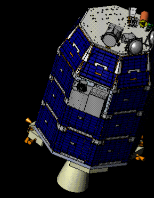

The Lunar Atmosphere and Dust Environment Explorer (LADEE) Mission

Highlights of Mission Results

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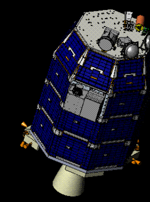
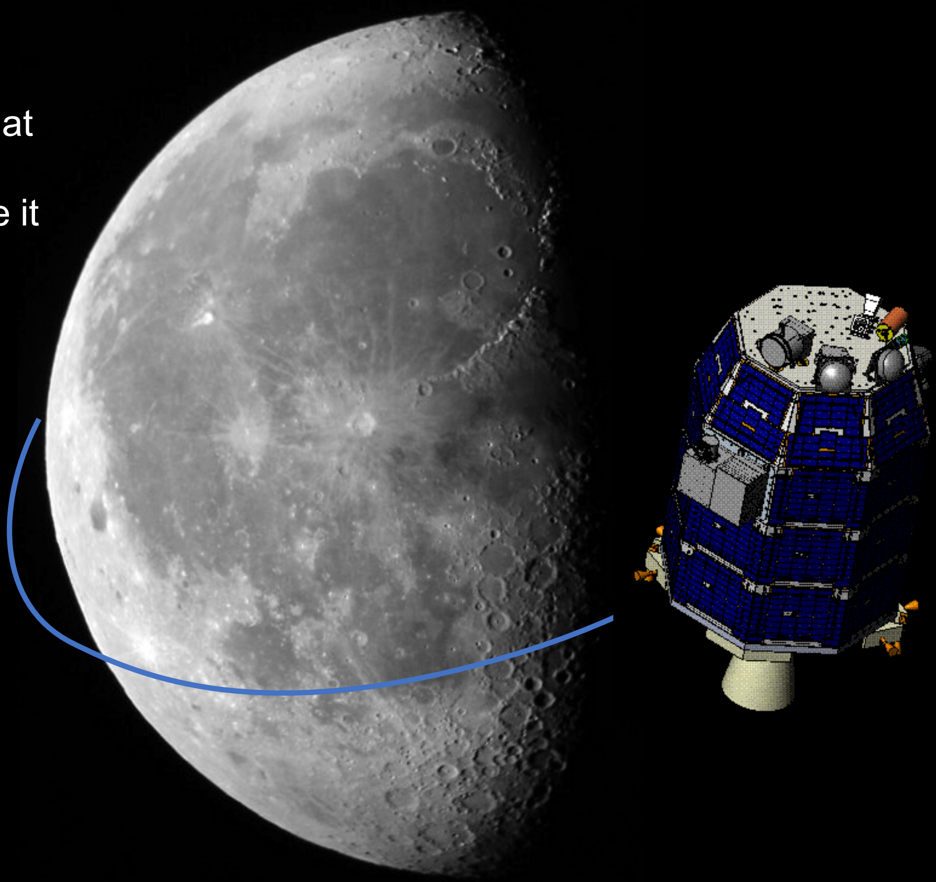
[4] Department of Astrophysical Sciences, Princeton University
[5] Department of Physics and Astronomy, University of Iowa
[6] Laboratory for Atmospheric and Space Physics, University of Colorado

LADEE at glance



Science:

- Determining the composition of the lunar atmosphere and investigating the processes that control its distribution and variability, including sources, sinks, and surface interactions, before it is perturbed by further human activity.
- Characterize the lunar exospheric dust environment and measure any spatial and temporal variability and impacts on the lunar atmosphere.



Technology:

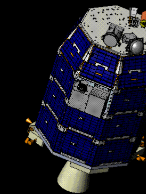
- Test laser communication capabilities.
- Demonstrate a low-cost lunar mission:

Mission Timeline:

- Launch: Sep. 2013
- End of Mission (Surface impact): Apr. 2014

Orbit:

- Low-altitude (25-100 km), retrograde, near equatorial



Instrumentation

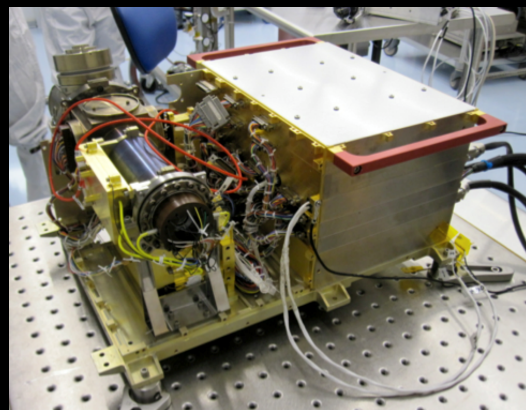
Neutral Mass Spectrometer (NMS)
MSL/SAM Heritage

