Lunar Volatiles Orbiter:
A Solar System Volatiles Mission
The Origin, Evolution and Fate of Volatiles on Airless Bodies

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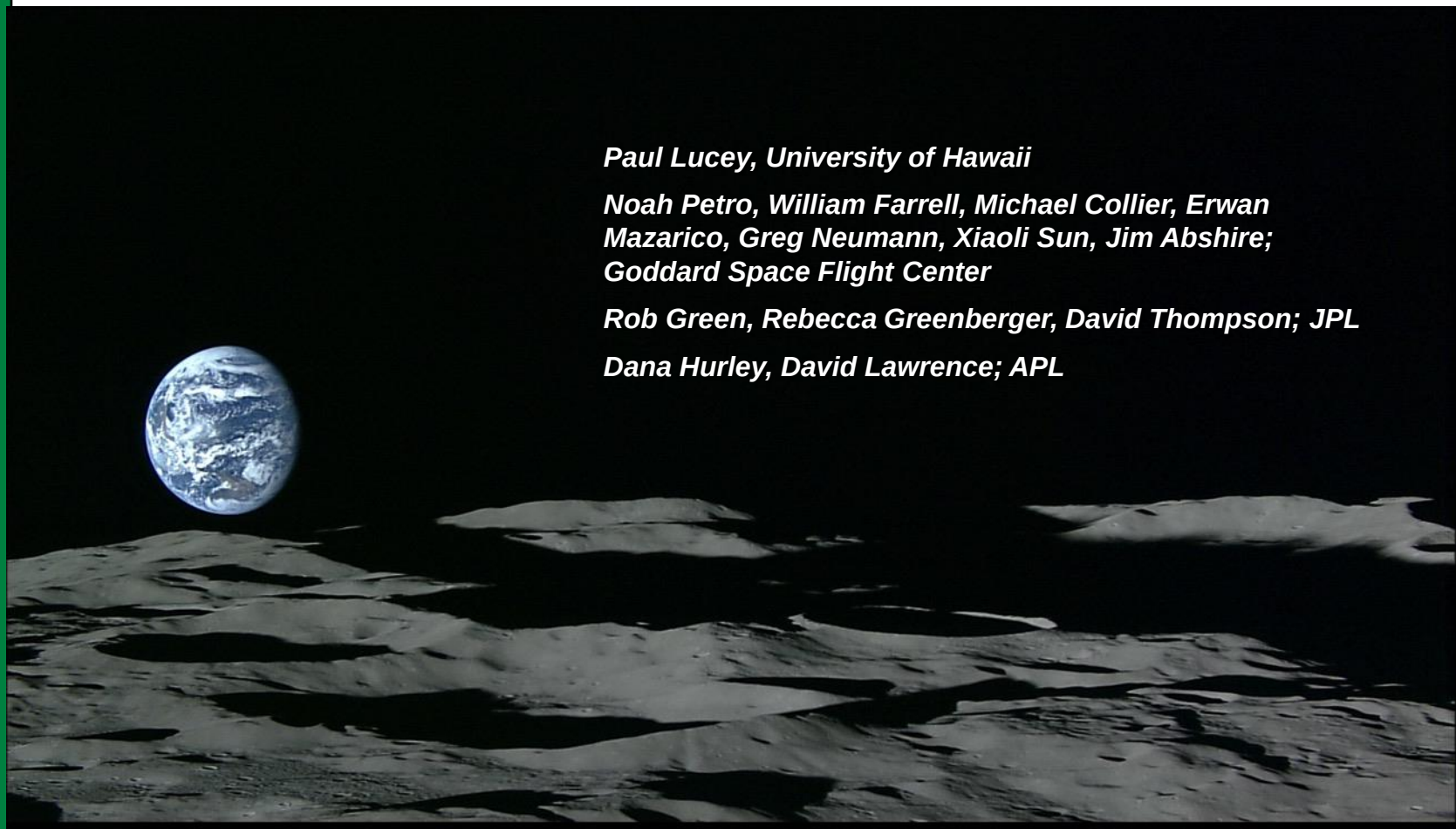
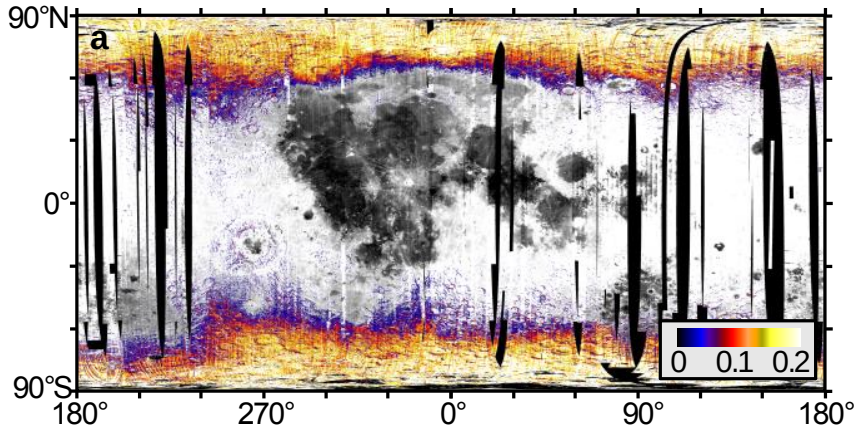
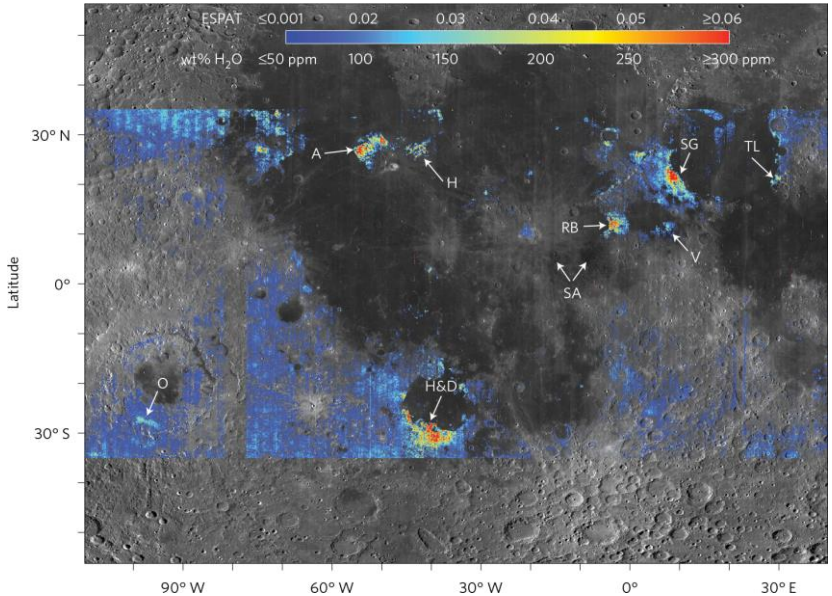


Post-LRO Orbital Measurements: Why?

