

SURFICIAL OH/H₂O ON THE MOON: MODELING DELIVERY, REDISTRIBUTION, AND LOSS. D. Hurley¹, ¹Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, dana.hurley@jhuapl.edu

Introduction: The surface of the Moon interacts strongly and persistently with the space environment. The top of the lunar regolith is exposed to bombardment by ions, photon, micrometeoroids, and cosmic rays. These interactions can affect the concentrations of constituents, the interaction of the regolith with the atmosphere, spectral properties, grain size/shape.

Recent observations of widespread OH and/or H₂O on the dayside lunar surface [1,2,3] call for a reanalysis of the expected effects of the solar wind interaction with the Moon's surface. One possible scenario for producing OH on the lunar surface is the direct production of OH by solar wind ion implantation in the lunar regolith. Laboratory experiments readily produce OH at damaged lattice sites through bombardment of silicates by ~1 keV protons [4]. An incident keV proton penetrates about 100 Å into the grain, creating defects as it exchanges momentum with the grain. Defect sites are favorable locations for forming an OH bond [5]. We consider the source, loss, and migration of solar wind hydrogen using more recent observations of the backscatter [6,7,8] and the surface distribution and reexamine the implications for delivery of solar wind produced water to the lunar cold traps [9,10].

Solar Wind Delivery: Since the Moon traverses through the solar wind throughout most of the month, the exception being the time when it crosses the Earth's magnetotail plasma sheet, we first investigate the solar wind as the source of the signature. We look purely from a supply perspective here, addressing retention/loss later in the paper.

The quiescent solar wind flux is $2 \times 10^8 \text{ p}^+ \text{ cm}^{-2} \text{ s}^{-1}$. The solar wind flows radially out from the Sun, but the motion of the Moon around the Sun causes an apparent aberration in the apparent direction of solar wind flow of 5°. The curvature of the Moon causes the flux to the lunar surface to fall with the cosine of the apparent solar wind direction. Thus, the solar wind flux, and therefore the supply rate of H for OH, is a function of solar zenith angle with a maximum at the subsolar point. This is the inverse of the observed distribution of OH. Therefore, it is impossible for prompt formation and a constant loss rate over the Moon to account for the observations.

Folding in the rotation of the Moon, the total fluence of H to a point on the lunar dayside increases throughout the lunation. The solar wind flux is essentially zero on the nightside so the fluence over the lunation is the sum over local times from dawn to dusk.

If the implanted SW H were to accumulate as OH without loss throughout the lunar day, the distribution would be as shown in Figure 1. In this simulation, we integrate the solar wind flux to each point on the Moon's surface from dawn until the local time shown in the figure. That total amount of hydrogen is assumed to be converted into OH in the lunar regolith at a concentration of 1000 ppm by weight. Assuming a constant abundance with depth, we convert the fluence into a layer thickness. With layer thicknesses of less than 1 μm, one day's worth of solar wind flux is not enough to supply the observed OH feature, which stems from a layer of 100s to 1000s of μm.

Figure 1 shows a distribution quite unlike the IR observations [2,3]. Because fluence accumulates throughout the lunar day, the peak values (corresponding to higher thicknesses in this figure) are at the evening terminator at low latitudes. In contrast, the observed abundances show no such trend and show an absence of OH at low solar zenith angles. Therefore prompt implantation cannot explain the observations.

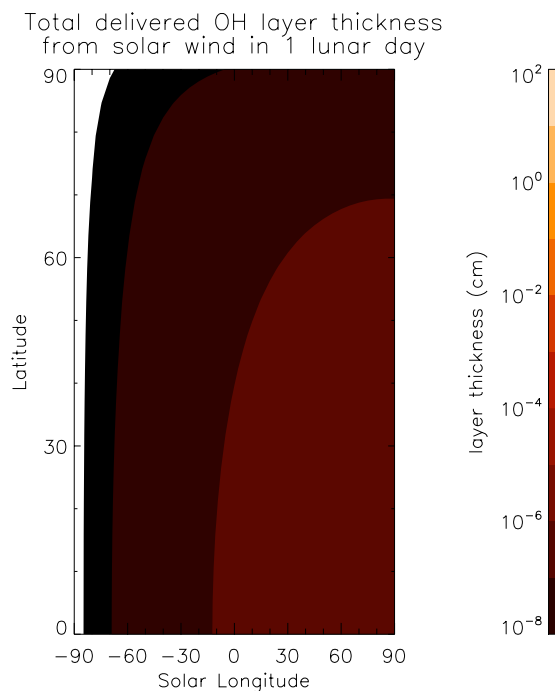


Fig. 1. We show the thickness of a surface layer of OH at concentration of 1000 ppm delivered by solar wind hydrogen over the course of one lunation without factoring in any loss terms. The 0 longitude line corresponds to local noon. The 90° latitude line is the pole.

Next we examine surface chemistry and prompt losses.