P. Mahaffy
NASA GSFC

In-situ measurement of exospheric species

2-150 Da

Unit mass resolution

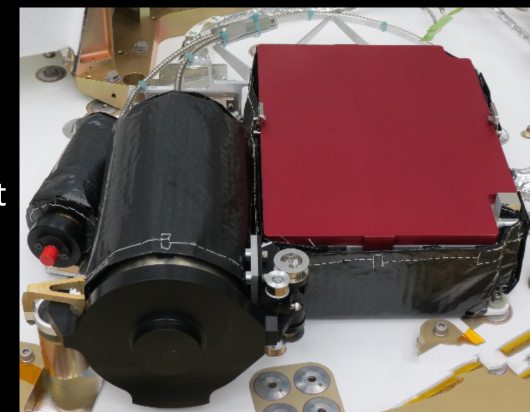


UV-Vis Spectrometer (UVS)
LCROSS Heritage

A. Colaprete
NASA ARC

Remote sensing measurements of dust and exosphere

250-810 nm



Lunar Dust EXperiment (LDEX)
HEOS 2, Galileo, Ulysses and Cassini Heritage

M. Horányi
LASP

In-situ measurement of dust

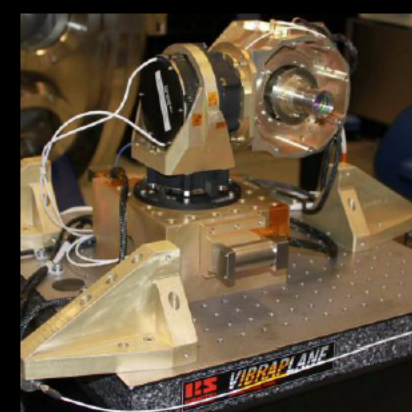
r >0.3 microns

Lunar Laser Com Demo (LLCD)
Technology demonstration

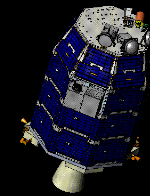
D. Boroson
MIT-LL

High data rate optical communication

51-622 Mbps

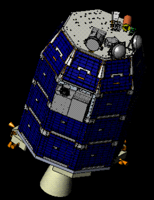


Key science results

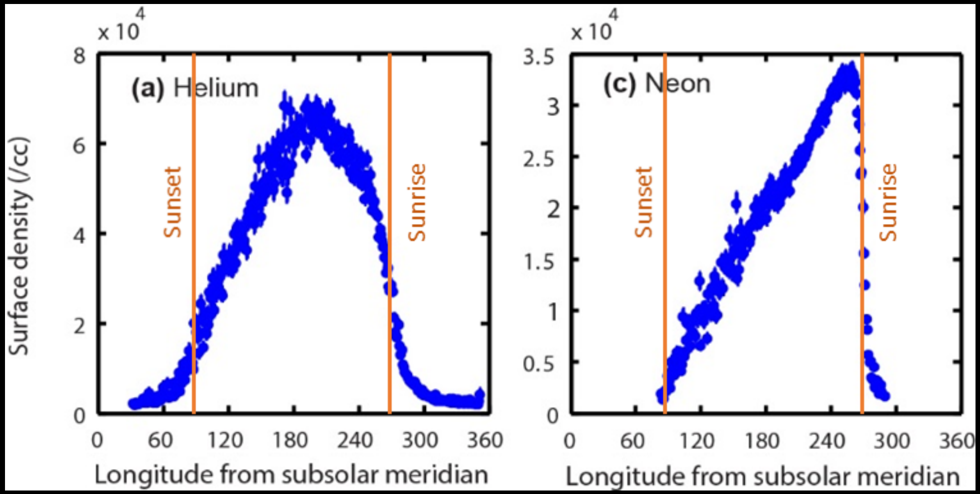


- Mapping of distribution and temporal variation of major constituents of the exosphere (He, Ne, Ar).
- Detection of several minor species in neutral and ion forms: CH_4, OH/H_2O, Na, Mg, Al, K, Ti, H_2^+, He^+, C^+, N^+, Ne^+, Na^+, K^+, CO^+, and Ar^+).
- Characterization of surface dependencies and external control of the exosphere by solar wind and meteoroid impacts.
- Observations of sporadic water releases that constrained on the water budget and cycle at the Moon.
- Observations of CH_4, C^+ , and CO^+ that provided indication of the presence of a Carbon cycle at the Moon.
- Detection and characterization of the lunar dust cloud.
- First of its kind direct characterization of meteoroid streams.

