LADEE Science Results and Implications for Exploration

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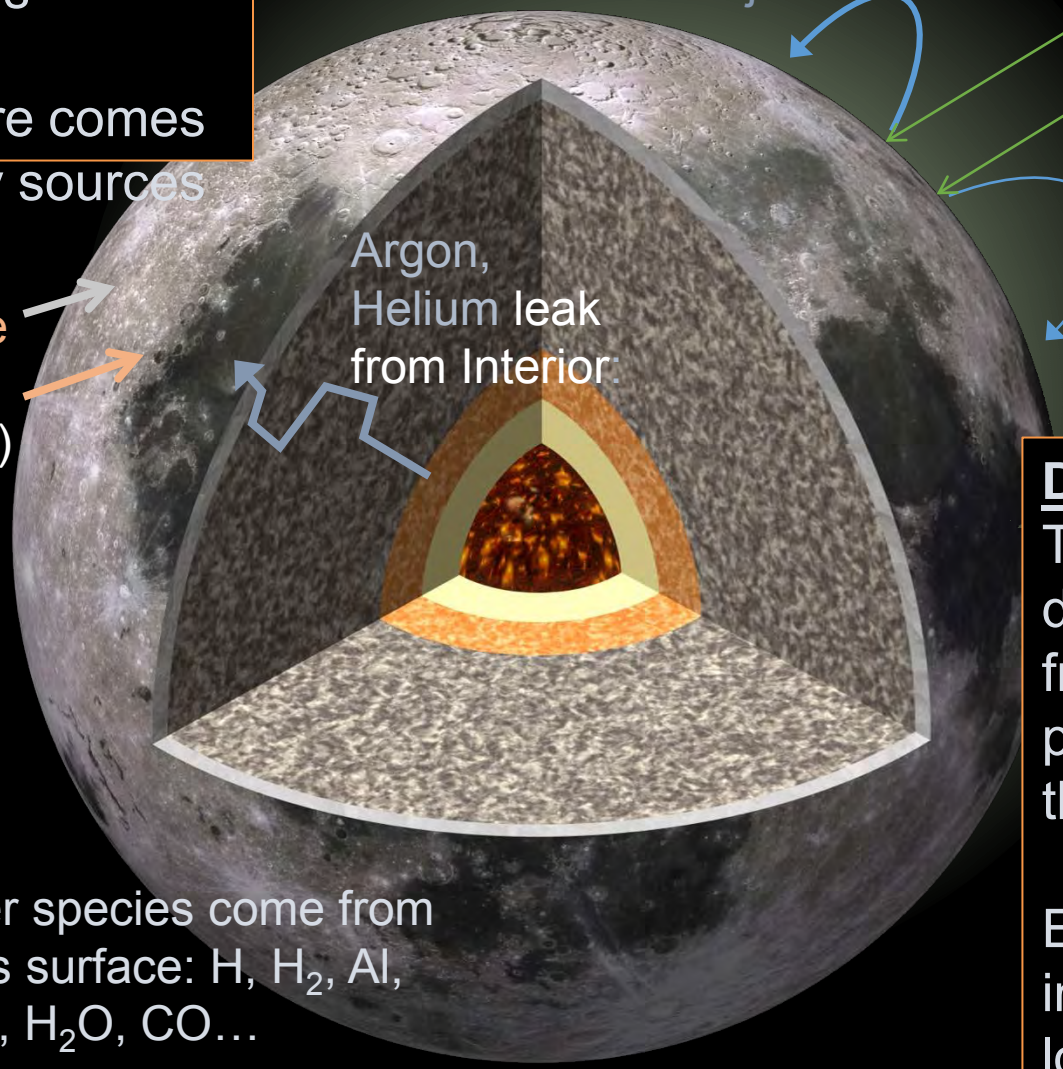
The Moon's Thin Atmosphere and Dust Shroud

Atmosphere:
The Moon's tenuous atmosphere comes from many sources



Dust:
The Moon's perpetual dust shroud comes from interplanetary particles bombarding the surface.

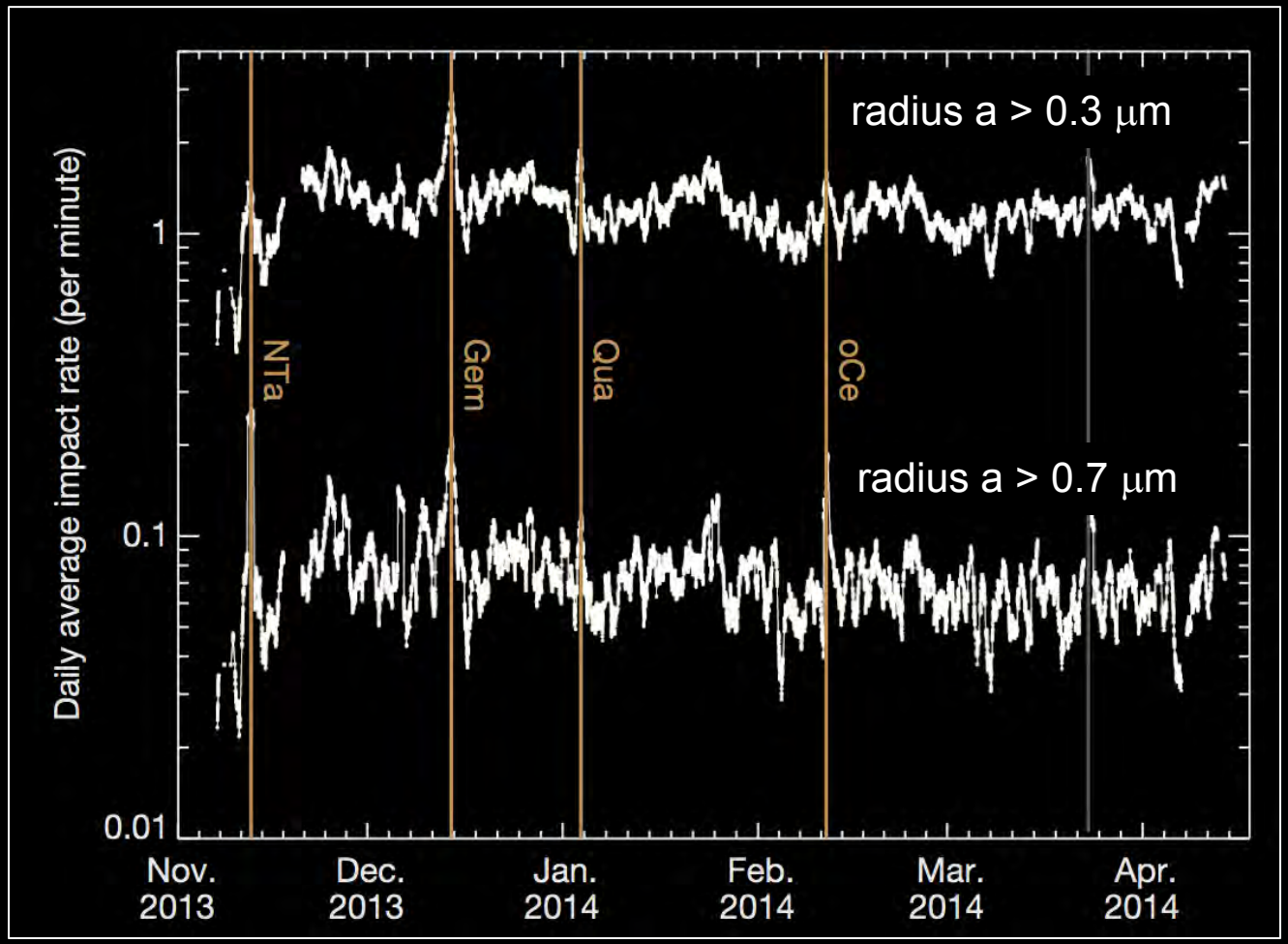
Ejecta from those impacts is continually lofted

Many other species come from the Moon's surface: H, H_2, Al, Na, K, OH, H_2O, CO…

