LAMP Observations of Lunar Volatiles

Retherford & LAMP Team

23 Oct. 2014

LEAG meeting, APL

ESM1 Proposal Traceability

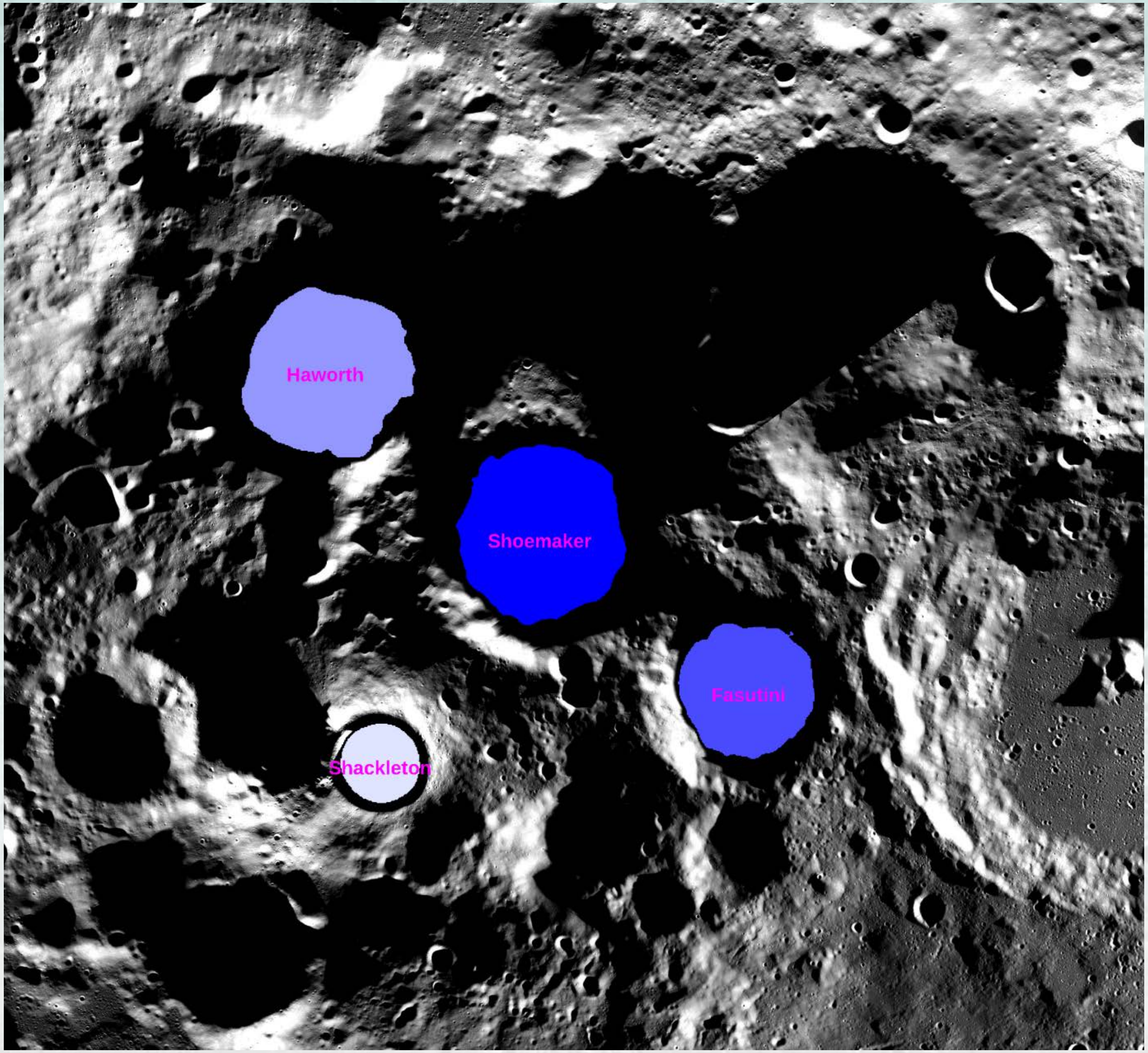
- **Volatile Deposits:** LAMP – High spatial resolution EUV/FUV reflectance measurements over the SP

- **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



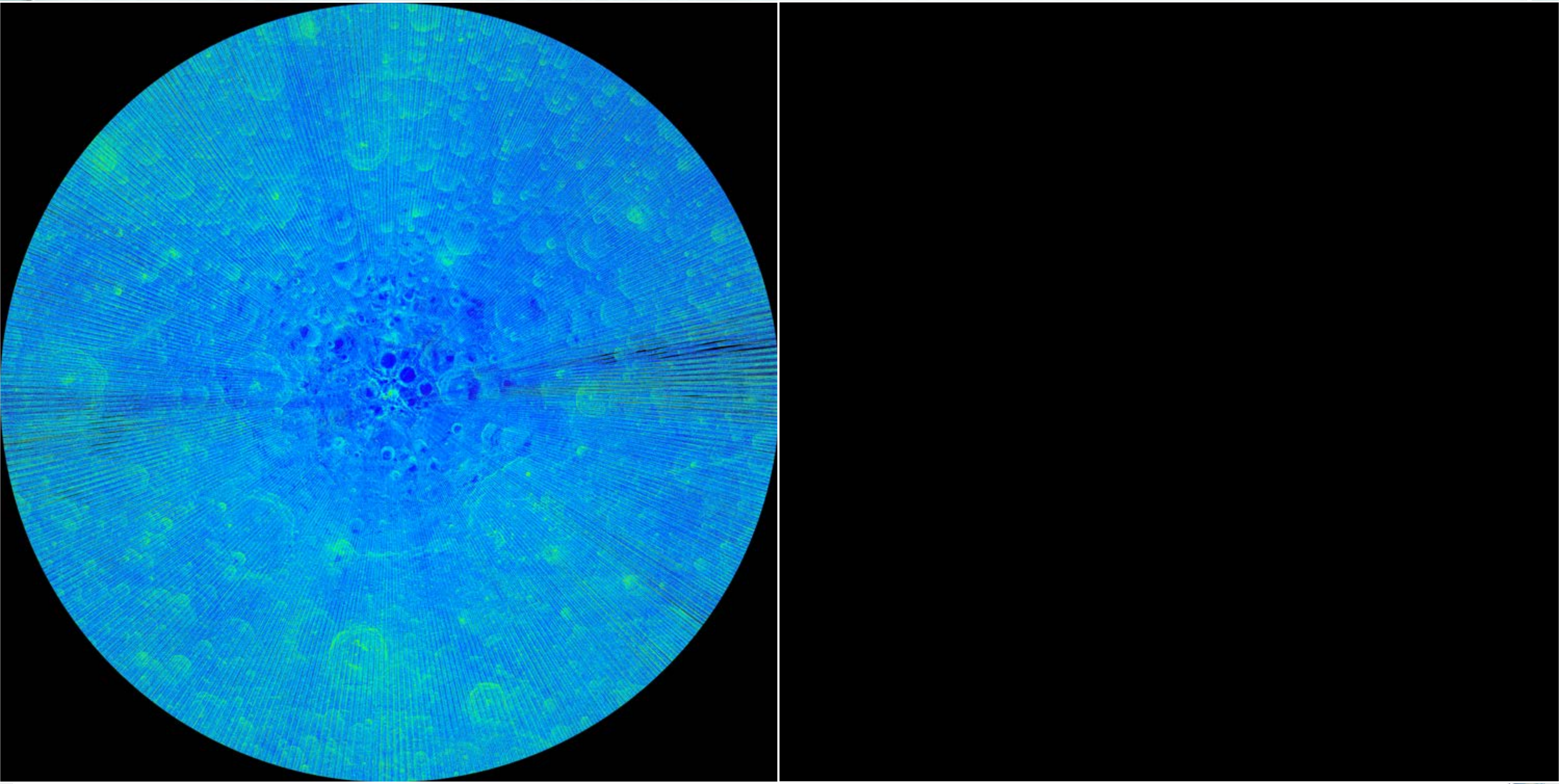
Gladstone et al. JGR, 2012

Water Frost Abundance

2.0%
1.0%
0.8%
0.3%

Many Interesting FUV Features

South | North

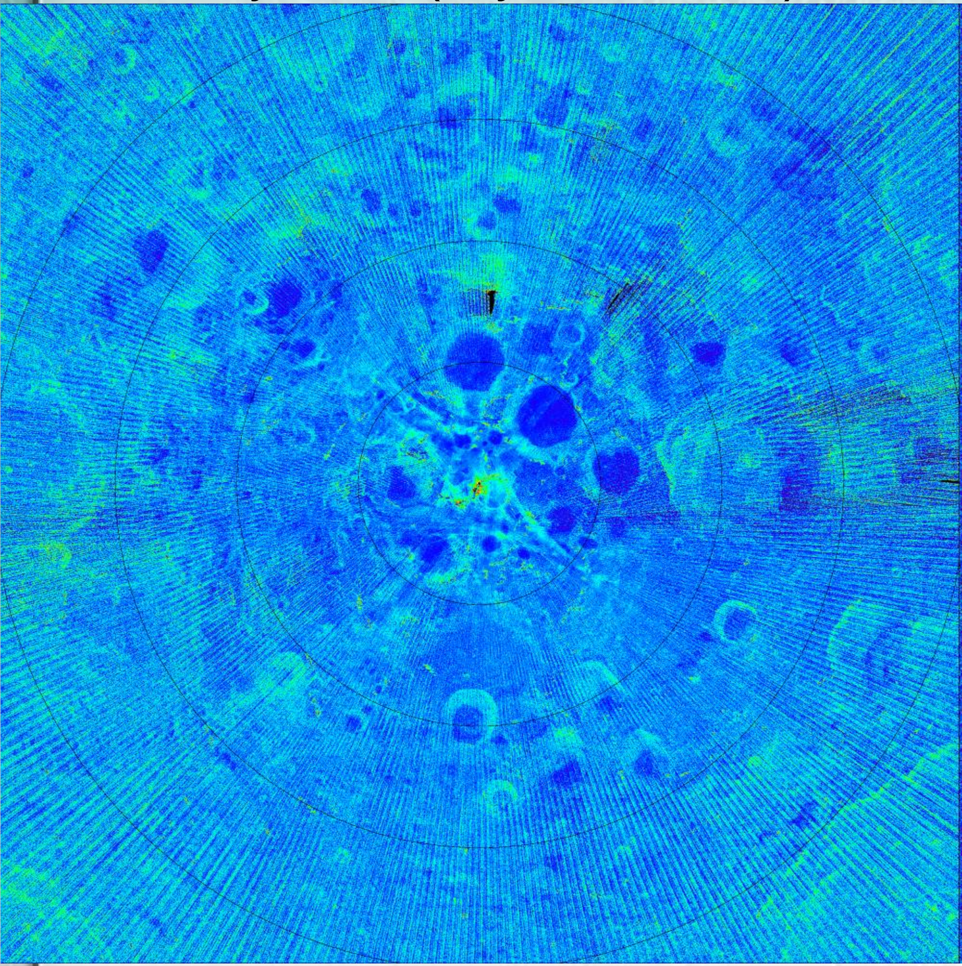


- Lyman-α nightside albedo maps of the poles (>60° lat.) at ~240 m × 240 m per pixel
- No sunlit features are found to have albedos as low as the PSRs
- *Space weathering processes explain higher far-UV albedos of crater peaks*

