LAMP Observations of Lunar Volatiles

Retherford & LAMP Team
23 Oct. 2014
LEAG meeting, APL
• **Volatile Deposits:** LAMP – High spatial resolution EUV/FUV reflectance measurements over the SP

• **Space Weathering:** LAMP/LROC UV – Repeat coverage over areas of high interest to increase S/N sufficiently to observe variations of ~3%

• **Lunar Exosphere:** LAMP - Measure the spatial and temporal variability of the lunar helium atmosphere and search for exospheric dust and other gas constituents during CMEs and enhanced meteoric fluxes.

• **Volatile Transport:** LAMP – Implement a broader and deeper assay of lunar atmospheric species to investigate exospheric transport efficiencies by species and determine constraints on contribution to visible glow from UV active atomic species – coordinate measurements with the LADEE spacecraft.
LAMP PSR Water Frost

Gladstone et al. JGR, 2012

Water Frost Abundance

- 2.0%
- 1.0%
- 0.8%
- 0.3%

Haworth
Shoemaker
Fayum
Shackleton
Many Interesting FUV Features

- Lyman-α nightside albedo maps of the poles (>60° lat.) at ~240 m × 240 m per pixel
- No sunlit features are found to have albedos as low as the PSRs
- *Space weathering processes explain higher far-UV albedos of crater peaks*
Lyman-alpha and FUV Albedos

- Nightside South Pole albedo maps

  Lyman-α (Sky IPM Source)  Far-UV Longwave (Starlight Source)
LAMP Detects Dayside Hydration

- LAMP dayside measurements with traditional sunlight illumination
- H$_2$O abundances are strongly correlated with surface temperature

Hendrix et al., JGR, 2012
LAMP Detects Dayside Hydration

Hendrix et al., *JGR*, 2012

- LAMP dayside measurements with traditional sunlight illumination
- H$_2$O abundances are strongly correlated with surface temperature
A New LAMP Spectral-Mapper

• We’ve always planned to provide maps in a spectral data cube format for ease of scientific analysis.

• Our previous global mapping work proved too slow for detailed spectra, yet remains the primary product with broad-bandpass

• Initial spectral data products included
  – Total photon maps (photons/cm²/sr/nm)
  – Wavelengths (68 wavelength bins, 2-nm wide, between 57.57 nm and 193.57 nm, splitting Lya into two bins)
  – Latitude/longitudes (degrees in the Moon_ME coordinate system)
  – Integration time map (sec)

• Regions currently limited to swaths of 20°x160°; we’ll keep working toward global coverage

• Will include south pole region, and our next version of global maps in the next PDS delivery on 2015-March-1
Search for Water Frost Time Variability in PSRs

Lyman-α Brightness by Month for 2010

Can We Identify Variations Related to Volatile Transport?
Sunlit peaks in accumulated off band maps not yet filtered out in the new spectral-mapper cubes; Regions with SZA>96° are decidedly not sunlit.
LAMP Observations Using Sunlight Scattered into PSR’s

LROC has imaged the inside of Shoemaker using light scattered off of the crater walls (top right from Koeber et al. 2014).

Using data excluded from that used to search for water, we can see some of the same features that LROC observes (bottom right).

Month by month illumination, summed for 2009-13

Half the year, sunlight is an issue/friend
LURE Measurements

- Wagner et al., 1987 redux *in progress*
- Apollo sample 10084 in house
- Also water frost FUV BRDF

Soils show a blue slope, consistent with weathering.

Crushed rocks are decidedly not weathered.

Karnes et al., *SPIE*, 2013 describes recent upgrades to the facility.
Three Modes of LAMP Atmosphere Observations

- **Above-Limb pointed**
  - Increases line of sight column density
  - Includes bright sky emission background

- **Nadir pointed**
  - Illuminated atmosphere on dark surface
  - Limited to near-terminator “Twilight”

- **Limb-terminator pointed**
  - Longer slant path of illuminated gas, no sky noise

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**LROC imaged LADEE**

Important Lunar Helium Variations Detected

- Variations in lunar helium are observed with LAMP and show strong correlations with the solar wind, confirming long-standing theory.
  - A clear decrease is observed during passages into the Earth’s magnetotail; Feldman et al., *Icarus*, 2012. Follows Stern et al. 2012 detection of helium.
  - Models show correlations with thermal release from the dayside surface (red points);

Monte Carlo model by Dana Hurley assumes a constant solar wind alpha flux of 1.2 x $10^7$ cm$^{-2}$ s$^{-1}$
Episodic Helium Variations

