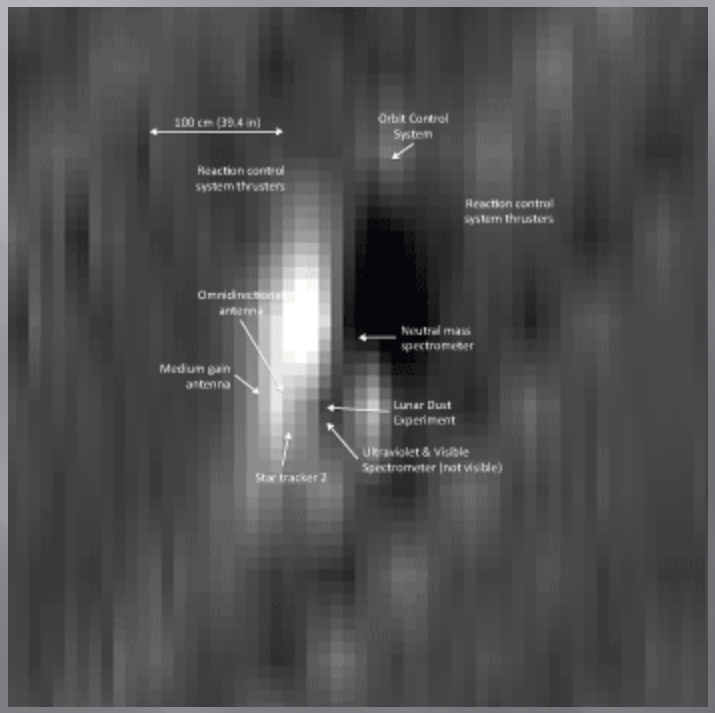
Lunar Volatile Transport in the Exosphere and from Impact Plumes: *LRO/LAMP Observing Campaigns Coordinated with LADEE*

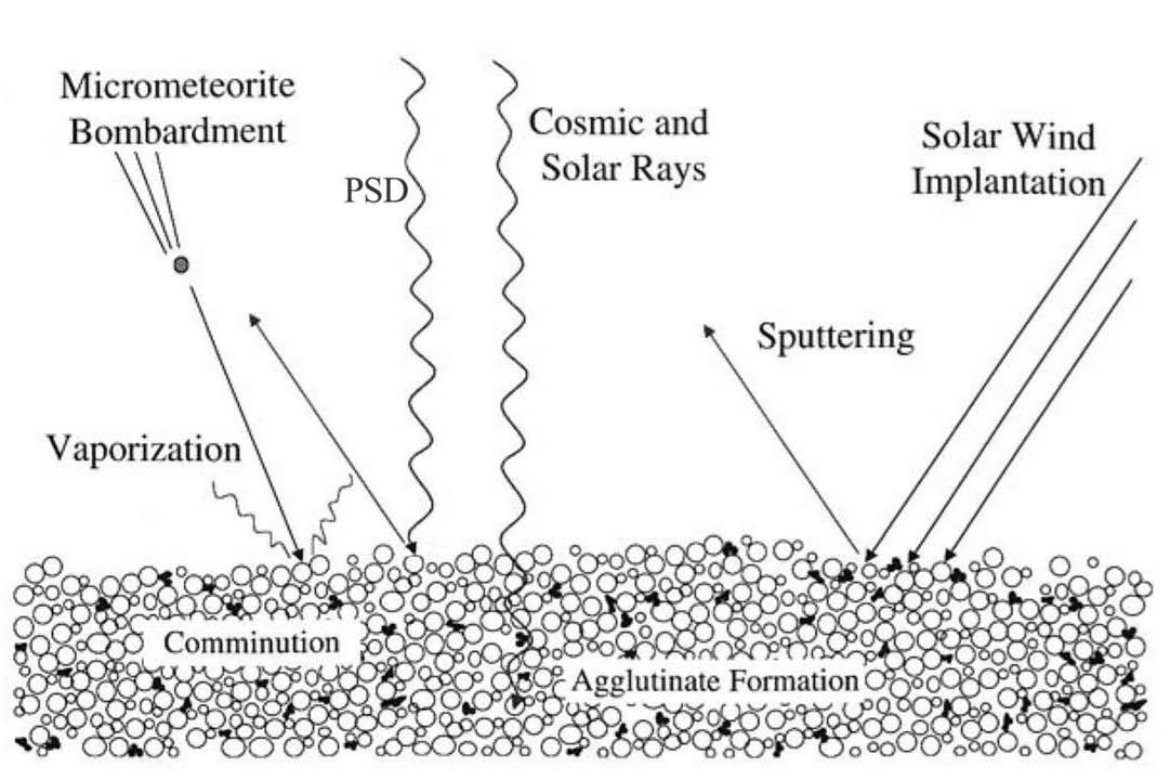


LROC imaged LADEE
http://www.lroc.asu.edu/news/index.php?/archives/857-Close-Encounter!.html

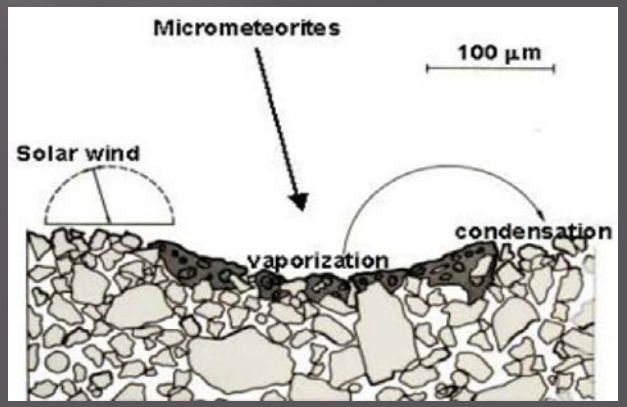
Kurt Retherford (SwRI)
Greathouse, Cook, Stern, Hurley, Gladstone, Feldman, Miles, Grava, Pryor, Stubbs, Glenar, Kaufmann, & the LRO/LAMP Team