Structure and dynamics of the exosphere

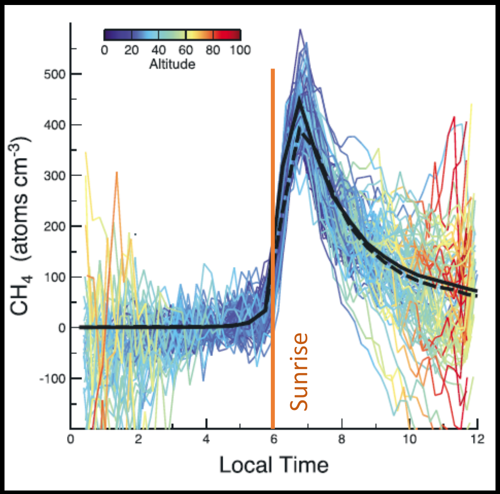


Non-condensable species (e.g., He and Ne)



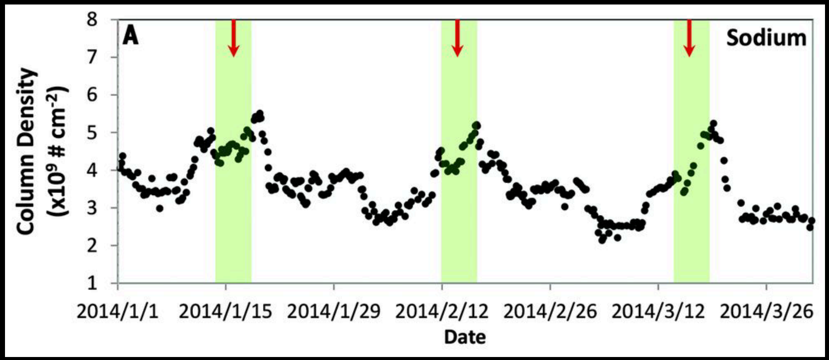
Benna et al., Geophys. Res. Lett., 2015

Condensable species (e.g., CH_4)



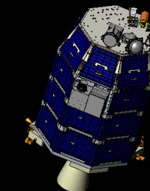
Hodges, Geophys. Res. Lett., 2016

Alkalis metals (e.g., Na)



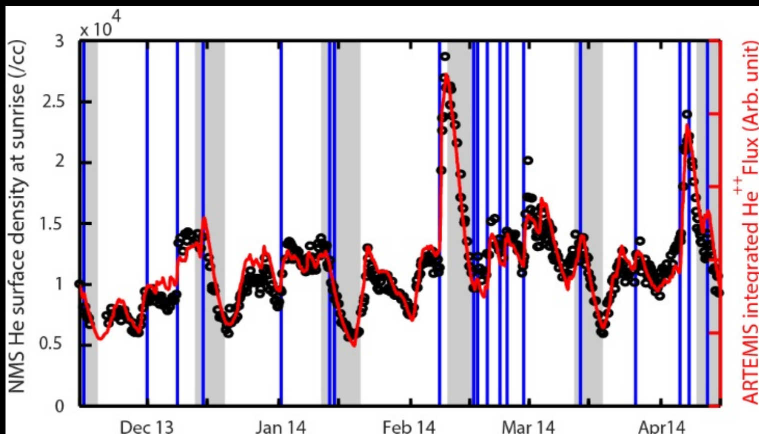
Colaprete et al., Science, 2016

- NMS and UVS characterized the diurnal variation of several volatiles species (He, Ne, Ar, CH_4, Na, and K).
- They showed that the local time distributions of these species are strongly linked to their release and transport processes.



Response to external inputs

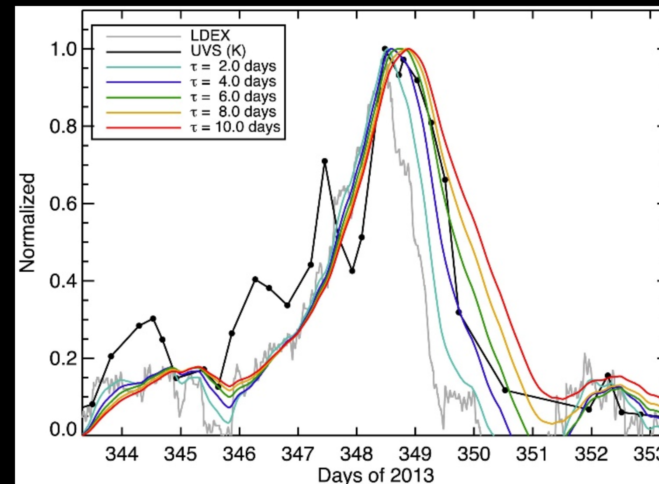
Solar wind control (e.g., He)



Benna et al., Geophys. Res. Lett., 2015

- NMS has shown that the majority of He is of solar wind origin, and thus tracks changes in the solar wind flux.
- NMS has also revealed an endogenous source (radiogenic decay of ^{232}Th and ^{238}U) that supplies the exosphere at ~20% the rate of solar wind.