A Dusty Atmosphere? LDEX Observations

LDEX: Exospheric Dust

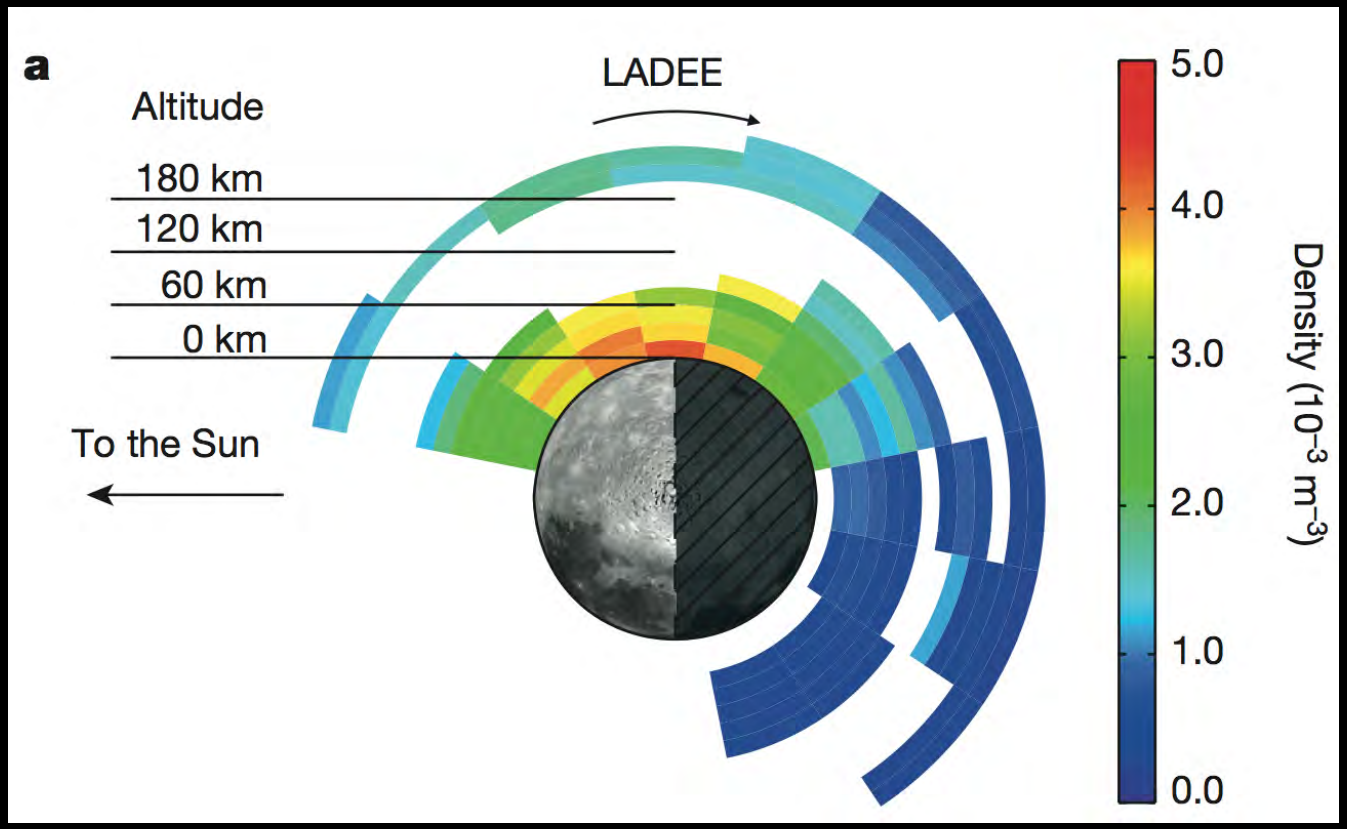
Horanyi, et al., *Nature*, 2015



- LDEX saw ~ 1 grain impact/min
- Impact rate of different sizes reveals power law distribution
- Increases seen at known meteoroid streams (eg. Geminids)
- At least one *unknown* 'stream' identified.

Dust Density vs. Altitude & LT

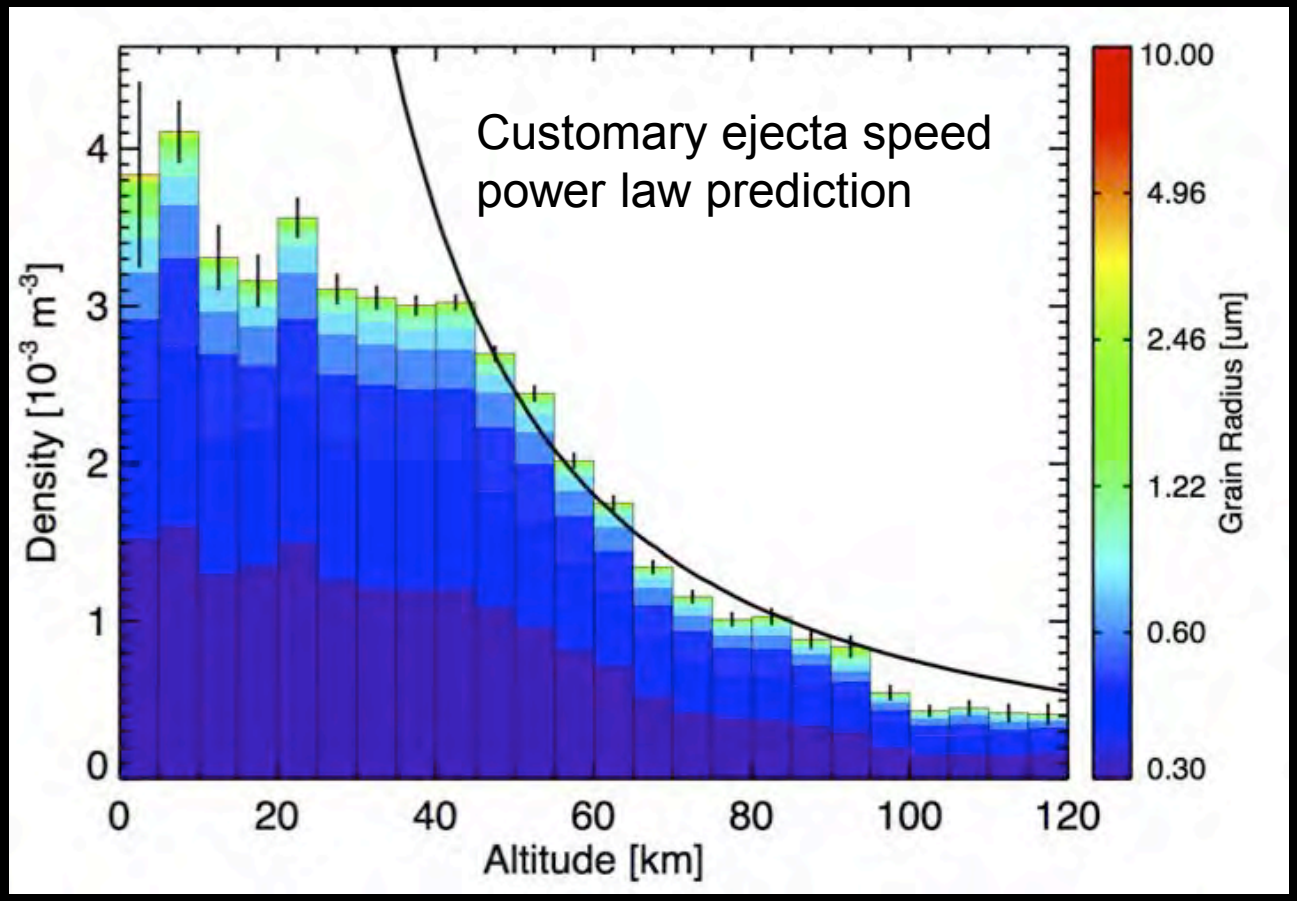
Horanyi, et al., *Nature*, 2015



- Dust densities clearly maximize on morning (upstream) side of Moon
- Densities greatest at low altitudes

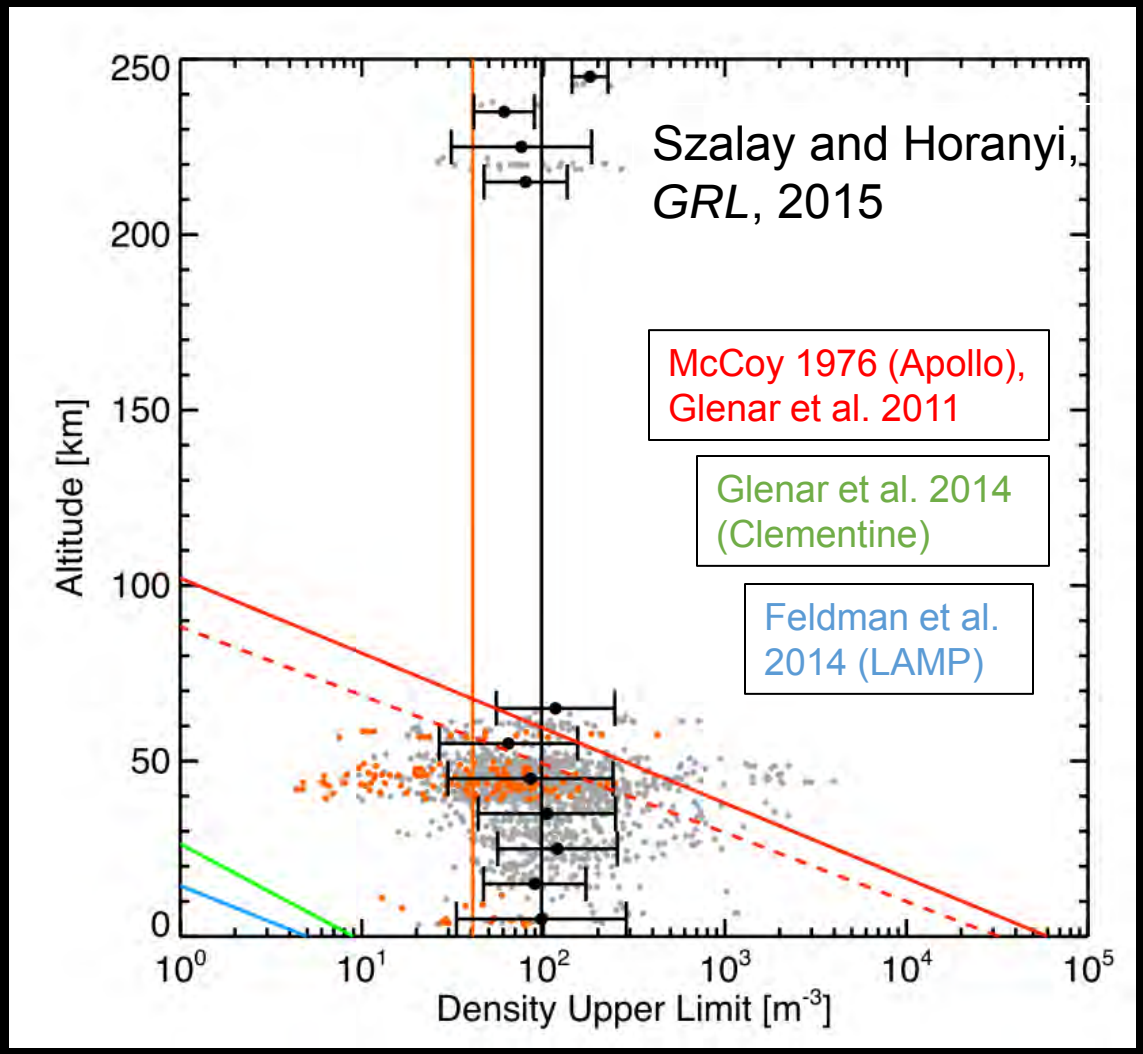
Dust Density vs. Altitude

Horanyi, et al., *Nature*, 2015



- Density appears to level off at lowest altitudes
- Ejecta depart from assumed power-law speed distribution with a single sharp cut-off minimum speed u_0 needs revision for speeds below about 400 m/s.
- At higher speeds the distribution follows a simple power law
- Estimated dust exosphere mass: ~120 kg.

