hendrix et al. [6] also report evidence of mobile water in the UV using data from LRO LAMP. They reported a clear temperature dependent signal in the 164-173 nm ratio and used these data to estimate the activation energy of desorption of water from the lunar surface of ~1.3 eV

Both the IR and UV interpretations suffer from ambiguities. The IR hydration band is very strongly temperature dependent, but there is thermal emission in spectra of lunar materials over this temperature range that admits the possibility that the apparent hydration signal is an artifact of thermal emission. Corrections of the data for thermal emission are controversial, and different methods arrive at different scientific conclusions about temperature dependence. The UV is immune to this thermal problem [6], so the detected signal cannot be attributed to a temperature artifact in the data. However, it is currently not known if the UV signal is due to molecular water--that can be mobile--or to hydroxyl which is likely immobile. The work of Tucker et al. [7] and Farrell et al. [8] have shown that temperature dependent metastable hydroxyl can form as solar wind hydrogen diffuses through the regolith, and this hydroxyl may cause the detected signal, explaining both the UV and IR measurements without the presence of migratory water.

**Evidence against ballistic transport:**

*LADEE***:** The most crucial constraint on ballistic transport is the direct measurement of the water in the exosphere by the LADEE Neutral Mass Spectrometer. Hurley et al. [9] studied the effect of limited and unlimited migration on exospheric water abundances in the context of the constraints imposed by LADEE. They found that in the presence of unlimited migration, efficiency of conversion of H to $H_2O$ must be less than on the order of $10^{-4}$ to $10^{-5}$ depending on the surface activation energy. This net conversion is far below current estimates of this efficiency (e.g 10,11). However, the ratio of exospheric $H_2$ measured by LAMP [12] to the upper limit to background $H_2O$ measured by LADEE [13] is on the order of $10^4$, so the loss may be attributed to low efficiency of formation of water from solar wind protons.

*LAMP*: Taken at face value, the results of Hendrix et al. [6] imply suppression of ballistic migration. Their estimate of the activation energy of desorption of water from the lunar surface the forces water to remain bound to the surface at temperatures below about 350K. Illuminated level surfaces that achieve this temperature do not occur above about 50 degrees latitude, even at local noon, suggesting migrating water will stick, permanently, thousands of kilometers from any cold trap [10]. This imprisoned water can be freed by micrometeorite impact and imparted with enough energy to reach any location on the Moon [13]. However, the cold traps occupy less than 1 part per thousand of the lunar surface, so a given water molecule is unlikely to encounter a cold trap in a single impact. Additionally, there is a greater than even chance that a water molecule will be accelerated to escape velocity in a micrometeorite impact [14]. With a probability of reaching a cold trap being one part per thousand, but being lost to space one chance in two, this path to stock the cold traps is distinctly unpromising.

**Supply and loss:** A key constraint on supply is the fact that the cold trap surfaces are largely ice free, so they cannot be in accumulation. Farrell et al. [15] showed that micrometeorite vaporization was the dominant loss mechanism at cold trap temperatures, and calculated a mass loss rate of $10^{-17}$ kg/m2-sec for 1% ice cover. A continuous supply of condensing vapor would be subject to 100 times this rate. To avoid accumulation, the supply must then be less than $10^{-15}$ kg/m2-sec

The mass of micrometeorites striking the Moon should also contribute water to the poles. Grün et al. [16] estimated $10^6$ kg per year of micro-meteorite mass falls onto the lunar surface. Hanner and Zolensky [17] estimate a few percent of this mass is water, thus the potential contribution to the poles is about $3x10^{-13}$ kg/m2-sec. For consistency with Farrell et al. [15], this requires a minimum net loss rate of about $0.3x10^{-2}$ of water introduced by micrometeorites. The meteorite source contains water, so unlike the solar wind, the meteoritic source does not incur a loss in production of water. A portion of the incoming water will be retained in impact glass, and on the order of 70% released [18]. If we assume 50% is lost to space due to the high temperature of the vapor, the net estimated loss to the transporting exosphere is only about 0.3. Thus a factor of 100 in loss is unaccounted, and may be the efficiency of ballistic transport. Again, this is a minimum loss to explain the lack of ice accumulation at the lunar poles.

Larger meteorites (>1 cm in diameter) also contribute a quasi-continuous supply of water. Using the annual flux of bolides reported by [19] and scaled to the Moon we compute a mass assuming a meteorite density of $2500 kg/m^3$. Integrating above 1 cm, this gives rise to an input mass to the Moon of $7x10^4$ kg/year, about 10 times less than micrometeorites. Applying the same polar delivery efficiency calculation as to the Grün estimate, this gives rise to a missing loss rate of about 10. Thus this source contributes a weaker constraint than the micrometeorites, but a constraint nonetheless.

In the case of solar wind, 31 g/sec of hydrogen is delivered to the Moon [20]. Assuming every hydrogen atom is incorporated into a water molecule and ends in a cold trap, the ice accumulation rate would be $5x10^{-11}$, so the efficiency from solar wind H ion striking the lunar surface to water a cold trap destination must be less than $10^{-5}$. The model of Hurley et al. [9] that includes unlimited migration produces this loss in the conversion of H to $H_2O$ to meet the LADEE constraint on exospheric water. While the required loss at this step is much lower than previously estimated, it may be consistent with the ratio of exospheric $H_2$ and $H_2O$.

**Conclusion:** Data from LADEE are only consistent with unlimited ballistic transport if very low H to $H_2O$ conversion efficiency is assumed [9], however, these model efficiencies are consistent with approximate balance with the Farrell et al. rate. Our estimate of the water contribution from micrometeorites requires a maximum loss efficiency of $3x10^{-3}$, and from macrometeorites $3x10^{-2}$. Contrast this with the assumption of ~ $3x10^{-1}$ loss rate often used [21].

If water molecules survive multiple contacts with the lunar surface but the high activation energies of desorption implied by the LAMP results are correct, water would be stalled at mid to high latitudes out of reach of the polar supply [10], and subject to continuous micrometeorite erosion.

In either case, poor migration efficiency would severely restrict the abundance of ice at the poles throughout time, thus measurement of the contemporary volatile system informs our under-standing of the state of lunar volatile deposits. The natural behavior of water can be directly measured with a suitably sensitive mass spectrometer in polar orbit, including migration efficiency, activation energy and direct measurement of the critical loss rate from the cold traps. Direct measurements of transport efficiency can be also be determined using orbital or surface mass spectroscopic measurements of spacecraft traffic or controlled releases of water very distant from the monitoring platform.

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