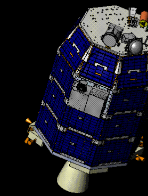
Micrometeoroid control (e.g., K)

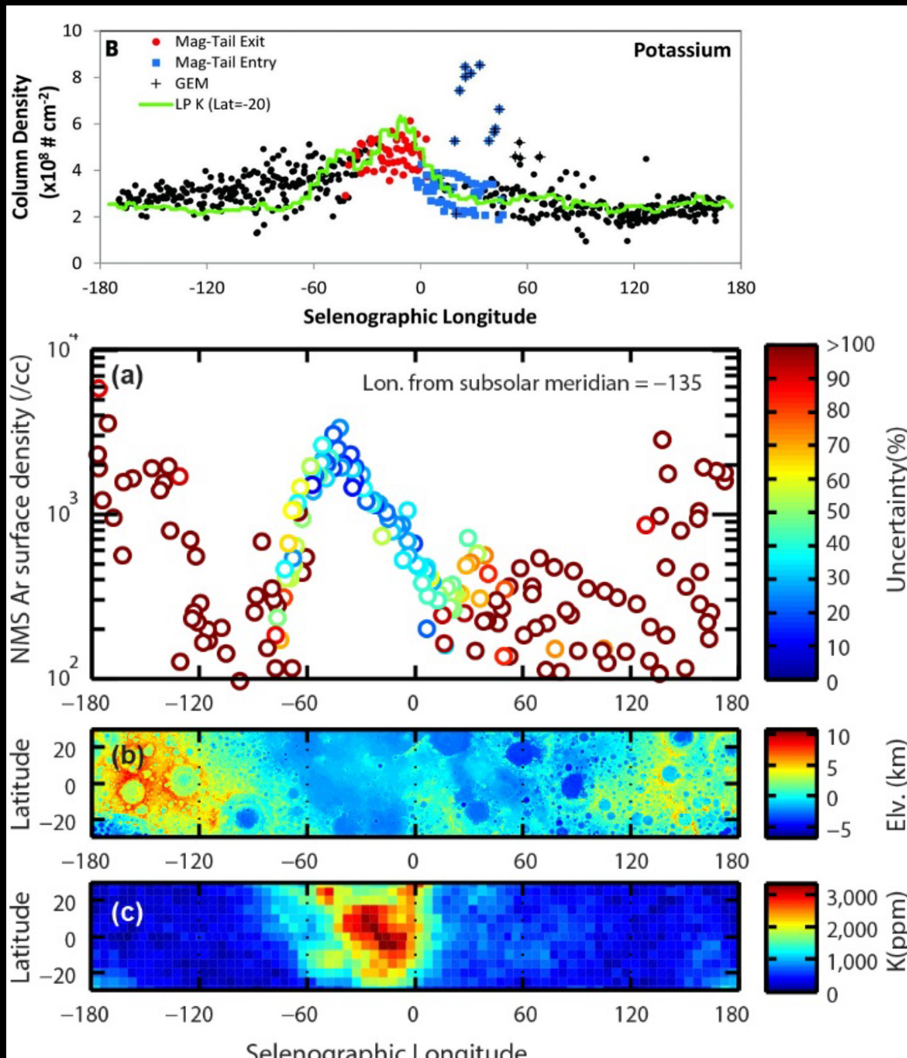


Szalay et al., Geophys. Res. Lett., 2016

- UVS and LDEX showed that the K exosphere responds well to the increase of surface bombardment by micrometeoroids during major meteor showers. However, Na does not.

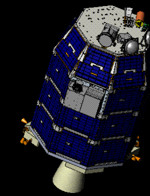
Surface - exosphere coupling





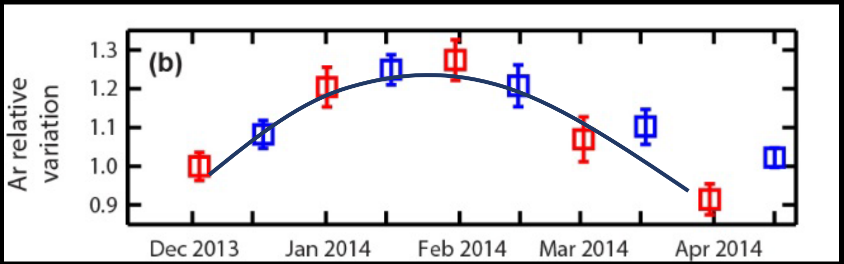
Combined from Benna et al., Geophys. Res. Lett., 2015, and Colaprete et al., Science, 2016

- NMS and UVS have revealed that the exospheric distribution of volatiles such as Ar and K translates spatial variation of their abundances and the nature of their interactions with the surface.
- Potassium exospheric distribution is correlated with the presence of the KREEP enrichment.
- Argon exospheric distribution exhibits a bulge over the western maria region. This is indicative of a localized area of regolith with lower activation energy for desorption.



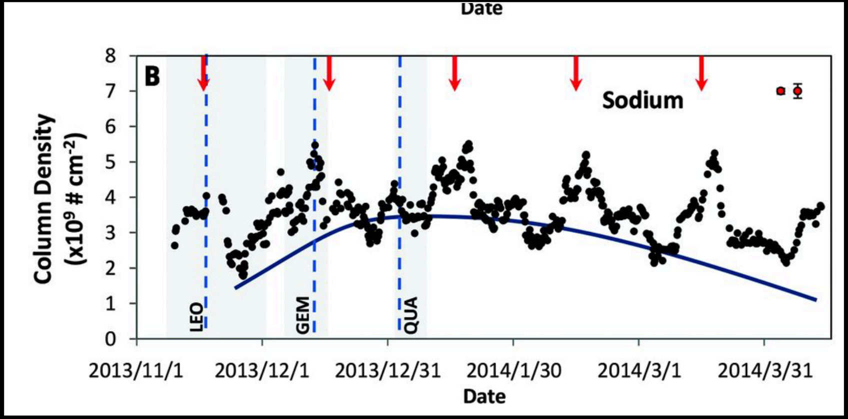
Long-term evolution of the exosphere

semiannual exospheric oscillations (e.g., Ar)



