

THE LADEE MISSION: THE NEXT STEP AFTER THE DISCOVERY OF WATER ON THE MOON. G. T. Delory^{1,2}, R. C. Elphic¹, A. Colaprete¹, P. Mahaffy³, and M. Horanyi⁴ ¹NASA Ames Research Center, Moffett Field, CA 94035-1000, ²Space Sciences Laboratory, University of California, Berkeley CA 94720 gdelory@ssl.berkeley.edu. ³NASA Goddard Space Flight Center, Greenbelt, MD, 20771 ⁴Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309.

Introduction: The recent discovery of significant amounts of water on the lunar surface and within a permanently shadowed region of the southern lunar pole has re-ignited the debate regarding the sources and dynamics of lunar volatiles. Whether lunar volatile deposits are primordial and static over periods as long as several Ga or are engaged in active processes involving present-day source and loss mechanisms remains a key question. The answer to this question bears directly on what volatile stratigraphy can reveal regarding the evolution of the Moon and the conditions in the early solar system. Volatiles may be found in the tenuous lunar atmosphere, a surface boundary exosphere whose composition and variability may provide direct insight into their transport and evolution. The Lunar Atmosphere and Dust Environment Explorer (LADEE), a small, low-cost lunar orbiter currently planned for a launch in 2012, carries an instrument payload specifically designed to study the lunar exosphere, and is thus an important and timely mission that will determine whether or not there are present-day dynamic processes contributing to the inventory of polar volatiles on the Moon.

Lunar Water: Measurements made by the Moon Mineralogy Mapper (M^3) aboard Chandrayaan-1, along with observations from both Cassini and the Deep Impact missions, confirm the presence of a surficial layer of H_2O and OH over significant areas of the Moon [2-4]. The water and hydroxyl are within the first few millimeters of the surface, may exist in layers only a few molecules thick, and appear to favor colder, poleward regions [3]. While there is some overlap with the hydrogen maps produced by Lunar Prospector (LP) [5], surficial water and hydroxyl are found at lower latitudes ($< 80^\circ$) and are also correlated with some freshly exposed materials, including the anorthositic highlands [2, 4]. Observations by EPOXI from Deep Impact reveal what may be a diurnal variation in surface concentrations [3], indicating the possibility that the observed H_2O and OH may be engaged in thermally-driven surface exchange processes. Meanwhile, the discovery by the Lunar CRater Observation and Sensing Satellite (LCROSS) of a significant amount of subsurface water in a lunar permanently shadowed region (PSR) makes it clear there are significant deposits of volatiles on the Moon, likely concentrated via cold-

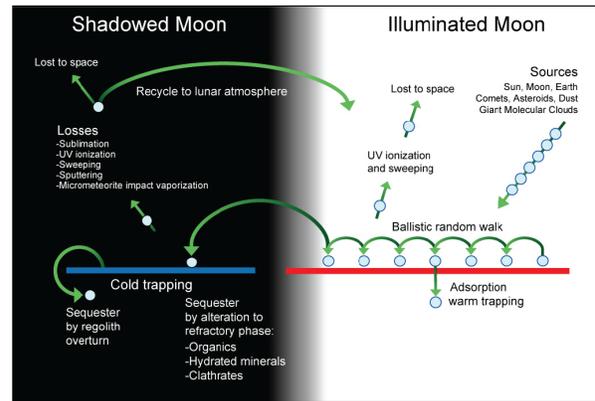


Fig. 1: Volatile cycling on the Moon (From [1])

trapping processes. While LCROSS represents a single point measurement, the presence of at least 100 kg of water in a ~ 20 m diameter region within Cabeus, together with the hydrogen measurements from LP, argue strongly that there are likely significant volatile deposits within PSRs.

Current Questions and Controversies: Now that there is strong evidence for the presence of significant concentrations of lunar volatiles, the next set of questions are concerned with their sources, and how they have evolved over time. The origin and past evolution of the water discovered by LCROSS – and its relationship to the water and hydroxyl seen over much broader regions on the surface by M^3 and other observations – remains a mystery. One prominent theory that could explain both the presence of surficial H_2O and OH as well as the cold-trapped volatiles invokes hydrogen from the solar wind as a volatile precursor [6]. Once implanted, solar wind hydrogen would react with Oxygen to form OH or H_2O , and subsequently undergo ballistic hopping across the surface under the influence of various capture and release mechanisms. Although the lifetime for H_2O in sunlight is short (~ 1 day), Monte-Carlo models indicate that even if only a small fraction of these encounter a PSR and become cold-trapped, concentrations consistent with LP measurements can accumulate in PSR regolith [7]. This theory is just one example; in general, elucidating the relationship between surficial water and the more concentrated deposits in the PSRs hinges on our understanding of the basic physics of lunar surface interactions, under the influence of the solar wind and other

plasmas, ultra-violet (UV) illumination, impacts both large and small, thermal conditions, and surface chemistry. The dynamics and mobility of surficial water and OH as measured by M³ is heavily debated. Despite hints from both EPOXI and M³ that water concentrations may change depending on illumination, experiments with Apollo samples and simulants indicate that water can be stable on lunar grains on the dayside lunar surface [8], even at temperatures above 500 C, and are thus “chemi-sorbed,” and hence unlikely to undergo thermal desorption on the Moon [9]. However the role of other space weathering effects at the Moon is far from clear – sputtering from the solar wind, photon stimulated desorption, impact gardening and vaporization are all additional processes that may play into the release, modification, redistribution, and destruction of water. Lunar water may also be released from the interior if there are any internal processes at work as indicated by the ubiquitous presence of ⁴⁰Ar [10]. Thus our understanding of the role of the surficial water as a source for the polar deposits is to a large extent limited by our lack of knowledge of the details behind lunar surface-water interactions.