Surface Interaction: Recent observations have constrained the amount of incident solar wind flux that is immediately backscattered from the Moon. Ion measurements from Kaguya MAP-PACE [6] detected the ionized component of the immediate, high-energy backscatter at 0.1-1%. This confirms previous estimates based on laboratory studies [11]. McComas et al [7] report the neutralized component of the solar wind proton backscatter (i.e., energetic neutral hydrogen) detected by the Interplanetary Background Explorer (IBEX) as 10% of the incident solar wind. On-board Chandrayaan-1, the Sub keV Atom Reflecting Analyzer (SARA) instrument detected up to 20% ENA backscatter [8]. The cumulative efficiency of these backscatter mechanisms is <21%. Therefore, at least 79% interacts more strongly with the regolith, i.e., has a residence time that needs to be considered. The lunar regolith reaches saturation levels of a few 100 ppm H. These layers are turned down into deeper layers by impacts. One can consider the thickness of the regolith at a specified hydrogen concentration as a one-time sink to the solar wind. Subtracting the “permanent” fraction and the immediately reflected fraction, there is still the majority of the solar wind hydrogen left to interact with the lunar regolith.

Of the material that is implanted in the regolith, a steady state must be achieved. Physical sputtering of implanted hydrogen occurs with a yield of 1.5% [12]. Because of the high release energy from physical sputtering [13], hydrogen released in this mechanism predominantly escapes from the Moon [9]. Chemical sputtering can release implanted hydrogen as H_2 , OH, or H_2O [14]. Although adsorbed water would be stable to > 500 K, ultraviolet radiation may also break the OH bonds at the extreme surface. The distribution of the ion flux and UV photon flux for sputtering and photon stimulated desorption falls off with the cosine of the solar zenith angle, i.e., the same as the source flux. Thus a rigorous investigation of the source versus loss processes is necessary to understand the surficial distribution of OH/ H_2O .

Mobility: Because steady state must be achieved, the amount of the solar wind protons is equal to the amount of hydrogen out once the regolith is saturated. How the hydrogen is ejected is crucial for understanding the distribution of OH on the surface. It is also a critical key to determining the flux of hydrogen bearing molecules to permanently shadowed regions (PSRs).

If the surface OH varies diurnally [2], then migration must play a role. There is not enough new material to form the diurnal signature in a lunation. Our Monte Carlo model follows molecules as they migrate

through the lunar exosphere on ballistic hops across the surface [9]. The program computes the frequency with which atmospheric particles encounter every part of the lunar surface. Combining this with a residence time, we produce a map of the surface density of adsorbed water. We compare those with the observations to set limits on the migration process, which has not been specifically measured. We investigate the parameter space that produces surface concentrations consistent with the observed abundance and time dependence. Thereby we place constraints on some of the poorly known values in the migration processes, e.g. the ejection mechanism, the residence time, and the sticking function.

We take the constraints imposed by the observation and the residence time we find in the simulation to recalculate the delivery rate to the lunar permanently shadowed regions. Our previous models showed that the delivery of water that was originally supplied by solar wind hydrogen was more than enough to account for the abundances determined by Lunar Prospector neutron measurements. With all of the new data pertaining to water in lunar PSRs, this analysis warrants another look. We compare those results to the latest analyses of neutron data [15, 16].

Summary: We revisit our analysis of the expected chemical forms and energies of the hydrogen inventory leaving the lunar regolith and use our Monte Carlo model to examine the delivery rate of exospheric hydrogen in any molecular form all over the Moon. We produce a map of migrating species, calculate surface density, and estimate the delivery rate to PSRs on the Moon.

References: [1] Pieters C. et al. (2009) *Science* 326, 568. [2] Sunshine J. et al. (2009) *Science* 326, 565. [3] Clark J. (2009) *Science* 326, 562. [4] Zeller E. J. et al. (1966) *JGR* 71, 20. [5] Siskind, B. et al. (1977) *J. Vac. Sci. Tech.* 14, 537. [6] Saito Y. et al. (2008) *GRL* 35, L24205. [7] McComas D. et al. (2009) *GRL* 36, L12104. [8] Weiser, M. et al. (2009) *PSS* 57, 2132. [9] Crider D. H. and Vondrak R. R. (2000) *JGR* 105, 26773. [10] Crider D. H. and Vondrak R. R. (2002) *Adv. Sp. Res.* 30, 1869. [11] Behrisch R. and Wittmaack K. (1991) *Sputtering by Particle Bombardment III*, 1. [12] Gruen D. M. et al. (1976) *J. Chem. Phys.* 65, 363. [13] Hofer (1991) *Sputtering by Particle Bombardment III*, 15. [14] Roth J. (1983) *Sputtering by Particle Bombardment II*, 91. [15] Teodoro L. et al. (2009) LEAG meeting. [16] Mitrofanov I. et al. (2009) LEAG meeting.