Benna et al., Geophys. Res. Lett., 2015

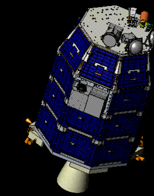
(e.g., Na)

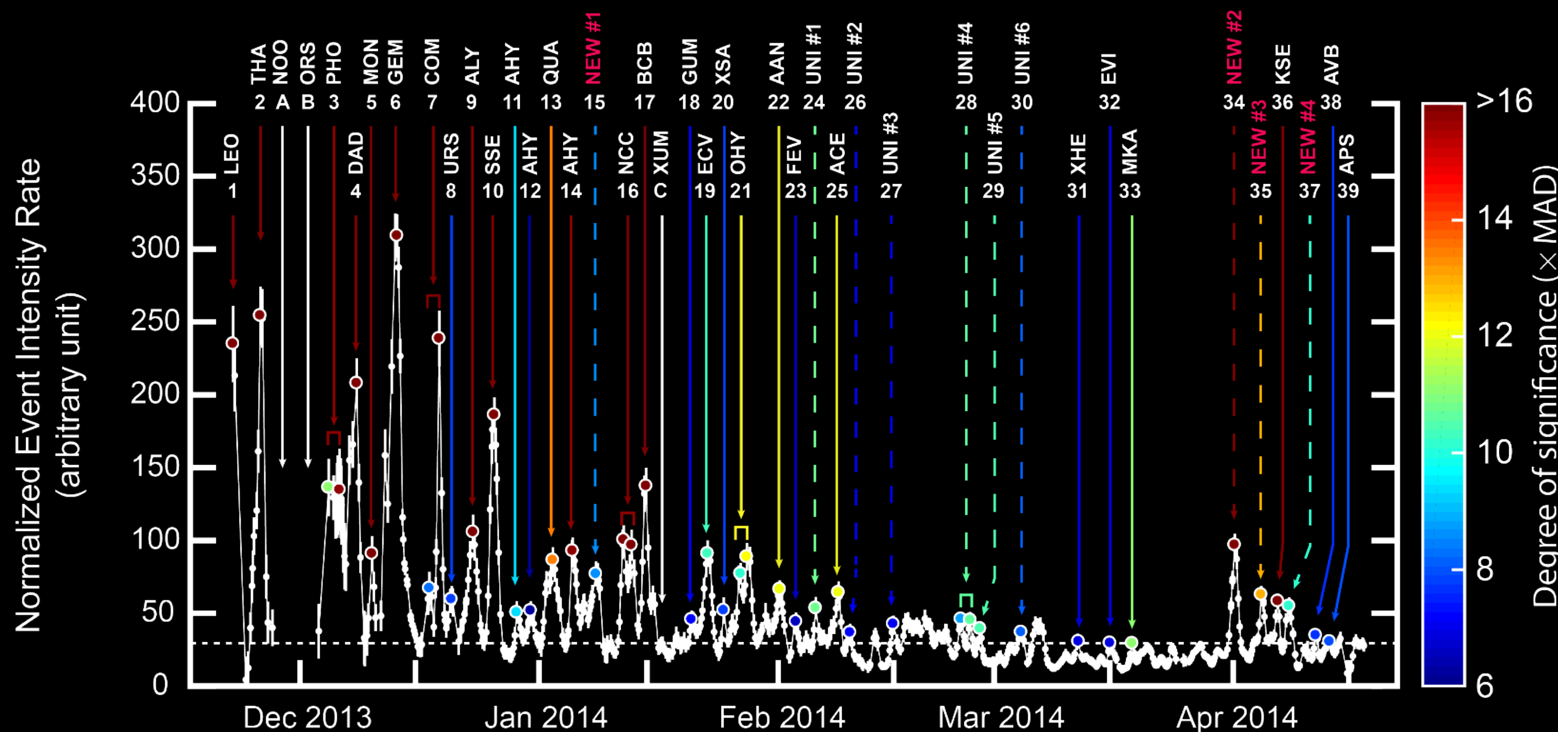


Colaprete et al., Science, 2016

- NMS and UVS have revealed that Argon and Sodium exhibit notable semiannual exospheric variations.
- The source of these oscillations remains unclear but data from LDEX strongly suggest a control by micrometeoroid bombardment.