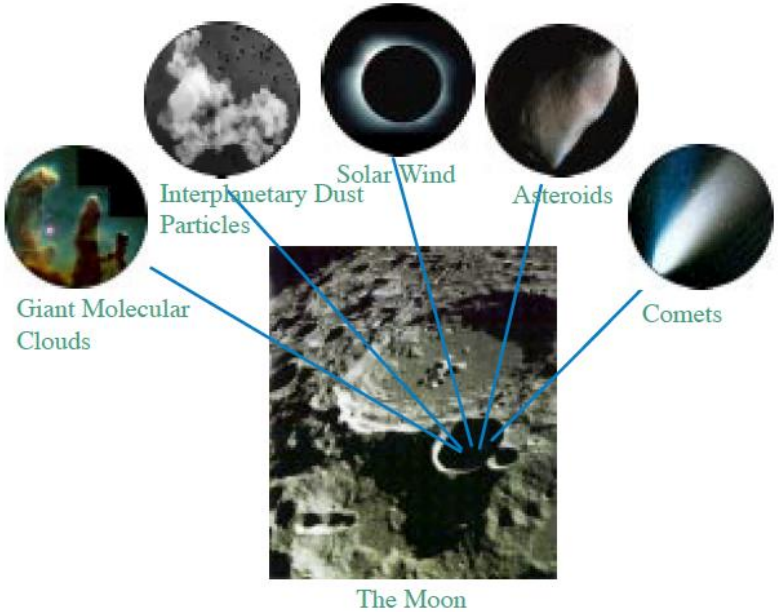


Klima and Petro (2017) above (OH band depth) and Milliken and Li (2017) below (wt equivalent H2O) show the data is subject to interpretation

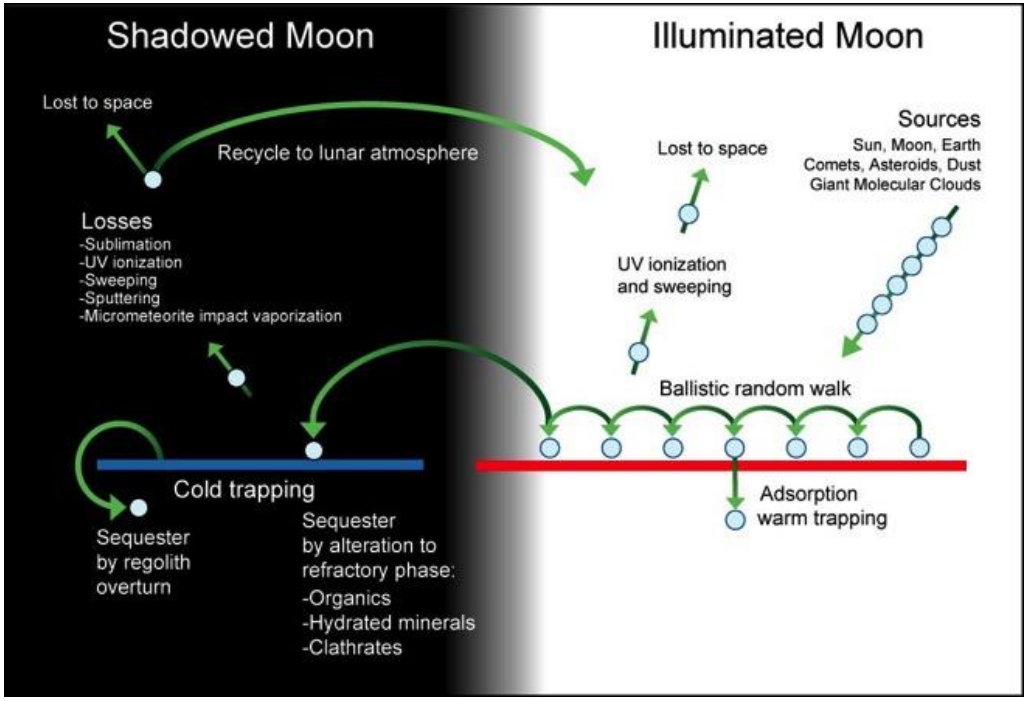


- **"Lunar Polar Volatiles: Assessment of Existing Observations for Exploration" HEOMD whitepaper highlights the known-knowns and unk-unk's for volatiles (Hurley et al., 2015)**
- **From "Bone Dry" (figurative) to bone dry (literal):**
  - **Discovery of lunar internal water (Saal et al. 2008)**
  - **Discovery of lunar surface water (Cassini, Chandrayaan-1, Deep Impact).**
  - **Discovery of buried water within PSRs (LCROSS).**
  - **Discovery of surface ice at Mercury poles (Neumann et al. 2013), different from what is observed at the Moon**
  - **Surface ice in permanent shadow (Zuber et al. 2013; Lucey et al. 2014;Hayne et al. 2015; Li et al. 2017)**
  - **Possible mobile surface water on the Moon (Sunshine et al. 2009; Hendrix et al. 2013; McClanahan et al. 2015; Schwadron et al., 2017)**
  - **Multiple interpretations of the M^3 data based on characterization of the thermal signature**
- **Build on detections and resolve ambiguities to produce definitive maps of abundances of specific chemical compounds including polar surface ice and organics, non-polar water and hydroxyl at 50-m resolution.**
- **Constrain buried hydrogen chemistry through characterization of small crater ejecta in permanent shadow and lofted grains from small meteorite impacts.**

Lunar Volatile System: Sources, Transport and Sinks



External sources of lunar volatiles



Lunar volatile transport system (Lucey et al. 2009)

- **Polar volatiles can originate from sources within the Moon, the solar system and beyond**
- **Water is transported to sinks across the lunar surface**
- **The polar environment is a key sink the the lunar volatile transport system**

Lunar Volatile System: Sources, Transport and Sinks

- **The Moon as a Water World**
  - **The chemical properties of molecular water and its resource potential make it a uniquely important volatile that may be decoupled from others in sourcing and transport**
  - **The detailed behavior of water with latitude on the surface and in the atmosphere is very poorly known**
  - **The distribution of surface water ice is patchy and the control on its distribution is unknown**
- **The Hydrogen Cycle**
  - **The solar wind is a key input to the lunar environment and may explain some of the key observations such as diurnally variable infrared and UV absorption**
  - **This hydrogen may be the source of OH and possibly involved in water creation**
  - **Understand how the solar wind *hydrogenation* connects to the observed *hydroxylation* and possibly connect to the lunar *hydration***
- **Ancient-modern Connection and the Ancient Volatile Supply**
  - **The connection between the contemporary volatile system and buried H detected by neutron spectroscopy and other volatiles by LCROSS is unknown. Do these reservoirs communicate, and is the buried system renewed by the current volatile supply?**
  - **Volatile inputs to the lunar system were much larger in the past, including more frequent comet and wet asteroid impact, and supply from volcanic eruptions. How can detailed understanding of the contemporary system inform understanding of the ancient deposition of volatiles. Impacts mobilizing older igneous rock, possible lower crust volatile reservoir**

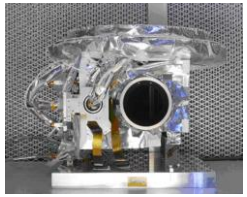
The Moon as a Water World

- What is the current abundance and state of water on the lunar surface?
- Is lunar surface water mobile?
- How do surface and near surface volatiles relate to sources, transport and sinks?
- What is the intrinsic abundance of internal water as revealed in water in major igneous rock types?

What Measurements Are Needed?