NESF 2014

Lunar Exosphere – Surface Interaction Sources

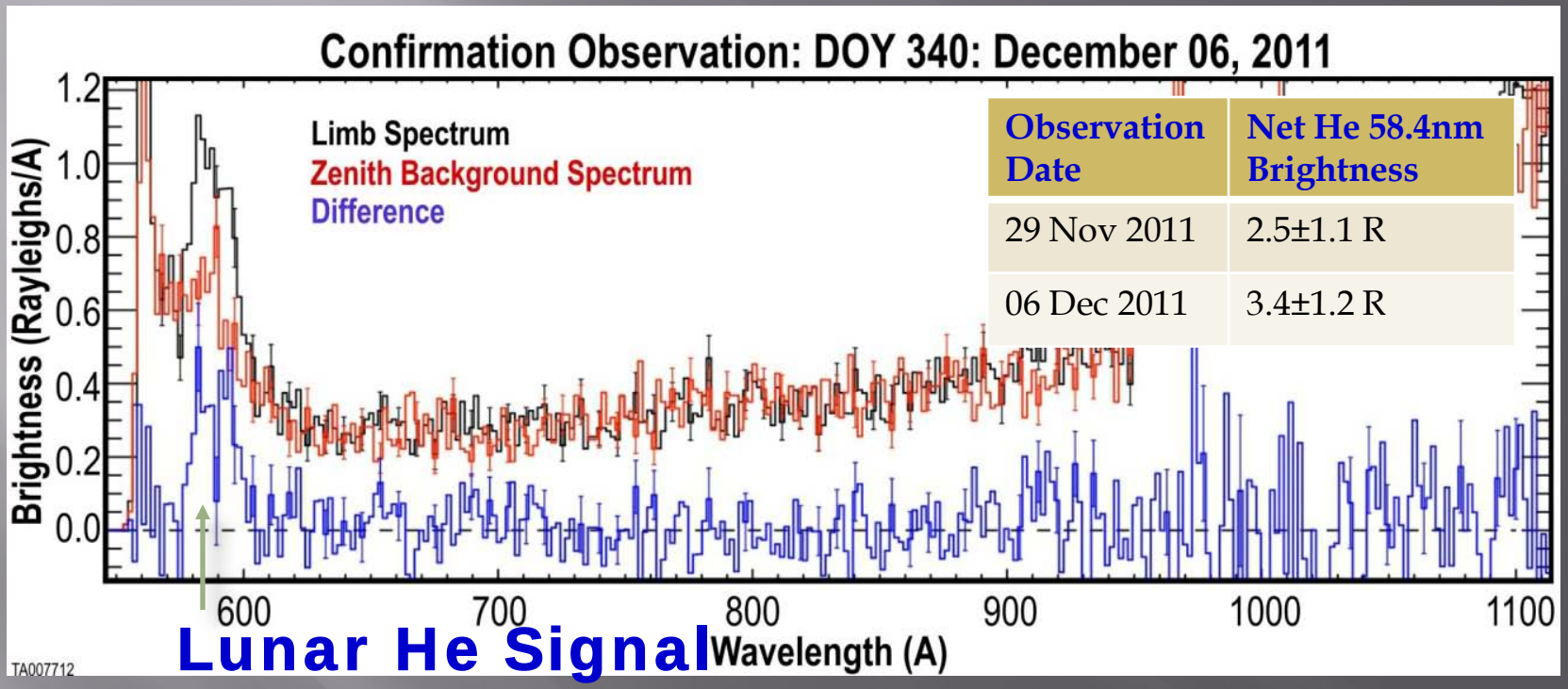


- Sources
  - Sputtering
  - Impact Vaporization
  - Photon Stimulated Desorption
  - Diffusion from Sub-surface
  - Chemical reactions
  - Other Assorted: Comets/impactors, landers, astronauts, etc.



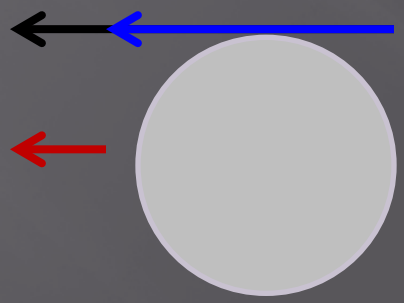
LAMP Helium Detection

- First remote detections, first since the Apollo LACE discovery of helium; Stern et al., *GRL*, 2012



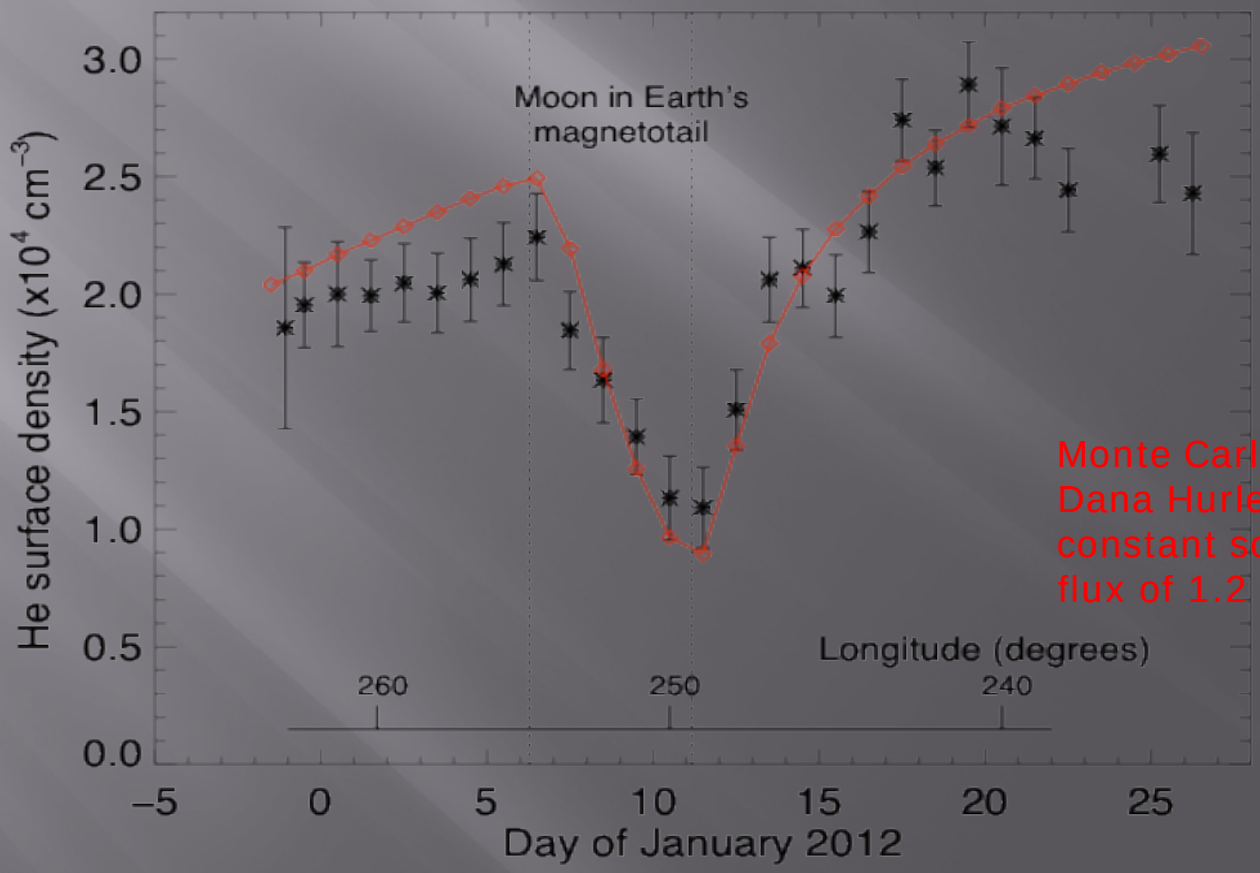
Observation Date	Net He 58.4nm Brightness
29 Nov 2011	2.5±1.1 R
06 Dec 2011	3.4±1.2 R

Dedicated LRO limb-pointings probed tangential columns across the poles (black) and sky background (red) when pointed zenith at equator. The near-moon He is their difference (blue).



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);

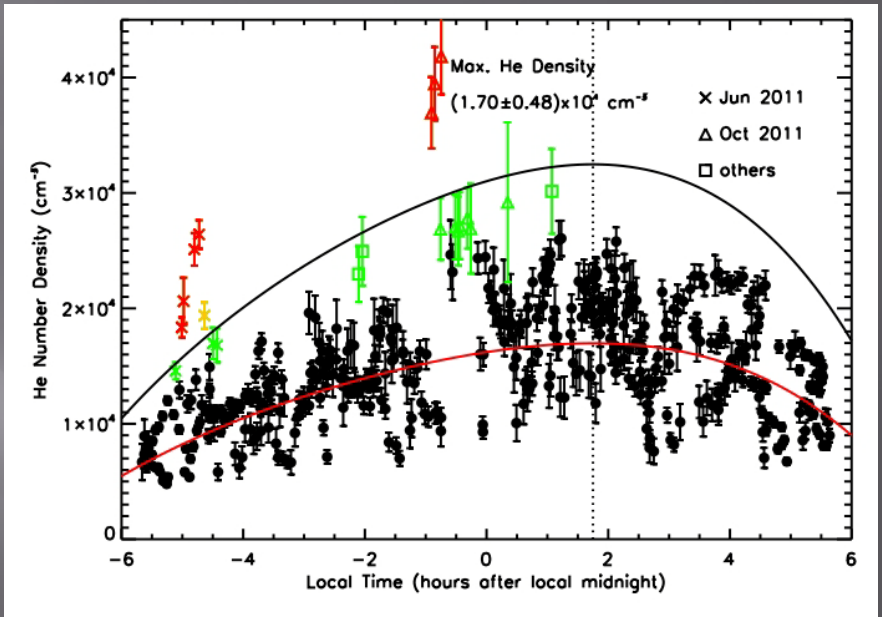


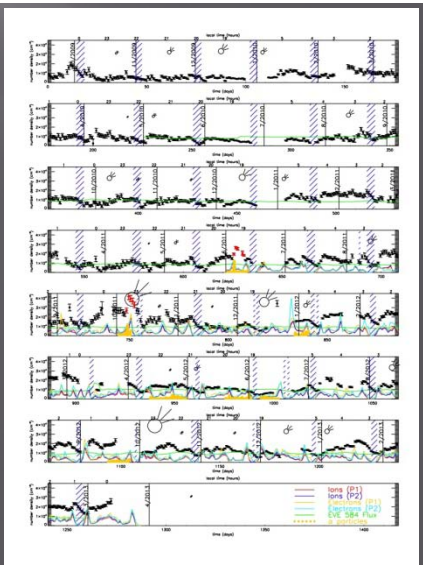
Monte Carlo model by Dana Hurley assumes a constant solar wind alpha flux of 1.2 x 10^7 cm^{-2} s^{-1}