Water released by micrometeoroid impacts

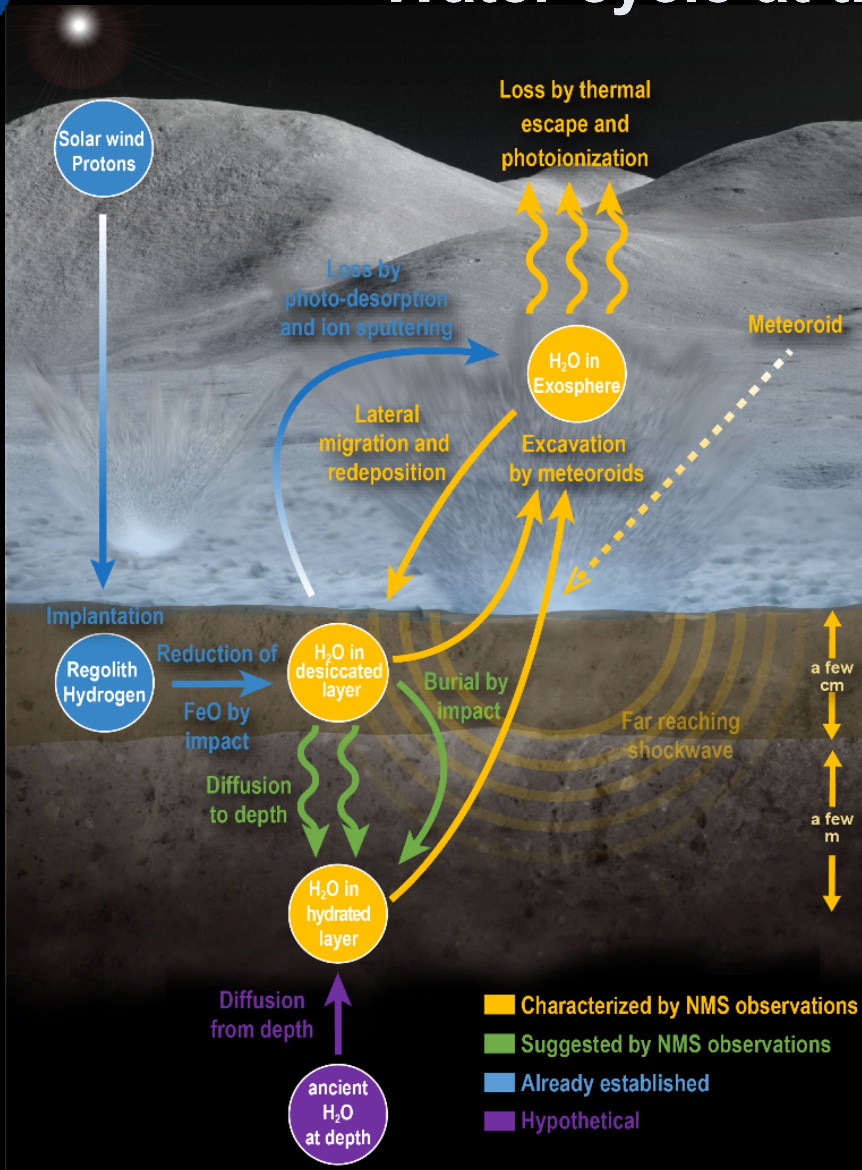




Benna et al., Nature Geo., 2019

- NMS detected water releases spike when the Moon encountered strong meteoroid streams (observed at the Earth as meteor showers).
- This provides strong indications that micrometeoroid impact + lateral transport provide a continuous source for the water ice observed in the PSRs.