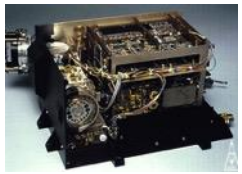
PPM detection of water day and night

Global Coverage, high resolution spectroscopy of the 3.0 µm band



Global mapping of molecular water

Hydrogen Mapping

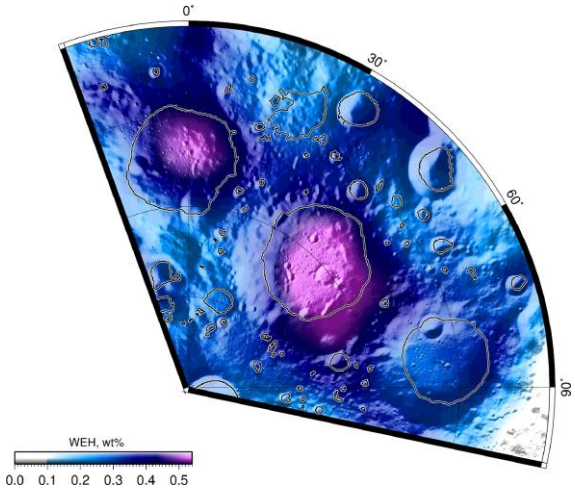


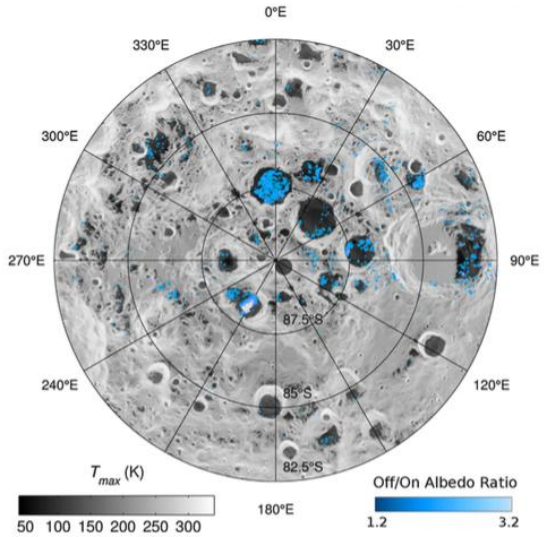
Flux of ions in and out of cold traps/poles

Instrument
Spectroscopic Infrared Reflectance LIDAR
Lunar Volatiles Spectrometer
Water Molecular Detector
Dust MS
Neutral Mass Spectrometer
Ion Mass Spectrometer
Gamma-Ray/Neutron Spectrometer

Limitations of current data

Sanin et al (2016) Icarus





Hayne et al. (2015) Icarus

- **Ambiguity between water and hydroxyl in current data**
  - **Is water present? Is it mobile?**
  - **What mineral hosts water or hydroxyl in endogenous exposures?**
- **Surface ice is present in permanent shadow but in very limited exposures**
  - **High uncertainties on individual locations**
  - **What is the depth distribution and lateral heterogeneity?**
- **Relative importance of sources is not constrained**
  - **What are the contributions from meteoroids, comets, outgassing, and solar wind, all potential substantial sources?**

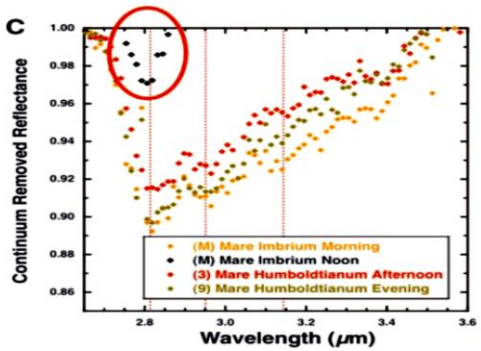
Water World: LVO Contribution

LVO measurements will definitively determine:

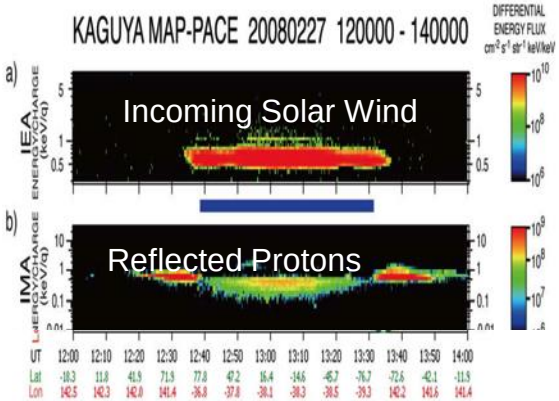
- The global distribution and chemical state of surface water in time, temperature and space
- The rate of input of water to the lunar water cycle, its transport through and loss from the volatile system, and its final sequester in sinks
- Depth distribution of volatiles and variability in polar regions
- The total inventory of surface endogenic water

- **Laser spectroscopy, 1.5-3.5 microns**
  - **Definitive detection of diurnal variation of water or hydroxyl through laser reflectance measurements**
    - **No thermal background contamination issues**
  - **Polar ice detection and mapping**
- **Imaging spectroscopy, 0.5-3.6 microns**
  - **Global mapping of volatile species**
  - **Low light ice spectroscopy in most permanent shadow**
  - **Detection of carbon compounds**
- **Molecular water detection and mapping**
  - **Definitive detection of molecular water using 6 micron water fundamental**
  - **No ambiguity with hydroxyl**
- **High resolution neutron/gamma spectroscopy**
  - **Abundance at depth for key small regions**

Hydrogen Cycle: Solar Wind and Surface Interactions



EPOXI OH (Sunshine et al., 2009)



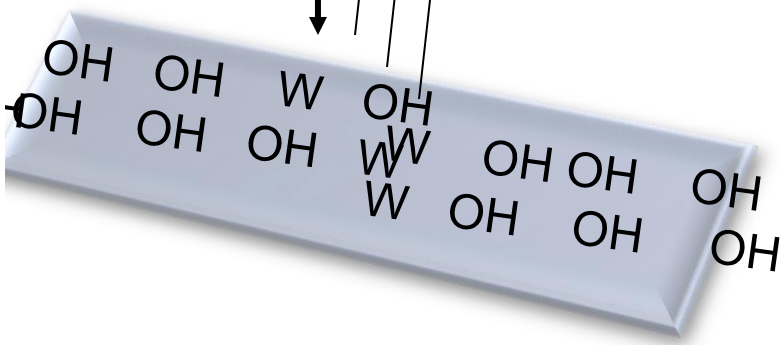
Kaguya reflect H+ PACE (Saito et al., 2008)

Solar Wind (H+)

H^+

H

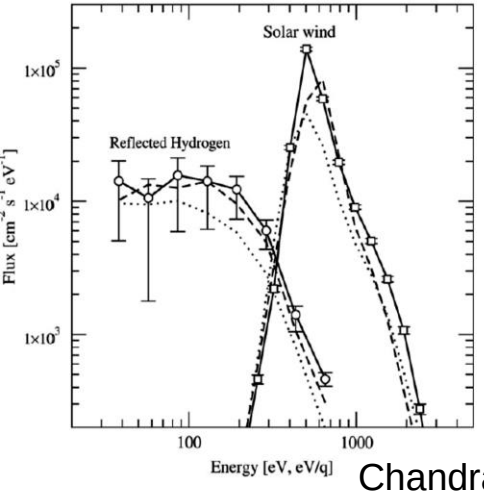
H_2



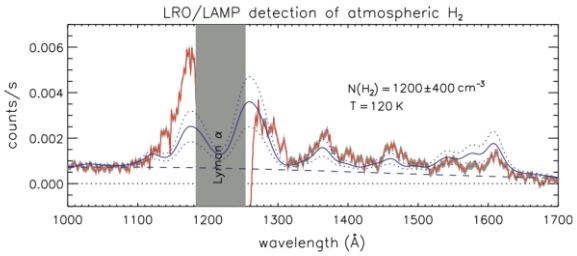
Incoming:
-Solar Wind Protons

Converted and Emitted from Surface:
-Reflected Protons (Kaguya)
-Hydrogen Molecule (LAMP detection)
-Hydrogen Atoms (IBEX, Chandrayaan-1)
-OH (during meteor stream, LADEE/UVS)

Residual H on Surface
-OH Veneer (EPOXI, M^3, Cassini)



Chandrayaan-1 neutral H SARA (Wieser et al., 2009)



FUV H_2
(Stern et al., 2013)