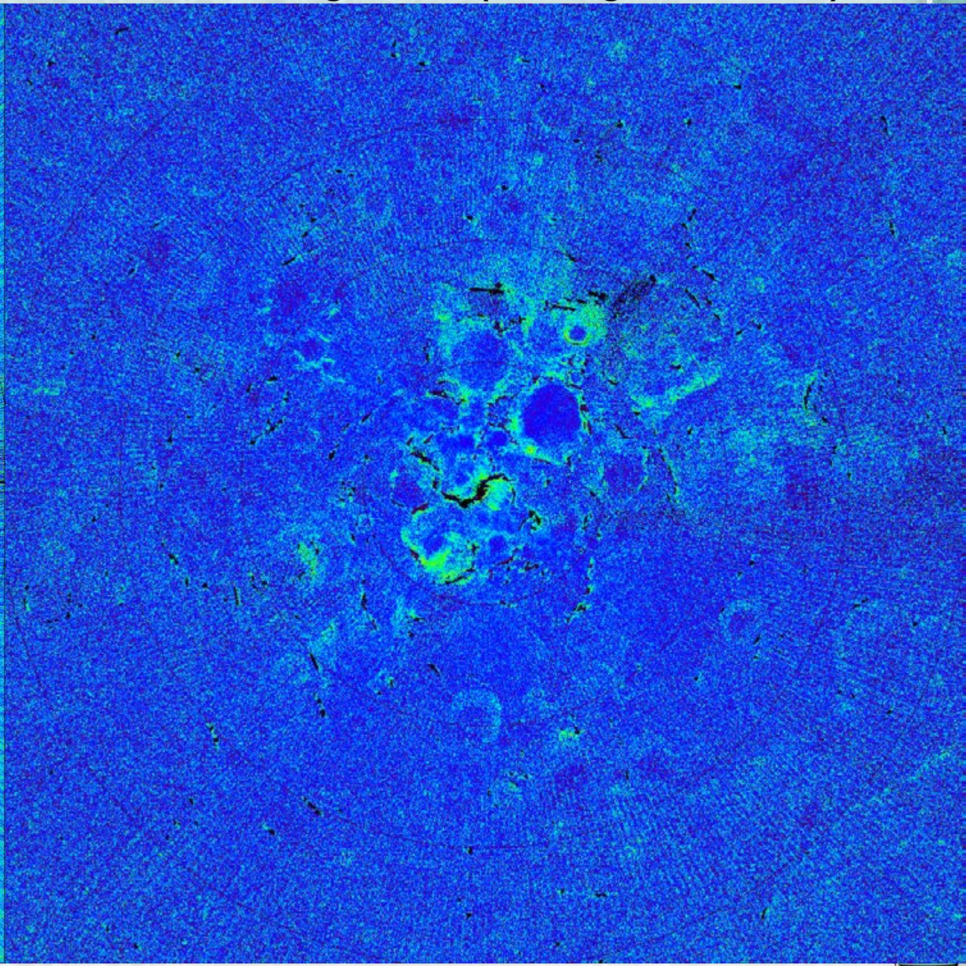
Lyman-alpha and FUV Albedos

- Nightside South Pole albedo maps

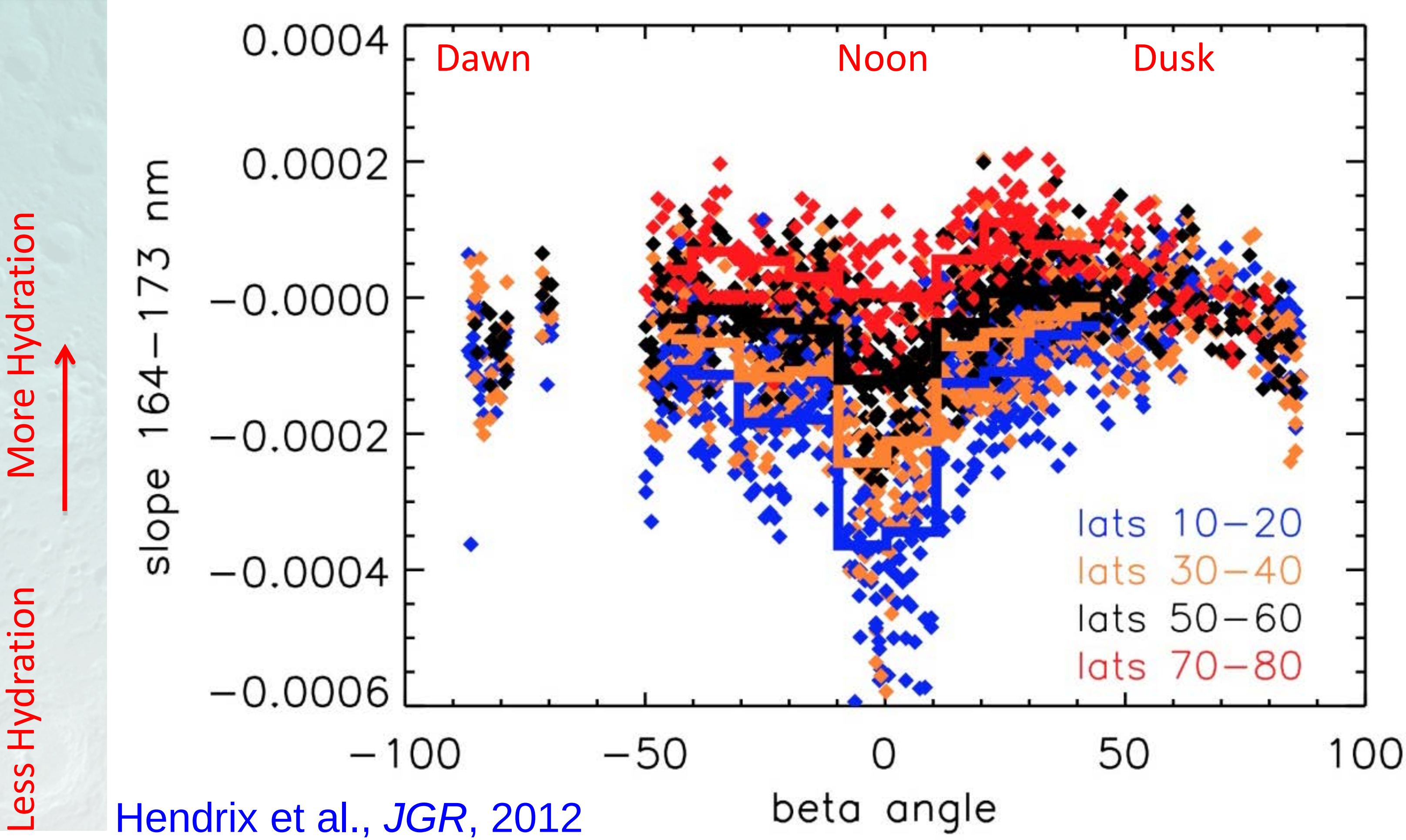
Lyman-α (Sky IPM Source)



Far-UV Longwave (Starlight Source)



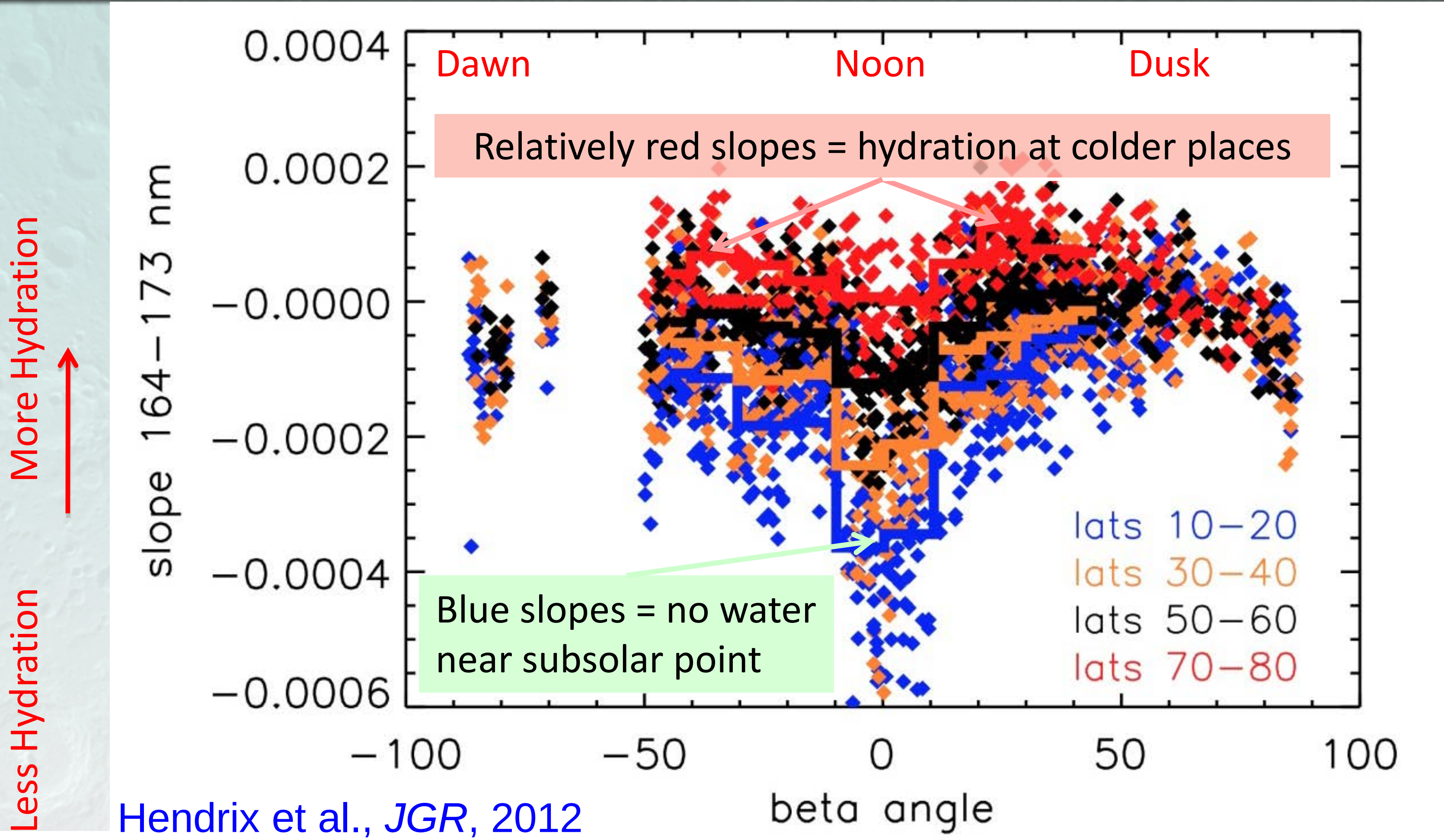
LAMP Detects Dayside Hydration



Hendrix et al., *JGR*, 2012

- LAMP dayside measurements with traditional sunlight illumination
- H_2O abundances are strongly correlated with surface temperature

LAMP Detects Dayside Hydration



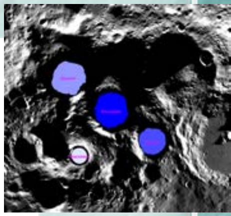
Hendrix et al., *JGR*, 2012

- LAMP dayside measurements with traditional sunlight illumination
- H_2O abundances are strongly correlated with surface temperature

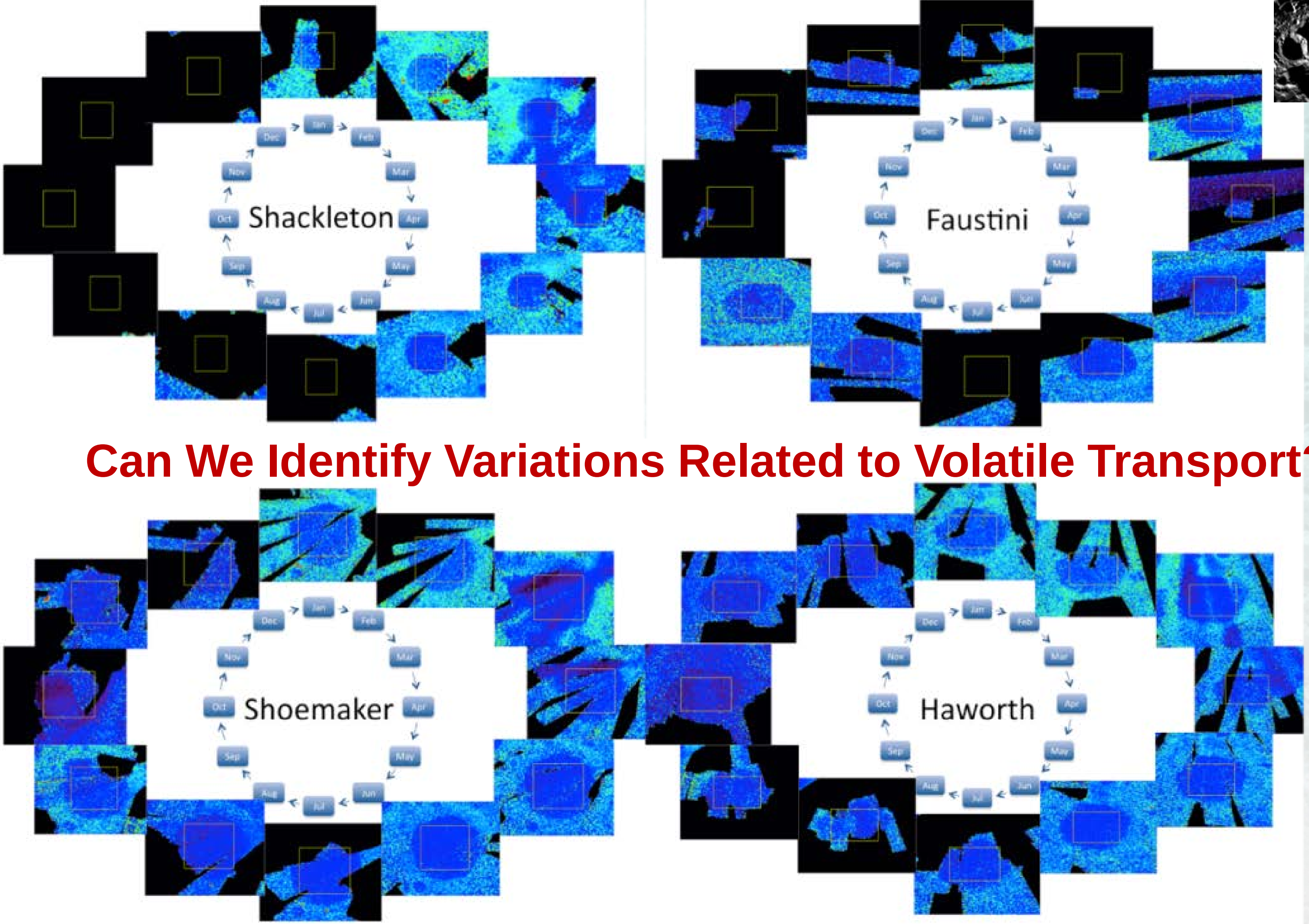
A New LAMP Spectral-Mapper

- 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/cm^2/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