- **Cook & Stern, Icarus, 2014**
- LACE detected maximum He density between local midnight and 3 am.
- Maximum density with LAMP found to be ~2 hours after local midnight
  - Similar LADEE-NMS results
  - $N_{\text{Ave}} \sim 2x$ lower than LACE
- Sporadic ‘flares’ by >3σ
- Differences due to solar wind? Internal sources of Helium?
LAMP and LADEE Comparison

LAMP

He Number Density (cm$^{-3}$)

Max. He Density
$(1.70 \pm 0.48) \times 10^3$ cm$^{-3}$

Jun 2011
△ Oct 2011
□ others

Local Time (hours after local midnight)

LADEE

LADEE NMS - $^4$He Scale Height and Maximum Surface Abundance: From 11-Nov-2013 To 09-Feb-2014

Maximum He surface abundance (1/0)

Time past midnight (Hours)
LAMP light curves provide key constraints to models of impact plumes
LAMP Argon Search

- A difficult data analysis approach, sifting through many systematic effects
- Best time to detect high levels of Ar is at **dawn and dusk**
  - LRO has passed through beta~90 ten times since launch
- Our spectrum is time averaged, ~1 hr before sunrise and after sunset
  - From LACE, we expect ~800 cm$^{-3}$ pre-dawn and ~9000 cm$^{-3}$ post-dusk
- Where does one look on the Moon?
  - LACE was at latitude 20°N
  - LADEE equatorial orbit at ~50 km altitude
  - Grava et al., *Icarus* (2014) predicts greatest numbers near equator at post-dusk
- Despite these instrument and observing geometry subtleties, curiously LAMP provides upper limits to argon densities that are below detections by both LACE and LADEE/NMS
Searching for Ar

- Coadd all nadir pointed data from within 30° of the equator at post-dusk and pre-dawn.

No Argon  
But nice $H_2$ quality
Tentative Ar Upper Limits

Post-Dusk Spectrum, LRO/LAMP

\[ N(\text{Ar}) = 675 \text{ cm}^{-3} \]
\[ N(\text{H}) = 19 \text{ cm}^{-3} \]
\[ N(\text{H}_2) = 332 \text{ cm}^{-3} \]

\[ N_{\text{Ar}} < 675 \text{ cm}^{-3} \]

Pre-Dawn Spectrum, LRO/LAMP

\[ N(\text{Ar}) = 57 \text{ cm}^{-3} \]
\[ N(\text{H}) = 1.6 \text{ cm}^{-3} \]
\[ N(\text{H}_2) = 741 \text{ cm}^{-3} \]

\[ N_{\text{Ar}} < 57 \text{ cm}^{-3} \]
Stern et al., Icarus, 2013

- Average “Twilight” Observation Residual: red, Fluorescence model: blue
• **Stern et al., Icarus, 2013**

• Average “Twilight” Observation Residual: red, Fluorescence model: blue

• Density 1200 cm$^{-3}$ consistent w/ Apollo 17 UVS upper limit: <9000 cm$^{-3}$

• H$_2$ solar wind sputtering source predicted 2100 cm$^{-3}$ (Wurz et al. 2012)

• Similar solar wind sources forming H$_2$ may form H$_2$O
Stay tuned for neutral atomic oxygen update in LRO ESM2

- New energetic neutral atom imaging results for sputtered O show 11-14 cm$^{-3}$ (Vorburger et al., JGR, 2014), within just $x2$ of LAMP
- LADEE-UVS detection of O as well ($\sim260$ cm$^{-3}$)
- Sifting out far-UV Earthshine signals to improve SNR
- Another important water/OH product to understand

- Cook et al. *Icarus*, 2013
- Important constraints for exosphere models
- We’re comparing notes with LADEE NMS & UVS

**Table 1**

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength (Å)</th>
<th>g-Factor (s$^{-1}$)</th>
<th>LAMP upper limits Brightness ($\mu$Rayleighs)</th>
<th>Surface density (cm$^{-3}$)</th>
<th>Previous upper limits</th>
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</table>
LAMP-LADEE Atmospheric Campaigns

- Dedicated slewed observations to increase exosphere signal quality 2-14 Dec. 2013 during the LRO solar $\beta \sim 90^\circ$
- LRO Roll-Slews show excellent helium emission – searches for additional argon and other features is ongoing