Inputs/Outputs to Surface Volatiles

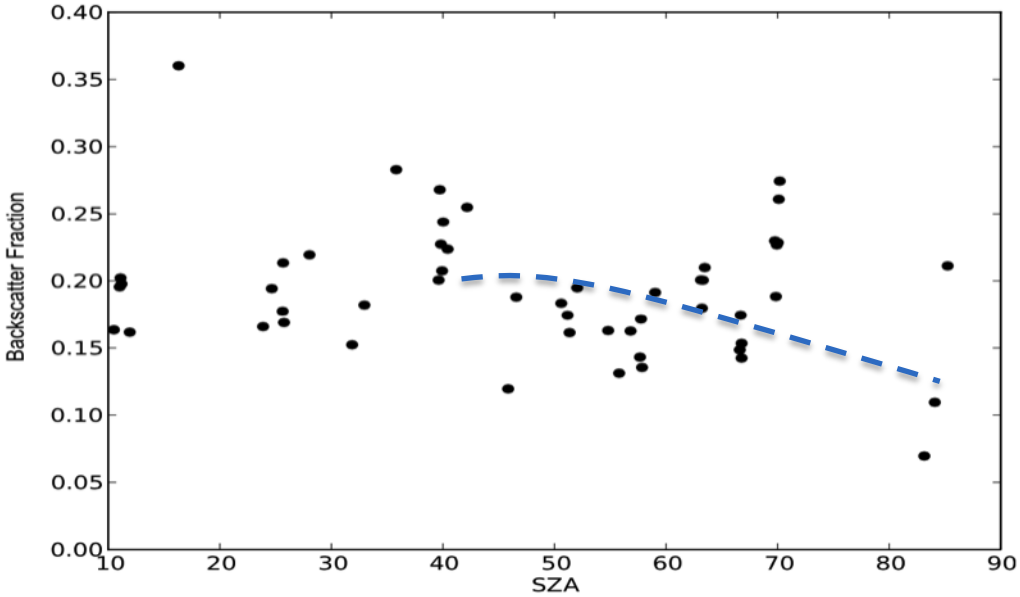


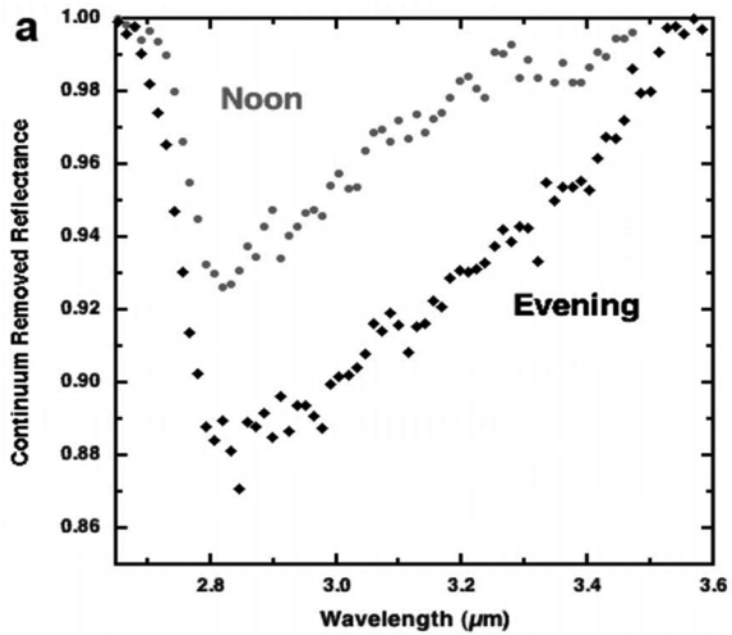
Figure 4. Solar zenith angle dependence of the backscatter fraction.

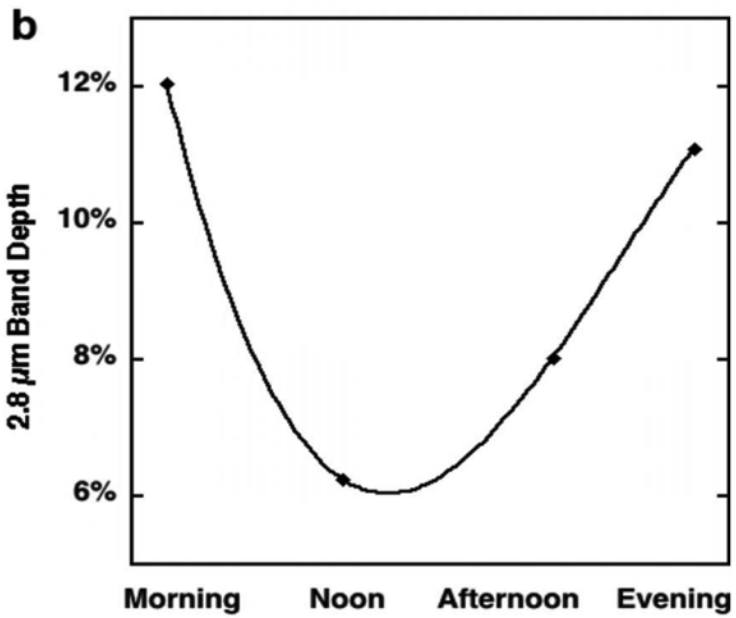
Chandrayaan-1 Energetic Neutral Atoms (SARA) system detected less emitted/backscattered H at large SZAs (but only a few points) [Futaana et al., 2012)

Surface H

On the surface, M^3 finds greater H retention in cool terminator regions at large SZAz [McCord et al., 2011]

Are these two independent observations connected?