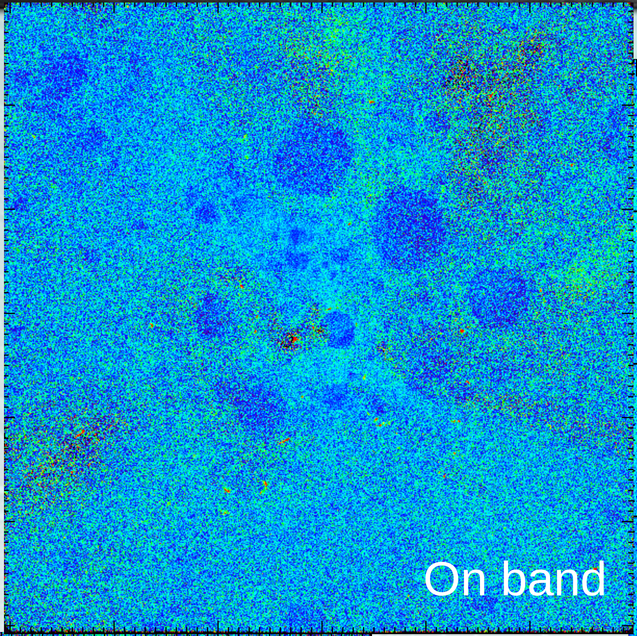


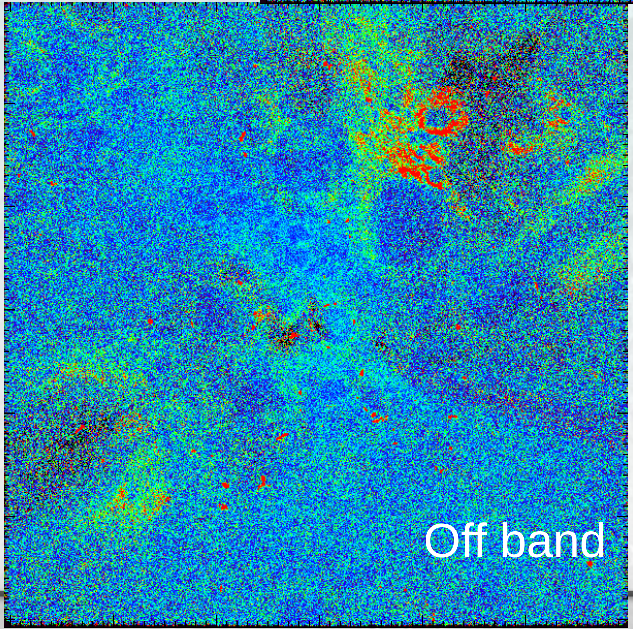
Lyman-α Brightness by Month for 2010

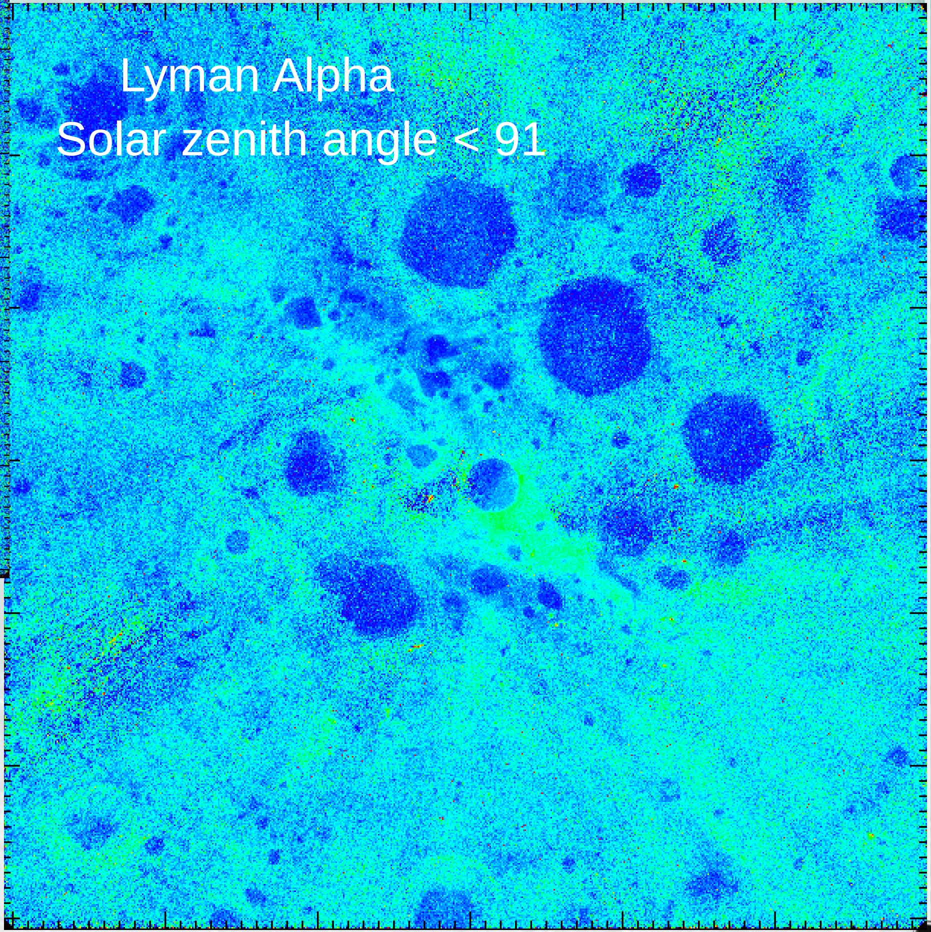


Can We Identify Variations Related to Volatile Transport?

South Pole Night Albedo Maps

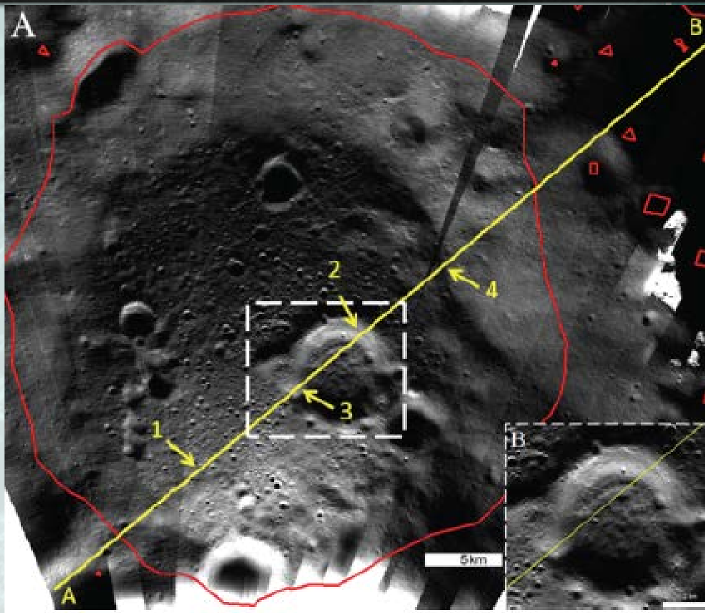






Sunlit peaks in accumulated off band maps not yet filtered out in the new spectral-mapper cubes; Regions with SZA>96° are decidedly not sunlit

LAMP Observations Using Sunlight Scattered into PSR's

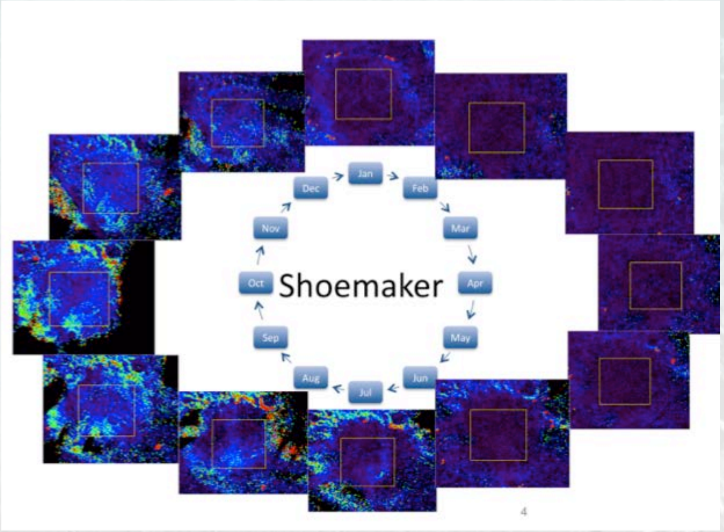


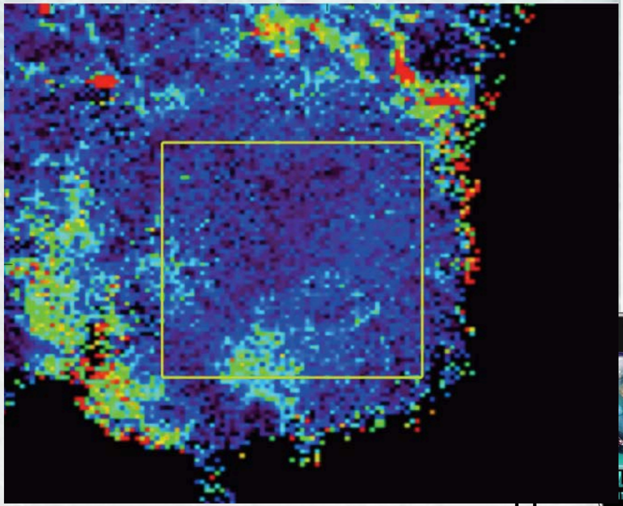
LROC has imaged the inside of Shoemaker using light scattered off of the crater walls (top right from Koeber et al. 2014).

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

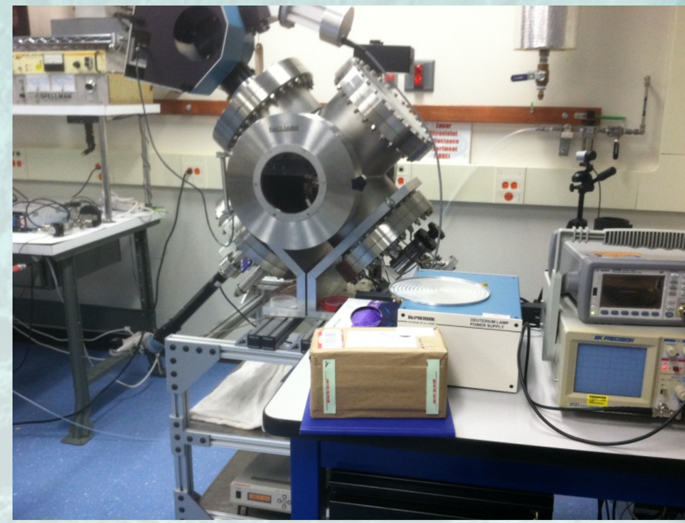
Half the year, sunlight is an issue/friend

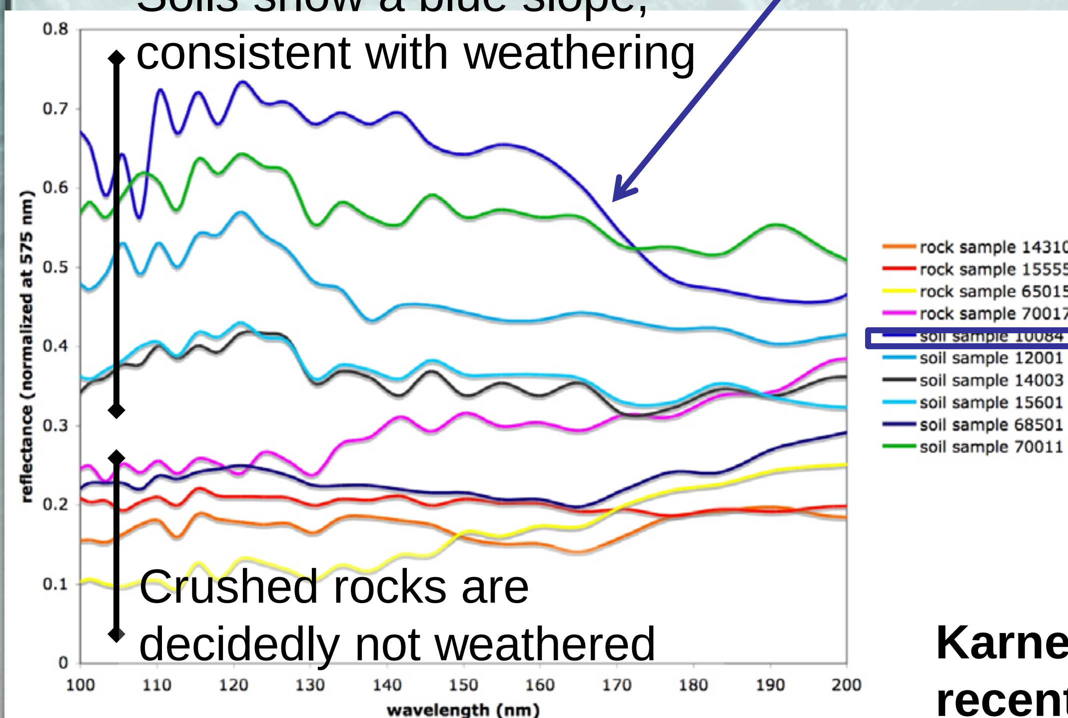




LURE Measurements

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



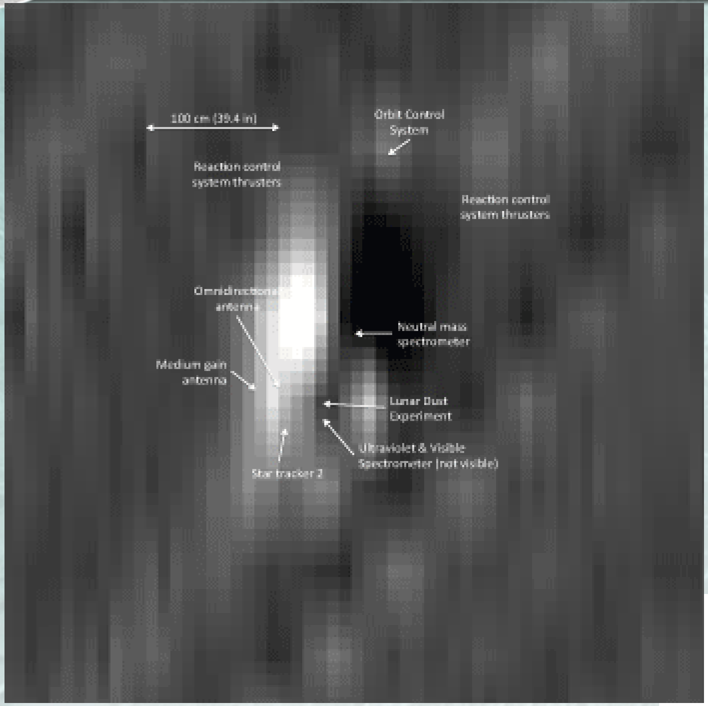


Soils show a blue slope, consistent with weathering

Crushed rocks are decidedly not weathered

Karnes et al., *SPIE*, 2013 describes recent upgrades to the facility

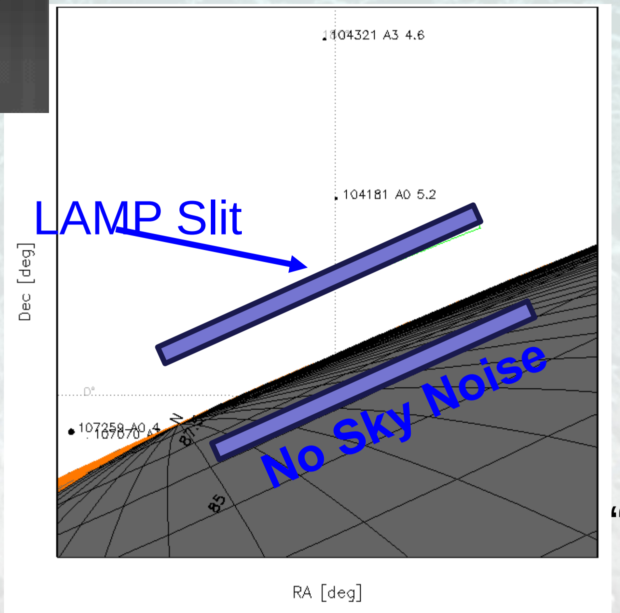
Three Modes of LAMP Atmosphere Observations