Grava et al., 2014
• LAMP is mapping out and searching for exposed water ice in PSRs using an innovative illumination technique and a far-UV spectral “fingerprint”
• LAMP dayside observations, like IR maps, are diagnostic of hydration, and support the diurnal behavior discovered by the M3/EPOXI/VIMS team
• LAMP images reflected sunlight in PSRs, when illumination is appropriate
• LAMP has set new upper limits to numerous expected exosphere constituents
• LAMP detected the H₂ exosphere, advancing “lunar hydrology” studies
• LAMP continues its search for Argon, an important tracer of internal radiogenic decay – LAMP should be sensitive to LACE and LADEE measured Ar densities, despite instrument artifacts and relatively less sensitivity at 104.8 nm
• LAMP remotely senses the global helium exosphere and its variability, including a few episodic ‘flares’ from either solar wind or internal outgasing
• LAMP “horizon glow” observations constrain lunar exospheric dust abundance by 2 orders of magnitude
• LAMP detected the GRAIL gas plumes constituents H and Hg and constrain their bulk expansion rates
• LAMP continues to study how water and other volatiles are formed, transported through the lunar atmosphere, and deposited on surfaces
LRO/ LAMP Mapping Results Summary

• LAMP is mapping out and searching for exposed water ice in PSRs using an innovative illumination technique and a far-UV spectral “fingerprint”
• LAMP-observed low Lyα albedos suggests high porosity or “fluffiness” (P~0.7) in most permanently shadowed regions (PSRs)
• LAMP-observed reddening at longer FUV wavelengths suggests 1-2% surface water frost in several PSRs
• LAMP dayside observations, like IR maps, are diagnostic of hydration, and support the diurnal behavior discovered by the M3/EPOXI/VIMS team
• LAMP far-UV maps are diagnostic of space weathering with many new features
• LAMP images reflected sunlight in PSRs, when illumination is appropriate
• LAMP continues to study how water and other volatiles are formed, transported through the lunar atmosphere, and deposited on surfaces
LAMP Exosphere Results Summary

- LAMP remotely senses the global helium exosphere and its variability, including a few episodic ‘flares’ from either solar wind or internal outgasing
- LAMP detected the $\text{H}_2$ exosphere, advancing “lunar hydrology” studies
- LAMP has set upper limits to numerous expected exosphere constituents, informing the set of LADEE detections and possible detections
- LAMP continues its search for Argon, an important tracer of internal radiogenic decay - LAMP should be sensitive to LACE and LADEE measured Ar densities, despite instrument artifacts and relatively less sensitivity at 104.8 nm
- LAMP “horizon glow” observations constrain lunar exospheric dust abundance by 2 orders magnitude, which informed LADEE LDEX, UVS, & Star-Tracker analyses
- LAMP detected the GRAIL A&B impact gas plumes constituents H and Hg and constrain their bulk expansion rates
- LAMP detected LCROSS impact light curves from $\text{H}_2$ and CO molecular fluorescence and resonantly scattered Hg, Mg, and Ca neutral atom emissions
- LAMP continues to study how water and other volatiles are formed, transported through the lunar atmosphere, and deposited on surfaces
Dana Hurley’s
Friends of Lunar Volatiles List

- FoLV@lists.hou.usra.edu
- https://lists.hou.usra.edu/mailman/listinfo/folv

- Recurring telecons on third Thursdays at 1 pm central time
In addition to normal calibrations and nadir pointed ops the LAMP project plans the following event-based observations in the ESM1:

- GRAIL Impacts
- Herschel Impact
- LADEE Mission Campaign(s)
- Horizon Glow observations (continue high solar-elongation obs.)
- Other impacts or landings (e.g., Chang’e 3)
- Solar Beta ~88-90° off-limb campaigns (limited to just the ~3 days)

Additional polar and nightside off-nadir pointing is planned to build signal in PSRs (e.g., LROC style <30° slews) and to study any angular dependency of our nightside photometry technique (a full range of roll angles per ROI, with a few ROIs).

- Good discussions with Robinson last year about LROC help in targeting these. LAMP PS Tommy Greathouse will lead this planning.
In addition to normal calibrations and nadir pointed ops the LAMP project plans the following event-based observations in the ESM1:

- **GRAIL Impacts**
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- LROC is already targeting these for us. Tommy Greathouse built a new spectral mapping tool that is indispensible for analyzing these data.
# LAMP Papers