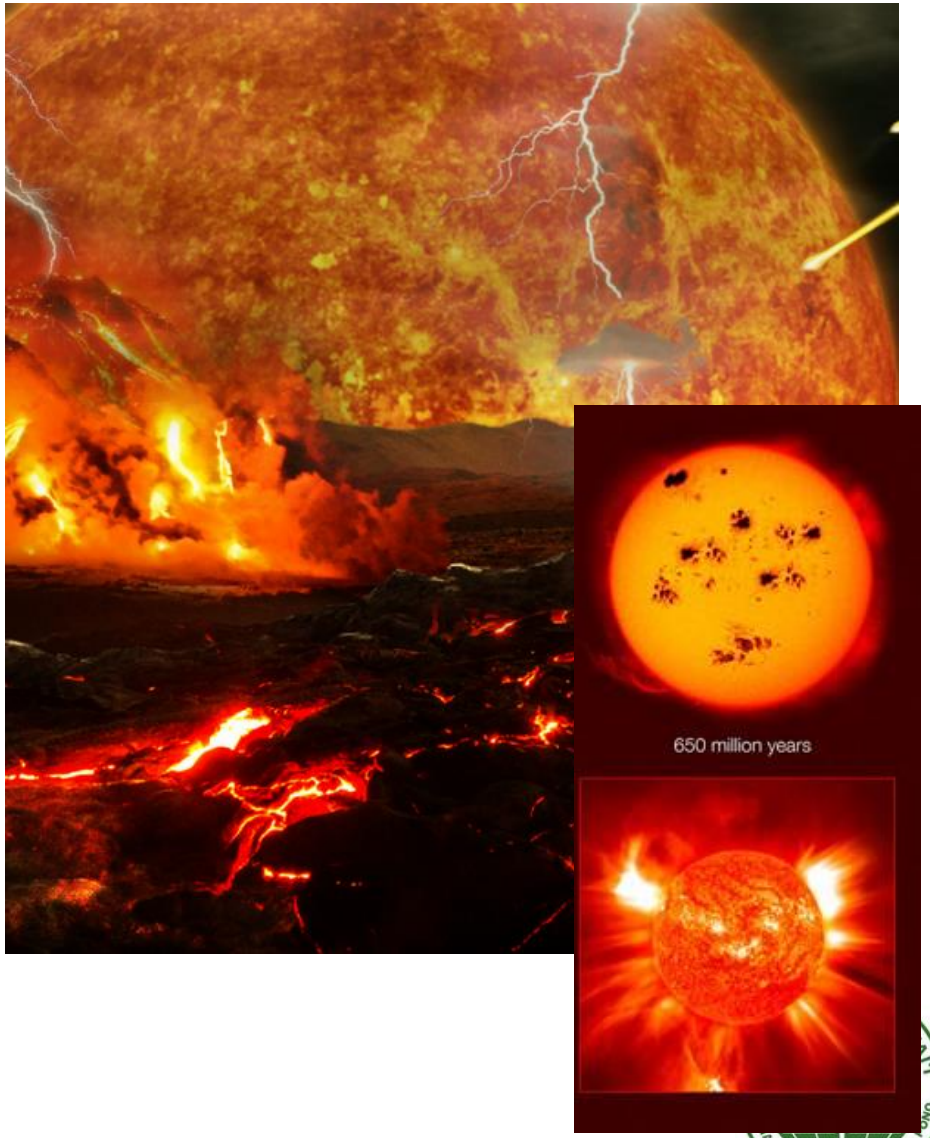
Hydrogen Cycle Measurements/Instruments

- For the first time trace the dynamic exospheric H content directly to its surface source below
  - Have both surface AND exospheric elements on same platform
- Determine if Moon is in equilibrium, loss or accumulation of incoming H
- Measure dynamic incoming H, outgoing H products (OH, H_2, etc) as a function of SZA, Temperature
- Measure H and OH variations with prevailing space weather
  - Solar Storms
  - Meteor steams
- Determine variations in surface hydroxyl that indicate exchange of H with surface

- Neutral mass spec (Exosphere OH, Water)
- Downward Facing Ion mass spec (Water ions, OH ions, Reflected protons)
- Upward Facing Ion Spectrometer (incoming solar wind protons)
- Neutral Energetic Atom (Energetic Backscattered H)
- Passive IR and Active Laser spectrometer (surface OH variations in space and time)

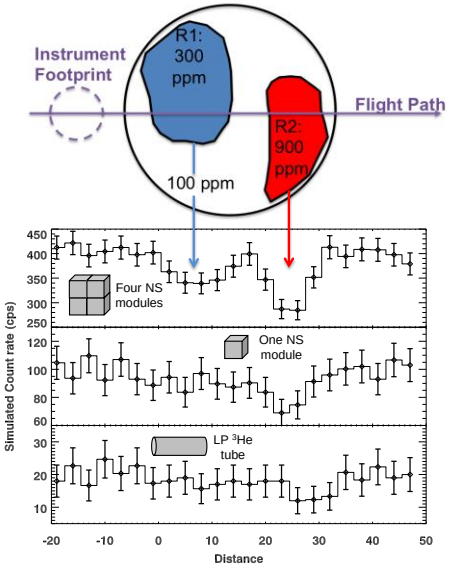
Ancient Volatile System

- Meteorite impact and volcanism provided much higher rates of volatile input than current rates
- Early Sun was more active
- Did higher rates enable stocking of ancient volatile reservoirs?
- LVO determination of contemporary volatile system loss rates and processes directly relates to ancient system
- Endogenous volatiles detected at some pyroclastic deposits, other volcanic features and central peaks
  - How do they inform ancient supply?

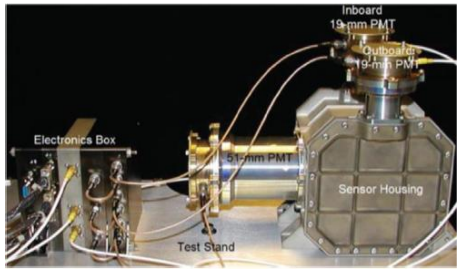


Ancient-modern connection

- **The connection between the contemporary volatile system and buried, and presumably ancient, H detected by neutron spectroscopy and other volatiles by LCROSS is unknown.**
  - **Do these reservoirs communicate?**
  - **Is the buried system renewed by the current volatile supply?**
  - **Are the volatile compositions the same?**
  - **How patchy are the volatiles at the sub-km scale?**



- **Bridging the gap**
  - ***in situ* measurements of meteorite-lofted dust provide localized composition**
  - **NMS enables specific volatile compositions**
  - **High resolution gamma ray and neutron spectroscopy**
    - **MESSENGER derived GRNS**
    - **Very low altitude passes**
    - **Determine correlation between exposed surface and buried ice deposits**

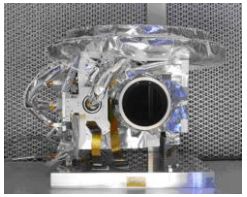


Ancient Volatile System: LVO Contribution

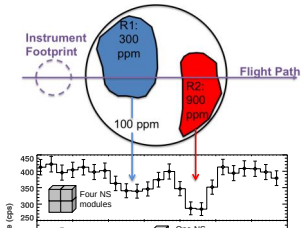
- **Scale LVO volatile cycle model to ancient supply rates**
- **Constrain ancient supply by:**
  - **Definitive characterization of the mineral host of endogenous volatiles**
    - **High resolution spectroscopy at 3 microns**
    - **Determination of water abundance using 6 microns**
  - **Definitive and comprehensive mapping of endogenous sites**
    - **Complete separation of thermal emission from solar reflectance eliminating ambiguity in absorption strength**
  - **Definitive maps improve estimates of ancient supply (e.g. Needham and Kring, 2017)**
    - **Pyroclastic and mare volcanism**
    - **Deep OH layer release by impacts**

- **3.0 µm characterization will determine water-related mineralogy**

- **6um spectrometer determines water abundance**



- **GRSNS low passes determine total hydrogen**



LVO: Enabling Exploration

- Detect and comprehensively map surface ice in PSR to 50-m resolution
  - Mitigate risks for all missions
  - Enabling of static landers
- Determine correlation of buried and surface ice
- Detection of polar organics
  - Definitive detection of surface water and quantification of water and hydroxyl abundances
  - Definitive detection and characterization of variation in water or hydroxyl
  - Pole to equator atmospheric water and hydrogen measurement

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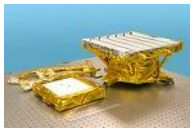
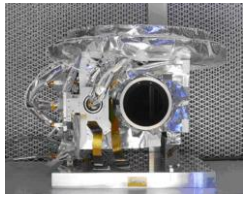
Preliminary Lunar Volatiles Orbiter Payload

SpIRRL: PPM detection of water day and night

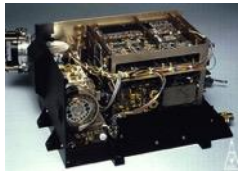


LVIS: Global Coverage, high resolution spectroscopy



WMD: Global mapping of molecular water

Neutron spectrometer: Hydrogen Mapping



Flux of ions in and out of cold traps/poles

Instrument	Provider	Mass/Power
Spectroscopic Infrared Reflectance LIDAR (SpIRRL)	GSFC	14 kg/ 45 W
Lunar Volatiles Imaging Spectrometer (LVIS)	JPL	8 kg/ 15 W
Water Molecular Detector (WMD)	GSFC	8 kg/ 15 W
Dust MS		
Neutral Mass Spectrometer		
Ion Mass Spectrometer	GSFC	8 kg/8 W
Gamma-Ray/Neutron Spectrometer	APL	2.5 kg/5 W

LVO Contributions for Science and Exploration

- **Detect and comprehensively map surface ice in PSR to 50-m resolution**
- **Determine correlation of buried and surface ice**
- **Detection of polar organics**

- **Definitive detection of surface water and quantification of water and hydroxyl abundances**
- **Definitive detection and characterization of variation in water or hydroxyl**
- **Pole to equator atmospheric water and hydrogen measurement**

Concept of Operations

- **Minimum mission requires one lunar rotation**
  - **12 rotations appropriately phased for seasonal coverage**
  - **More rotations provide more time base coverage, improved spectroscopy of ice in PSR**