Search for "Levitated" Dust

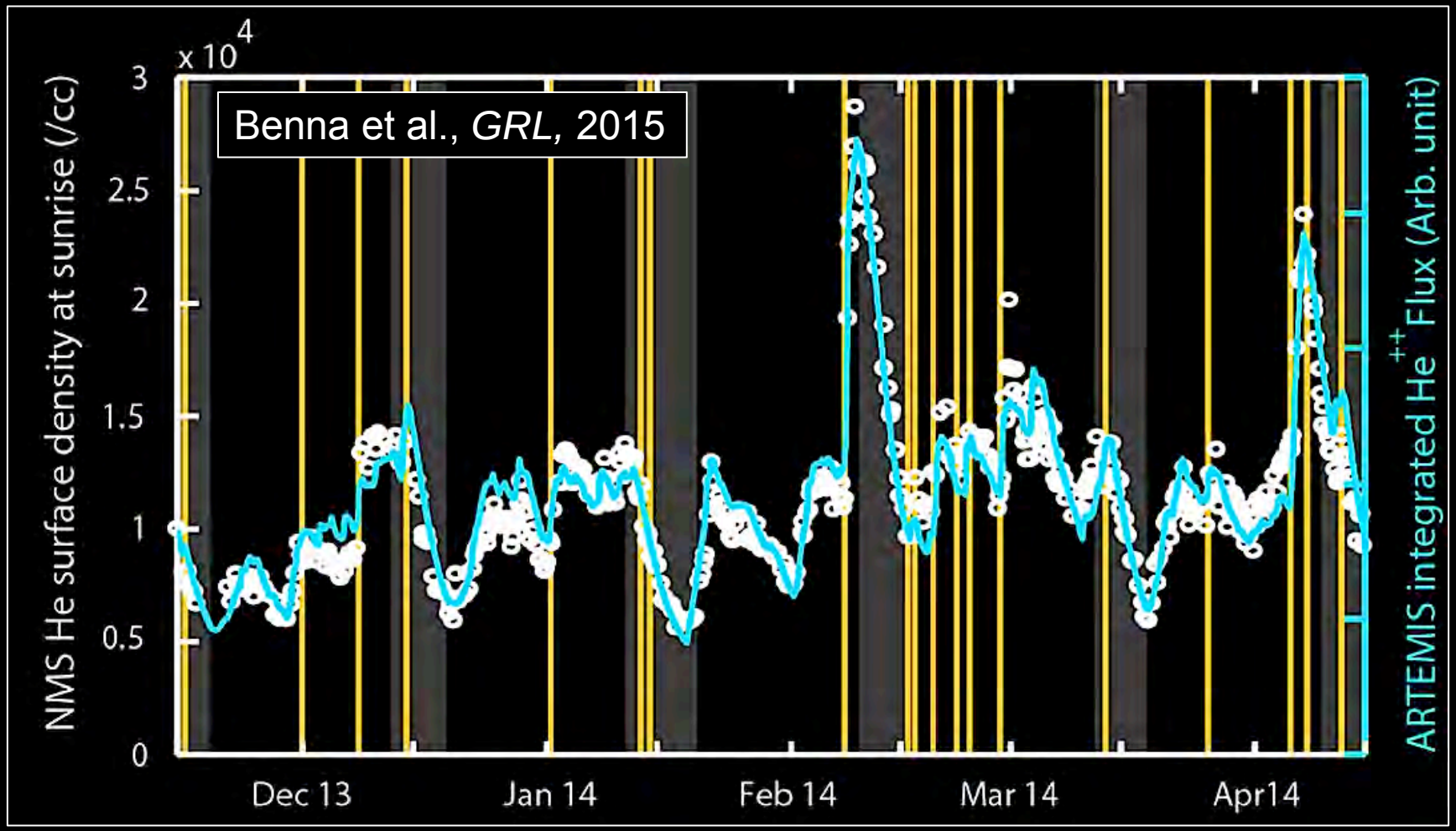


- Small $\leq$ 0.1 μm grains
- LDEX measures current from such grains
- Densities < 100 m^{-3}
- Even at lowest LADEE altitudes, no significant signal
- Other analyses provide lower upper limits
- <u>This still leaves the Surveyor near-surface horizon glow unexplained.</u>

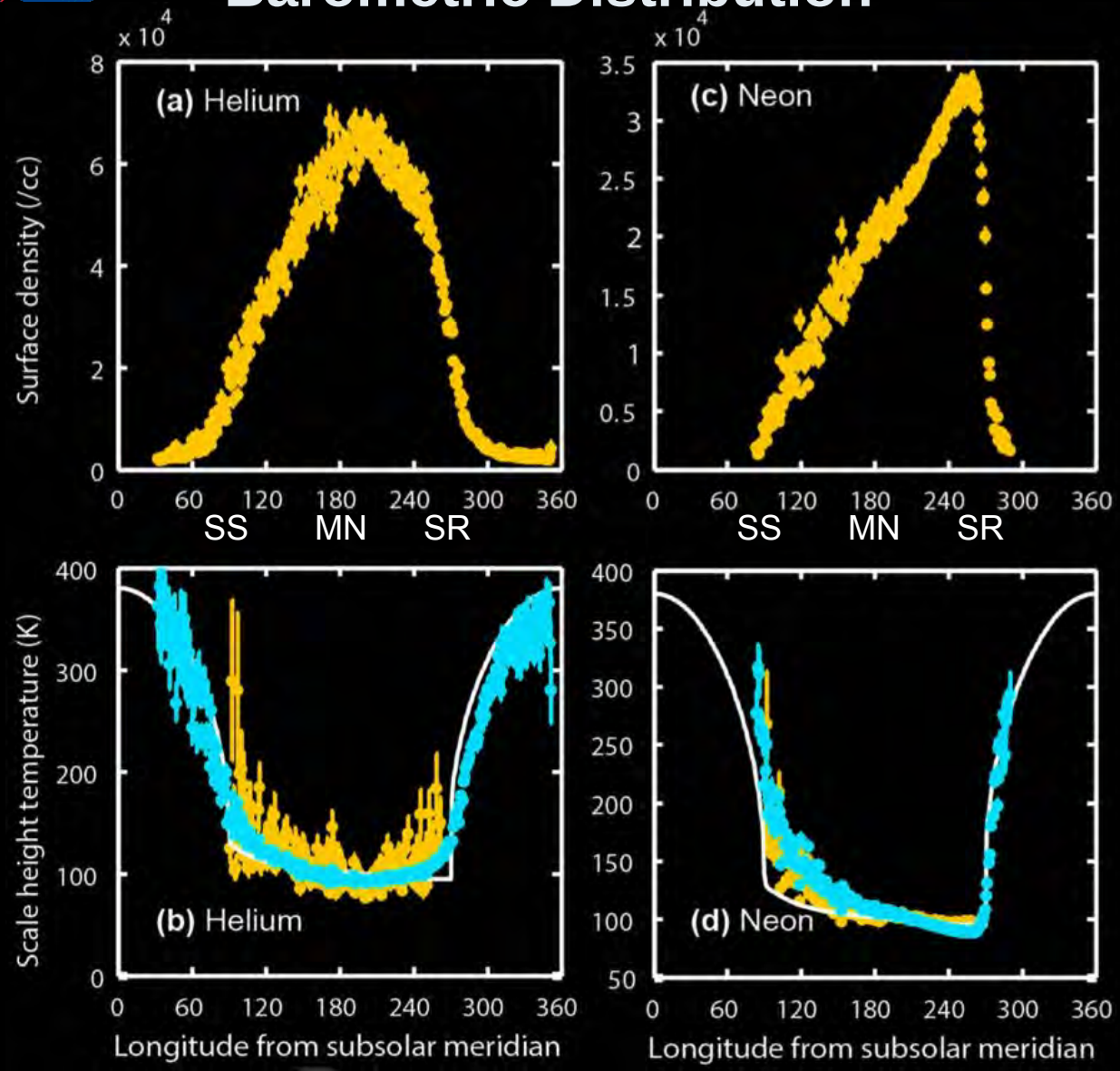
The Lunar Exosphere: He, Ne and Ar Observations

Exospheric Helium and Solar Wind He^{++}

- Most helium in lunar exosphere comes from solar wind (thanks Artemis!)
- Loss time scale ~4.5 days
- Est. interior source of He: 2×10^6 cm^{-2} s^{-1}



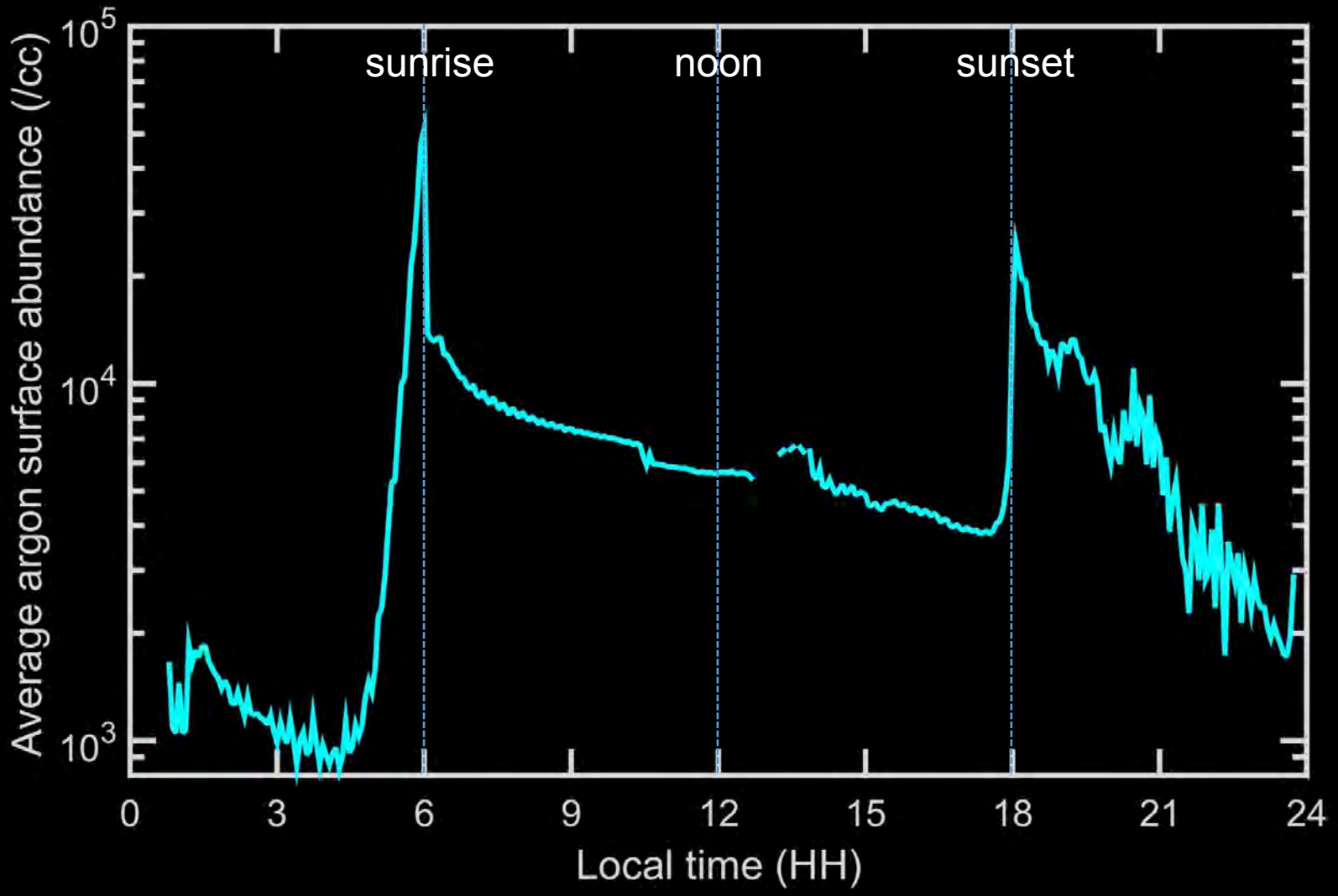
^{4}He and ^{20}Ne Follow Expected Barometric Distribution