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<th>Subject</th>
<th>Title</th>
<th>Authors</th>
<th>Status</th>
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<td><strong>PSR Results</strong></td>
<td>LAMP Far-Ultraviolet Spectra of the Moon’s PSRs</td>
<td>Gladstone et al.</td>
<td><em>JGR-E</em>, 117, E00H04, 2012</td>
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<td><strong>PSR Results</strong></td>
<td>2D Distribution of Volatiles in PSRs</td>
<td>Hurley et al.</td>
<td><em>GRL</em>, 39, L09203, 2012</td>
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<td><strong>IPM Results</strong></td>
<td>Lyman-α Models for LRO-LAMP Based on MESSENGER-MASCS and SOHO-SWAN</td>
<td>Pryor et al.</td>
<td><em>ISSI IPM Book</em>, 2013</td>
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<td><strong>Atmosphere</strong></td>
<td>Lunar atmospheric helium detections by the LAMP UV spectrograph on the LRO</td>
<td>Stern et al.</td>
<td><em>GRL</em>, 39, L12202, 2012</td>
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## LAMP ESM1 Papers

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<td><em>Icarus, 225, 681-687, 2013</em></td>
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<td><em>Icarus, 226, 1210-1213, 2013</em></td>
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<td>Sporadic Increases In Lunar Atmospheric Helium Detected by LRO-LAMP</td>
<td>Cook &amp; Stern</td>
<td><em>Icarus, 236, 48-55, 2014</em></td>
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<td>GRAIL Impact</td>
<td>LRO/LAMP Observations of the GRAIL Impact Plumes</td>
<td>Retherford et al.</td>
<td>In preparation for <em>JGR Planets</em></td>
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<td>LCROSS Lightcurves</td>
<td>Detailed LCROSS Light Curves Modeling</td>
<td>Hurley et al.</td>
<td>In preparation for <em>JGR Note</em></td>
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<td>Surface</td>
<td>Evidence for Exposed Water Ice in the Moon’s South Polar Regions from LRO UV Albedo and Temperature Measurements</td>
<td>Hayne et al.</td>
<td>Submitted to <em>Icarus special issue 2014</em></td>
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## LAMP Papers In Prep.

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<td>Argon Follow-up</td>
<td>Stern, Cook, et al.</td>
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Western Equatorial Hemisphere
WAC Map matched to LAMP res.
LAMP Lya: Spectral Reversal
LAMP constrains the exospheric dust concentrations of 100-200 nm grains to >2 orders of magnitude less abundant than estimated by Apollo 15 observations.

- Feldman et al., *Icarus*, 2014
- $N_{\text{vertical col}} < 10$ grains cm$^{-2}$
- Similar LADEE-coordinated limits
Comet C/2013A1 Siding Spring

- **C/2013 A1 (Siding Spring)** is an Oort cloud comet
- Just encountered Mars on Oct. 19; Sun closests approach on Oct. 25
- Earth Closest Approach Sept. 5 at 0.89 AU
  - 11:40; 431608773
  - 13:40; 431615968
- **LAMP OI 130.4 nm detection!**
- Quick-look Spectrogram shows not solar spectrum (no CII 133.5nm)
- LROC-WAC likely also saw the comet in these observations
- OI 130.4 nm detected at \( \sim0.9 \) counts/sec \( \Rightarrow \sim0.8 \) R
- CI 165.7 nm also detected at \( \sim0.01 \) count/sec \( \Rightarrow \sim0.04 \) R
- Likely Ly-Beta 102.6 nm at \( \sim0.01 \) count/sec \( \Rightarrow \sim0.15 \) R

- LAMP Imaged the Coma:
  - Extends spatially beyond one pixel, \( \sim1 \) deg.
- The LAMP pixel of 0.3 deg translates to 700,000 km at the comet, and the OI profile is consistent with a \( \sim1.e6 \) scale length
New 63° Pitch Maneuver in ESM1

- Dedicated “phases” for planning in 2-week periods over LADEE era
- Most of the ~14 phases involved simple 1-per-day pitch slews
  - Increase slant path while viewing nightside to avoiding sky noise
- Serendipitous color Earth views by LROC WAC
• Evidence for Exposed Water Ice in the Moon’s South Polar Regions from LRO UV Albedo and Temperature Measurements

Figure 3: Ultraviolet spectral variations with temperature, for the three LAMP wavelength bands affected by the presence of

Figure 4: Distribution of exposed water frost, based on LAMP UV spectra having: a) Lyman-α albedo < 0.03, and b) off/on albedo ratio > 1.2. Note the strong correlation with the lowest temperature cold traps (grayscale indicates annual maximum temperature).
Amanda Hendrix is working to understand the interesting Compton-Belkovich region.

The Compton region spectrum shows the ‘reddest’ spectral slope of all the LAMP regions investigated with our dayside mapping, but is apparently not associated with the thorium anomaly in C-B.

More at Hendrix’s plenary talk at DPS in a few weeks.