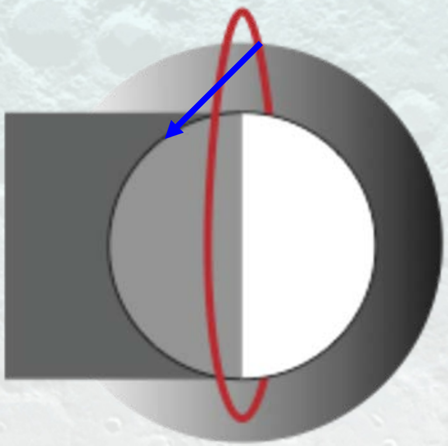


LROC imaged LADEE

http://www.lroc.asu.edu/news/index.php?/archives/857-Close-Encounter!.html

- 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

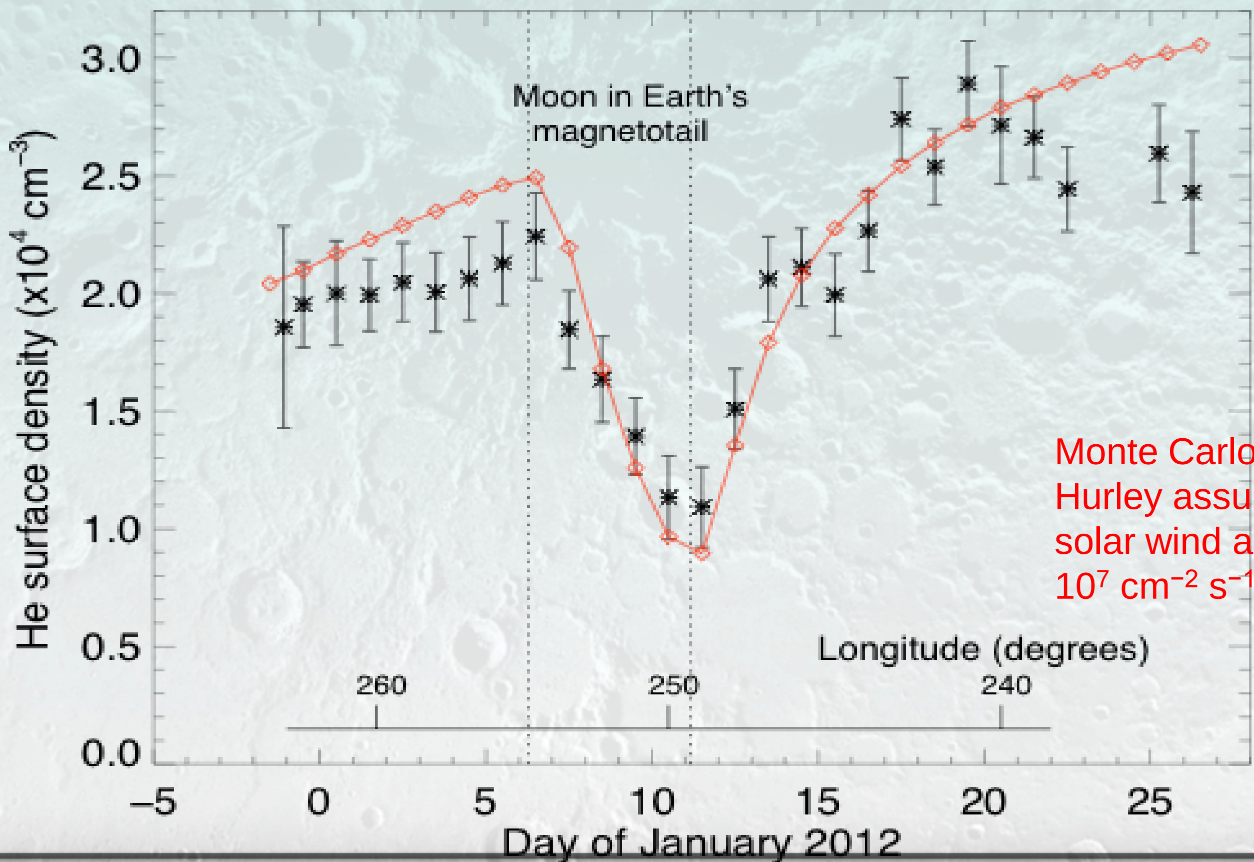




“Frozen orbit” at Twilight

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);

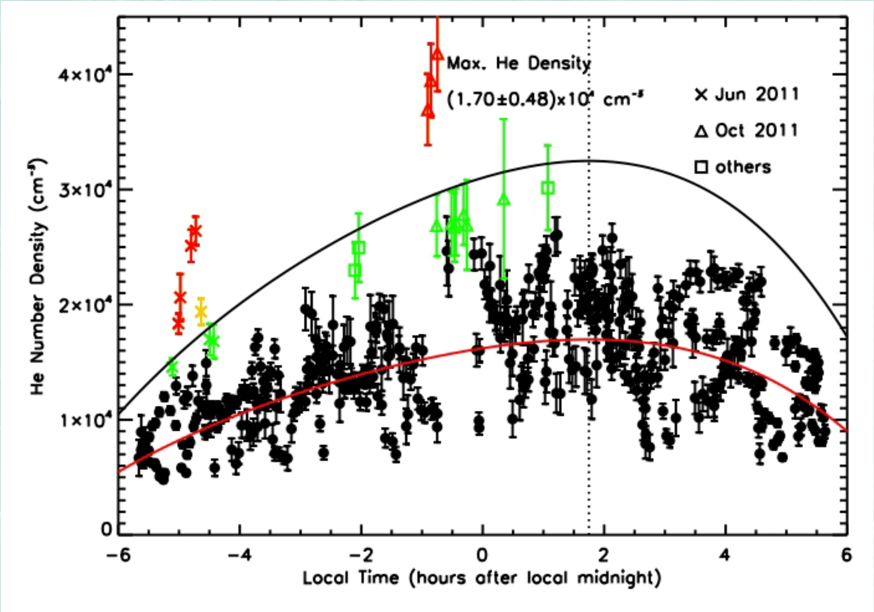


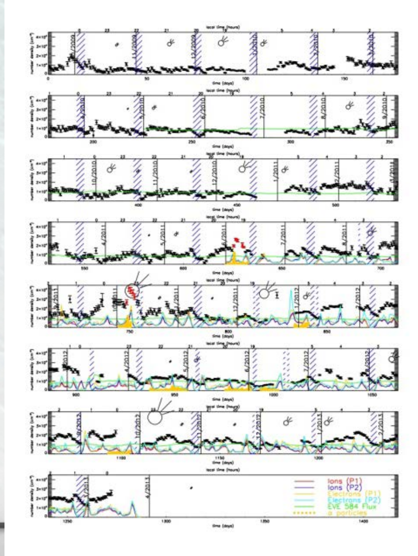
Monte Carlo model by Dana Hurley assumes a constant solar wind alpha flux of 1.2 x 10^7 cm^{-2} s^{-1}

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_{Ave} ~ 2x lower than LACE
- Sporadic ‘flares’ by >3σ
- Differences due to solar wind? Internal sources of Helium?