Highly Responsive to NASA Exploration Goals

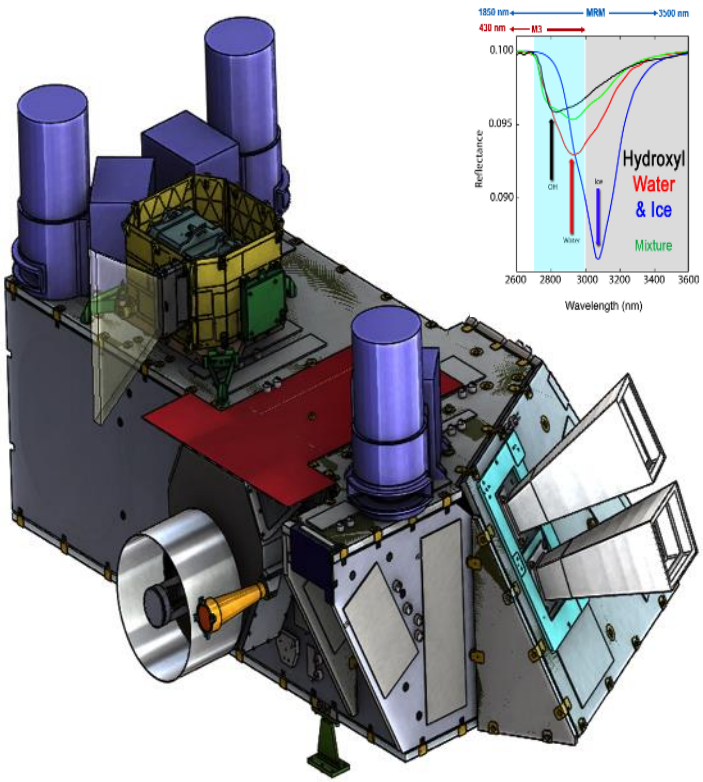
- **NRC Report "The Scientific Context for Exploration of the Moon"**
  - **Recommended that a high priority investigation should be to *"Characterize the volatile compounds of polar regions on an airless body and determine their importance for the history of volatiles in the solar system"***
- ***Strategic Knowledge Gaps for the "Moon First" Human Exploration Scenario***
  - *Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar cold traps.*
  - *Geotechnical characteristics of lunar cold traps.*
  - *Charging and plasma environment within and near PSR.*
  - *Mineralogical, elemental, molecular, isotopic make up of volatiles.*
  - *Physical nature of volatile species (e.g., pure concentrations, intergranular, globular).*
  - *Technology for excavation of lunar resources.*

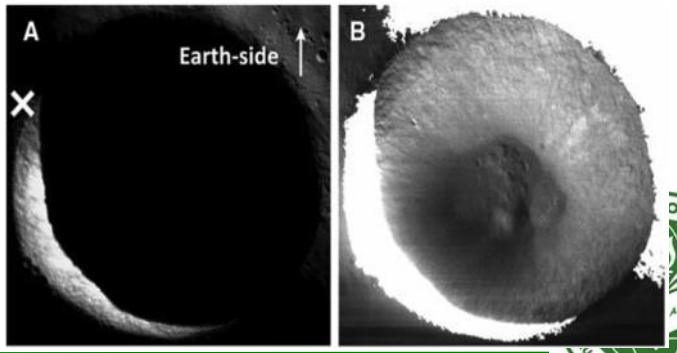
Lunar Volatiles Orbiter is Highly Responsive to NASA Planetary Science Decadal Survey

- **Study of solar system volatiles is cross-cutting theme in 2010 Decadal Survey. Examples:**
  - ***Building new worlds*:** " … accretion, supply of water, chemistry …"
  - ***Planetary Habitats*:** " … primordial sources of organic matter, …" " … solar system habitats with necessary conditions, organic matter, water, energy, and nutrients to sustain life …?
  - ***Working of Solar Systems*:** "…chemical and physical processes that shaped the solar system …"
- ***Lunar Volatiles Orbiter will address important inner planets questions***
  - ***Origin and Diversity of Terrestrial Planets***
    - *"What are the compositions, distributions, and sources of planetary polar deposits?"*
    - *"[Develop] an inventory and isotopic composition of lunar polar volatile deposits to understand their emplacement and origin, modeling conditions and processes occurring in permanently shadowed areas of the Moon and Mercury and continued observation of Mercury's volatile deposits to understand their origin."*
  - ***Understand Evolution of Terrestrial Planets/Origin of Life***
    - *"How are volatile elements and compounds distributed, transported, and sequestered in near surface environments on the surfaces of the Moon and Mercury? What fractions of volatiles were outgassed from those planets' interiors, and what fractions represent late meteoritic and cometary infall?"*
    - *"What are the chemical and isotopic compositions of hydrogen-rich (possibly water ice) near the Moon's surface?"*
    - *"[Constrain] the character of volatile chemical compounds on Venus, the Moon and Mercury. [Determine] A) the state, extent, and chemical and isotopic compositions of surface volatiles particularly in the polar regions on the Moon and Mercury; B) the fluxes of volatiles to the terrestrial planets (e.g., by impact) over time."*
    - *"What are the mechanisms by which volatile species are lost from terrestrial planets, with and without substantial atmospheres (i.e., Venus versus the Moon), and with and without significant magnetic fields (i.e., Mercury versus the Moon)?"*
    - *"What are the proportions of impactors of different chemical compositions (including volatile contents) as functions of time and place in the solar system?"*
  - ***Understand Processes that … Constrain Long-Term Climate Evolution***
    - *"Do volatiles on Mercury and the Moon constrain ancient atmospheric origins, sources, and loss processes?"*

Improvements over previous observations

- Extended wavelength range (600-3600 nm at 10 nm spacing) targeted to volatile analysis
  - Fully captures 2.7-3.0 µm OH fundamental, permitting determination of volatile speciation combined with mineral associations
- Higher spatial resolution (25 m/pixel from 50 km orbit) with more spatial pixels (1200)
  - Identify spatial variations in volatile content and species at fine spatial scale
- Higher signal to noise ratio and accuracy
  - Discriminate subtle changes in volatile bands and increase likelihood of seeing OH/H_2O overtones and combination tones at 1.4 and 1.9 µm, if present
  - Use a slow slew for high SNR to measure water bands in permanently shadowed regions illuminated by well characterized terrain scattered light.
- Complete initial global coverage achieved within 2 months





Passive and Active Measurements of Surface Volatiles: Ideal complements

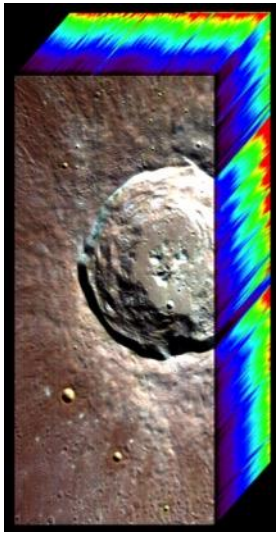
- **Passive IR**
  - **Strengths**
    - Hyperspectral, good chemical phase discrimination
    - Wide field of view, high spatial resolution = excellent and rapid global coverage
  - **Weaknesses**
    - Signal is combined reflectance and emission, unresolved relationship between band and water abundance
    - Spectroscopy using stray light not been previously demonstrated, unknown issues may arise

- **Multiband LIDAR**
  - **Strengths**
    - Pure reflectance, band strength proportional to abundance
    - Operates day and night, including PSR
  - **Weaknesses**
    - Few bands, limited chemical discriminability
    - Profiler, limited coverage