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

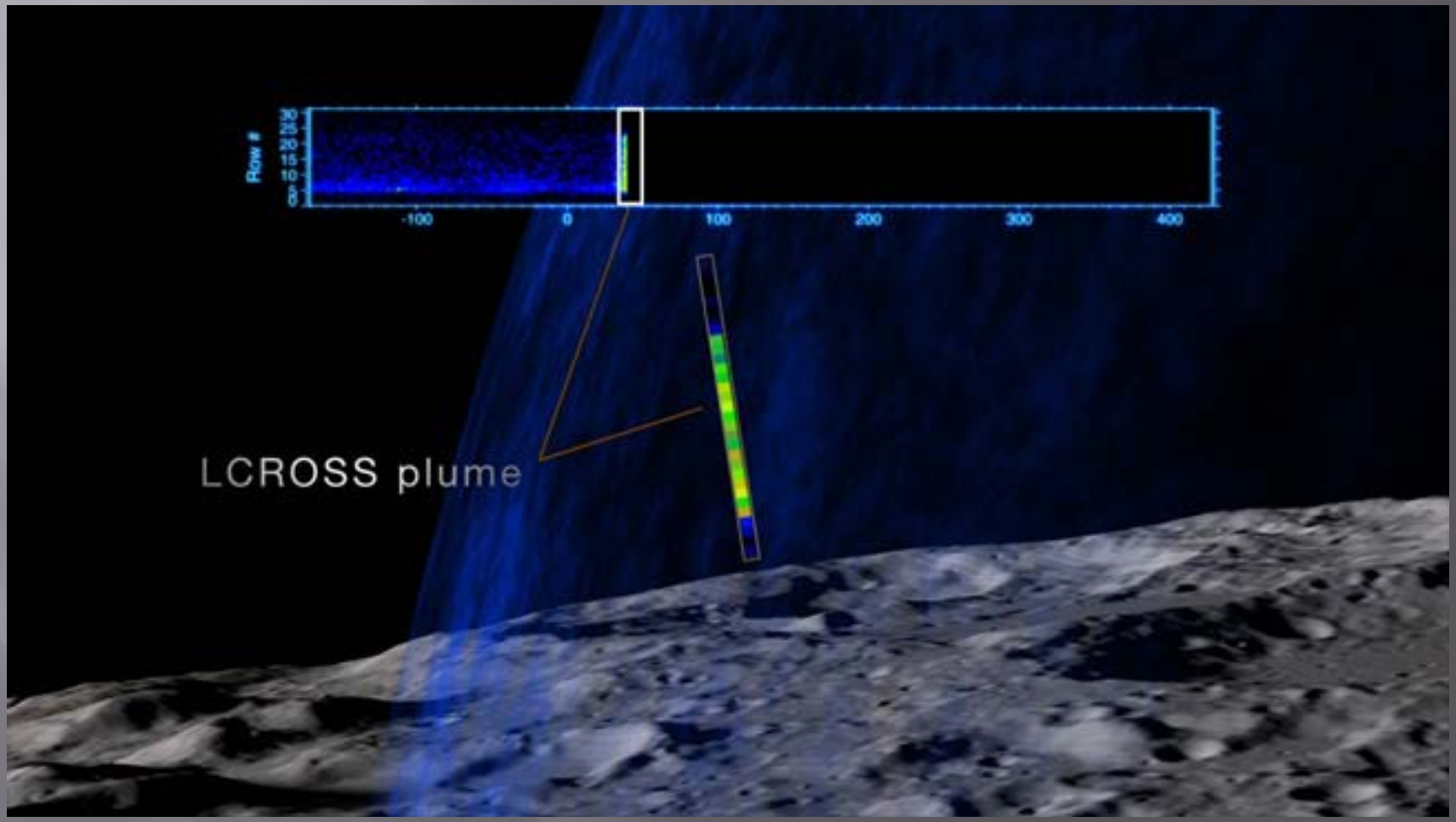




Daily He Number Density vs. Time

LAMP Impact Plume Data

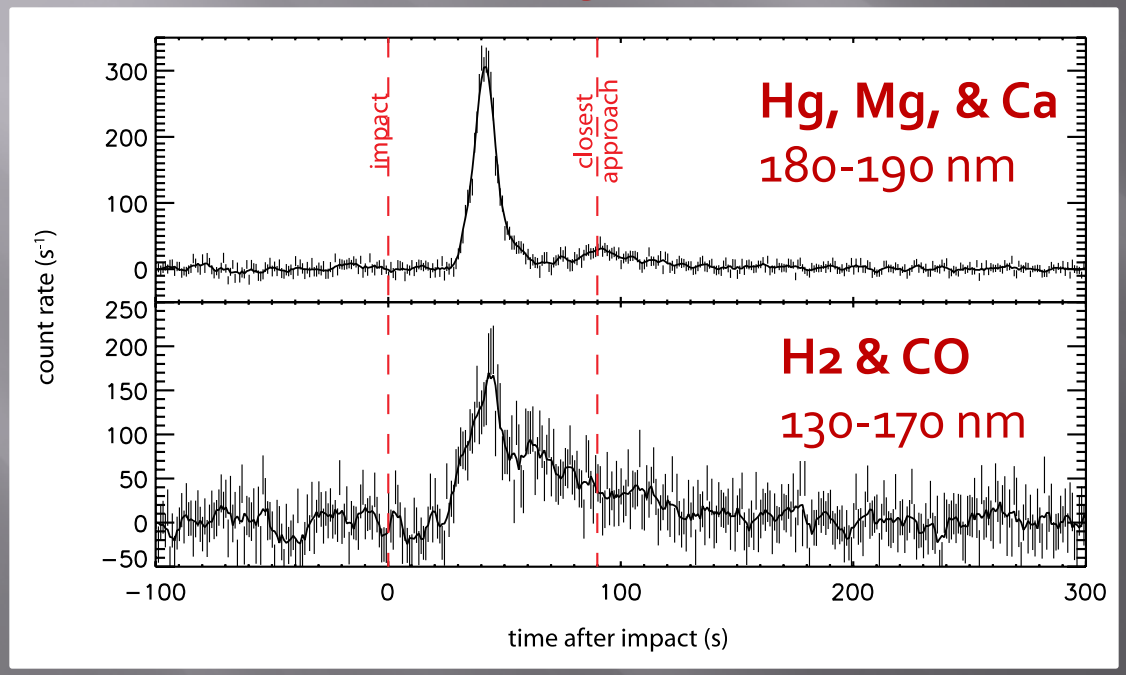
- **LAMP's LCROSS & GRAIL light curves are a rich data set for constraining detailed plume models**



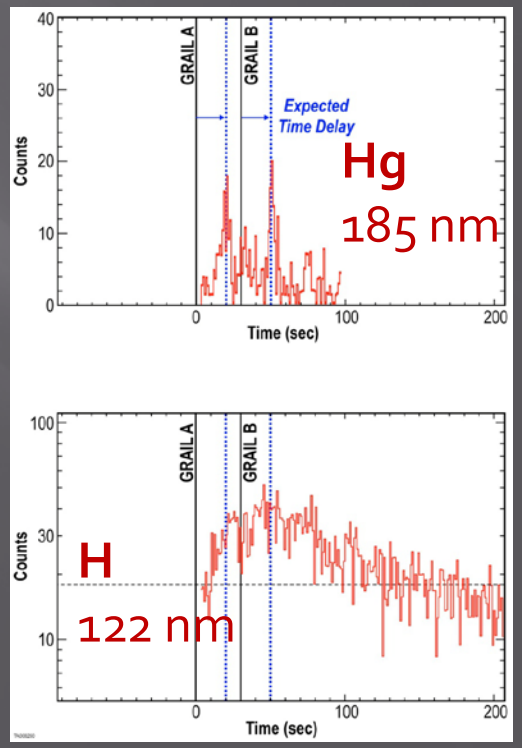
LCROSS and GRAIL Mission Impacts

- LAMP observed both LCROSS and GRAIL impacts.
- LADEE impact observation was planned but time guessed wrong