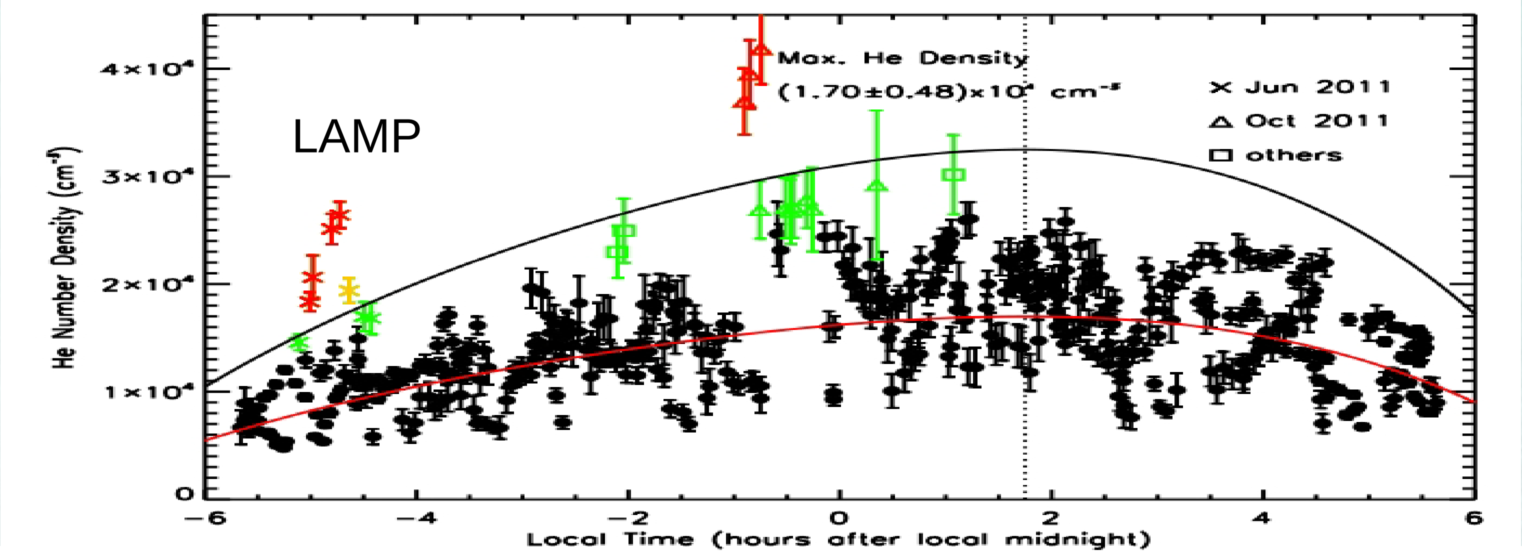
He Number Density vs. Local Time

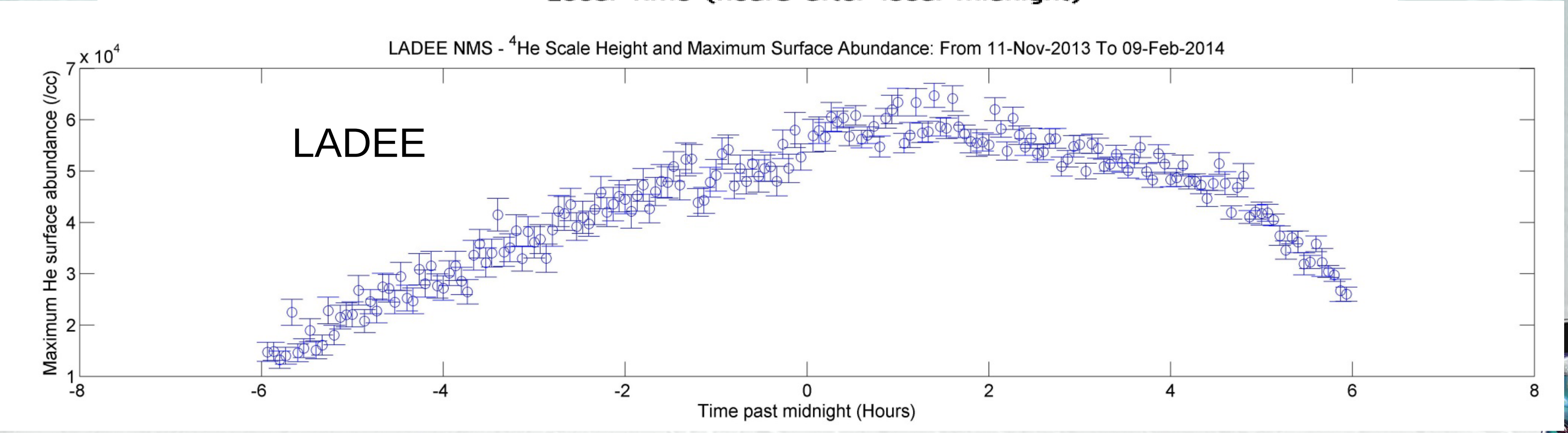




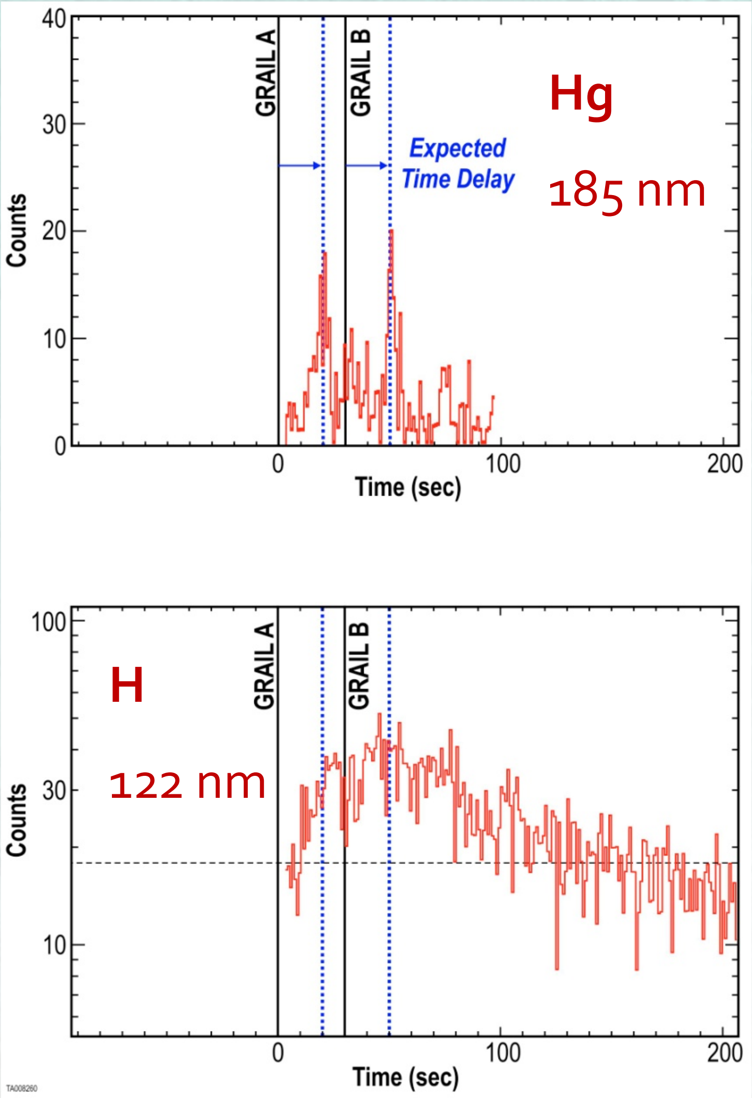
Daily He Number Density vs. Time

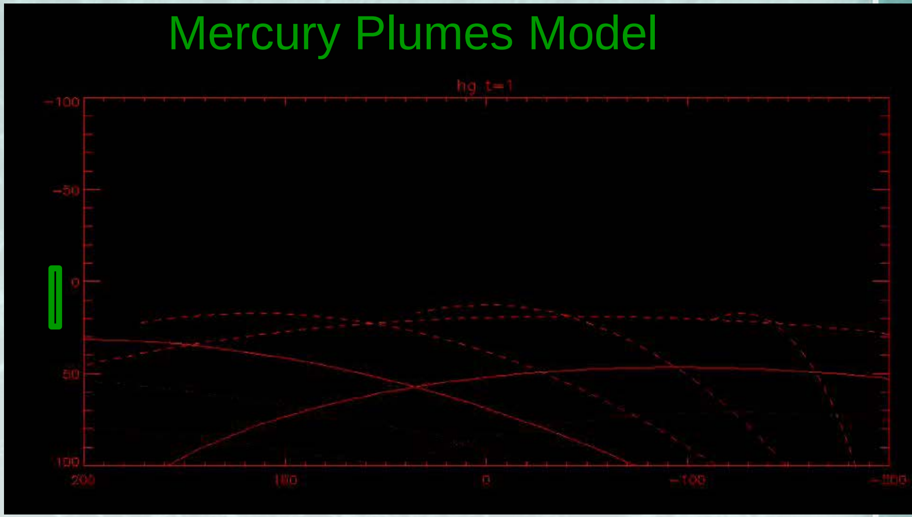
LAMP and LADEE Comparison

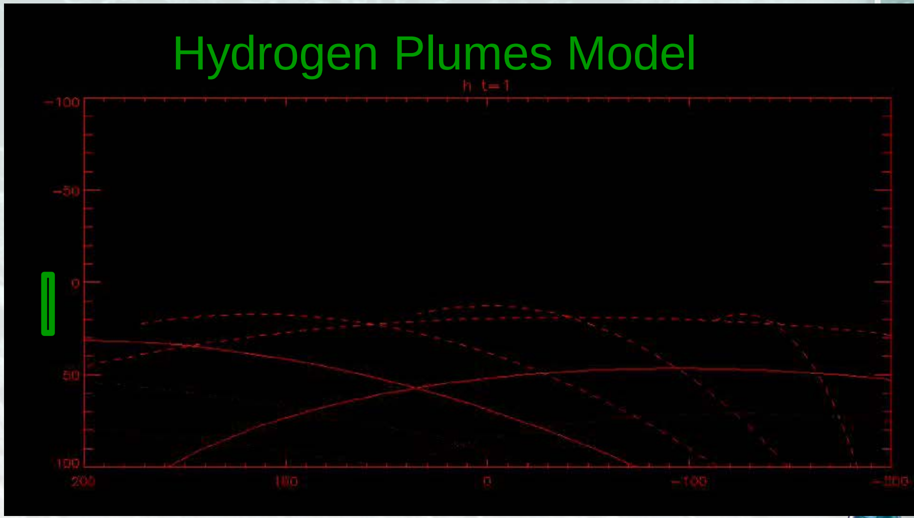




GRAIL Impact: LAMP Mercury and Hydrogen Time Evolution







LAMP light curves provide key constraints to models of impact plumes

LAMP Argon Search

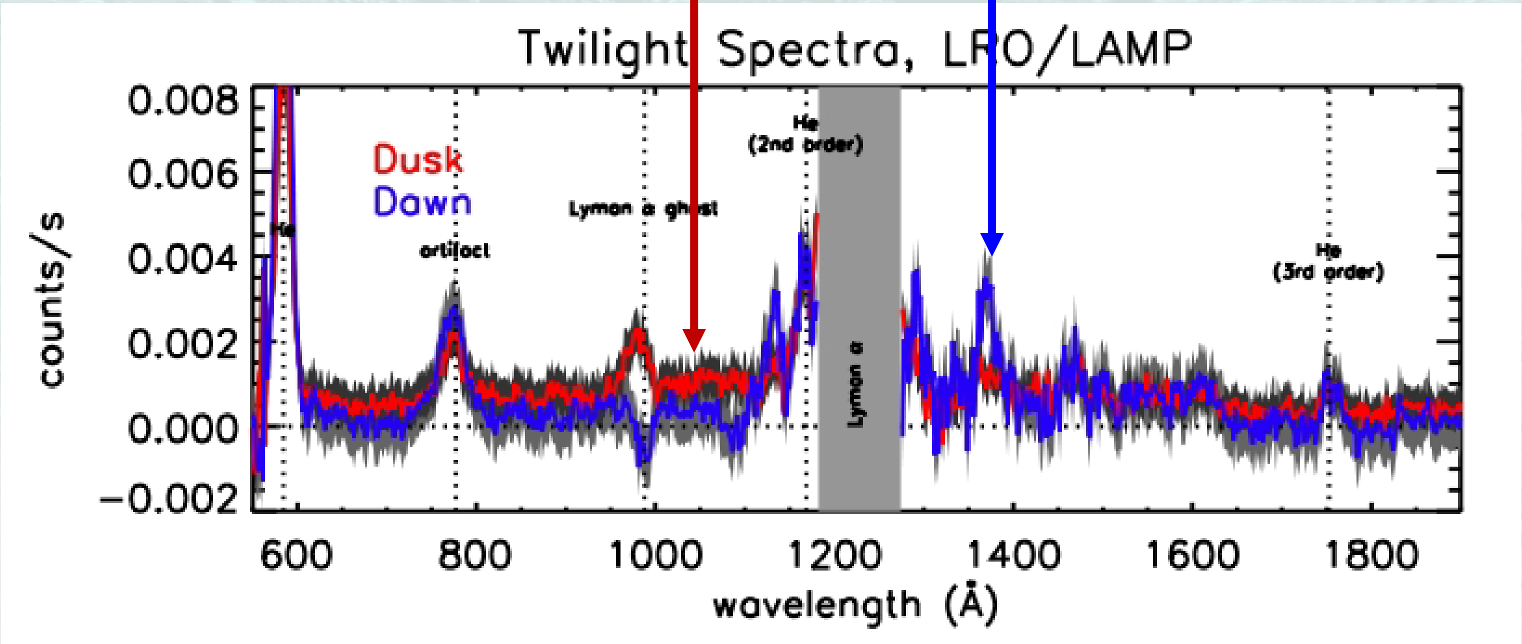
- A difficult data analysis approach, sifting through many systematic effects
- Best time to detect high levels of Ar is at **dawn and dusk**
  - LRO has passed through beta~90 ten times since launch
- Our spectrum is time averaged, **~1 hr before sunrise and after sunset**
  - From LACE, we expect ~800 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

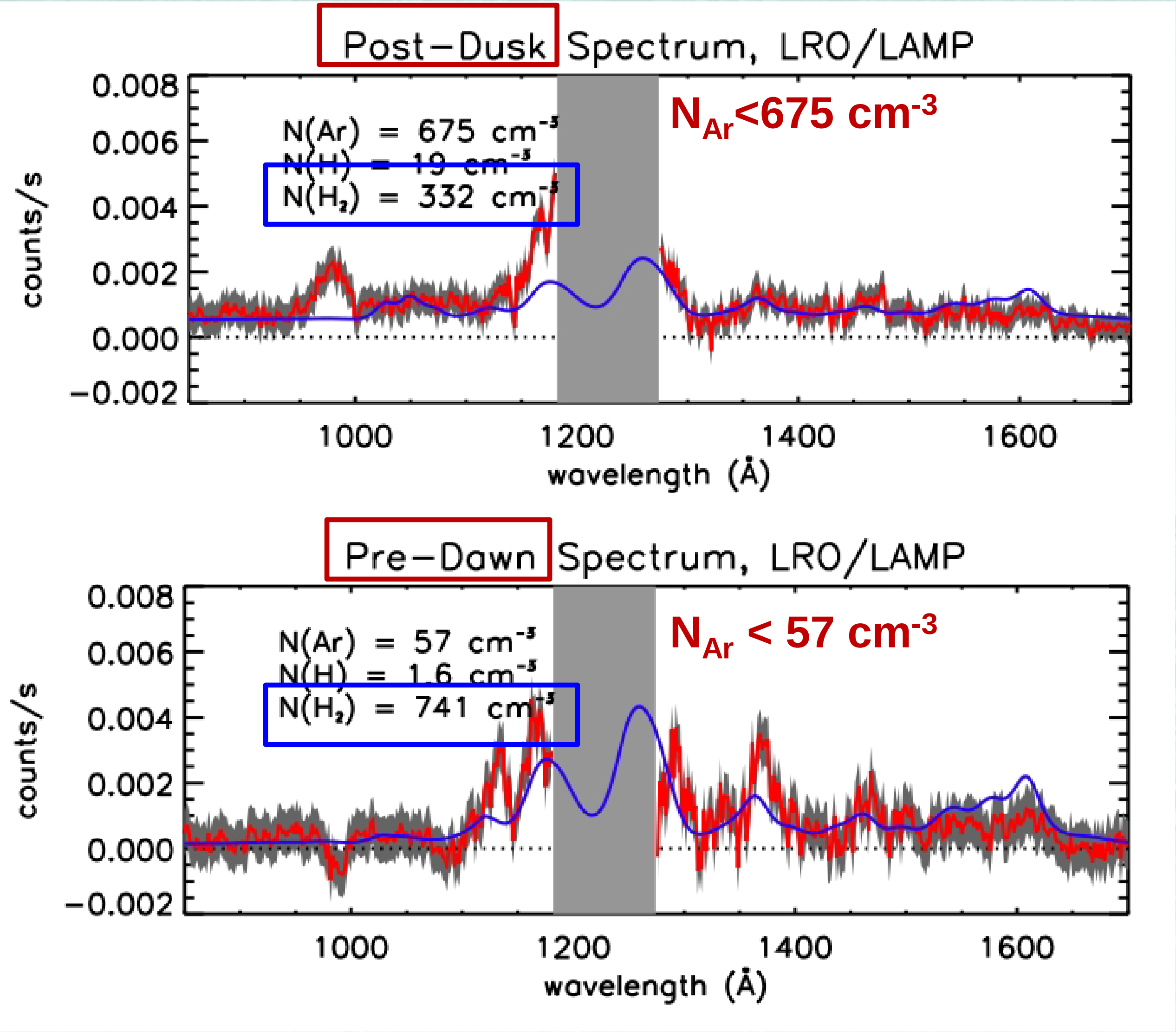
- Coadd all nadir pointed data from within 30º of the equator at post-dusk and pre-dawn.