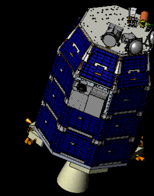
Water cycle at the Moon

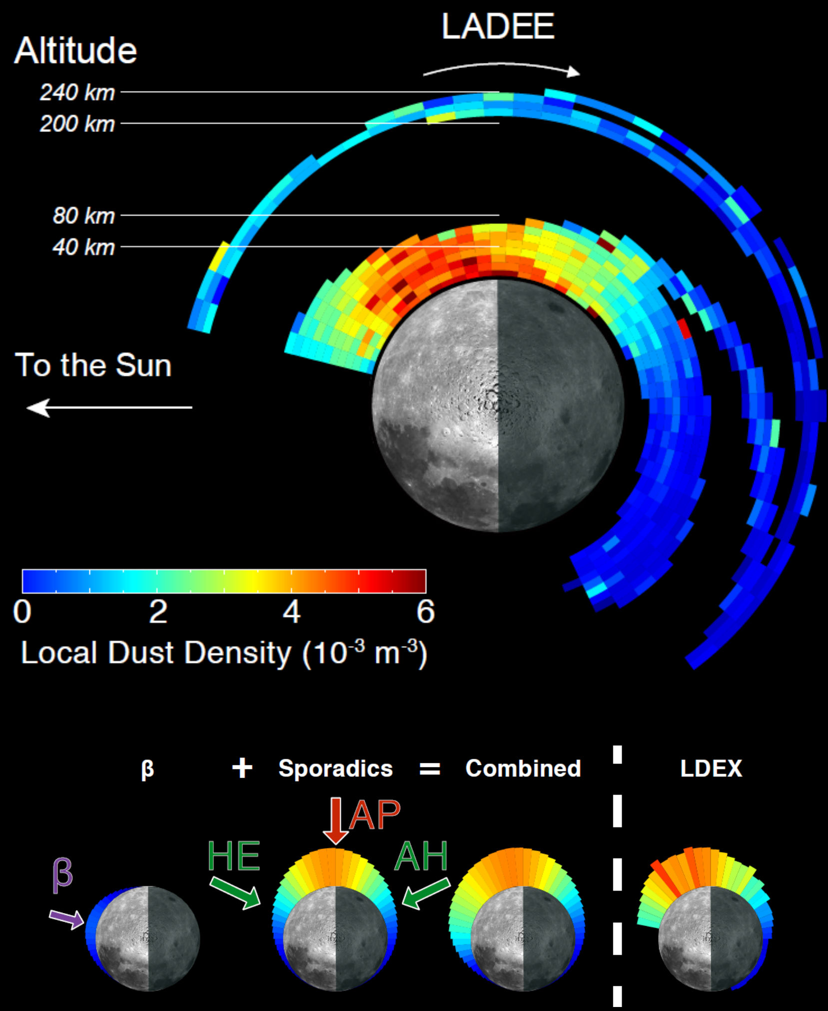


Benna et al., Nature Geo., 2019

- The analysis of the amount and intensity of water releases reveals that the uppermost few centimeters of lunar soil are very dry (< 5 ppm). Below this thin layer, water is present at average concentrations of up to 500 ppm by weight.
- The release rate of water indicates that the Moon is presently in a net water loss regime (50 – 200 tons/year) that is not balanced by solar wind-driven production.
- This is most likely ancient water that was either delivered long ago or was present at lunar formation.

Lunar dust cloud

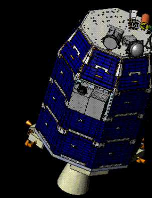




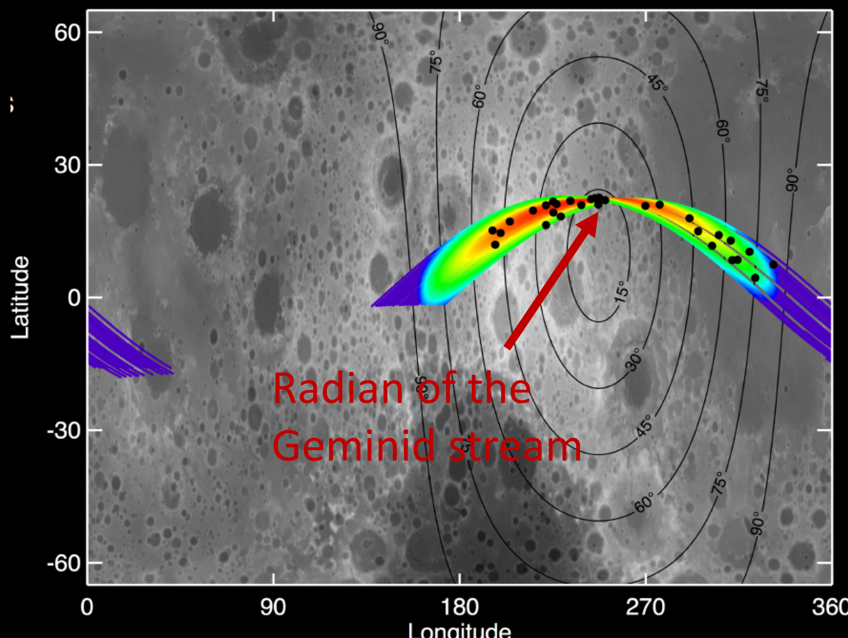
Adapted from Horanyi et al., Nature, 2015 and Szalay et al., Astrophys. J. lett, 2020.

- LDEX has detected and characterized a tenuous but persistent asymmetric dust cloud around the Moon (grain radii ~0.3 to >0.7 μm).
- The dust cloud is caused by ejecta from high-speed cometary dust particles on eccentric orbits and from β-meteoroids (small grains being pushed out of the solar system by radiation pressure).
- LDEX did not find evidence for electrostatically-lofted dust down to altitudes of a few kilometers.

Characterization of meteor streams

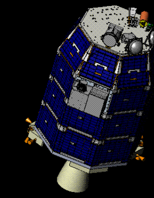


Distribution of bursts detected by LDEX around peak of Geminids



Adapted from Szalay et al., Icarus, 2016

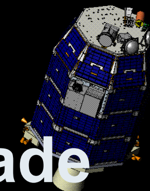
- LDEX provided the first of its kind direct characterization of meteoroid streams using detection of burst events.
- The timing and location of the most intense period of bursts is used to independently determine the radiant of several meteoroid streams.