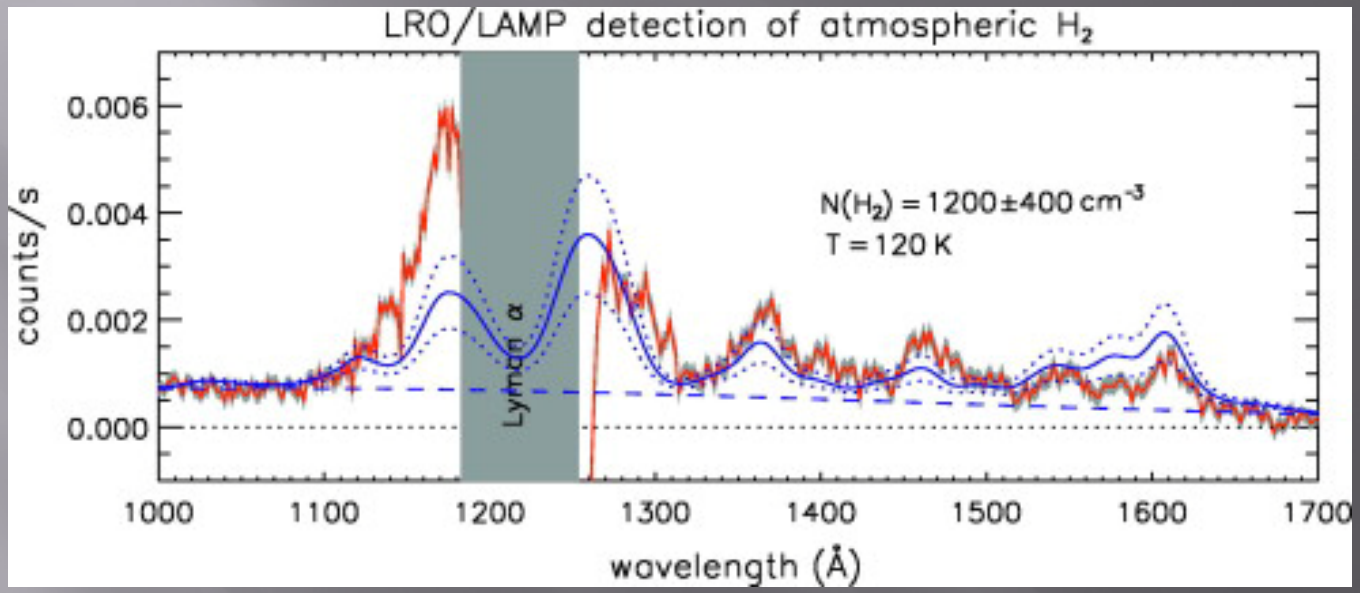
LCROSS Lightcurves



GRAIL A+B Lightcurves

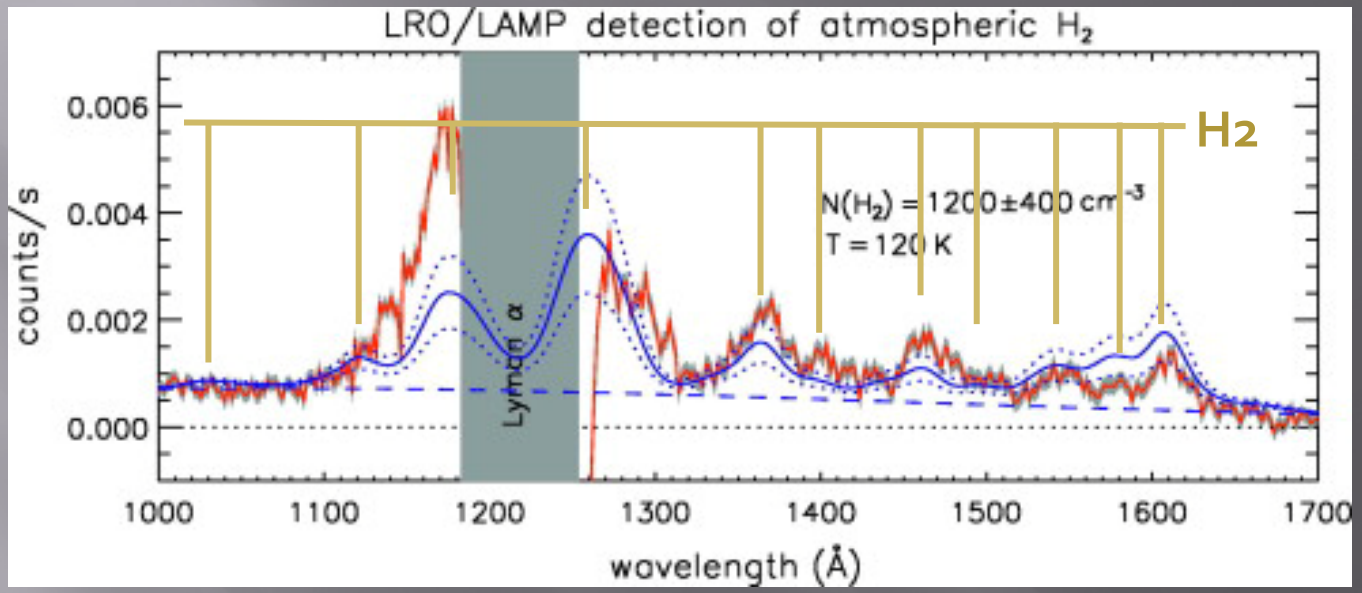


LAMP Detects Molecular Hydrogen Atmosphere

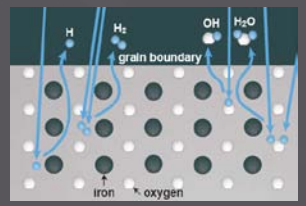


- Stern et al., Icarus, 2013
- Average “Twilight” Observation Residual: red, Fluorescence model: blue

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			Previous upper limits	Ratio (previous/current)
			Brightness (μRayleighs)	Surface density (cm^{-3})		Surface density (cm^{-3})	
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		$<1.4 \times 10^{4}$[a]	20

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

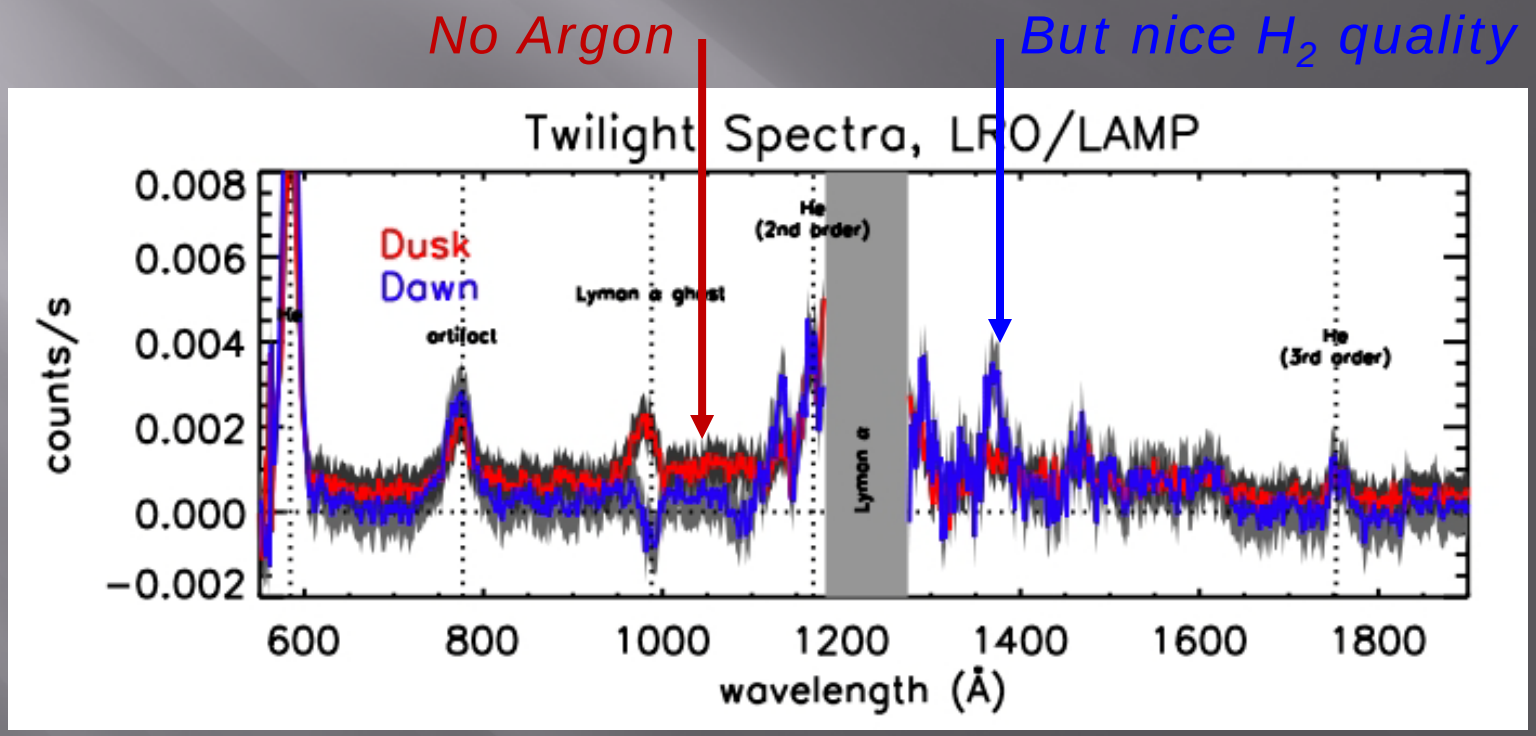
- Stay tuned for neutral atomic oxygen update in LRO ESM2
  - New energetic neutral atom imaging results for sputtered O show 11-14 cm^{-3} (Vorburger et al., JGR, 2014), within just x2 of LAMP
  - LADEE-UVS detection of O as well (~260 cm^{-3})
  - Sifting out far-UV Earthshine signals to improve SNR
  - Another important water/OH product to understand