No Argon

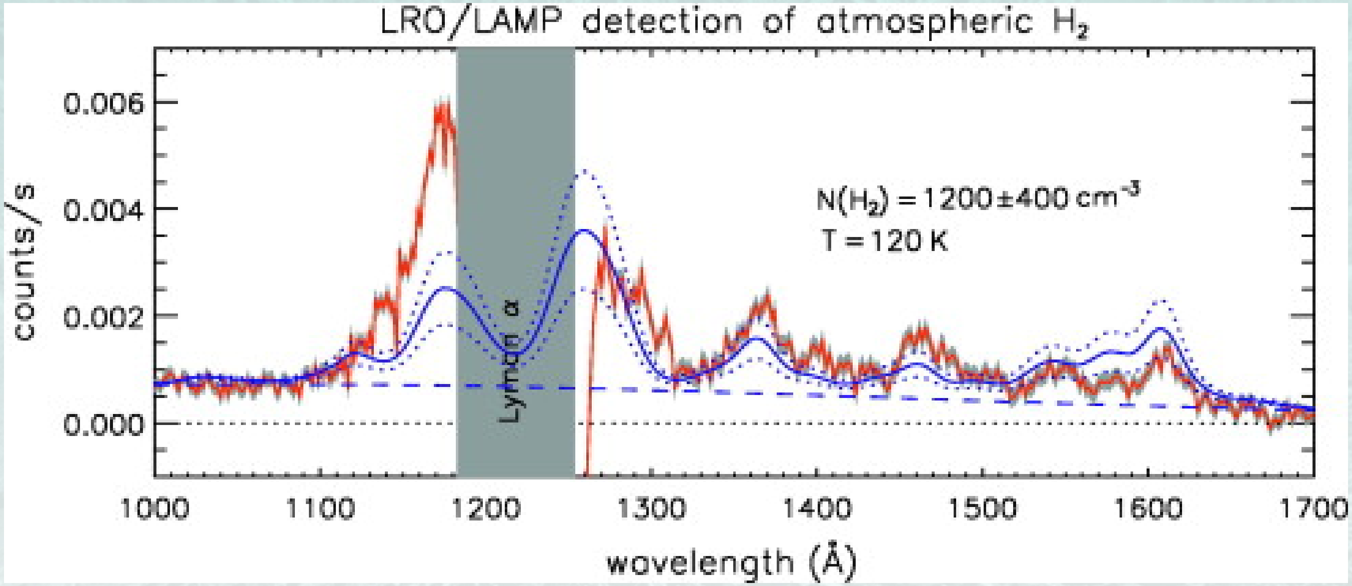
But nice H_2 quality



Tentative Ar Upper Limits

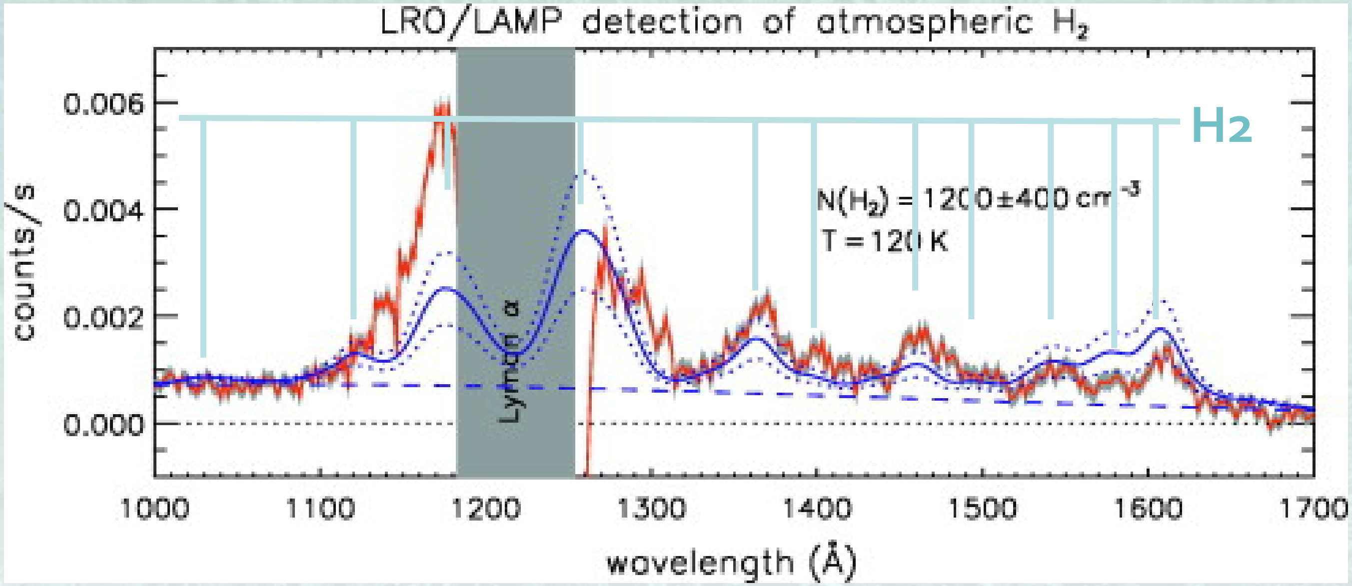


LAMP Detects Molecular Hydrogen Atmosphere

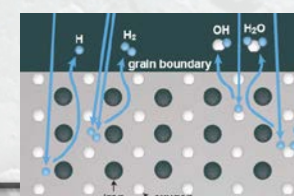


- **Stern et al., Icarus, 2013**
- Average “Twilight” Observation Residual: red, Fluorescence model: blue

LAMP Detects Molecular Hydrogen Atmosphere



- **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_2O



LAMP Atmosphere Upper Limits: Orders of Magnitude Improved

Table 1
The measured upper limits for 27 species.

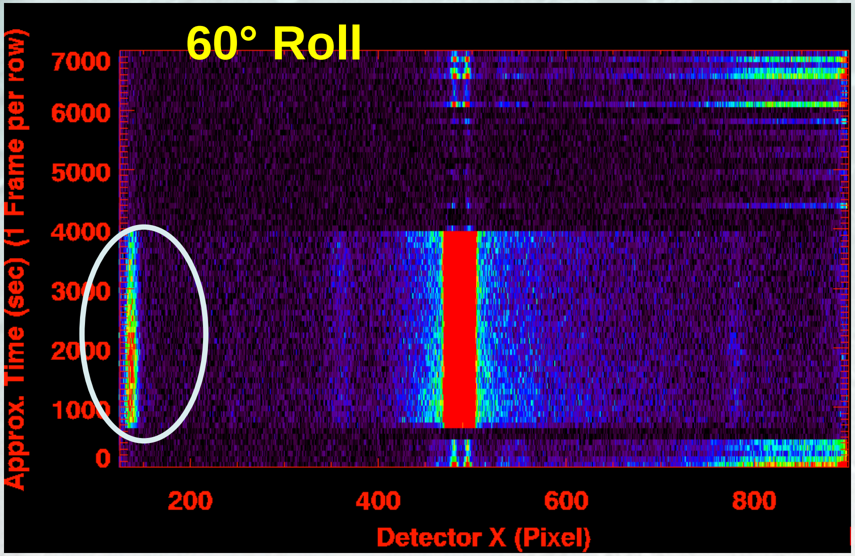
Species	Wavelength (Å)	g-Factor (s^{-1})	LAMP upper limits: Brightness (μRayleighs)	LAMP upper limits: Surface density (cm^{-3})	LADEE	Previous upper limits: Surface density (cm^{-3})	Ratio (previous/current)
H	1025.7	4.3×10^{-6}	460	24	LADEE	<17[a]	0.71
B	1825.7	1.0×10^{-4}	86	0.46		None known	∞
C	1656.9	2.2×10^{-5}	56	1.6		<200[a]	125
C^+	1335.7	4.4×10^{-5}	47	0.63		None known	∞
N	1135.0	1.4×10^{-7}	66	340		<600 (2σ)[b]	1.8
N^+	1085.7	1.2×10^{-6}	220	130		None known	∞
O	1304.9	8.9×10^{-6}	58	5.4	261	<500[a]	93
O^+	834.5	5.8×10^{-7}	480	680		None known	∞
Ne[c]	630.5	2.5×10^{-7}	1100	4400	*NMS	8×10^{4}[d]	18
Mg	1827.9	3.5×10^{-5}	87	3.4	2.5	<6000 (5σ)[e]	1800
Al	1766.4	2.2×10^{-4}	150	1.1	*NMS	<55 (5σ)[f]	50
Si	1845.5	1.8×10^{-4}	91	0.90	<50	<48 (5σ)[a]	53
P	1775.0	5.6×10^{-5}	110	4.2		None known	∞
S	1807.3	7.3×10^{-5}	80	2.3		<150[a]	65
Cl	1335.7	8.2×10^{-6}	47	15		None known	∞
Ar	1048.2	5.3×10^{-8}	420	2.3×10^{4}		3.5×10^{4}	1.5
Ca	1883.2	1.8×10^{-5}	89	16	<37	<1 (5σ)[a]	0.06
Sc	1744.7	2.5×10^{-5}	150	24		None known	∞
Mn	1785.3	5.3×10^{-6}	68	78		None known	∞
Fe	1851.7	1.4×10^{-5}	98	45		<380 (5σ)[a]	8.4
Co	1822.4	1.5×10^{-5}	87	41		None known	∞
Zn	1589.6	4.2×10^{-6}	103	220		None known	∞
As	1890.4	9.6×10^{-4}	103	1.4		None known	∞
Xe	1469.6	2.1×10^{-6}	100	3000		<3000[a]	1.0
Au	1879.8	2.4×10^{-5}	110	1100		None known	∞
Hg	1849.5	7.0×10^{-4}	97	39		None known	∞
CO	1510	1.9×10^{-7}	77	710		<1.4×10^{4}[a]	20

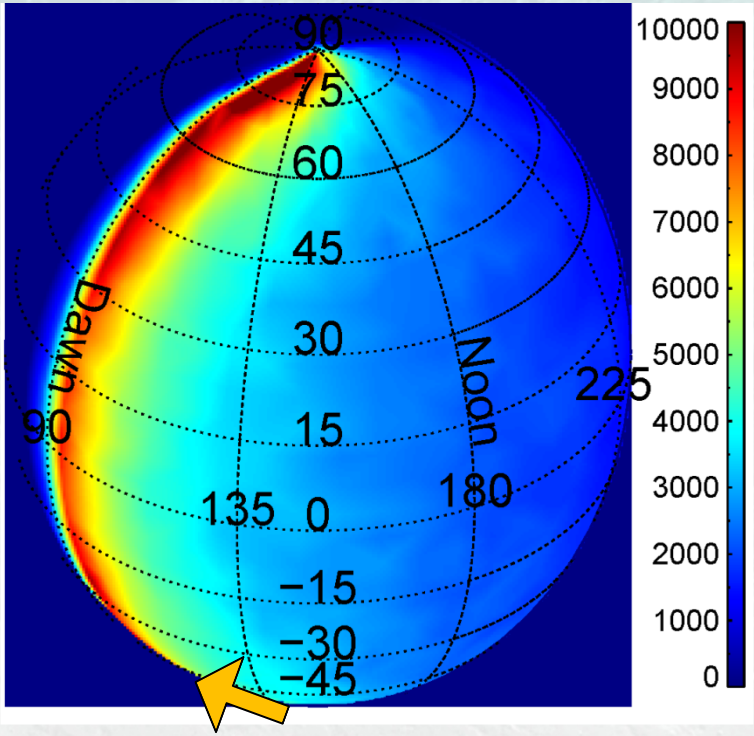
- **Cook et al. *Icarus*, 2013**
- Important constraints for exosphere models
- We're comparing notes with LADEE NMS & UVS

- 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 (~260 cm^{-3})
  - Sifting out far-UV Earthshine signals to improve SNR
  - Another important water/OH product to understand

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 an other features is ongoing





Grava et al., 2014

ESM1 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 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 H_2 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

Backup

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 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 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

LAMP ESM1 Plans

Operational Requirements

- 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.

LAMP ESM1 Achievements
Operational Requirements

- 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~~
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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

Subject	Title	Authors	Status
LAMP Instrument	LAMP: The Lyman Alpha Mapping Project on NASA's Lunar Reconnaissance Orbiter Mission	Gladstone et al.	*Space Sci. Rev.,* 150, 161-181, 2010
LCROSS Results	LRO-LAMP Observations of the LCROSS Impact Plume	Gladstone et al.	*Science*, 330, 472-476, 2010
LCROSS Lightcurves	Modeling of the Vapor Release from the LCROSS Impact: II. Observations from LAMP	Hurley et al.	*JGR-E*, 117, E00H07, 2012
PSR Results	LAMP Far-Ultraviolet Spectra of the Moon's PSRs	Gladstone et al.	*JGR-E*, 117, E00H04, 2012
PSR Results	2D Distribution of Volatiles in PSRs	Hurley et al.	*GRL*, 39, L09203, 2012
IPM Results	Lyman-α Models for LRO-LAMP Based on MESSENGER-MASCS and SOHO-SWAN	Pryor et al.	*ISSI IPM Book*, 2013
Dayside Spectra	The Lunar Far-UV Albedo: Indicator of Hydration and Weathering	Hendrix et al.	*JGR-E , 117, E12001,* 2012
Atmosphere	Lunar atmospheric helium detections by the LAMP UV spectrograph on the LRO	Stern et al.	*GRL*, 39, L12202, 2012
Atmosphere	Variability of the Lunar Helium Atmosphere	Feldman et al.	*Icarus*, 221, 854-858, 2012

