MULTI-INSTRUMENT STUDIES OF LUNAR VOLATILES IN THE LRO EXTENDED MISSION: GLOBAL-SCALE OBJECTIVES. Kathleen E. Mandt[1], Noah Petro[2], John Keller[2], G. Wes Patterson[1], Amanda Hendrix[3], Dana Hurley[1], Cesare Grava[4], Tim McClannahan[2], Andrew Jordan[5], Kurt Retherford[4], Nathan Schwadron[5]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA; [2]Goddard Space Flight Center, Greenbelt, MD, USA; [3]Planetary Science Institute, Boulder, CO, USA; [4]Southwest Research Institute, San Antonio, TX, USA; [2]Institute for the Study of Earth, Oceans, and Space, UNH, Durham, NH, USA. (Kathleen.Mandt@jhuapl.edu).

Introduction: The Planetary Science Decadal Survey, *Visions and Voyages* [1] sets characterization of the lunar volatile cycle as a top priority for lunar exploration, seeking to answer the following questions: (1) What are the sources of volatiles? (2) How do volatiles move across the surface and within the exosphere on different time scales? and (3) What is their ultimate fate? To answer these questions, the Lunar Reconnaissance Orbiter (LRO) fourth extended mission (ESM4) will take a multi-instrument approach to investigating global volatile processes that will evaluate how the transport of volatiles across the surface of the Moon and in the exosphere influence the distribution of volatiles with depth and location.

Diurnal Variation of Hydrogen: Previous observations create uncertainty as to whether hydration varies diurnally on the lunar surface and subsurface. As illustrated in Fig. 1 for far-ultraviolet (FUV) observations, surface near-infrared [2,3] and FUV [4] observations indicate that hydration (OH or H_2O) is low near local noon and increases toward the terminators and toward higher latitudes [3]. However, controversy exists in interpreting infrared observations. A new Moon Mineralogy Mapper (M^3) thermal correction was recently used to suggest that observed variations are due to temperature [5], but EPOXI mission data observed diurnal variation after correcting for thermal effects [3].

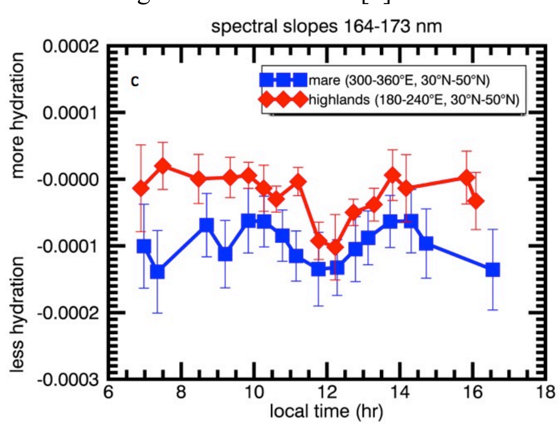

Fig. 1. Diurnal signature of surface hydration using the LRO Lyman Alpha Mapping Project (LAMP).

Subsurface variations may also exist, but observed trends differ from surface observations. LRO Cosmic Ray Telescope (CRaTER) albedo protons (< 10 cm), illustrated in Fig. 2, imply that hydrogen abundance is greater near dawn than dusk [6]. The deeper LEND observations may suggest diurnal migration of large concentrations of hydrogen peaking at dawn [7], although this result may be affected by temperature variations in the regolith [8].

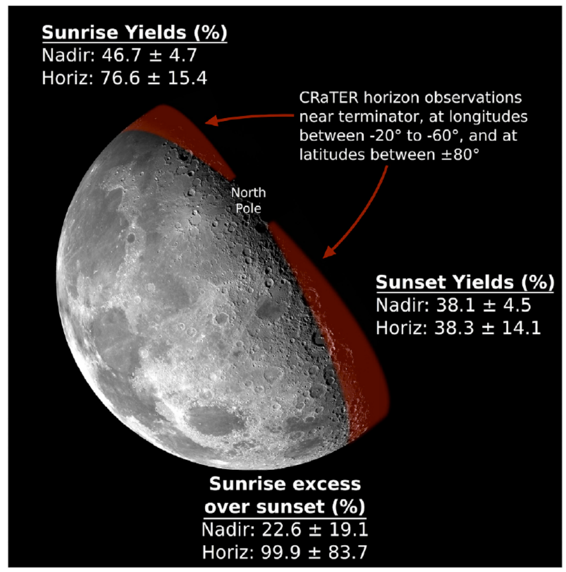

Fig. 2. Possible diurnal signature of subsurface hydration using CRaTER (From [6]).