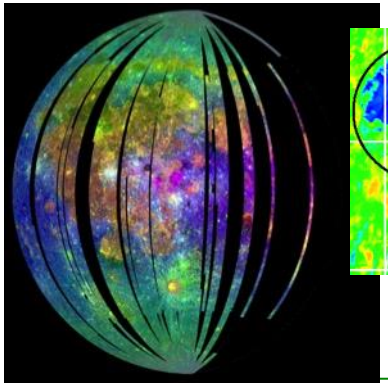
- **Synergy**
  - Multiband LIDAR provides unique separation of reflectance and emission in HSI data swath, extends pure reflectance to global coverage
  - Multiband LIDAR covers the poles and night side for temporal measurements
  - Image motion compensation enables limited HSI within permanent shadow

Lunar Volatile Imaging Spectrometer (LVIS)
600 to 3600 nm at 10 nm spacing

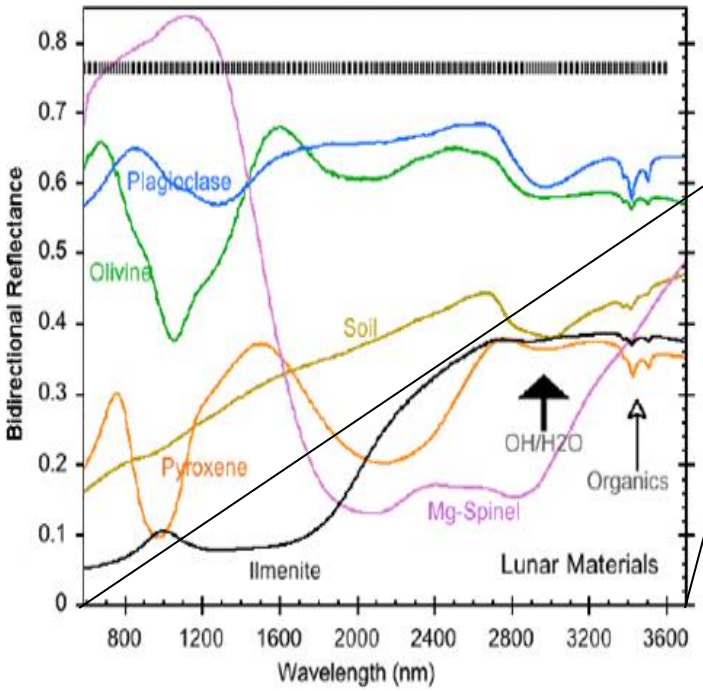
Calibrated Image Cube



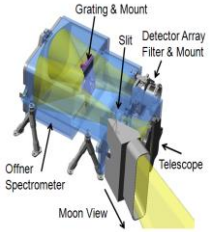
Resource Products



1200 Parallel Spectrometers



Proven Design

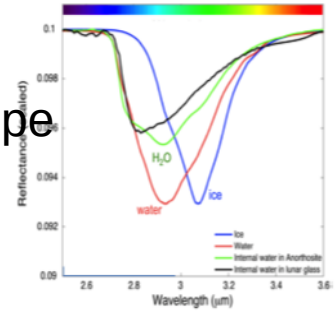


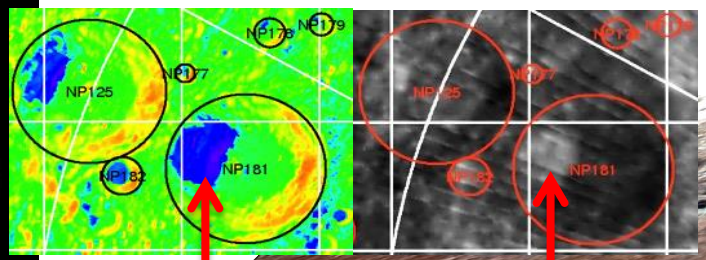
Detector Array

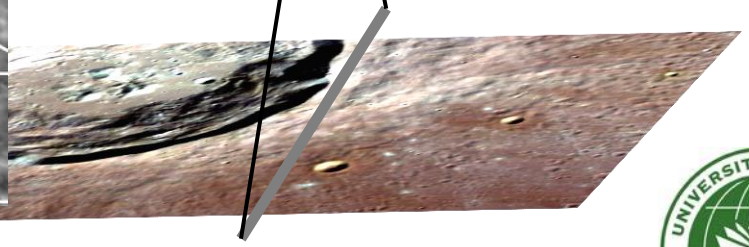
Spectrometer

Slit

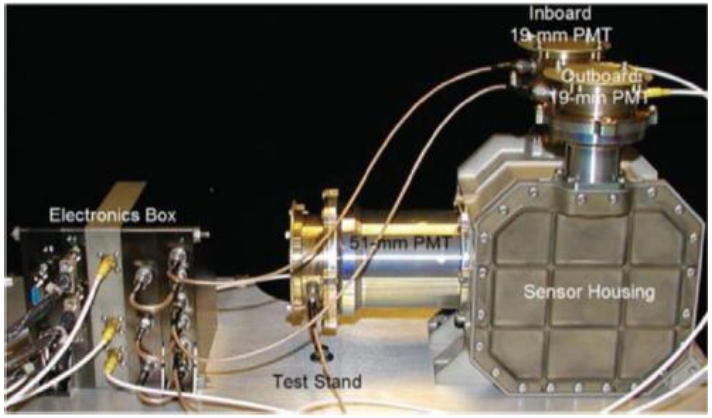
Telescope



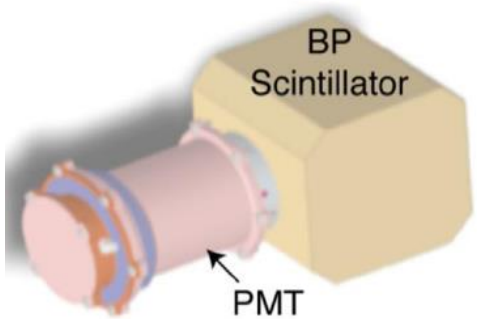




Sinks of Surface and Near-Surface Volatiles: Low-Altitude Neutron Measurements



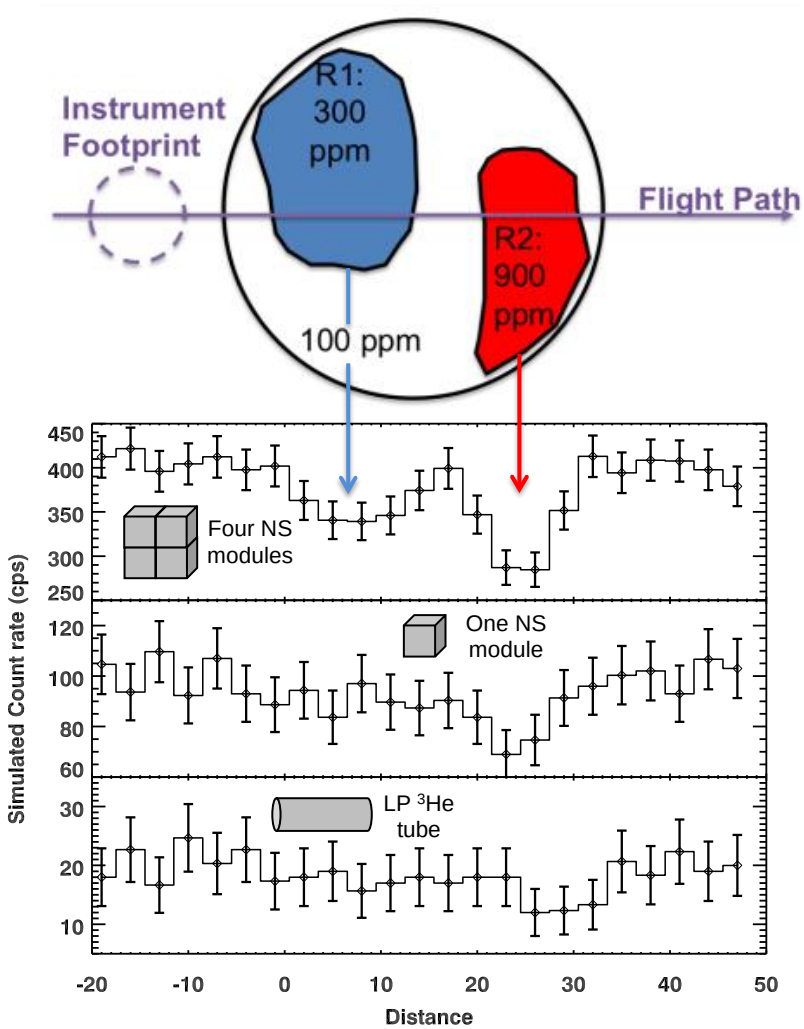
MESSENGER NS



Simplified 1-module NS for low-altitude measurements

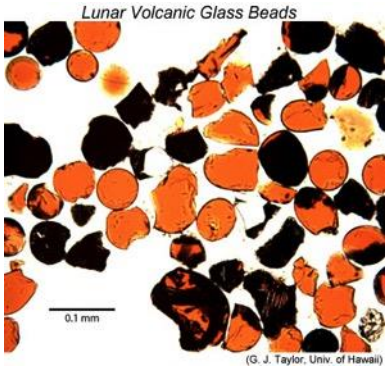
- **Low-altitude (avg. 15 km) neutron measurements provides unambiguous high-spatial resolution hydrogen measurements**
- **MESSENGER-type Neutron Spectromter (NS) provides 5X greater sensitivity than prior NS**
  - **Epithermal neutrons measure hydrogen**
  - **Fast neutrons measure hydrogen burial depth**
- **Four-module version provides 20X greater sensitivity than prior NS**
  - **7 kg; 2 W**
  - **Enables rapid, robust measurements of lunar PSRs**

Low-Altitude Measurement

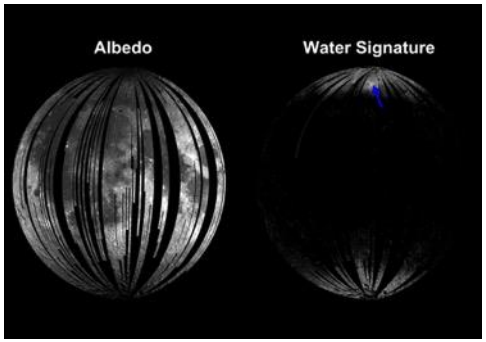


- **In one very-low altitude pass (~5 km), 4-module NS quantifies spatial variations in 30-km diameter PSR**