LAMP ESM1 Papers

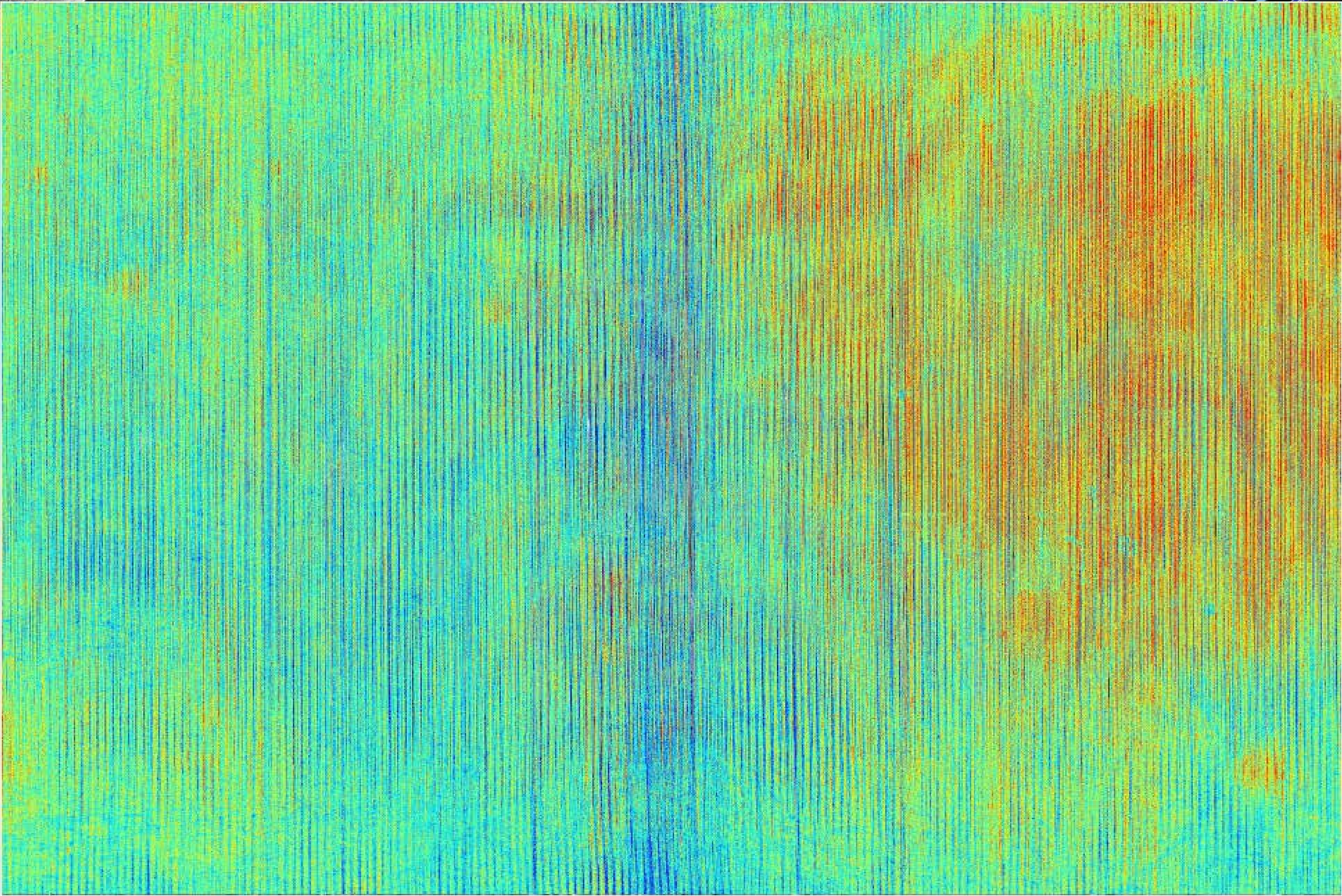
Subject	Title	Authors	Status
Atmosphere	New Upper Limits on Numerous Atmospheric Species in the Native Lunar Atmosphere	Cook et al.	*Icarus*, 225, 681-687, 2013
Atmosphere	Lunar Atmospheric H_2 Detections by the LAMP UV Spectrograph on the Lunar Reconnaissance Orbiter	Stern et al.	*Icarus, 226, 1210-1213*, 2013
Atmosphere	Sporadic Increases In Lunar Atmospheric Helium Detected by LRO-LAMP	Cook & Stern	*Icarus, 236*, 48-55, 2014
Atmosphere	Search for Lunar Horizon Glow with LAMP on the Lunar Reconnaissance Orbiter	Feldman et al.	*Icarus, 233*, 106-113, 2014
GRAIL Impact	LRO/LAMP Observations of the GRAIL Impact Plumes	Retherford et al.	In preparation for *JGR-Planets*
Atmosphere	Lunar Exospheric Argon Modeling	Grava et al.	*Icarus,* doi:10.1016/j.icarus.2014.09.029
Atmosphere	An analytic function of lunar surface temperature for exospheric modeling	Hurley et al.	*Icarus*, doi:10.1016/j.icarus.2014.08.043
LCROSS Lightcurves	Detailed LCROSS Light Curves Modeling	Hurley et al.	In preparation for *JGR Note*
Surface	Evidence for Exposed Water Ice in the Moon's South Polar Regions from LRO UV Albedo and Temperature Measurements	Hayne et al.	*Submitted to Icarus special issue 2014*

LAMP Papers In Prep.

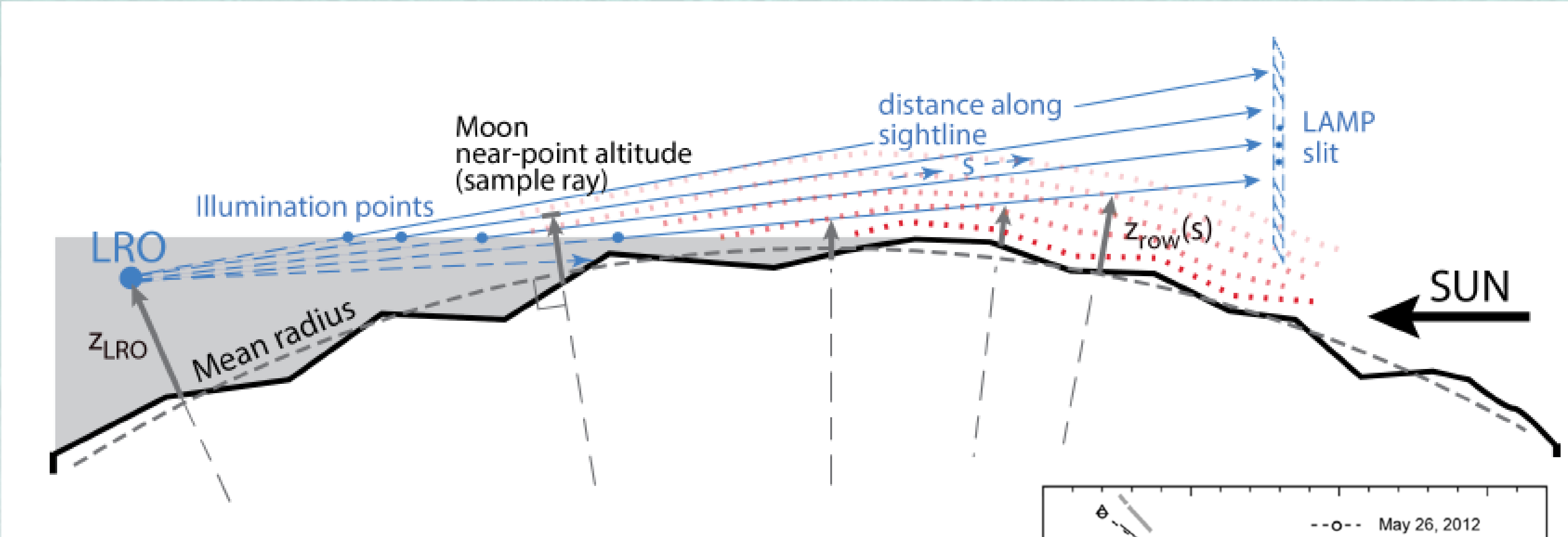
Subject	Title	Authors	Status
Polar Surface	LRO/LAMP FUV Albedo Maps	Retherford et al.	In prep. for *JGR-E*
LAMP Instrument	LRO/LAMP Calibration: I. First four years in-flight	Retherford et al.	In prep. for *JATIS*
LAMP Instrument	LRO/LAMP Calibration: II. MCP Gain Degradation Characterization	Retherford et al.	In prep. for *JATIS*
Surface	LURE Water Frost FUV Reflectance	Retherford et al.	In prep. for *GRL*
Heliophys.	LAMP Earth and Geotail Scans	Gladstone et al.	In prep.
Surface	Lunar FUV Albedo Variations: Weathering & Hydration in Regions of Interest	Hendrix et al.	Planned
Surface	Migration of OH and H2O across the lunar surface	Hurley et al.	Planned
Atmosphere	Argon Follow-up	Stern, Cook, et al.	Planned

Western Equatorial Hemisphere WAC Map matched to LAMP res.

LAMP Lya: Spectral Reversal



Exospheric Dust Upper Limits from LAMP Disk-occulting Measurements



- 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

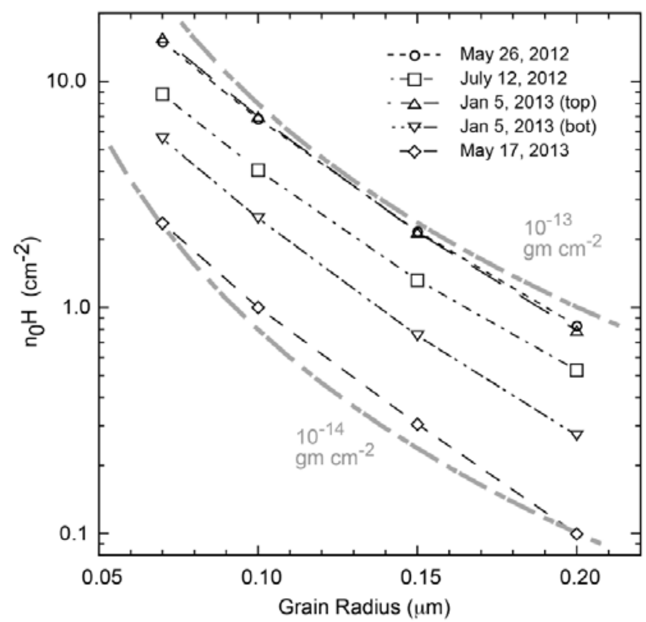
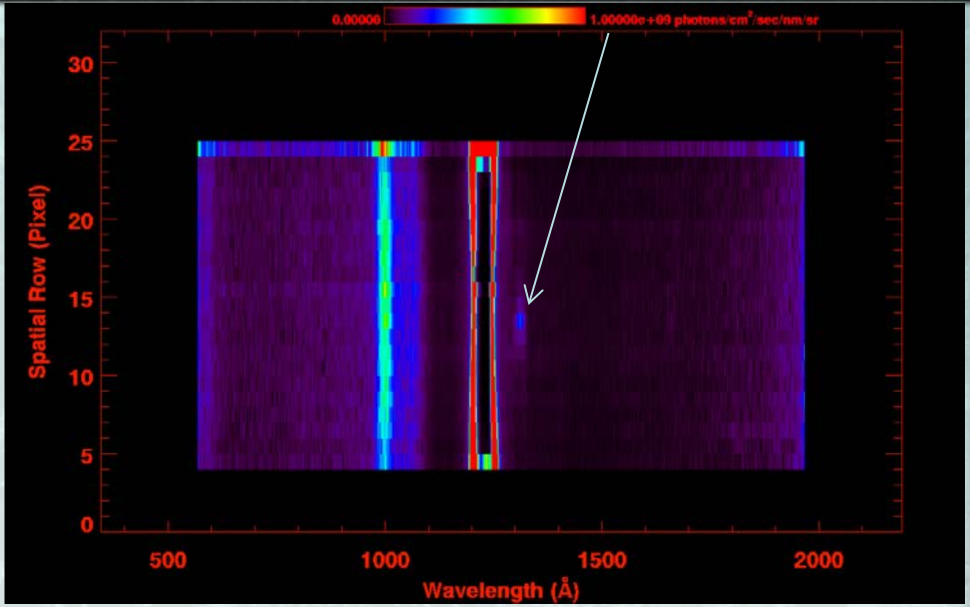
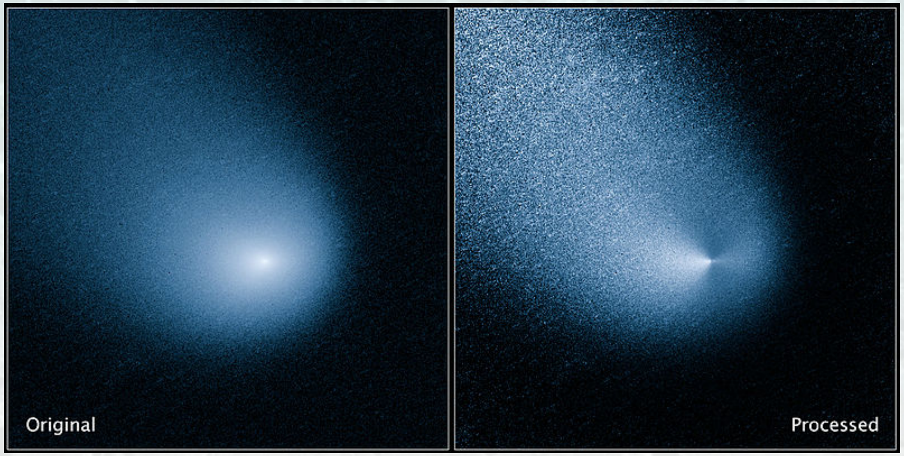


Figure 8: Summary of dust upper limit models for the LAMP observations, parameterized in terms of vertical dust abundance n_0H vs grain radius. Curves showing constant overlying dust mass (grain density = 3.0 gm cm^{-3}) have been added to the plots.

