**ANATOMY OF THE LUNAR WATER EXOSPHERE.** D. M. Hurley[1], P. Prem[1], M. Benna[2], R. R. Vondrak[2], W. M. Farrell[2], A. R. Hendrix[3], P. G. Lucey[4], [1]Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel MD 20723, USA (dana.hurley@jhuapl.edu), [2]NASA Goddard Space Flight Center, Greenbelt MD 20771, USA, [3]Planetary Science Institute, Boulder CO, USA, [4]University of Hawaii, Manoa HI, USA.

**Introduction:** Does water migrate across the lunar surface and accumulate in cold traps in lunar polar regions? There are multiple data sets that support one side or the other; however, there are no observations that are universally accepted as conclusive proof or disproof. This presentation conveys these observations and associated modeling. We discuss the present interpretations with regard to exospheric water migration, implications for ongoing migration as a source of volatiles to lunar cold traps, and important measurements that will solve this problem.

**The Lunar Water Exosphere:** Because the lunar atmosphere is usually a surface bounded exosphere, individual aspects of the exosphere can be modeled and examined separately. Here, we demonstrate the potential anatomy of the lunar water exosphere under various sources, surface interactions, and losses using our Monte Carlo model [1-3].

*Sources.* Potential sources of water in the lunar exosphere include water released by meteoroid bombardment (*n.b.*, this includes water brought in by the meteoroid and water liberated by the impact from lunar materials) and water sputtered from the surface through solar wind ion bombardment. The meteoroid source distribution is centered on the dawn equatorial region with other localized enhancements also in the morning hemisphere [4-5]. The release of water by micrometeoroid impacts is energetic owing to the high impact velocity [6-7]. The solar wind source is centered on the equatorial region near noon local time, and the energy of release varies with local surface temperature [8].

*Surface Interactions.* Although there are many unknowns regarding the interaction of water with the lunar surface, we can place important constraints on these interactions by investigating limiting cases. We explore the minimum where particles only take one hop in the exosphere. Once they are released, they continue until they escape or make contact with the surface again and are not allowed to be re-released. In doing so, we get the exospheric distributions shown in Fig. 1 (for a meteoroid source) and Fig. 2 (for a solar wind source). Then, we repeat the run including rerelease from the surface, assuming complete thermalization. The difference (Fig. 3) is the migrating exosphere.

These simulations demonstrate that the equatorial night side of the Moon is a special location where the dominant component is the source from meteoroids. In situ measurements of exospheric density there would constrain that source. In contrast, the polar region and dayside have multiple components.

During the Earth's magnetotail passages, the solar wind source is temporarily shut off, while the meteoroid source and the migrating exosphere should remain. Dayside measurements during a magnetotail passage constrain the magnitude of the migrating exosphere through comparison to the nightside exosphere.

Finally, measurements on the dayside when the Moon is in the solar wind would detect the prompt solar wind source, the migrating exosphere, and the prompt meteoroid source.

**Evidence Supporting Water Migration:** The theory of water migrating to lunar polar regions was proposed before the Apollo program [9], although it remains an unsolved mystery. Analysis of returned Apollo soils revealed the presence of nano-phase iron, proposed to be formed by the reduction of FeO in the presence of solar wind protons which should have formed OH or $H_2O$ [10]. Theoretical work has analyzed the transport and relative source rates of water migration in the lunar exosphere [11].

More recently, tantalizing observations of a OH/$H_2O$ absorption feature in IR spectra [12-13] and FUV spectra [14] on the illuminated surface of the Moon, potentially with a diurnal variability, reenergized the concept of a migrating water exosphere. However, the abundance of OH/$H_2O$ on the surface and the distribution as a function of latitude and local time remain open questions. The amount of water inferred from the spectra depends on the thermal correction applied to the data [15-16]. In addition, the inferred magnitude of the diurnal variation depends on the phase correction applied [14,17].

**Evidence Contraindicating Water Migration:** Since the Apollo Lunar Surface Experiment Package (ALSEP) Lunar Atmosphere Composition Experiment (LACE) instrument detected Ar in the lunar exosphere that sticks to the lunar nightside [18], Hodges has postulated that the adsorption properties of Ar are contraindicative of $H_2O$ on the surface of the Moon [18-21]. The argument is that $H_2O$ adsorbs more readily to lunar regolith than Ar, and would fill available adsorption sites, leaving them unavailable for Ar.

Simulations of a migrating water exosphere predict an enhancement in adsorbed water near dawn owing to a buildup of adsorbed water on the cold nightside [3,22-23]. However, observations of surface OH/ $H_2O$ do not appear to have an asymmetry across noon.