  - **Measurement compared with 1-module NS and the LP sensor**

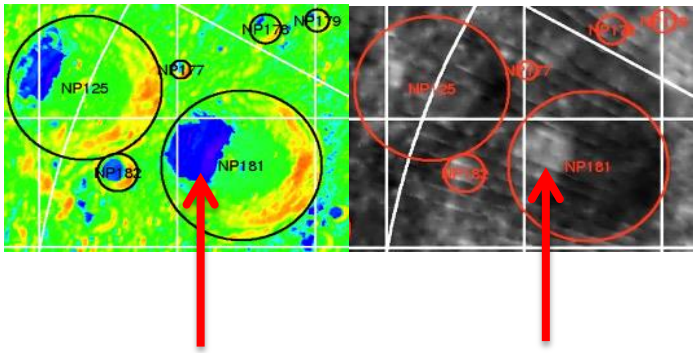
Post-LRO Orbital Measurements: Why?



Saal et al find water in lunar glasses; multiple detections in lunar samples since then



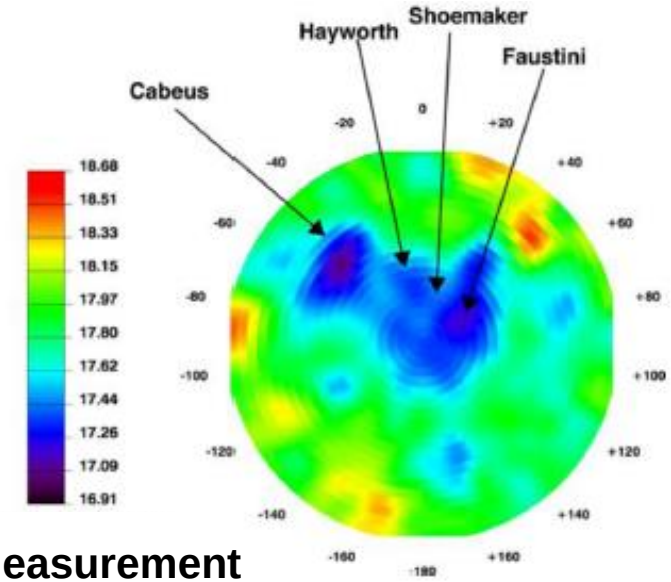
M^3 finds water absorptions near poles; Cassini and Deep Impact data corroborate detection



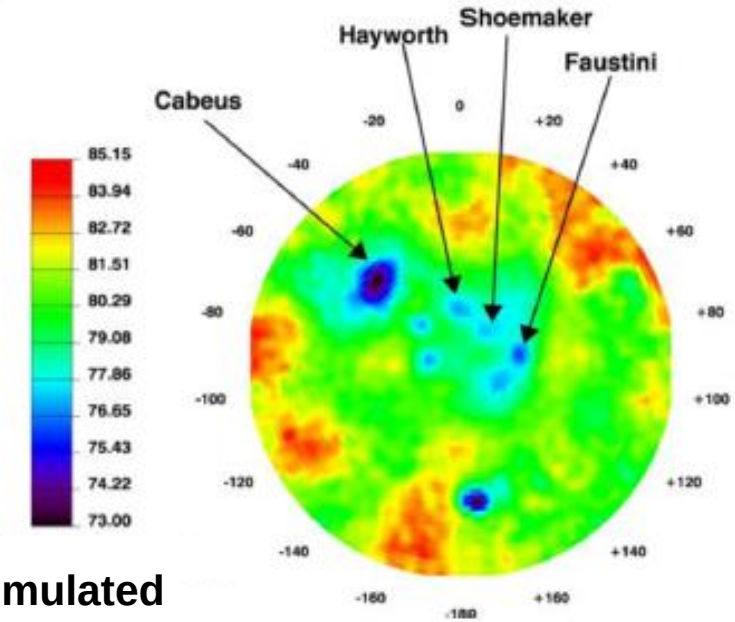
Lunar normal albedo shows enhanced reflectance within PSRs (Lucey et al., 2014).

- From "Bone Dry" (figurative) to bone dry (literal):
  - Discovery of lunar surface water (Cassini, Chandrayaan-1, Deep Impact).
  - Discovery of lunar internal water (Saal et al. 2008)
  - Discovery of buried water within PSRs (LCROSS).
  - Discovery of surface ice at Mercury poles (Neumann et al. 2013), different from what is observed at the Moon
  - ~~Possible~~ surface ice in permanent shadow (Zuber et al. 2013; Lucey et al. 2014;Hayne et al. 2015; Li et al. 2017)
  - Possible mobile surface water on the Moon (Sunshine et al. 2009; Hendrix et al. 2013; McClanahan et al. 2015; Schwadron et al., 2017)
- Questions now center on <u>processes</u> as revealed through inventory
  - Definitive answers to basic questions
  - ~~Focus on thorough measurement of strongest water indicator:~~
    - ~~Absorption at 3 um~~
    - ~~Few ppm sensitivity~~

Low-Altitude Measurement



LP measurement



Simulated low-altitude

- **In three-months @ 15 km avg. altitude, 4-module NS quantifies hydrogen within PSRs poleward of 80°S (30 ppm sens.)**
- **In same time, NS quantifies burial depth within PSRs @ 30 km spatial resolution via fast neutrons**