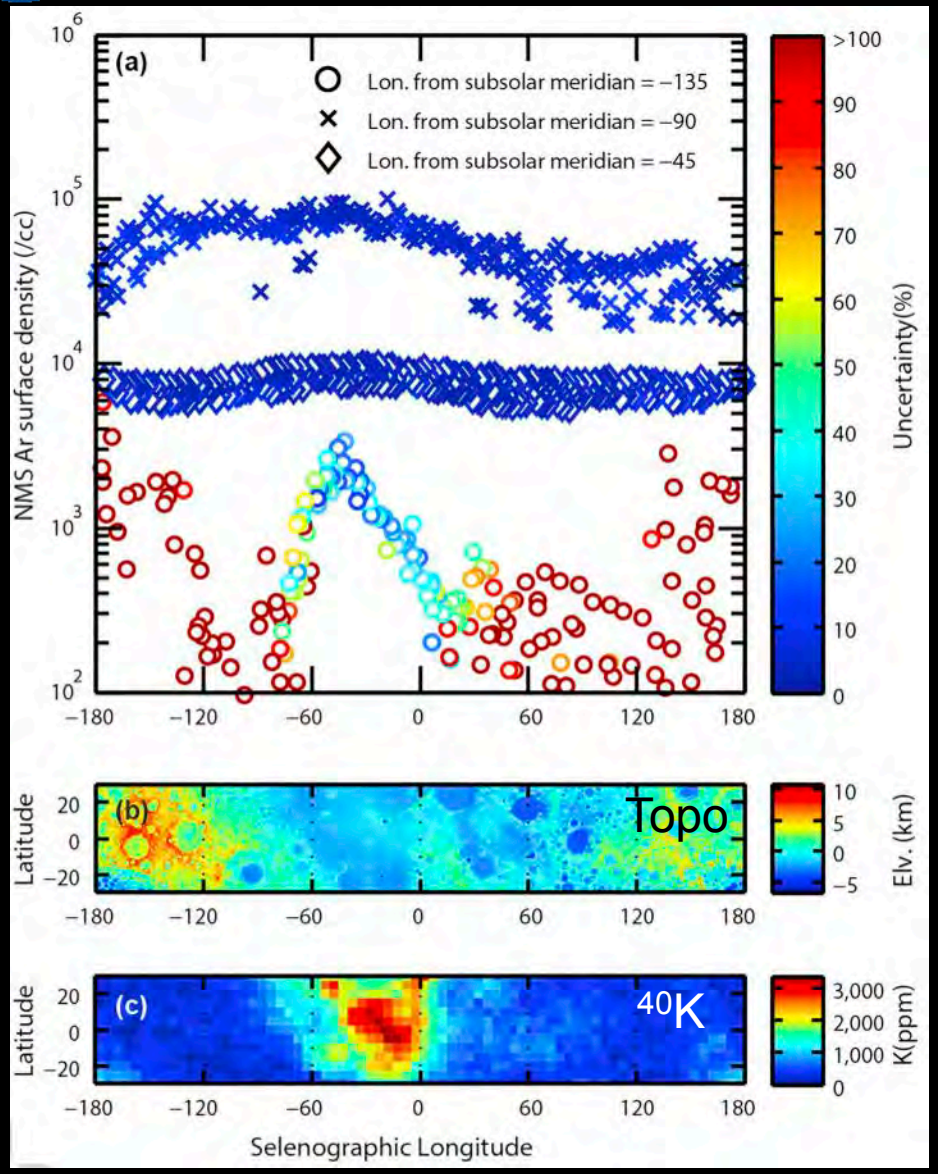
- Neon confirmed!
- Follow exospheric equilibrium for noncondensable gases.
- $nT^{5/2}$ = const.
- Scale height temperature follows surface temperature.
- Differences between He and Ne result from different ballistic length scales.

Benna et al., *GRL*, 2015

Full Diurnal ^{40}Ar Cycle



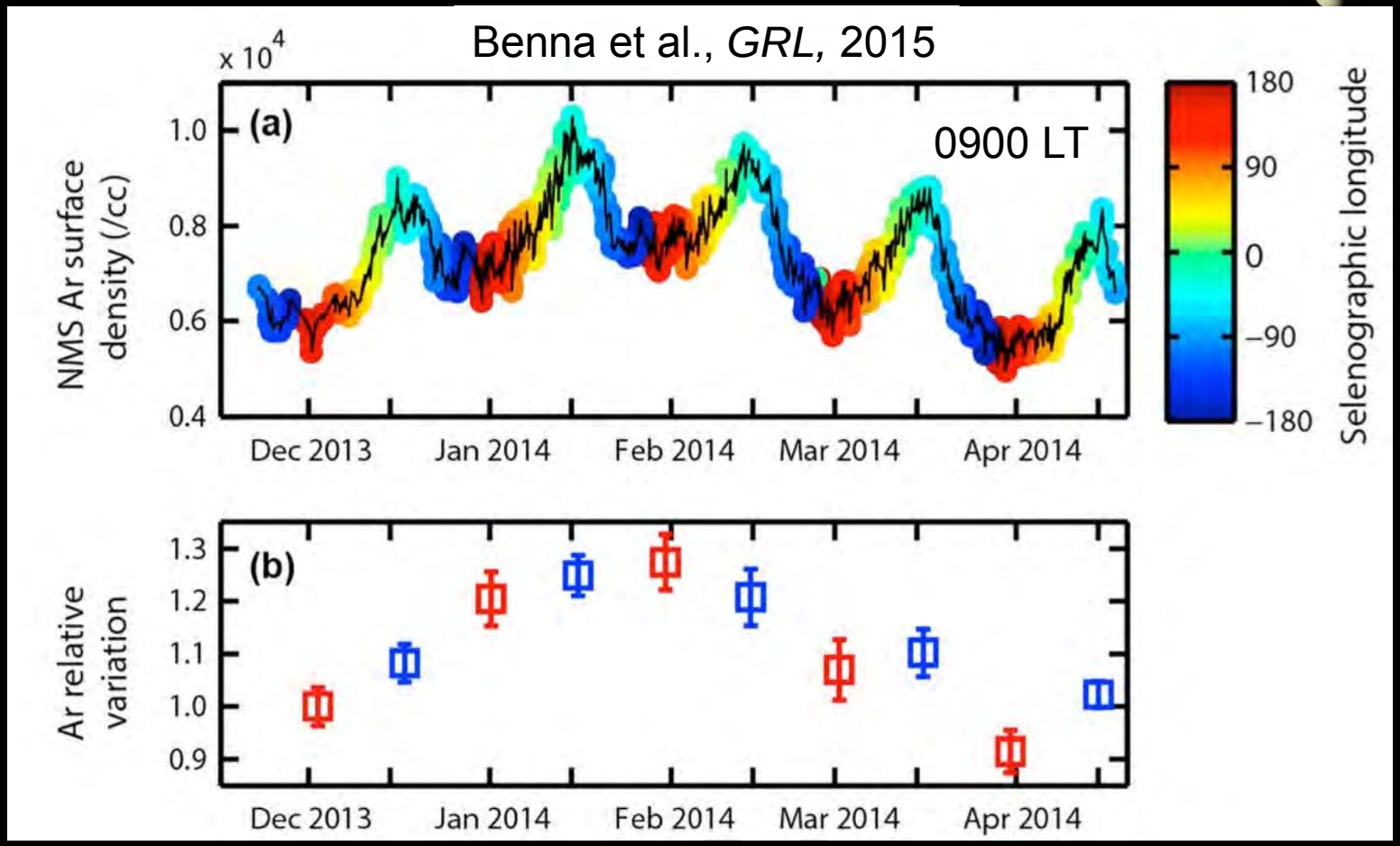
Variability of ^{40}Ar with Selenographic Longitude



- Persistent maximum over the western maria
- Procellarum KREEP Terrane
- Greatly enhanced in radiogenic species (incl ^{40}K) at surface
- ^{40}Ar escapes from *liquidus*, not solidus – at depth
- Additional meteoroidal impact vaporization source?