The Next Step: While ongoing laboratory and remote sensing observations may continue to shed light on these issues, the upcoming LADEE mission will provide an immediate and direct assessment of the role that present-day dynamic processes play in volatile sources and dynamics. A surface boundary exosphere is by necessity heavily dependent on the composition and dynamics of its lower boundary, in this case the lunar surface. The mere existence of a lunar exosphere implies that cold trapping at the poles is not sufficient to condense the entire atmospheric mass [1]; hence there must be a dynamic interplay between source and loss mechanisms. LADEE will study the composition and dynamics of the lunar exosphere and dust from the vantage point of a low altitude, ~50 km equatorial orbit over a period of 100 days [11]. Two instruments will study the lunar exosphere directly: an ultra-violet/visible spectrometer (UVS) and a neutral mass spectrometer (NMS) [12]. Detection of significant OH and/or H₂O in the lunar exosphere by either instrument will indicate that these constituents are regularly captured and released from the lunar surface, with more permanent capture at the lunar poles as one possible endpoint in their dynamic transport. LADEE will be able to constrain a subset of the processes that may be responsible for volatile dynamics by measuring exospheric variability as a function of environmental parameters. Measurements across the lunar terminator will reveal the importance of thermal desorption, while regular passage out of the solar wind and through the Earth’s magnetotail may demonstrate the importance



Instrument Payload:

Neutral Mass spectrometer (NMS)
Ultraviolet/Visible Spectrometer (UVS)
Lunar Dust Experiment (LDEX)
Lunar Laser Comm Demo (LLCD)

Launch: Mid-2012

Launch Vehicle: Minotaur IV+V

Fig. 2 – LADEE spacecraft and instruments

of plasma sputtering. Continual processes such as micrometeorite bombardment, and perhaps episodic larger impacts, will also be examined as potential contributors to volatile delivery and release. If LADEE finds a dynamic, water-laden exosphere, this would argue for an active lunar surface in which a present-day water cycle is at work, and the surficial H₂O and OH detected by M³ and others is either lost to space or ends up sequestered in a PSR. This process would also imply the presence of a continual source, for example hydrogen in the solar wind, among other possibilities. Equally important is the null result: should LADEE fail to detect water or OH, the implication would be for a more static lunar surface, in which OH and H₂O are immobilized through any number of mechanisms, via chemi-sorption or as part of hydrated minerals, among others. Hence the surficial water participates little in any larger scale volatile generation or emplacement [9, 13], and other more episodic sources can be invoked, including comets and meteorites [14], dense interstellar clouds [15], or perhaps internal activity [16]. Which of these mechanisms – or combination thereof – is responsible for the presence of lunar water bears directly on our interpretation of its composition and distribution for future landed missions that may sample volatiles directly. In either case, measurements of the lunar exosphere obtained on LADEE will no doubt provide important pieces in the current puzzle of the origin and evolution of water on the Moon.

References: [1] Lucey, P.G. (2009) *ELEMENTS*, 5(1), 41-46. [2] Pieters, C.M., *et al.* (2009) *Science*, 1178658. [3] Sunshine, J.M., *et al.* (2009) *Science*, 1179788. [4] Clark, R.N. (2009) *Science*, 1178105. [5] Feldman, W.C., *et al.* (2001) *J. Geophys. Res.*, 106(E10), 23231-51. [6] Crider, D.H., *et al.* (2002) *Adv. Space Res.*, 30, 1869-1874. [7] Crider, D.H., *et al.* (2003) *J. Geophys. Res.*, 108g, 15-1. [8] Hibbitts, C.A., *et al.* (2009) *LPSC*, Vol. 40, 1926. [9] R. R. Hodges, J. (2002) *J. Geophys. Res.*, 107(E2). [10] Hodges, R.R., *et al.* (1974) *Icarus*, 21(4), 415-426. [11] Delory, G.T., *et al.* (2009) *LPSC*, Vol. 40, 2025. [12] Mahaffy, P.R., *et al.* (2009) *LPSC*, Vol. 40, 1217. [13] R. R. Hodges, J. (2002) *J. Geophys. Res.*, 107(E12), 8-1-8-5. [14] Arnold, J.R. (1979) *J. Geophys. Res.*, 84. [15] Talbot, R.J., Jr., *et al.* (1977) *Astrophys J Suppl S*, 34, 295-308. [16] Schultz, P.H., *et al.* (2006) *Nature*, 444(7116), 184-186.