LAMP Argon Search

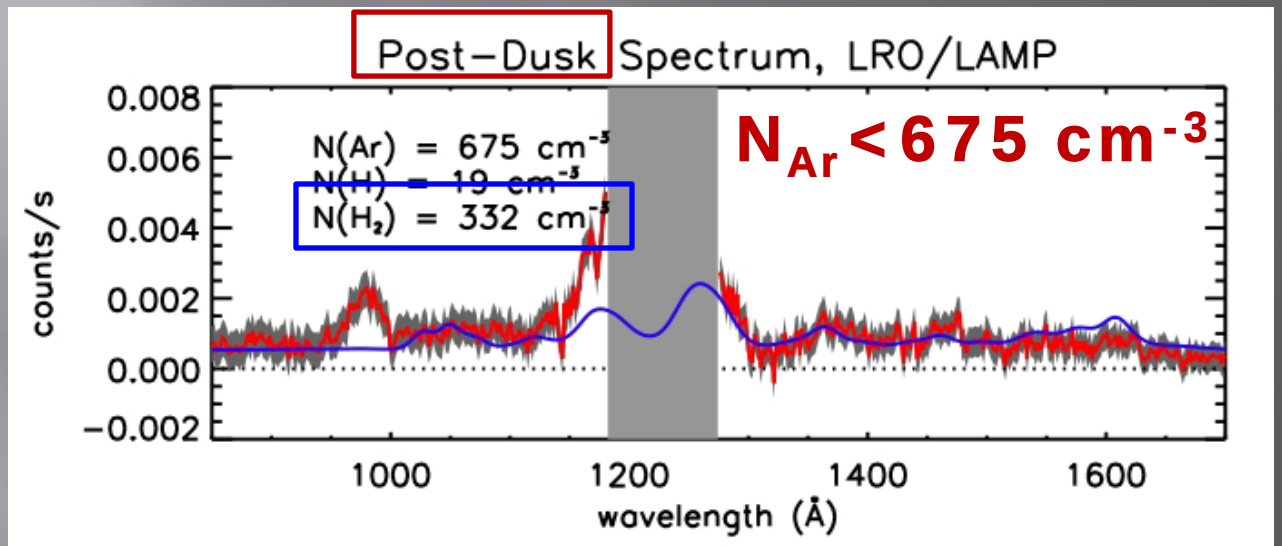
- A difficult data analysis approach, sifting through many systematic effects
- We've backed away from the analysis shown at LPSC 2014 by Cook et al. with a tentative argon detection
- Best time to detect high levels of Ar is at **dawn and dusk**
  - LRO has passed through beta~90 ten times since launch
- Our spectrum will be 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., *submitted to Icarus*, (2014) predicts greatest numbers near equator at post-dusk