The present set of observations suggests large uncertainties and a critical need for further investigations. Surface observations may be consistent with solar wind supplying hydrogen to the surface, which could be transported through the exosphere to become a source for ice in Permanently Shadowed Regions (PSRs) [e.g. 9]. However, if hydrogen varies diurnally below the surface, then a more unusual transport process must be operating [e.g. 7]. The key question for ESM4 is *How does hydration (OH, H_2O) vary on the surface and near-surface as a function of latitude and local time?*

The Lunar Exosphere: Determining the exosphere's composition and dynamics is necessary to understand volatiles transport to and from cold traps. LAMP provided detections of He and H_2 emissions in the far-UV [10,11], but the LAMP upper limits for argon exosphere near the dawn terminator are lower than abundances measured by mass spectrometry [12,13]. Possible explanations for these conflicting observations include a localization of argon gas not yet sampled by LAMP observing strategies or a misidentification of this species in mass spectrometer data.

Species that LAMP will target during ESM4 include He and H_2, oxygen, and ^{40}Ar. Continued observations of He [14] and H_2 will further clarify the role of solar wind in replenishing the lunar exosphere. This is particularly important for H_2, a product of solar wind proton interaction with the lunar regolith. Knowing the conversion rate of solar wind protons to H_2 will help determine the fraction of solar wind that can form water [15]. Additionally LAMP initiated a new operating mode with a ~10% increase in throughput that may allow LAMP to detect oxygen and ^{40}Ar. Mass spectrometry found correlations between exospheric ^{40}Ar at the lunar surface and moonquakes [12], suggesting that ^{40}Ar, which has its origin in the lunar crust, can diffuse to the exosphere via outgassing through cracks. A detection with LAMP of a local enhancement could be used to identify a venting source and test the hypothesis that cracks through which radiogenic gases leak into the exosphere are located close to circular fault systems at the edges of *maria* [16]. This would also help resolve the difference between far-UV and mass spectrometer observations. The key question for ESM4 is *What is the global density, composition, and variability of the lunar exosphere before it is disturbed by further human exploration?*

Space Environment: ESM4 will enable the first comparison of how the Moon's atmospheric and radiation environments respond to changing solar activity in two subsequent solar cycles. LRO launched at the beginning of cycle 24, and ESM4 is poised to operate through the beginning of cycle 25. As Fig. 1 demonstrates, solar cycle 24 has been anomalous. Its minimum was so weak and prolonged that CRaTER measured the highest fluxes of galactic cosmic rays (GCRs) observed during the space age [17]. Currently, solar activity is declining to a new minimum, signaling the start of cycle 25. CRaTER measurements show that the radiation environment is worsening faster than expected [18]. There is also new evidence that the Sun is moving into a grand minimum, or a series of weak solar cycles, like the Maunder, Dalton, or Gleissberg minima [18,19]. To understand and predict how this variability will affect the atmospheric and radiation environments, observations are needed with CRaTER, LEND, and LAMP from two different solar cycles. The key questions for ESM4 are *Will the start of the next solar cycle be the same or different from the last? Do all solar minima look the same in terms of the Lunar radiation environment? What are the implications of these differences in environment to space weathering processes and human exploration?*

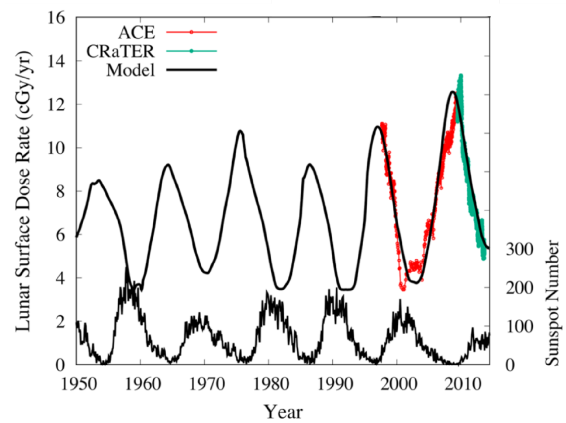

Fig. 3. The Moon's space radiation environment has been increasing throughout most of the space age: radiation dose rates projected to the lunar surface (red, green, and upper black curves) and the sunspot number (lower black curve). ESM4 is poised to measure the radiation and atmospheric environments during what is expected to be an even weaker solar cycle. (From [18]).

Conclusions: LRO LAMP, CRaTER, and LEND observations of diurnal hydration using during ESM4 will provide new hydration data at the surface and at a range of depths for all times of day and almost all latitudes that will constrain the mode and significance of hydrogen transport. LAMP observations of the exosphere in the new operating mode will be able to detect new species in the exosphere and/or significantly reduce the upper limits of several species, with a particular emphasis on the puzzling missing argon signal in LAMP observations. Finally, CRaTER and LEND observations will determine how the Moon's comprehensive radiation environment has changed from the previous solar cycle to a potentially weaker one, and will support predictions about whether the Sun is entering a grand minimum.

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