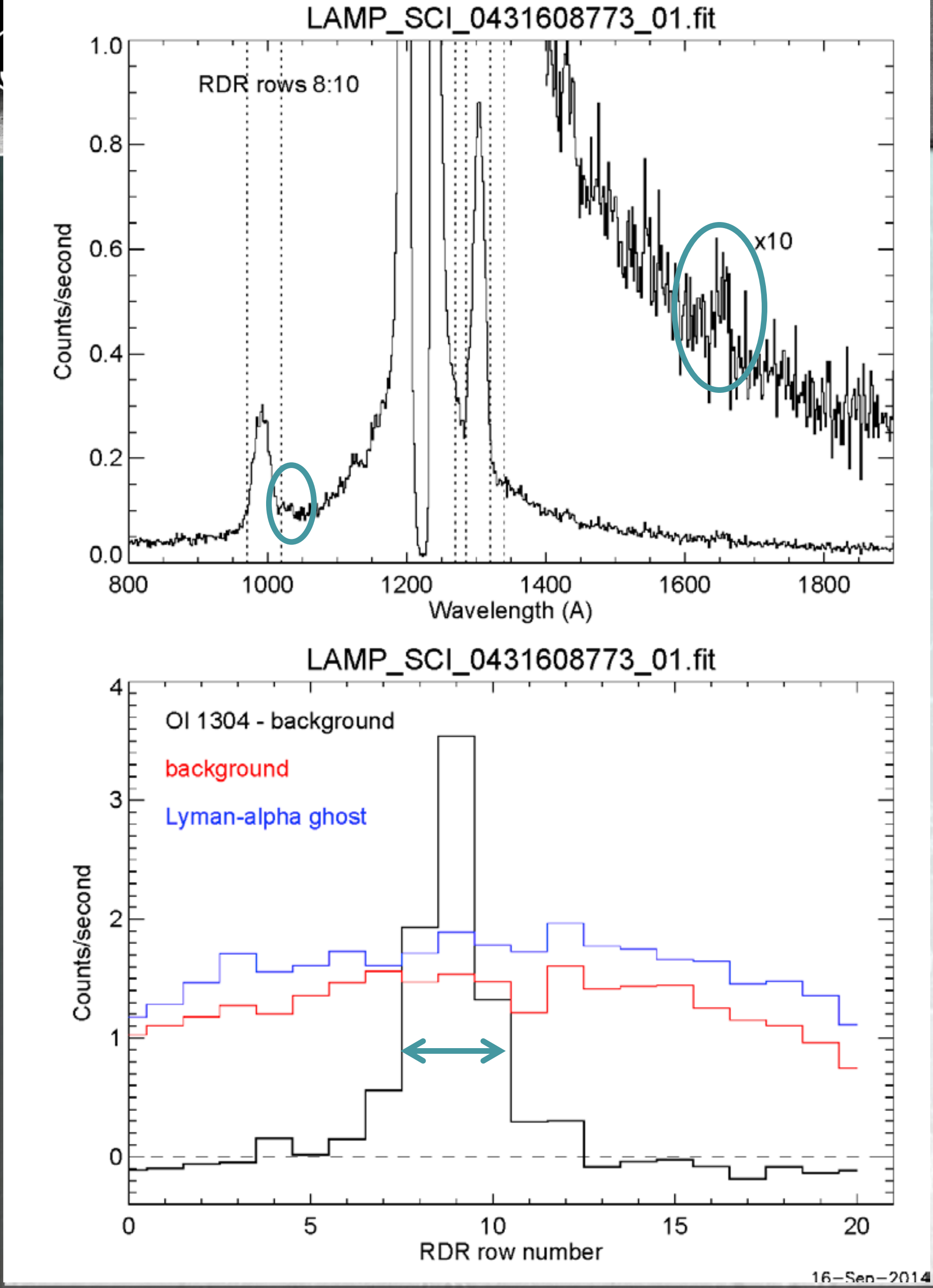
Comet C/2013A1 Siding Spring

- **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





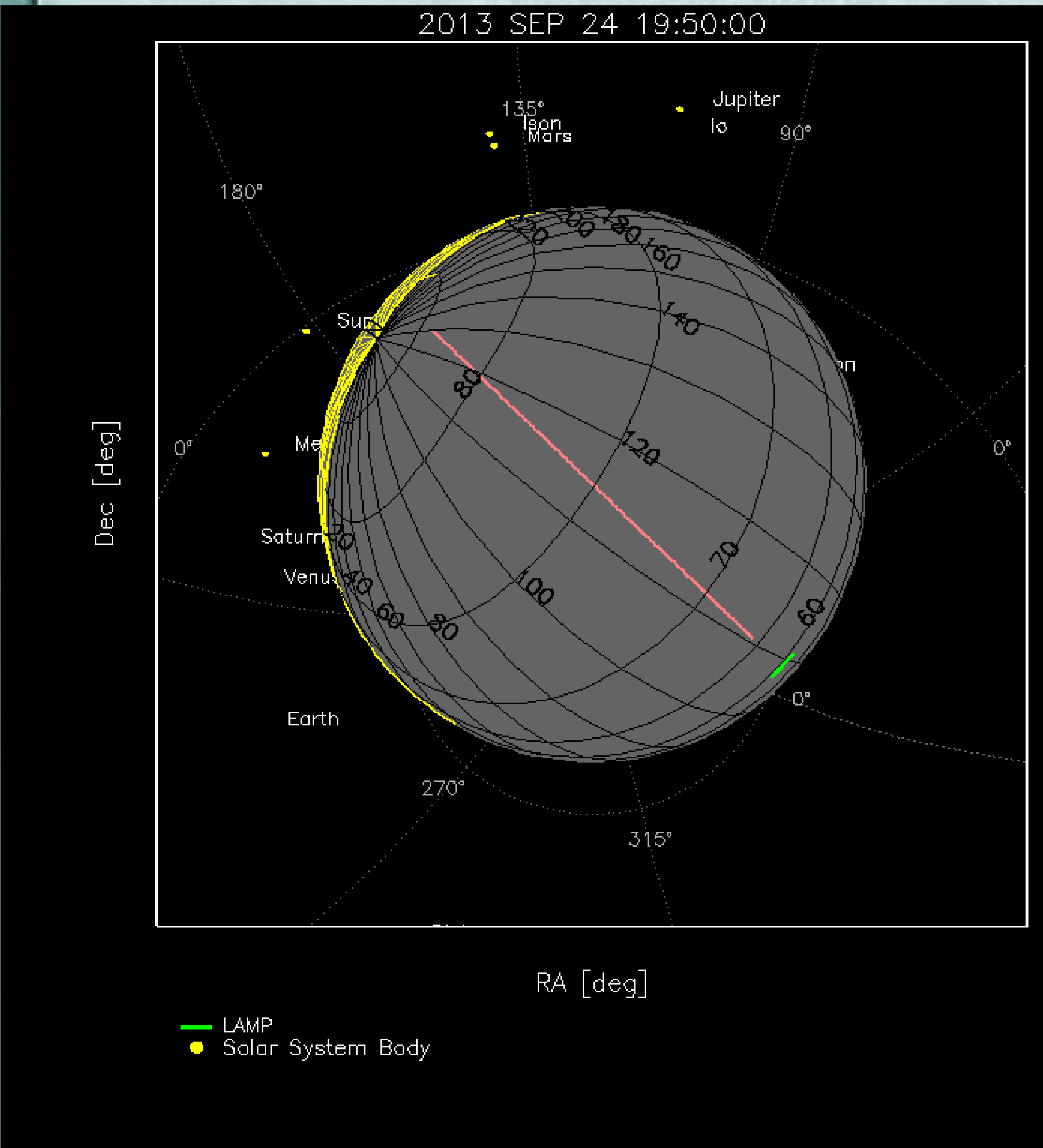
Comet C/2013A1



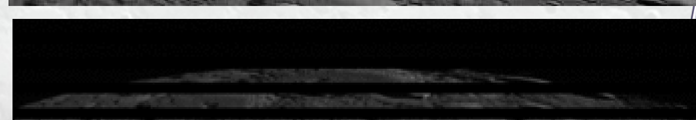
- OI 130.4 nm detected at ~0.9 counts/sec => ~0.8 R
- CI 165.7 nm also detected at ~0.01 count/sec => ~0.04 R
- Likely Ly-Beta 102.6 nm at ~0.01 count/sec => ~0.15 R

- **LAMP Imaged the Coma:** Extends spatially beyond one pixel, ~1 deg.
- The LAMP pixel of 0.3 deg translates to 700,000 km at the comet, and the OI profile is consistent with a ~1.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



Paul Hayne's Icarus Paper & LEAG Talk

- Evidence for Exposed Water Ice in the Moon's South Polar Regions from LRO UV Albedo and Temperature Measurements
  - http://www.hou.usra.edu/meetings/leag2014/pdf/3013.pdf

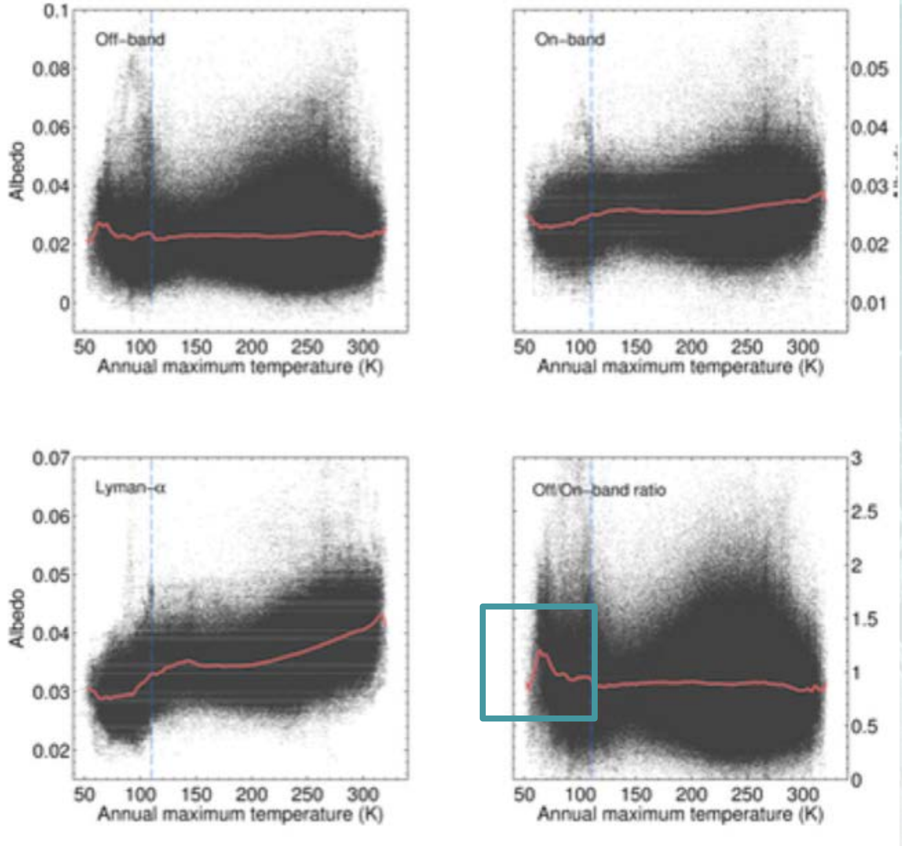


Figure 3: Ultraviolet spectral variations with temperature, for the three LAMP wavelength bands affected by the presence of

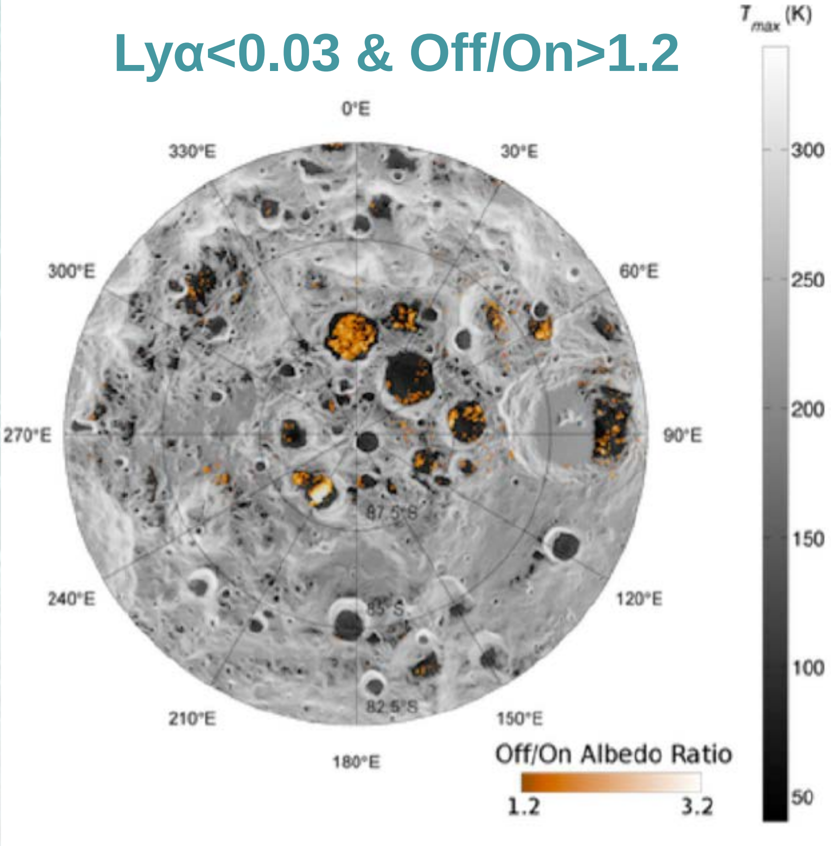


Figure 4: Distribution of exposed water frost, based on LAMP UV spectra having: a) Lyman-a albedo < 0.03, and b) off/on albedo ratio > 1.2. Note the strong correlation with the lowest temperature cold traps (grayscale indicates annual maximum temperature).

LAMP Detailed Far-UV Regional Studies

- 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