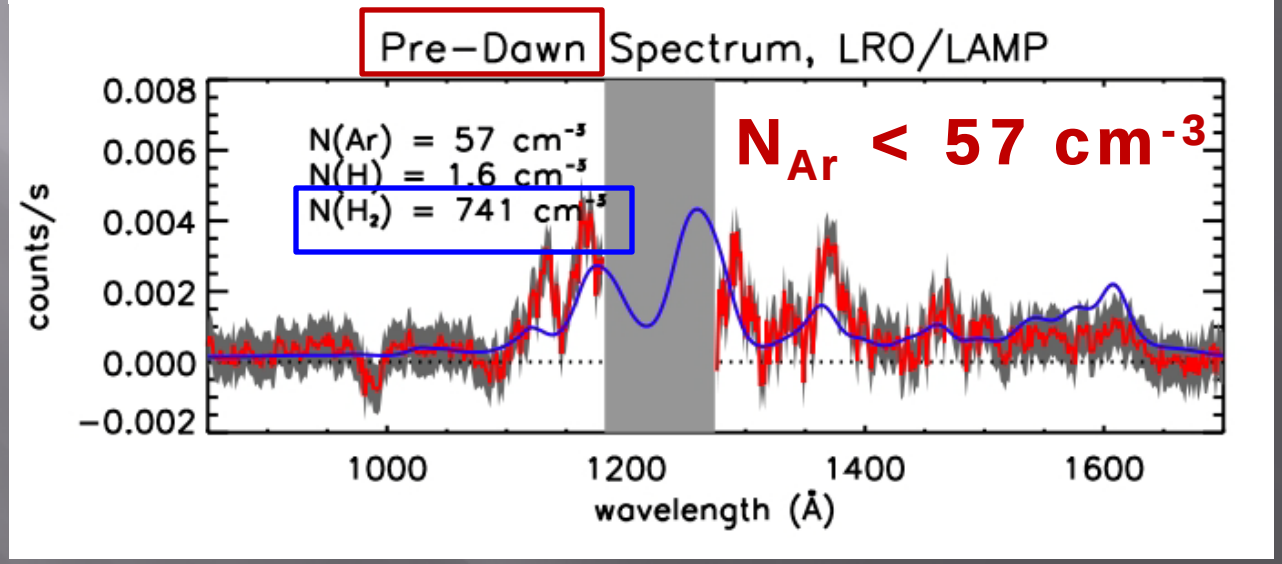
Searching for Ar

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

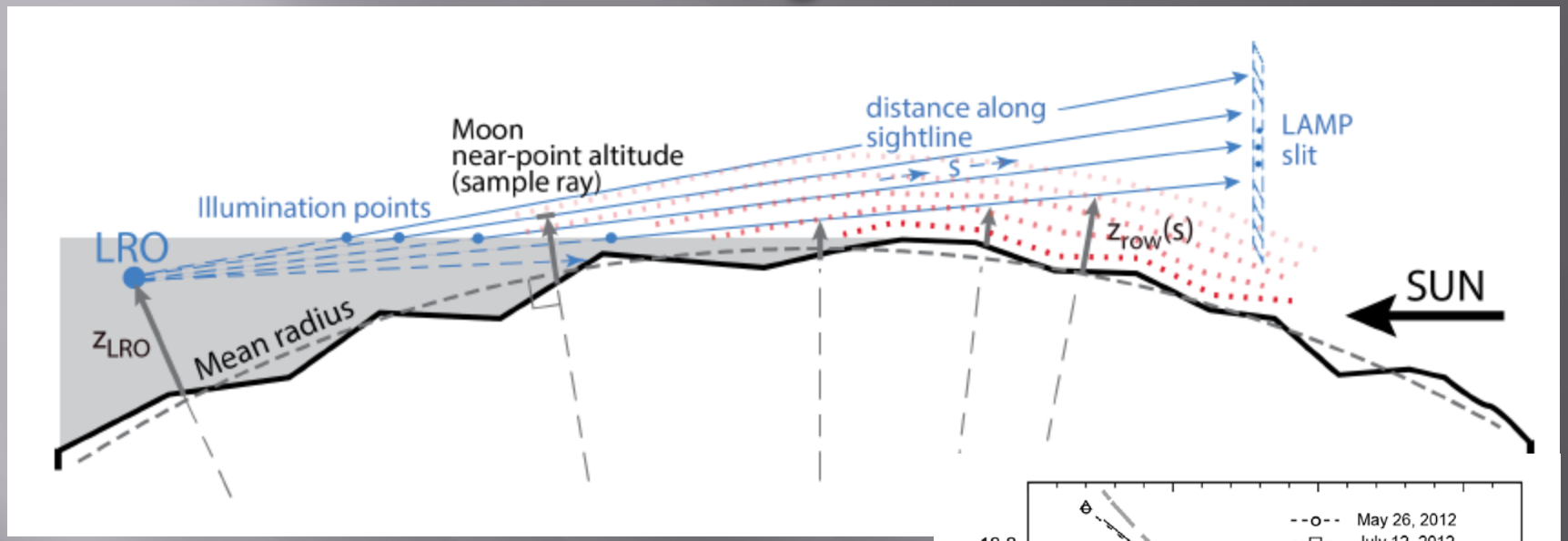


Tentative Ar Upper Limits





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

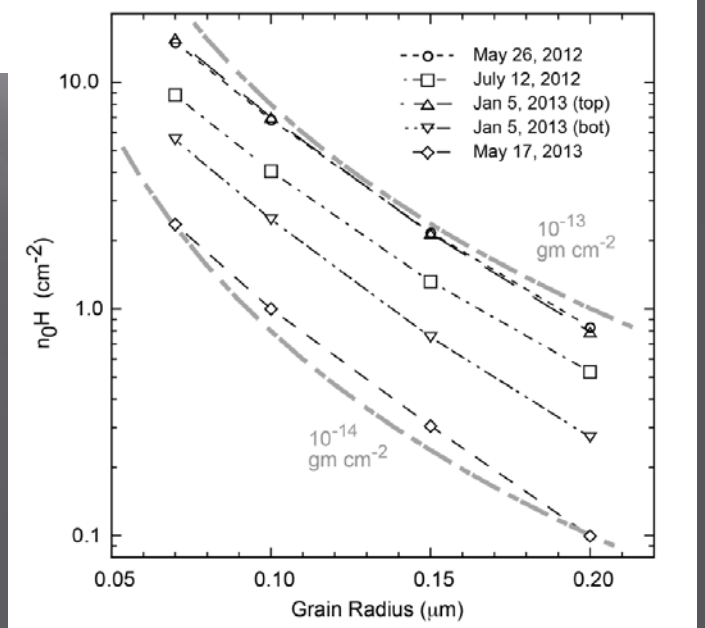
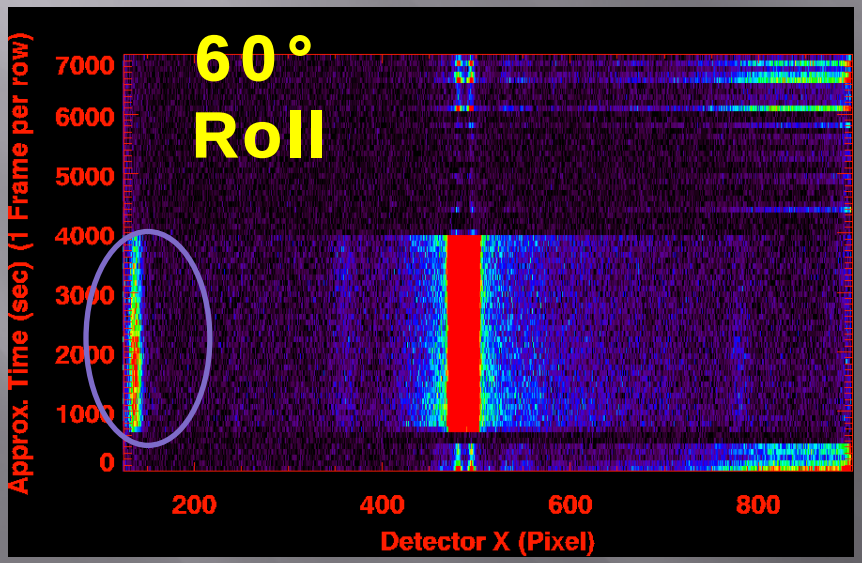
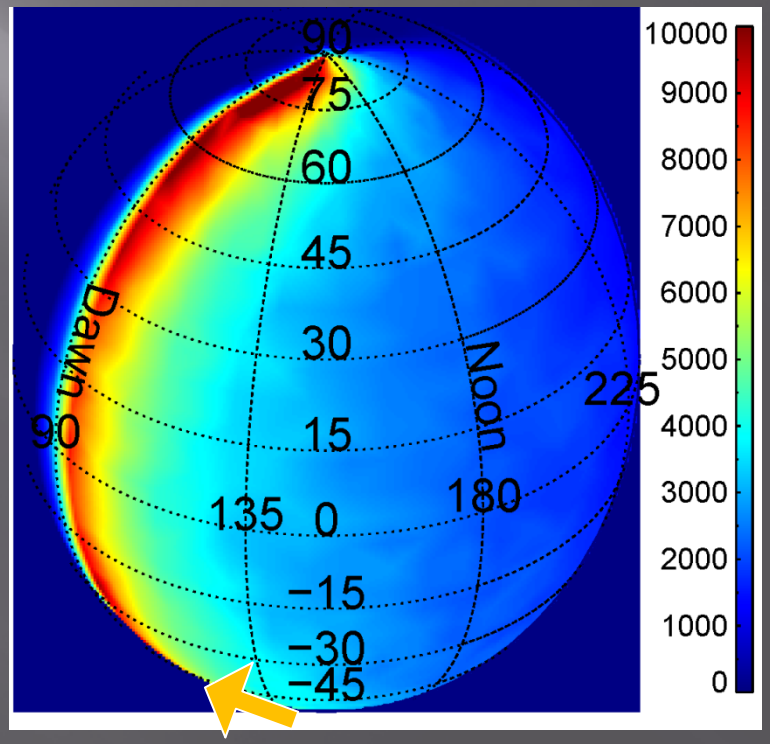


Figure 8: Summary of dust upper limit models for the LAMP observations, parameterized in terms of vertical dust abundance n_0H vs grain radius. Curves showing constant overlying dust mass (grain density = 3.0 gm cm^{-3}) have been added to the plots.

LAMP-LADEE Atmospheric Campaigns

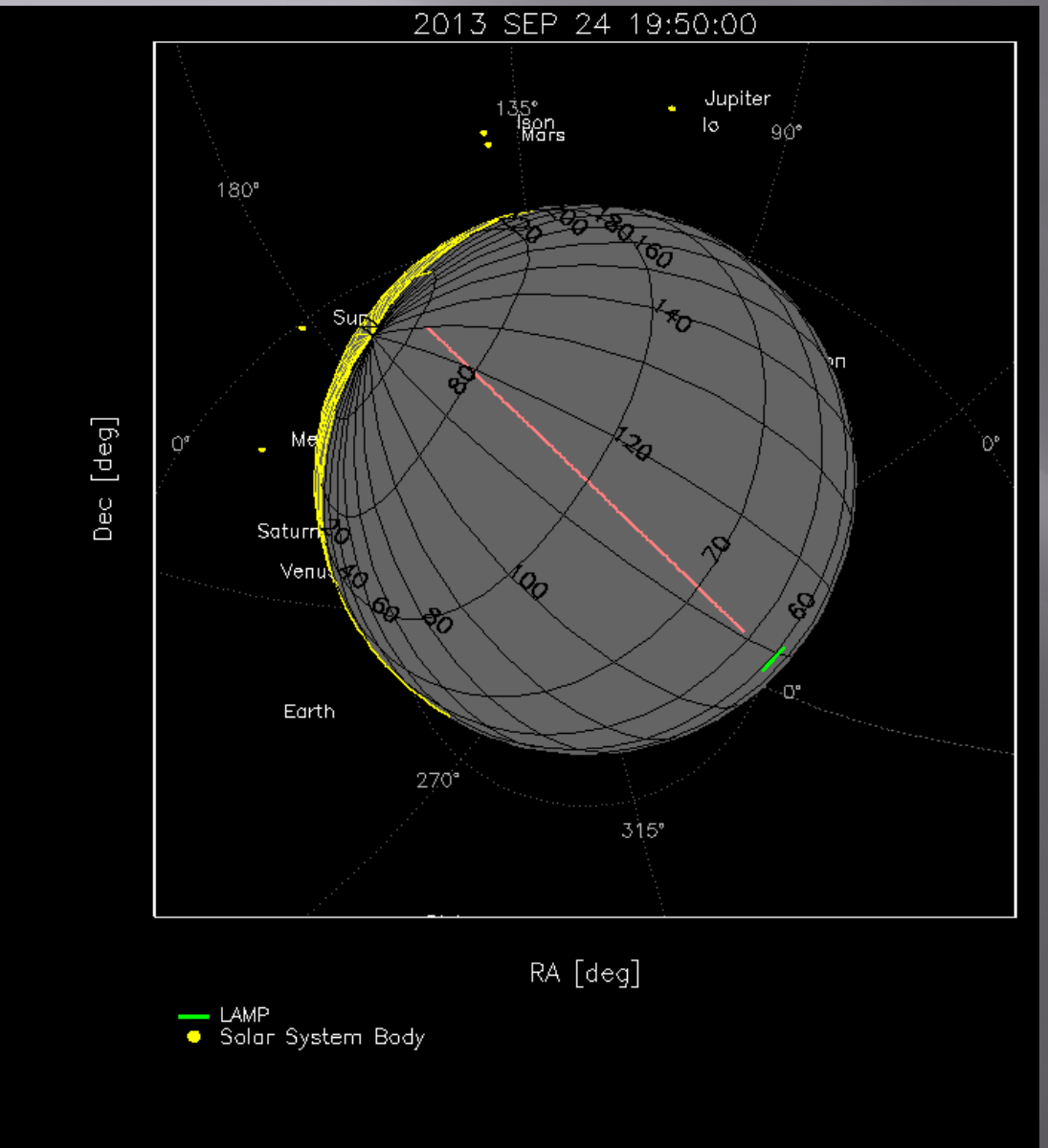
- Dedicated slewed observations to increase exosphere signal quality 2-14 Dec. 2013 during the LRO solar β~90°
- LRO Roll-Slews show excellent helium emission – searches for additional argon an other features is ongoing