Similarly, models set predictions of the expected abundance of water in the lunar exosphere if migration is an efficient process. As shown here, reasonable expectations for exospheric water density are >50 $H_2O$/ $cm^3$. However, the LADEE NMS has set the upper limit of an ambient background (i.e. persistent) water exosphere lower at < 1 $cm^{-3}$ [21,24]. The NMS data has been interpreted as sporadic water releases from meteoroid impacts [24]. This indicates that water released into the lunar exosphere does not persist through many hops, as once considered [3,23]. However, the LADEE NMS was not designed to detect water and there are extreme limitations to the interpretation of the data.

**Conclusion:** Water must be released into the lunar exosphere. Now the questions are centered on whether water molecules take one hop or multiple hops in the exosphere? Is the water released in meteoroid bombardment synthesized in the impact or merely released by the impact? In what molecular form is solar wind H released? Answering these questions requires exosphere measurements resolved in time and space.

LADEE UVS is sensitive to OH and has made a positive detection of OH in the exosphere [25]. However, quantification, understanding the distribution, and relating it to whether it was derived from water is ongoing work. Crucially, revamped measurements of water in the lunar exosphere are critical to understanding if water migrates. Additionally, measurements of the surface hydration that can be decoupled from thermal and phase effects are important.

**References:** [1] Hurley D.M. (2011) *JGR 116*, 2010JE003793. [2] Hurley D.M. et al. (2016) *Icarus 273*, 45-52. [3] Crider D. and Vondrak R. (2000) *JGR 105*, 26,773-26,782. [4] Horanyi M. et al. (2015) *Nature*, 324-326. [5] Szalay J. and Horanyi M. (2015) *GRL 42*, 10,580-10,584. [6] Cinatla M. J. (1992) *JGR 97*, 946-973. [7] Hurley D.M. and Benna M. (2018) *PSS 162*, 148-156. [8] Roth J. (1983) Sputtering by Particle Bombardment II, 91-146. [9] Watson K. et al. (1961) *JGR 66*, 3033-3045. [10] Housley R.M. et al. (1973) LPSC 4th, 2737-2749. [11] Arnold J.R. (1979) *JGR 84*, 5659-5668. [12] Pieters C.M. et al. (2009) *Science 326*, 568-572. [13] Sunshine J.M. et al. (2009) *Science 326*, 565-568. [14] Hendrix A.R. et al. (2012) *JGR 117*, 2012je004252. [15] Bandfield J. et al. (2018) *Nat. Geosci. 11*, 173-177. [16] Li S. and Milliken R. (2016) *JGR 121*, 2081-2107. [17] Clark R. (2009) *Science 326*, 562-564. [18] Hodges R.R. (1975) *Moon 14*, 139-157. [19] Hodges R.R. (1991) *GRL 18*, 2113-2116. [20] Hodges R.R. (2002) *JGR 107*, 2000JE00149. [21] Hodges R.R. (2018) *GRL 45*, 7409-7416. [22] Shorghofer N. (2014) *GRL 41*, 4888-4893. [23] Butler B.J. (1997) *JGR 102*, 19,283-19,292. [24] Benna M. et al. (2017) AGU FM, P43F-06. [25] Colaprete A. et al. (2015) LPSC 46th, 2364.

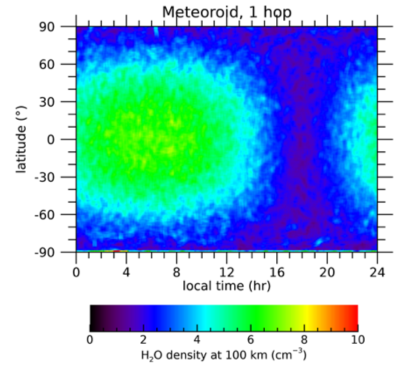


*Figure 1. Modeled exospheric density from meteoritic release of water assuming particles take 1 hop.*

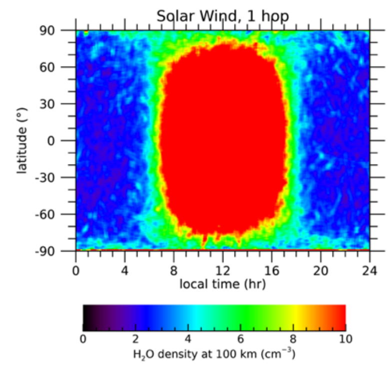


*Figure 2. Modeled exospheric density from solar wind release of water assuming particles take 1 hop.*

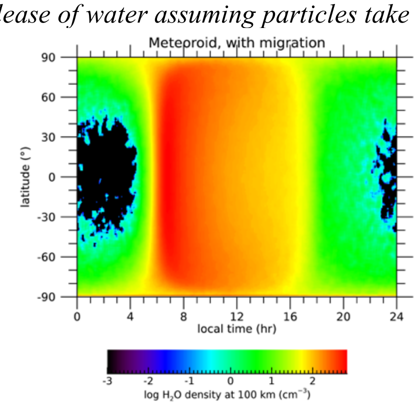


*Figure 3. Modeled exospheric density from meteoroid release of water assuming particles migrate. The color scale is a log scale. The contribution from the first hop (Fig. 1) has been removed.*