Benna et al., *GRL*, 2015

Long Term Variability of ^{40}Ar with Time

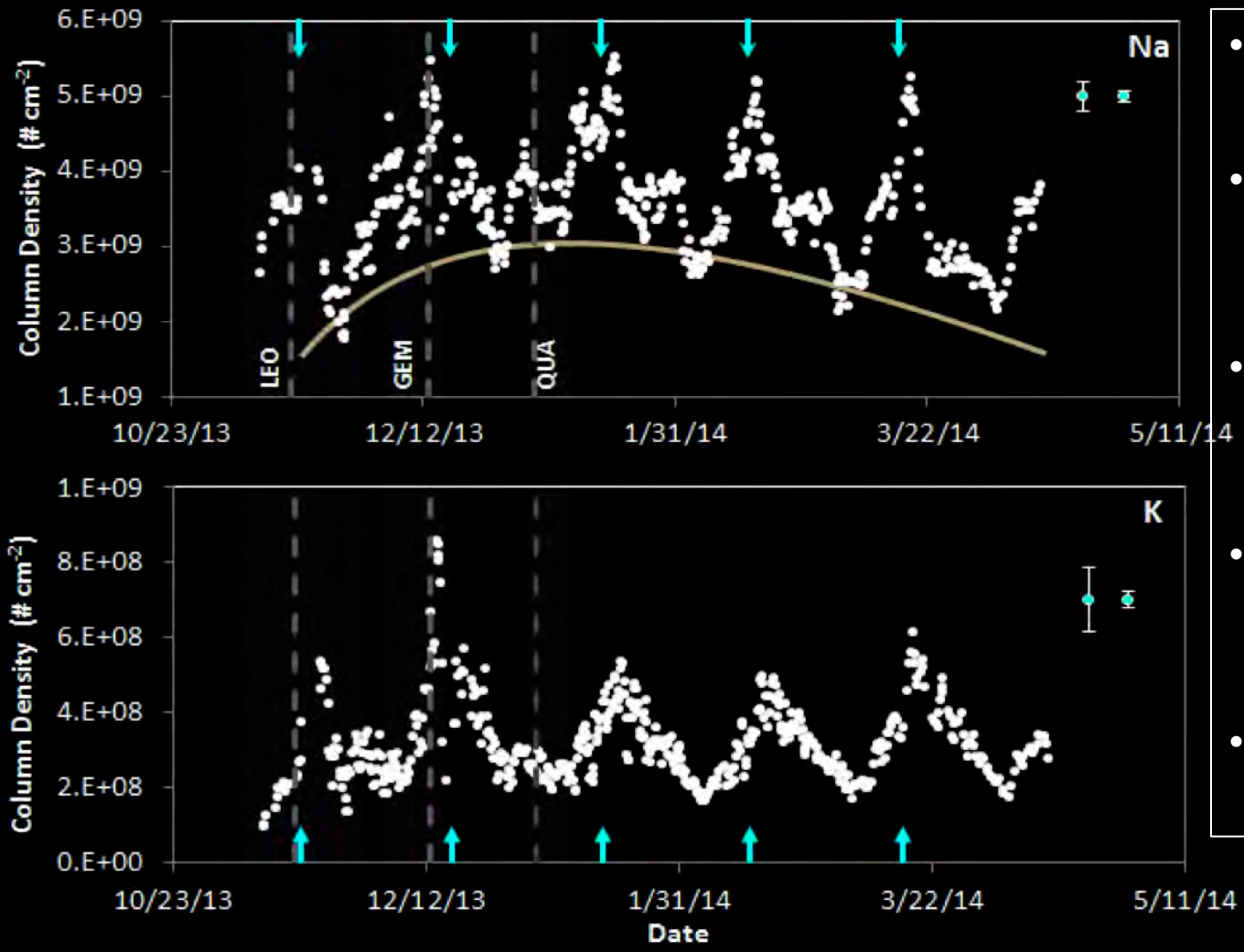


- Initial increase in total ^{40}Ar abundance, followed by decrease
- LACE (Apollo 17) observed similar long-term variation.

The Lunar Exosphere: Na and K

UVS: Sodium and Potassium

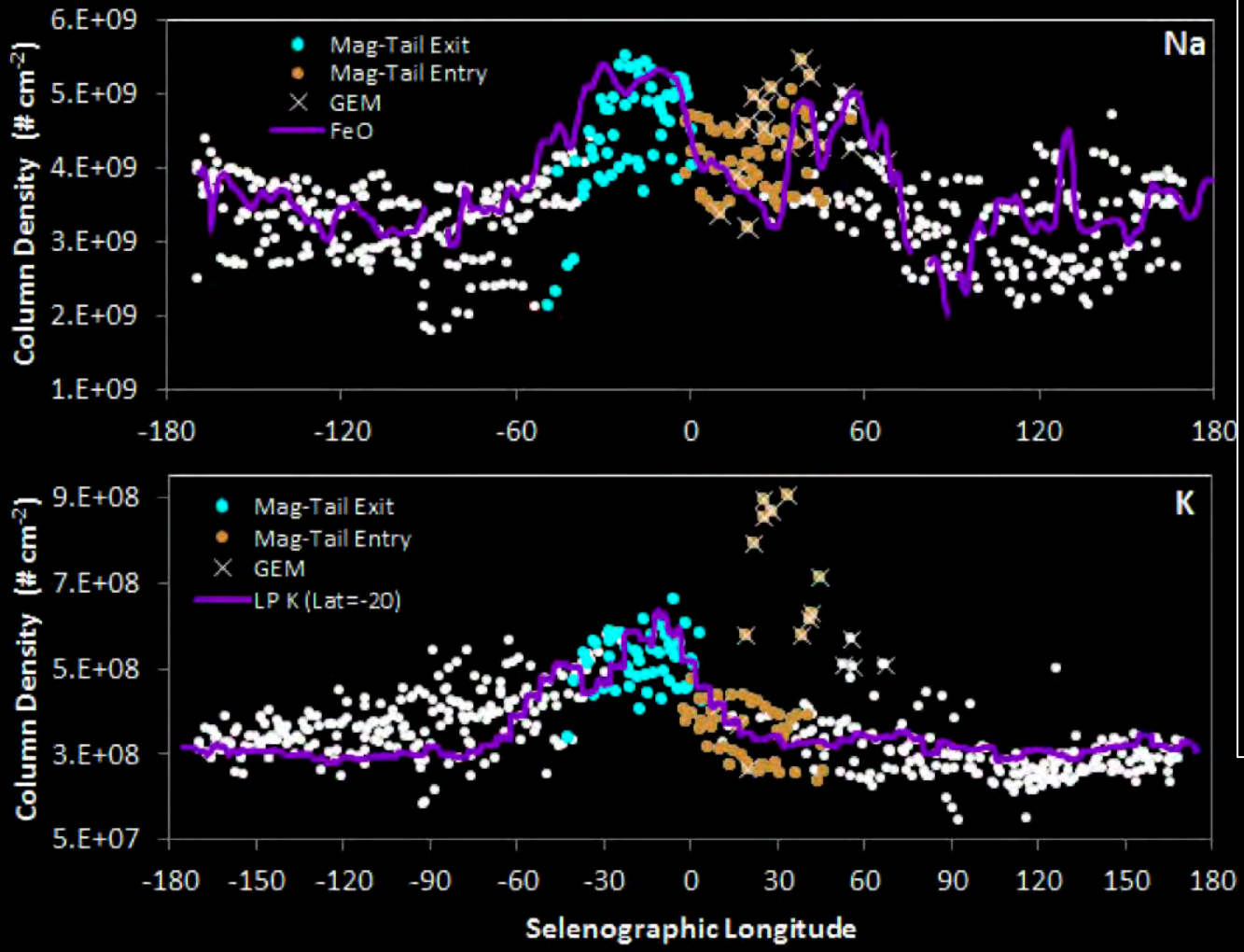
Colaprete et al., ESF, 2015



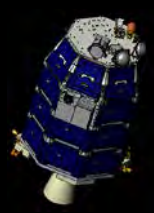
- Clear diurnal variations.
- Na decreases in magnetotail (no sputtering).
- Na increases abruptly after exit into solar wind.
- Both Na and K increase at Geminids
- Na long-term variation like ^{40}Ar?

UVS: Na and K vs. Selenographic Longitude

Colaprete et al., ESF, 2015



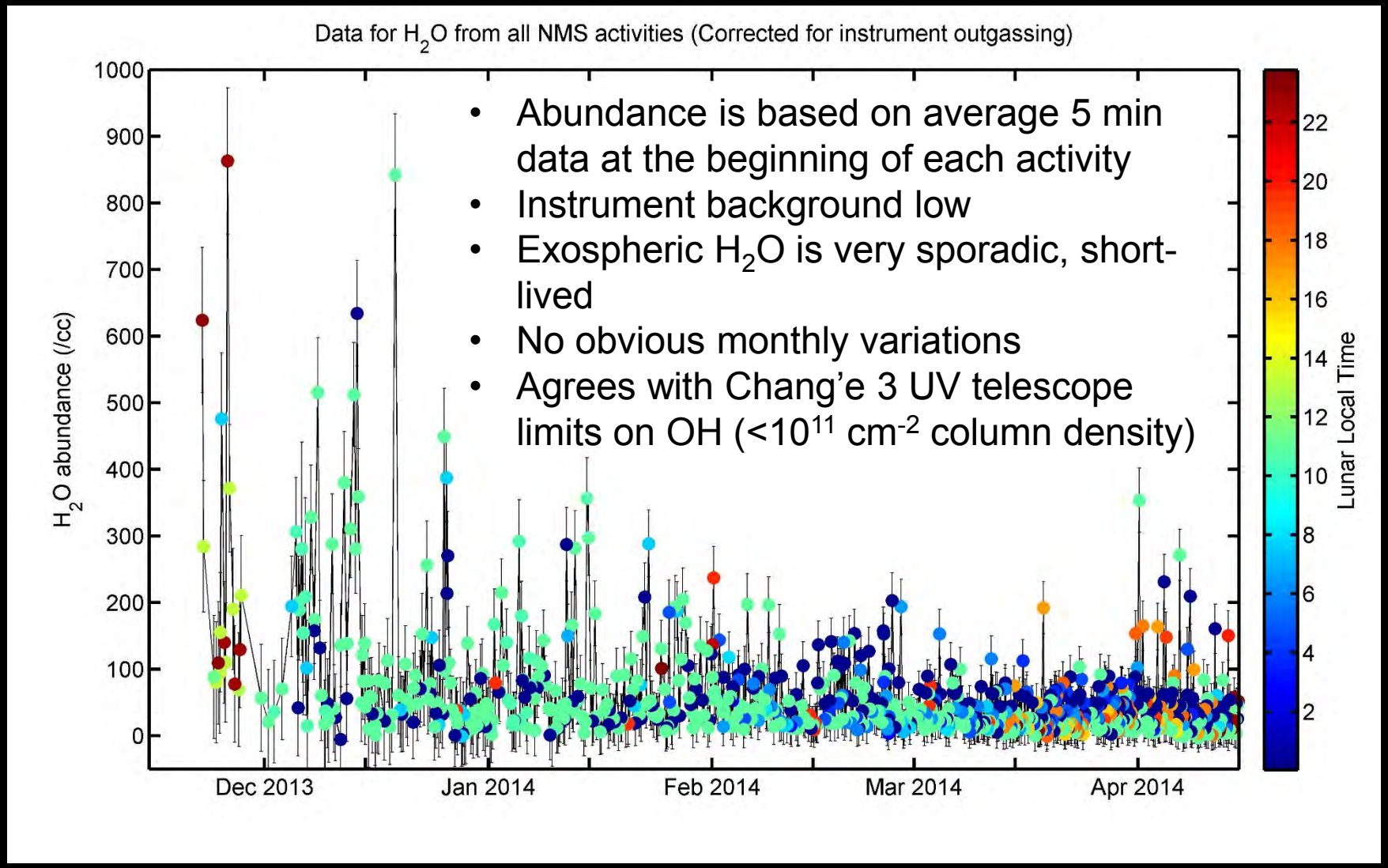
- Na higher over maria.
- K higher over PKT.
- Subsolar longitudes for magnetotail exit also -30 to -45E
- Much more work being done on Na and K – modeling and analysis (Sarantos)



