RELATIVE MAGNITUDES OF WATER SOURCES TO THE LUNAR POLES. P. G. Lucey1, E. Costello, D. M. Hurley2, P. Prem3, W. M. Farrell4, N. Petro5, and M. Cable4, 1Hawaii Institute of Geophysics and Planetology, University of Hawai`i at Mānoa, Honolulu, HI (lucyey@higp.hawaii.edu), 2APL, Johns Hopkins University, Laurel, MD, 3NASA Goddard Space Flight Center, Greenbelt, MD, 4JPL, Pasadena, CA

Introduction: The lunar south pole is enjoying intense scrutiny recently in part because of the many lines of evidence for the presence of water ice that may support human activity. The main recognized sources for polar water are the impacts of comets and water-bearing asteroids [1], the solar wind [2], and the newly recognized importance of volcanism as a water source [3]. Balancing these sources are loss mechanisms including sublimation, sputtering, Lyman alpha radiation, and meteorite impact. Recently Farrell et al. [4] showed that the erosive force of micrometeorites dominates over all these mechanisms within cold traps where sublimation is very slow.

Are the lunar poles in accumulation, loss or in balance with respect to water? The presence of presumably thin surface ice deposits supports a dynamic system owing to the rapid loss from small impact vaporization[9]. But over longer timescales, what is the rate of supply relative to loss? We estimate the contributions from impact, solar wind and volcanism over the Copernican, Eratosthenian and Upper Imbrian (post-Orientale) when the polar cold traps may have been in operation, and compare these to the steady loss to micrometeorites.

Results: We begin with the Copernican where more solid estimates are available and summarized in Table 1. Ong et al. 2010 [5] made detailed estimates of the mass of water from comets and asteroids retained after impact over 1 Ga: roughly $10^{15}$ and $10^{16}$ g respectively. We assign a transport loss of a factor of 10 [6], leaving $10^{15}$ and $10^{16}$ g to be deposited at the poles. These values are consistent with a simple estimate of water mass from large Copernican crater impactors assuming an average density of 2.5 g/cc, an impactor to crater size ratio of 1/10, and an average water fraction of 1/10 and a vapor fraction retained of 1/10 also yielding $10^{17}$ g, and $10^{16}$ g deposited at the poles. For smaller impactors we integrate [7] from $10^{3}$ to $10^{5}$ m and find $10^{15}$ retained and $10^{14}$ deposited. Finally, from Grun et al. [8] we find for < 1mm impactors $10^{16}$ g water retained, and $10^{15}$ g deposited over the Copernican at the poles.

Contrast this with an estimate of water derived from solar wind. Hurley et al. [9] give about 30 g/s of protons striking the Moon on average for a total mass of protons of $10^{15}$g over 1 Ga. If we assume 1 part per thousand eventually is converted to water, and 10% of that reaches a cold trap, a total of $10^{14}$ g of water is supplied to the poles by the solar wind over the Copernican.

To assess the relative contribution of volcanism, we scale the impact sources to earlier epochs. For the Eratosthenian we assume a 5 times higher impact flux, and a somewhat longer duration to apply a factor of 10. For the post-Orientale Imbrian, we scale the Copernican rate by 100x. The most salient comparisons are the thicknesses of ice deposits. We use the estimated mass fluxes and assume a total area of cold trap of $3\times10^{4}$ km$^2$ [10]. In the Eratosthenian we estimate 3 m of ice based on the masses given by Needham et al. but a more generous transport efficiency of 0.1 to be consistent with the impact sources. The Upper Imbrian shows 30 m of potential ice thickness from volcanism.

The source mass and thicknesses are compared to losses. The Farrell et al. 2019 rate corresponds to a loss of 30 cm over a billion years. Because small impactors drive the Farrell et al. estimate, we similarly scale the loss rate, resulting in 3-m loss in the Eratosthenian and 30-m loss in the Upper Imbrian.