The Legacy of LADEE (1)
New questions and knowledge gaps

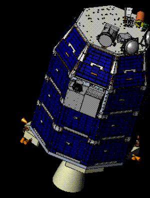
- LADEE's observations of water established a global loss rate due to micrometeoroids impact:
  - What are the other sources and sinks that control the water cycle ?
  - How does the water cycle play into the current state of the PSR ?
- LADEE observation of dust ejecta inferred a gardening rate of lunar regolith: How does it relate to the long-term gardening rates inferred from Apollo drill cores and LRO observations?
- LADEE observed a strong response of He to solar activity: How does this translate to reactive species (e.g. C-, N- and O- molecules) ?
- How does the exosphere of the Moon respond to uptick in the chemical and physical disturbances generated by increased human exploration ?

The Legacy of LADEE (2)
New target observations for the next decade



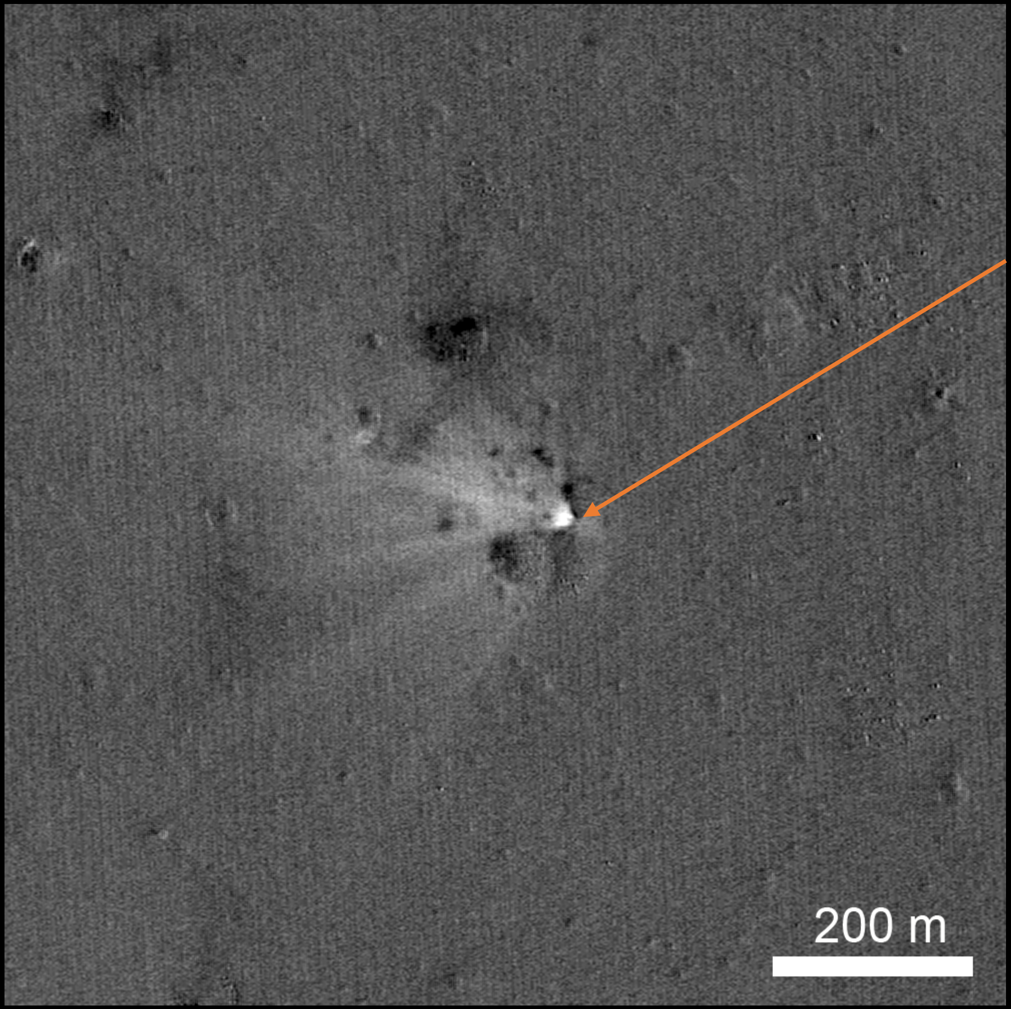
- ❖ Expand measurements of exospheric dust, neutrals, and ions:
    - From a polar orbit.
    - At low altitude on the dusk side.
    - Taken during the other half of the year (May-Oct).
- ❖ Coordinated surface and orbital measurements.
- ❖ Improved spatial resolution of water distribution on the surface and the exosphere.
- ❖ Orbital measurements to detect global transient or long lasting surface activities.
- ❖ Composition of dust ejecta to allow for surface chemical/isotopic mapping, including PSRs, from orbit.

Summary



- Despite its relatively short mission duration, LADEE yielded a rich and compelling set of observations using its three science instruments:
- These observations:
  - ✓ Expended the inventory of the known volatiles that makes the lunar exosphere.
  - ✓ Characterized the selenographic and temporal variations of major exospheric constituents.
  - ✓ Identified and explored few of the processes by which surface, solar wind, and meteoroids control the lunar exosphere and affects volatile migration to the PSRs.
  - ✓ Established the presence of a dust cloud as a permanent feature of the lunar space environment.

Q&A



LADEE impact site (near Sundman V crater eastern rim)