The Lunar Exosphere: H_2O, OH and Others

Closed Source H_2O observations

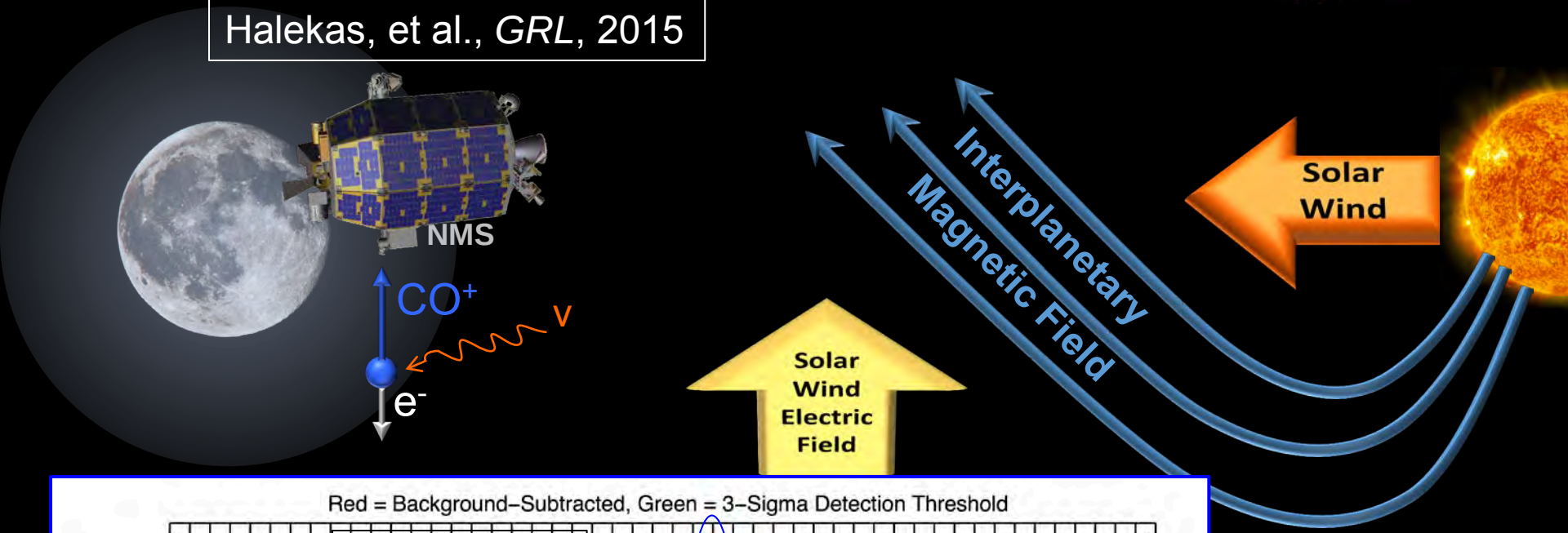
(see talk by Benna tomorrow)

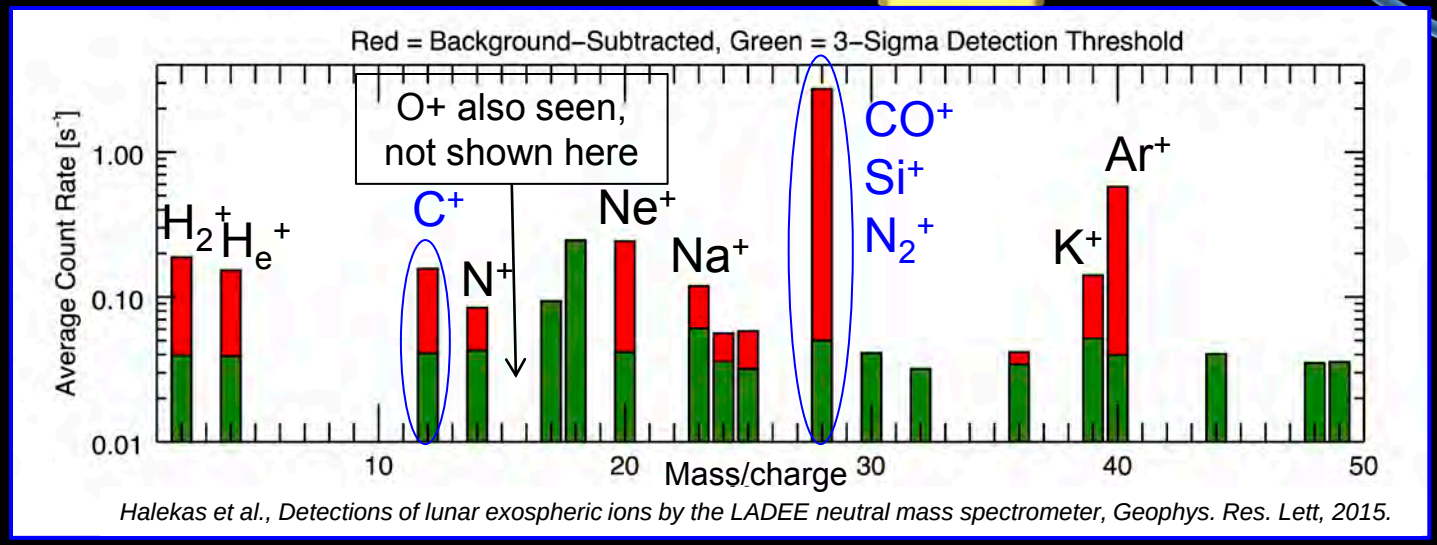


- Abundance is based on average 5 min data at the beginning of each activity
- Instrument background low
- Exospheric H_2O is very sporadic, short-lived
- No obvious monthly variations
- Agrees with Chang'e 3 UV telescope limits on OH ($<10^{11}$ cm^{-2} column density)

Exospheric Ion Measurements Reveal Multiple Species

Halekas, et al., *GRL*, 2015





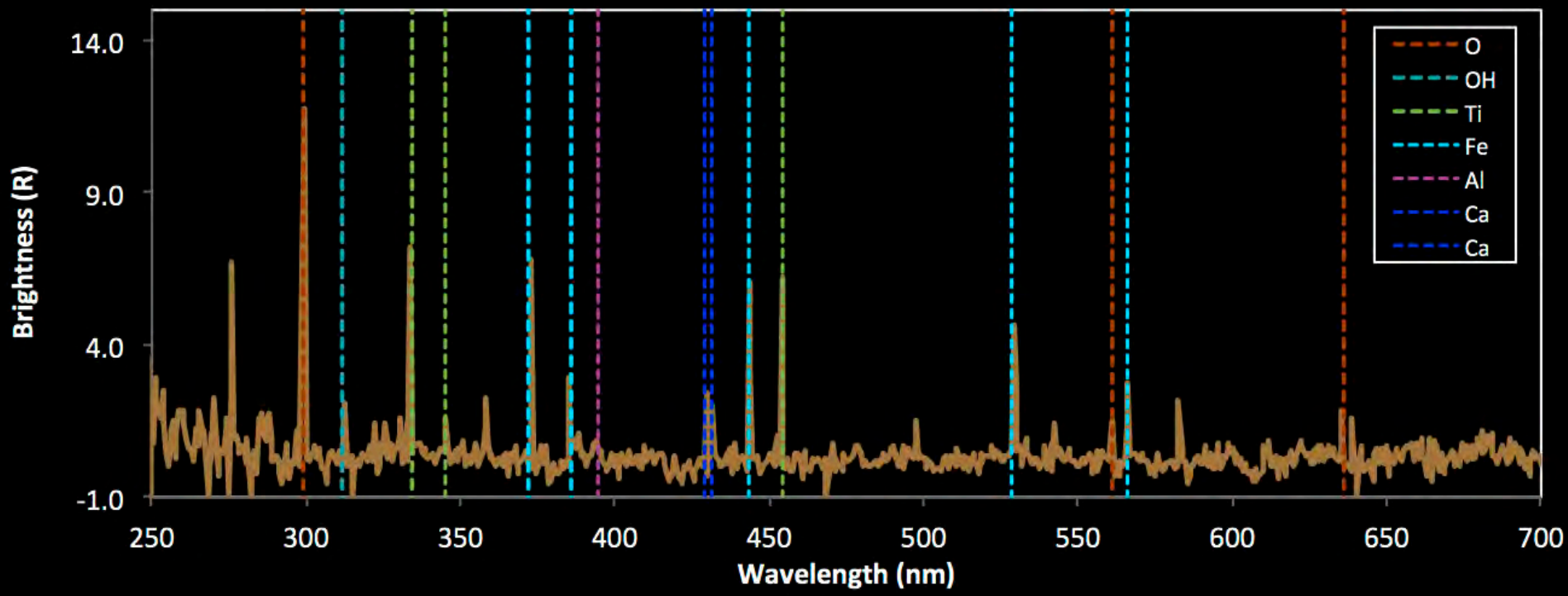
Halekas et al., Detections of lunar exospheric ions by the LADEE neutral mass spectrometer, Geophys. Res. Lett, 2015.

Mass 28 is ambiguous: however, based on significant carbon detection, CO^+ is likely.