Discussion: Focusing on the Copernican, Ong et al.'s wet asteroid estimate is the major potential contributor of water, with an equivalent cold trap thickness of about 20-m. Ong et al. did point out that the water

<p>| Table 1. Order of Magnitude Masses and Deposit Thicknesses from Major Sources |
|---------------------------------|----------------|----------------|----------------|</p>
<table>
<thead>
<tr>
<th></th>
<th>Retained (g)</th>
<th>Deposited at Poles in Copernican (g)</th>
<th>Deposit Average Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comets</td>
<td>$10^{15}$</td>
<td>$10^{16}$</td>
<td>2 m</td>
</tr>
<tr>
<td>Asteroids</td>
<td>$10^{16}$</td>
<td>$10^{17}$</td>
<td>20 m</td>
</tr>
<tr>
<td>Large Copernican crater impactors</td>
<td>$10^{17}$</td>
<td>$10^{16}$</td>
<td>2 m</td>
</tr>
<tr>
<td>Impactors $10^{-3}$ to $10^{-1}$ m$^3$</td>
<td>$10^{15}$</td>
<td>$10^{14}$</td>
<td>2 cm</td>
</tr>
<tr>
<td>Impactors &lt; 1 mm$^8$</td>
<td>$10^{16}$</td>
<td>$10^{15}$</td>
<td>20 cm</td>
</tr>
<tr>
<td>Solar wind$^9$</td>
<td>$10^{14}$</td>
<td>30 cm</td>
<td>30 cm</td>
</tr>
<tr>
<td>Volcanism$^3$</td>
<td>-</td>
<td>-</td>
<td>3 m</td>
</tr>
<tr>
<td>Micrometeorite loss$^4$</td>
<td>-</td>
<td>30 cm</td>
<td>30 m</td>
</tr>
</tbody>
</table>


estimate was sensitive to the largest impactors, so we favor the lower estimate derived from observed Copernican craters giving about 2 m thick equivalent ice deposited in the Copernican. This is crudely similar to the Farrell loss rate, especially if regolith turnover can be assigned as a net loss process. This suggests in the Copernican supply and loss are roughly in balance and may explain the lack of widespread Mercury-like ice deposits.

The Farrell et al. loss probably eliminates the solar wind as a net source for polar ice deposits. Solar wind likely supplied water relatively continuously, supplemented by water formed from solar wind OH during small impacts [11]. Over thousands of year timescales both solar wind and micrometeorite loss are more or less continuous, and roughly in balance.

The contribution of the large Copernican impactors is qualitatively different. In these events mm to cm thick ice deposits are suddenly emplaced, and can endure on the order of millions of years of micrometeorite erosion. Over the same timescale, ice deposited on the floors of steep walled craters and other favorable topographic lows are subject to burial by on-going mass wasting observed even today locally protecting these thin deposits from surface erosional processes.

Prior to the Copernican, both volcanism and the effects of collisional atmospheres may become important [3,12]. Assuming similar transport efficiencies, the 3 m of ice provided by volcanism during the Eratosthenian is less than that of large impactors, but is still a large fraction. However, we assume the impact loss is also more vigorous at this time making volcanic ice deposits more susceptible to erosion. However, eruptions are envisioned to be short and intense, making preservation in depositional environments favorable. The possibility of collisional atmospheres from both impact and volcanism may dampen the effectiveness of micrometeorite erosion. This is particularly important during the upper Imbrian where volatile inputs may overwhelm the ability of the atmosphere to dissipate (but add the effect of impact erosion of the atmosphere). A persistent atmosphere may also fundamentally alter the thermal environment. These possibilities are balanced against scant evidence of a reactive atmosphere in the lunar regolith, and geologic features such as the Orientale pyroclastic ring that demand emplacement in vacuum.

The ice layer thicknesses predicted for the Upper Imbrian in contrast to the subtle evidence for abundance lunar ice deposits. However, the regolith overturn rate and reach prior to the Copernican may place preserved ice deposits below the view of neutron spectrometers, as suggested by the statistically anomalous depth of cold polar craters on both the Moon and Mercury [13].

**Conclusions:** The supply and loss of water to the poles is crudely in balance over all epochs which may explain the weak evidence for extensive polar ice deposits. However, the stochastic nature of ice deposition from large impacts and volcanism may favor preservation in depositional environments such as the floors of craters and other features that favor rapid burial. LCROSS may have sampled just such an environment. Future missions should target remote sensing of recent small impacts into such features to seek evidence of buried volatiles.

The effects and properties of collisional atmospheres should be studied in detail given their important implications for drastic alteration of the lunar environment and volatile transport and loss efficiencies.

The efficiency of transport through the exosphere is critically dependent on whether water molecules can survive interactions with the surface. If desorption activation energies are high or dissociative adsorption is favored, ballistic transport of water by hopping may not be effective, choking off supply to the poles.

Finally, volcanism provides less water input to the poles than impact, but not drastically so. The presence of sulfur in the LCROSS plume may be evidence of a volcanic contribution.