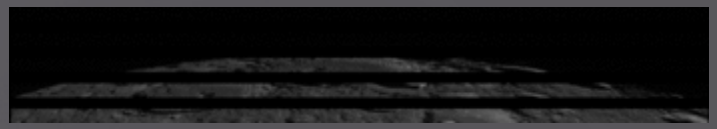


Grava et al., *submitted*, 2014

New 63° Pitch Maneuver



- 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



LAMP Exosphere Results Summary

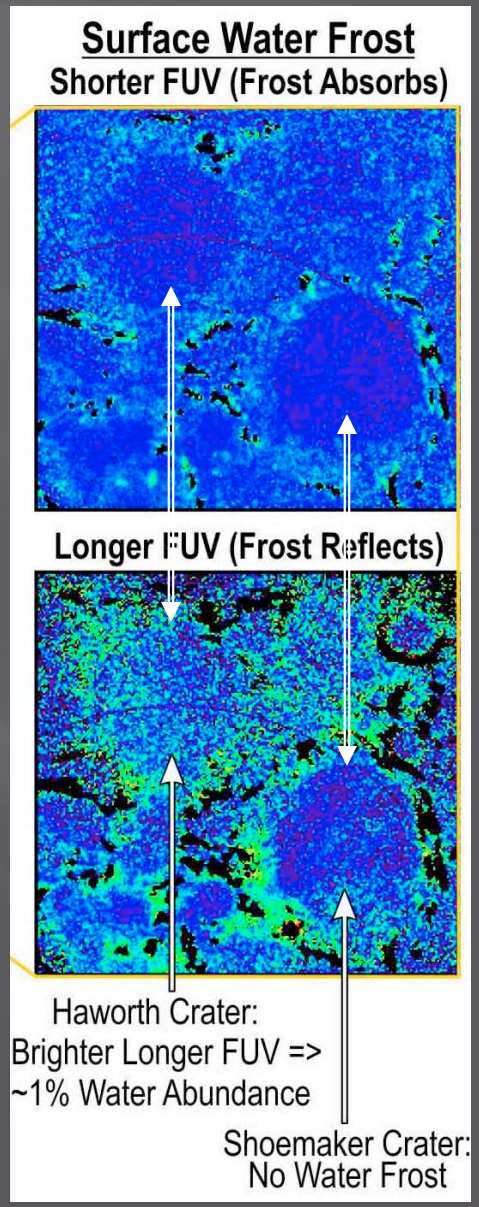
- LAMP remotely senses the global helium exosphere and its variability**, including a few episodic 'flares' from either solar wind or internal outgasing**
- **LAMP detected the H_2 exosphere, advancing "lunar hydrology" studies**
- LAMP has set upper limits to numerous expected exosphere constituents, 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 of magnitude, which informed LADEE LDEX, UVS, and S-T analyses
- LAMP detected LCROSS impact light curves from H_2 and CO molecular fluorescence and resonantly scattered Hg, Mg, and Ca neutral atom emissions
- LAMP detected the GRAIL A&B impact 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 Evidence of Surface Water Frost in Lunar Polar Craters

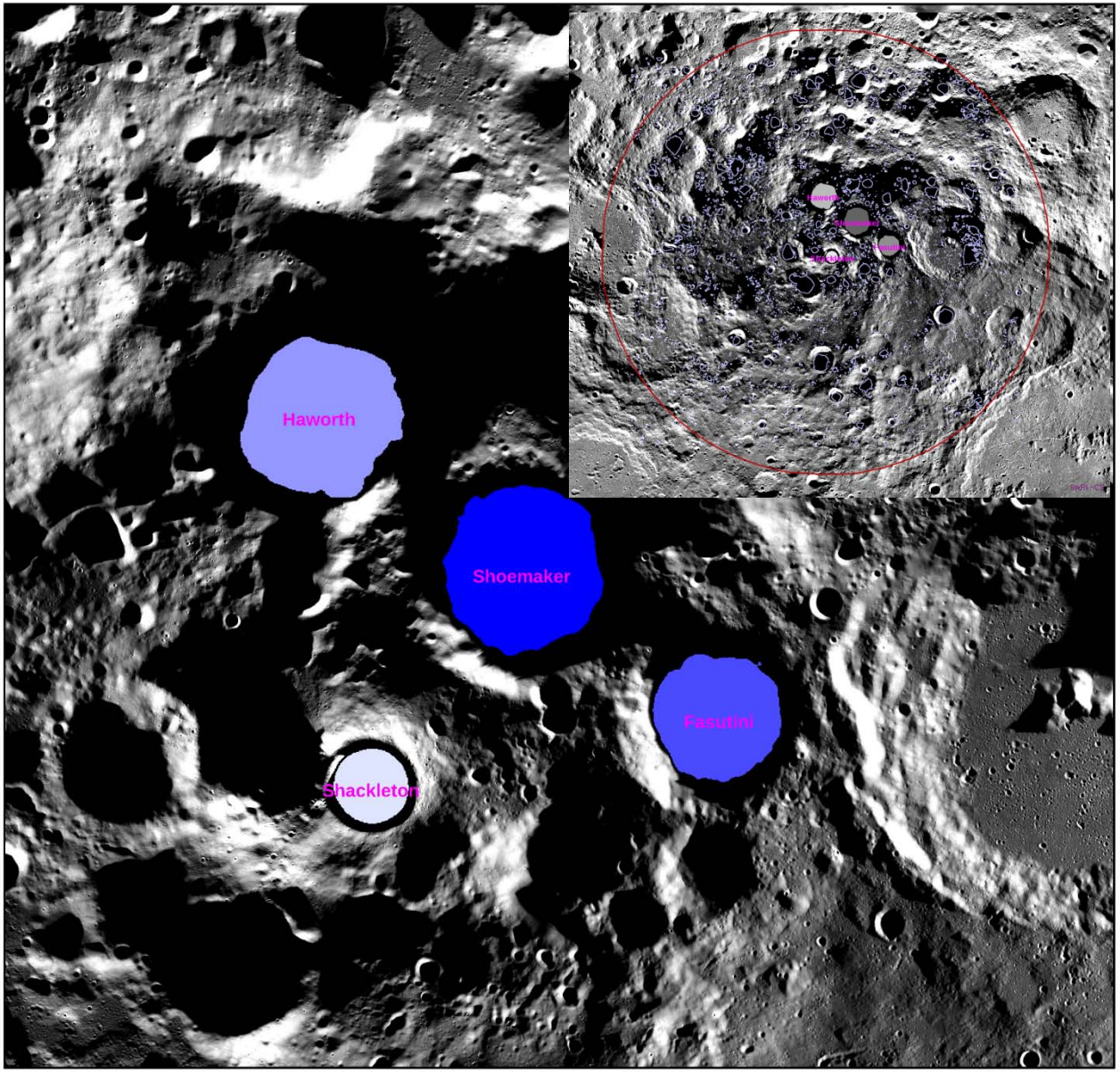
LAMP's nightside Lyman-α maps show lower albedos (dark blue), consistent with higher porosity surfaces.