UVS: Post- minus Pre-Geminids

Initial comparison of Pre- and Post Geminids Dawn Limb Spectra

- Only spectra from S/C in shadow (lunar umbra), near-dawn local times.
- Dark current &instrument bias corrected, “hot pixels” removed.
- >100 spectra co-added to improve signal-to-noise ratio.
- O, OH, Ti, Fe, Al, Ca identified



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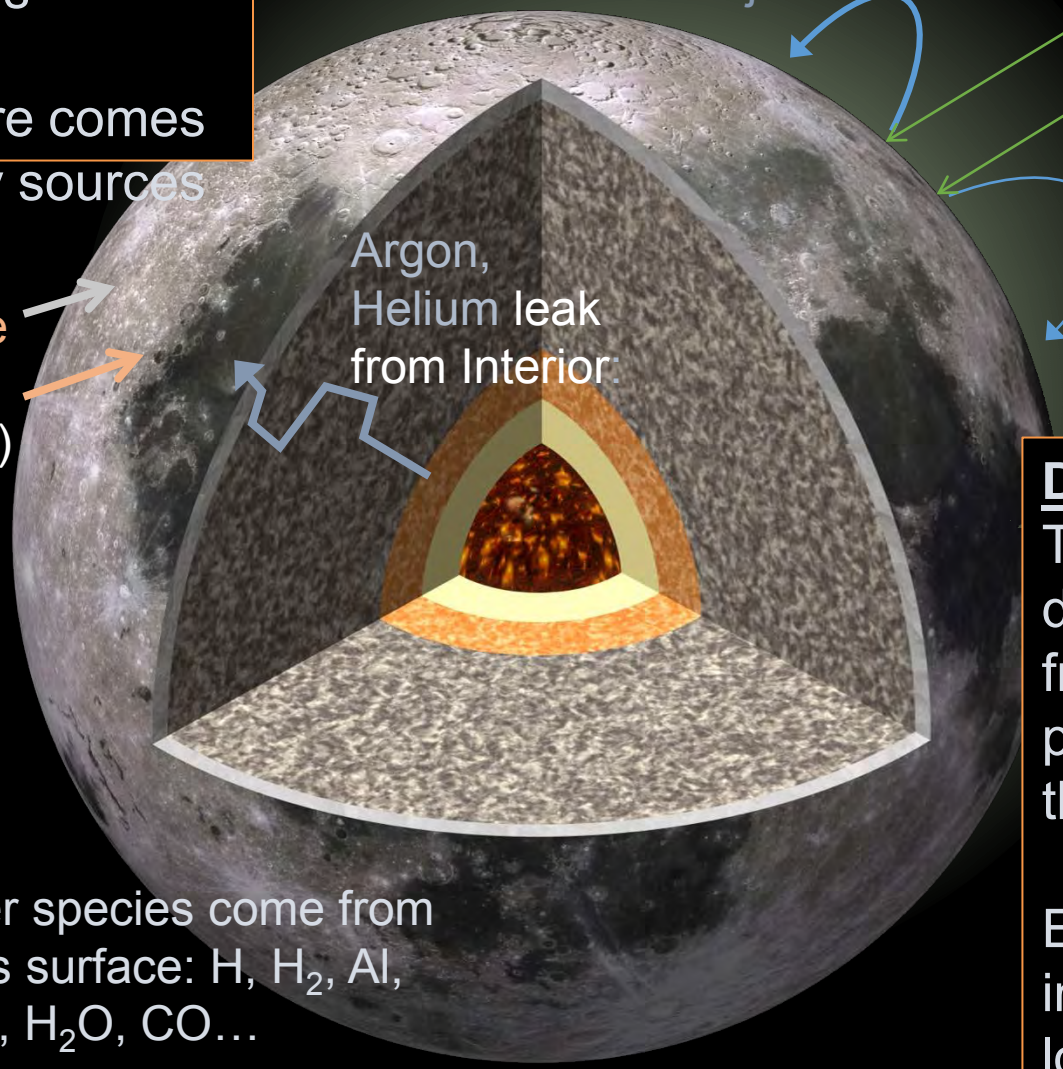

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Many other species come from the Moon's surface: H, H_2, Al, Na, K, OH, H_2O, CO…

Exploration and Future Science

Exploration:

- "Mostly harmless" – dust is very tenuous
  - Did not/could not address "Surveyor horizon glow"
- No evidence of inimical compounds (except Hg!)
- Now have an idea of meteoroidal volatile input (eg. sporadic H_2O - see talks by Benna et al, Hurley et al tomorrow)

Science:

- Molecular transport in Surface Boundary Exosphere (different species have different binding energies)
- What does leakage rate of He and ^{40}Ar say about state of the lunar interior? (global seismic network)

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The Lunar Atmosphere and Dust Environment Explorer Mission (LADEE) Hardcover – June 16, 2015

by Richard C. Elphic (Editor), Christopher Russell (Editor)

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This volume contains five articles describing the mission and its instruments. The first paper, by the project scientist Richard C. Elphic and his colleagues, describes the mission objectives, the launch vehicle, spacecraft and the mission itself. This is followed by a description of LADEE's Neutral Mass Spectrometer by Paul Mahaffy and company. This paper describes the investigation that directly targets the lunar exosphere, which can also be explored optically in the ultraviolet. In the following article Anthony Colaprete describes LADEE's Ultraviolet and Visible Spectrometer that operated from 230 nm to 810 nm scanning the atmosphere just above the surface. Not only is there atmosphere but there is also dust that putatively can be levitated above the surface, possibly by electric fields on the Moon's surface. Mihaly Horanyi leads this investigation, called the Lunar Dust Experiment, aimed at understanding the purported observations of levitated dust. This experiment was also very successful, but in this case their discovery was not the electrostatic levitation of dust, but that the dust was raised by meteoroid impacts. This is not what had been expected but clearly is the explanation that best fits the data.

Originally published in Space Science Reviews, Volume 185, Issue 1-4, 2014.

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Initial LADEE Publications

Szalay, J. and M. Horanyi, The Search for Electrostatically Lofted Grains Above the Moon with the Lunar Dust Experiment (2015) ***Geophys. Res. Lett.*** (accepted), DOI: 10.1002/2015GL064324

Benna, M., P. R. Mahaffy, J. S. Halekas, R. C. Elphic and G. T. Delory, Variability of helium, neon, and argon in the lunar exosphere as observed by the LADEE NMS instrument (2015) ***Geophys. Res. Lett.***, 42, 28 May 2015, 3723–3729, DOI: 10.1002/2015GL064120

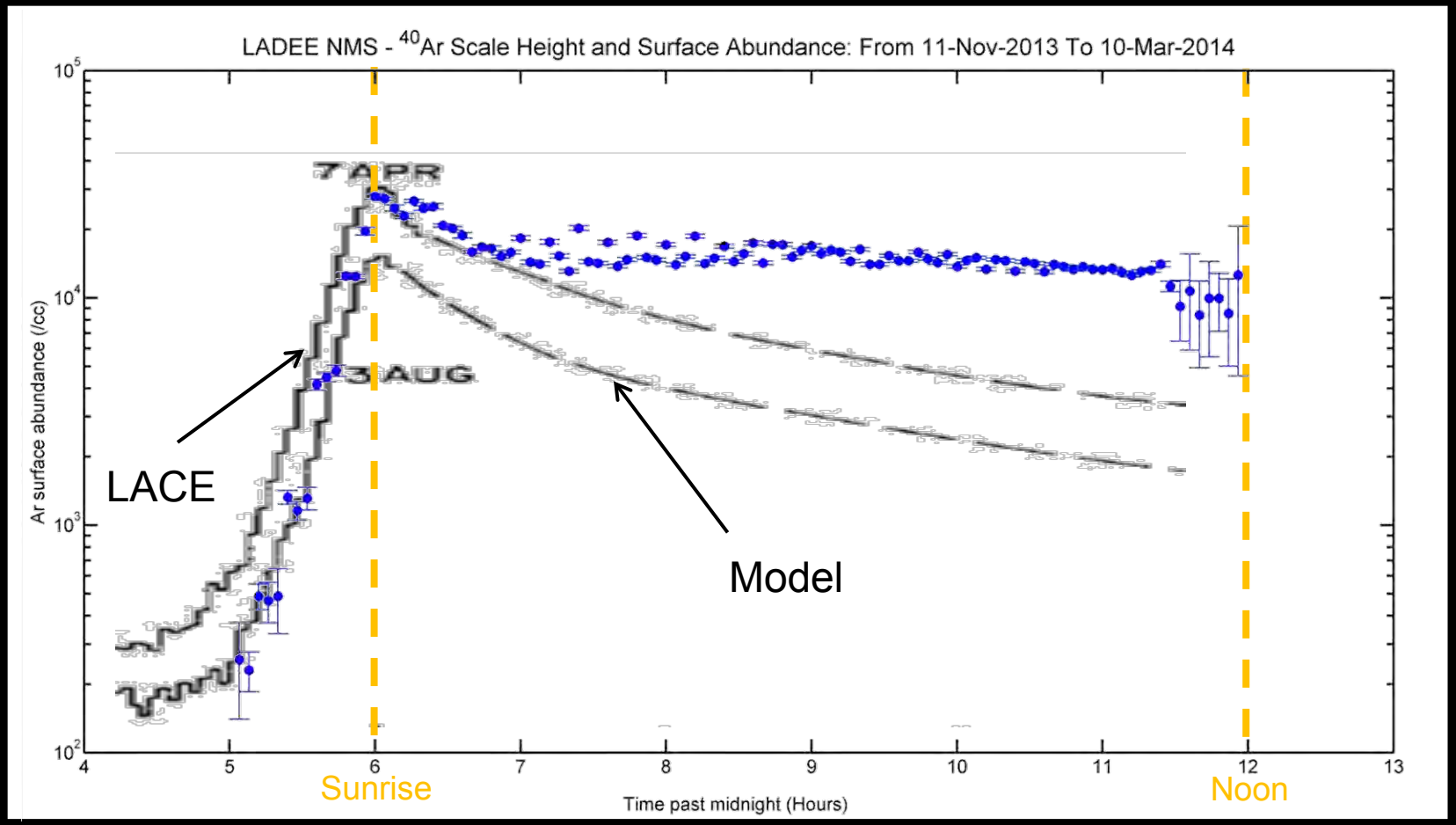
Horányi, M., J. R. Szalay, S. Kempf, J. Schmidt, E. Grün, R. Srama & Z. Sternovsky (2015) ***Nature***, 522, 324–326, doi:10.1038/nature14479

Halekas, J. S., M. Benna, P. R. Mahaffy, R. C. Elphic, A. R. Poppe, and G. T. Delory (2015), Detections of lunar exospheric ions by the LADEE neutral mass spectrometer, ***Geophys. Res. Lett.***, 42, doi:10.1002/2015GL064746.