Comparisons of star-illuminated surfaces at FUV wavelengths with a diagnostic water spectral signature (shortward and longward of 160 nm) indicate that PSRs such as Haworth crater (inset) are best explained by 1-2% abundances of water frost right at the surface.



LAMP provides the first indications of surface water frost in permanently shadowed polar craters

LAMP PSR Frost % Summary



Visual Summary of Gladstone et al., *JGR*, 2012 Results

Name	Water Fros
Shackleton	2
Haworth	1
Shoemaker	0.3
Fasutini	0.8

Legend

Water Frost % [redacted]

0.3000 - 0.6750

0.6750 - 0.9000

0.9000 - 1.2500

1.2500 - 2.0000

WAC_GLOBAL_P900S0000_100M

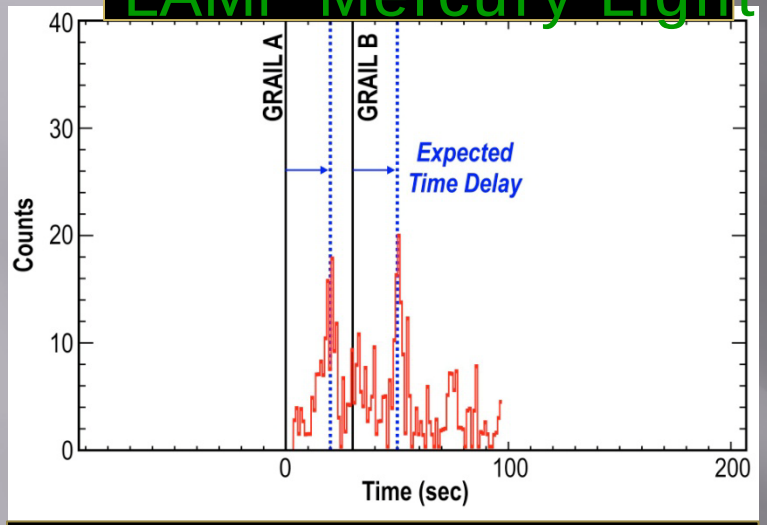
0.0175633

0.266069

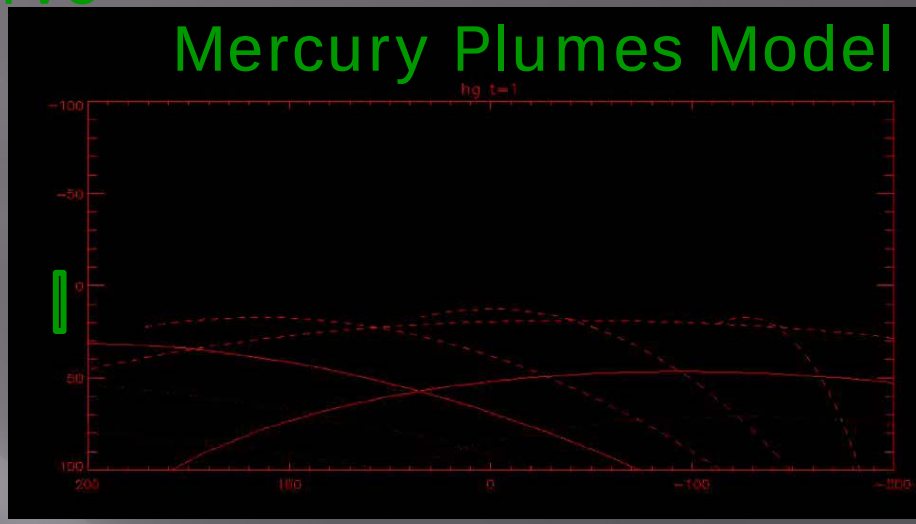
e

GRAIL Impact Mercury and Hydrogen Time Evolution

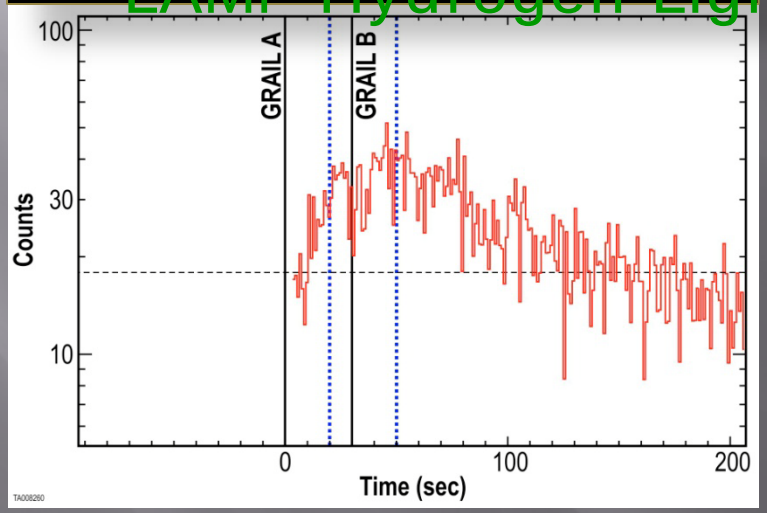
LAMP Mercury Light Curve



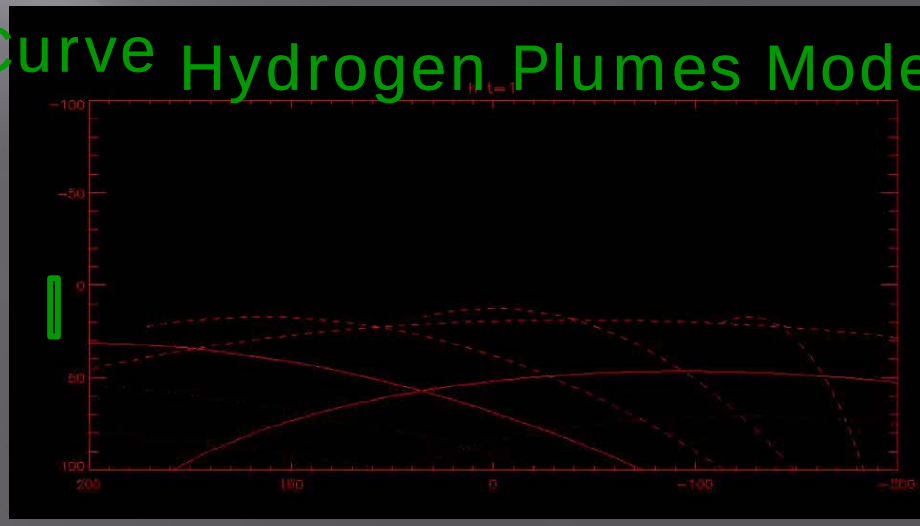
Mercury Plumes Model



LAMP Hydrogen Light Curve



Hydrogen Plumes Mode



LAMP light curves provide key constraints to models of impact plumes

Lunar Exosphere and Volatiles

Exciting times for lunar exosphere and surface volatile studies!

- Lunar Reconnaissance Orbiter
  - Sub-surface, surface, & PSR water signatures
  - LCROSS & GRAIL impact plume gas and thermal response
  - Lunar helium & H2 exosphere
  - Galactic cosmic ray interactions
- ARTEMIS
  - Plasma & Fields
  - Magnetotail crossings
  - Crustal field interactions
- LADEE
  - Gas, Ions, & Dust
- M3, EPOXI, Cassini dayside hydration data
- Richness of International Mission Collaborations
- Ground-based observing
- Earth-based observing – IBEX & Kaguya energetic neutral atoms, ROSAT X-ray
- Laboratory studies
- SSERVI focused research
- Comparative Planetology – Mercury, Outer Planet Satellites, Small bodies, etc.

Outline

- Exosphere Introduction
- LAMP Inst. Summary
- Helium Variability
- LCROSS & GRAIL Impact Plume Gas Results
- H2 detection and variability
- Gas species upper limits, and comparison to LADEE
- Argon Search and Modeling
- LRO/LAMP Horizon Glow Dust Upper Limits
- LADEE Campaign planning & first-looks
- Volatile Transport “hydrological cycle” & Future work