Hurley, D. M., M. Sarantos, C. Grava, J.-P. Williams, K. D. Retherford, M. Siegler, B. Greenhagen, D. Paige, An analytic function of lunar surface temperature for exospheric modeling (2015), ***Icarus****, 255,* 159, doi:10.1016/j.icarus.2014.08.043.

Hurley, D. M., et al., Understanding Temporal and Spatial Variability of the Lunar Helium Atmosphere Using Simultaneous Observations from LRO, LADEE, and ARTEMIS (2015), *Icarus (accepted).*

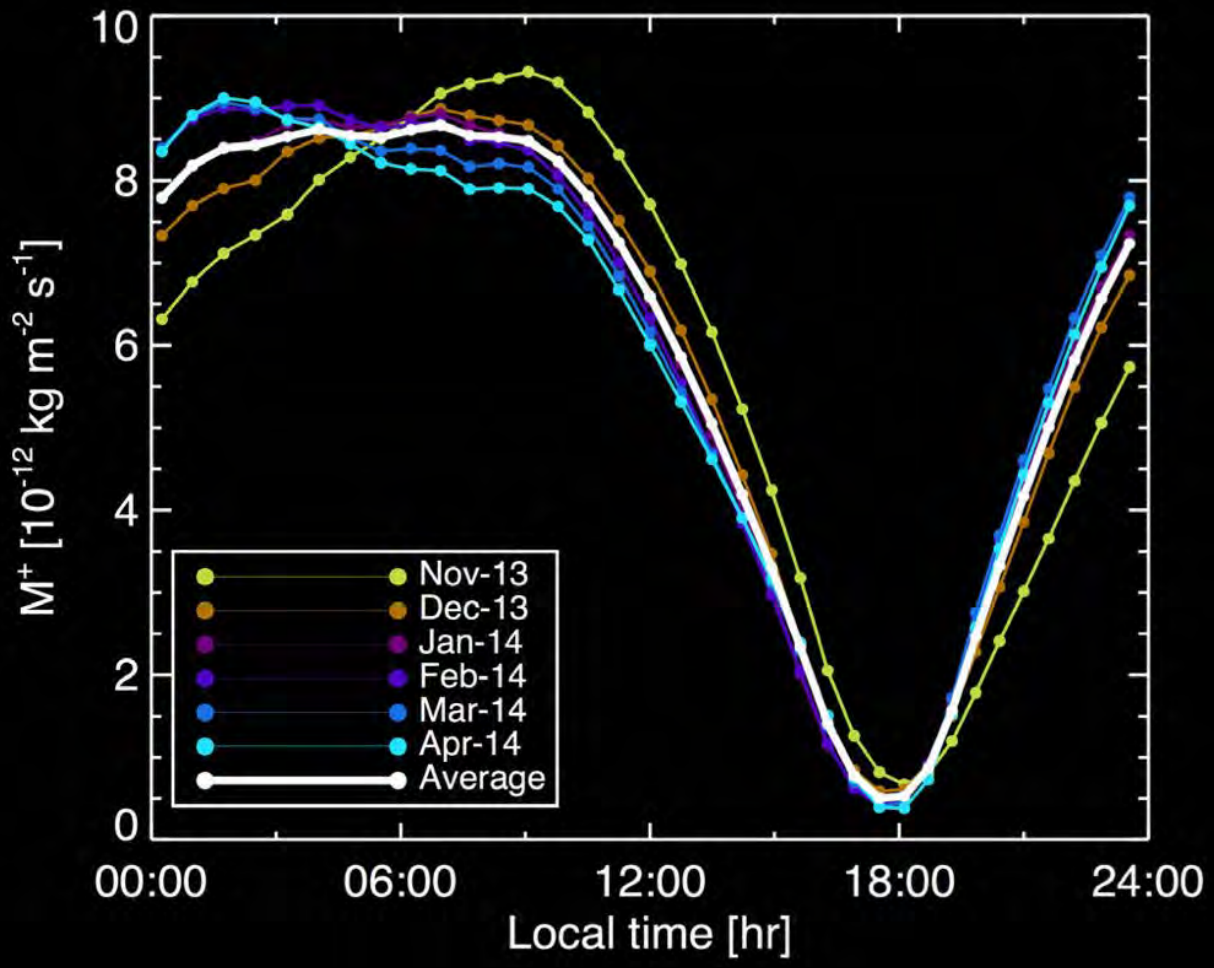
Diurnal Variability of ^{40}Ar



Apollo 17 -LACE data from Hodges and Hoffman, 1975

Dust Mass Production Fn

Horanyi, et al., *Nature*, 2015



- During LADEE mission, peak is broad, centered on dawn
- But interplanetary mass flux changes with Earth-Moon orbit about sun
- Different months have different peak locations in LT.

LADEE Overview/Instrument Papers

Elphic, R.C., et al. (2014) The Lunar Atmosphere and Dust Environment Explorer Mission, ***Space Sci. Rev.***, 185, 1-4, doi:10.1007/s11214-014-0113-z

Mahaffy, P., et al., The Neutral Mass Spectrometer on the Lunar Atmosphere and Dust Environment Explorer Mission (2014) ***Space Sci. Rev.***, 185:43, DOI: 10.1007/s11214-014-0043-9

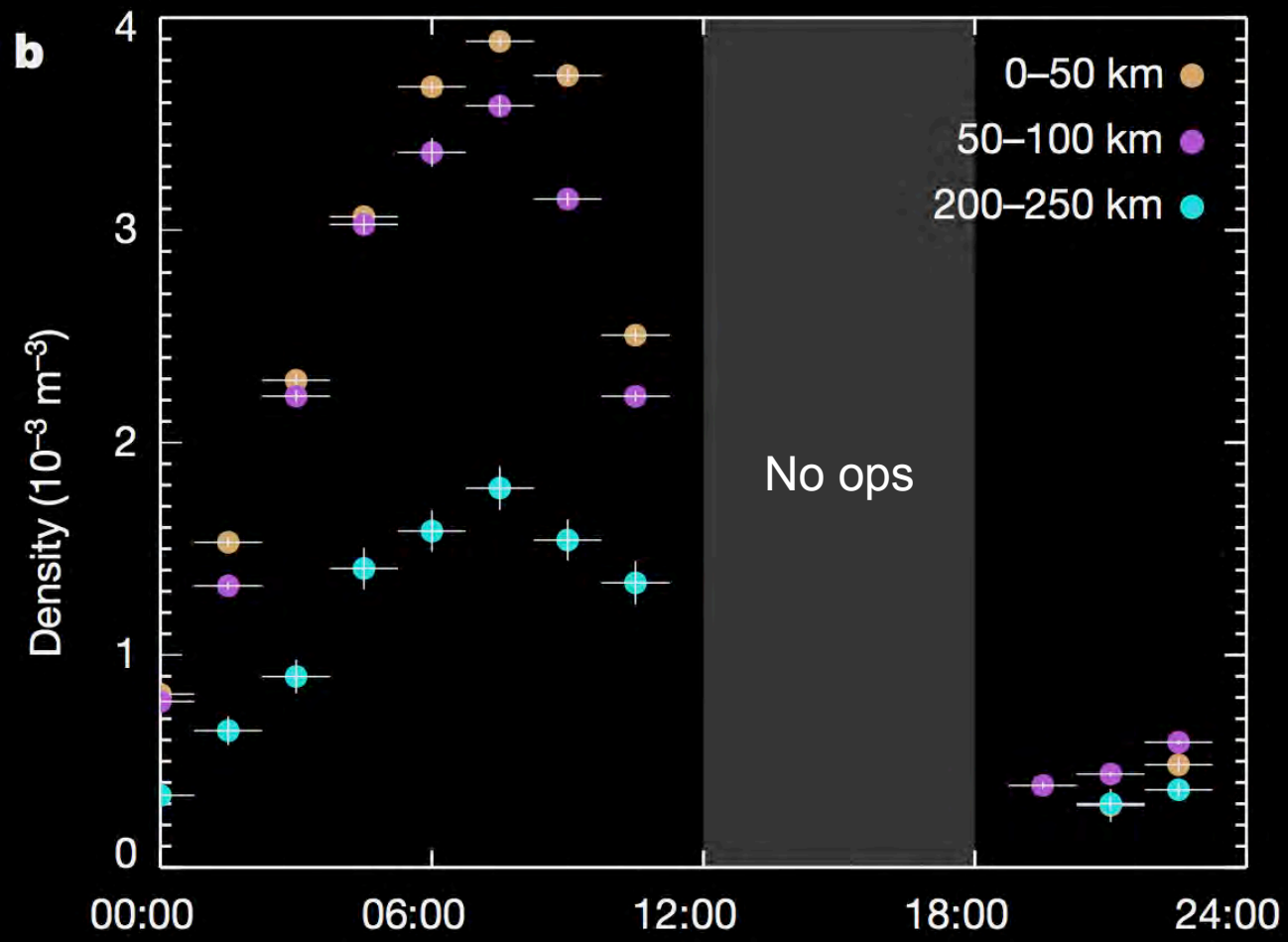
Horanyi, M, et al., The Lunar Dust Experiment (LDEX) Onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) Mission (2014), ***Space Sci. Rev.***, 185:93, DOI: 10.1007/978-3-319-18717-4_5

Colaprete, A., et al., An Overview of the LADEE Ultraviolet-Visible Spectrometer (2014), ***Space Sci. Rev.***, 185:63, DOI: 10.1007/978-3-319-18717-4_4

Boroson, D., et al., The Lunar Laser Communication Demonstration: NASA's First Step Toward Very High Data Rate Support of Science and Exploration Missions (2014), ***Space Sci. Rev.***, 185:63, DOI: 10.1007/978-3-319-18717-4_6

Dust Density vs. LT

Horanyi, et al., *Nature*, 2015



- During LADEE mission, peak is post-dawn
- Density appears to level off at lowest altitudes