Lunar Water Frost, Exosphere, and LCROSS Plume Observations with the Lyman Alpha Mapping Project (LAMP) on the Lunar Reconnaissance Orbiter (LRO)

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Dr. Kurt Retherford, About Myself

- I’m an astronomer. A planetary scientist.
- Graduate School in Physics & Astronomy at Johns Hopkins University, Baltimore
- Undergraduate at University of Wisconsin Madison
- Senior Research Scientist at SwRI, 9 years
- Study the atmospheres and auroral emissions from planets and satellites using (mostly) ultraviolet light observations
- Involvement in Space Missions
  - Deputy PI of Lunar Reconnaissance Orbiter (LRO) Lyman-Alpha Mapping Project (LAMP)
  - New Horizons Jupiter Encounter Science Team member / Alice UV spectrograph team
  - U.S. Co-I on Mars Express SPICAM investigation
  - FUSE and HST/STIS Instrument Definition Team member
Outline

• Lunar Science & Exploration Overview
• Water Frost Search
• Lunar Reconnaissance Orbiter (LRO)
• LAMP Instrument
• New Far-UV Maps
• LCROSS Impact Plume Observations
• Summary
Lunar Exploration

- The Lunar Reconnaissance Orbiter (LRO) mission was the first mission to be developed in NASA’s renewed lunar program.

- What measurements are needed to better enable manned missions?
  - Image and characterize landforms
    - Determine safest landing sites
    - Explore the polar regions
  - Identify locations with key in situ resources
    - Lunar water ice may one day be a useful resource in the future of manned solar system exploration

- NASA’s plans for returning to the moon are being revised.
Lunar Science Overview

- After Apollo, what remains to be learned?
- Permanently Shadowed Regions (PSRs) at poles
  - One of the most exotic places in solar system
- Lunar atmosphere: an exosphere
  - So tenuous, it is difficult to observe and study the key/interesting species (e.g., H, O, H₂, H₂O, Ar, He)
  - Will be polluted by new missions
  - How does this gas transport along the surface and collect at the poles?
Permanently Shadowed Regions (PSRs)

- Craters at the poles are permanently in shadow
  - No sunlight or earthshine falls within them
- Crater rims and mountains are often in sunlight
- Maps of terrain within PSRs have only recently been made available with NASA’s LRO (2009), India’s Chandryaan-1 (2008), and Japan’s Kaguya (2007) spacecraft
Lunar Water Formation/Delivery

Vondrak & Crider,
American Scientist,
2003

- Solar wind protons react with Moon rocks to form $\text{H}_2\text{O}$
- Comets periodically deliver large amounts of $\text{H}_2\text{O}$
- Remaining primordial water is another possible source
Lunar Atmosphere Transport

Sodium Corona:
Potter et al., JGR, 2000

Vondrak & Crider,
American Scientist, 2003
Lunar Water Ice Trapping

- PSRs are cold regions, new LRO data indicate as cold as ~25 K
- Volatiles in the PSRs are very stable to sublimation
  - Only photolyzed by UV star light and interplanetary hydrogen light
  - Solar wind ion impact dissociation
- Mixing of ice into the soil by micrometeorite bombardment is thought to bury ice
  - Protects water from loss by UV photolysis
  - Does this process actually happen?
Detections of Water on Moon

Three IR measurements (Pieters et al., Sunshine et al., and Clark et al., Science, 2009) confirm that even the dayside surface shows unexpected signs of water molecules.

Retherford Seminar
Hydrogen in PSRs

- Lunar Prospector measured enhancements of epithermal neutron flux at the poles and especially in PSRs
- This signal indicates higher concentration of hydrogen below the surface
- Hydrogen is consistent with H$_2$O ice but could also be hydrated rock compounds
- Other evidence for water ice was considered controversial (e.g., radar imaging), but the new detection of water on the sunlit surface lends credence to these assertions
- LRO LEND is confirming and improving this type of subsurface hydrogen (water) measurements
Lunar Reconnaissance Orbiter
Launched June 18th 2009
LRO - LCROSS Coordination

- Joint launch with Lunar Crater Observation and Sensing Satellite (LCROSS)
  - Shepherding satellite
  - Centaur rocket upper stage

- LCROSS impacted surface on October 9th, 2009
Polar Science with LRO

South Pole Topography – LRO/LOLA

North Pole Visible Image - LROC/WAC
LAMP Instrument

LAMPvideo_forreview MPEG
**LAMP:**
- Mass: 6.08 kg
- Power: 4.8 W
- λ Range: 57-196 nm
- λ Resolution: 3 nm (filled slit)
LAMP on LRO

THE LAMP TEAM

Grad students: Paul Miles, and David Horvath
Undergrads: Paul Rojas, Paige Bailey, Michelle Kassel, Maggie Nagengast, Preston Karnes, Eric Bassett

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LAMP Measurements

• Observe nadir and use a push-broom motion to scan the slit on the surface to create 2D maps

• Sensitive enough to view the reflected signal of starlight and Lyman-alpha sky-glow on the nightside and in PSRs

• We close the instrument door, which has a small pin hole, to reduce the intensity when on the dayside to prevent saturation of the detector
LAMP Water Frost Search
LAMP’s Innovative Technique: Lyman-alpha Skyglow

- Since the permanently shadowed regions are dark, how can we ever see into them?

- The sky is aglow in Lyman-alpha light from hydrogen atoms spread throughout the solar system and interstellar space
  - Would look like an overcast sky
  - Naturally shines down on the moon’s PSRs

- Star light is another illumination source we exploit

Nozomi S/C image
FUV Stellar Illumination
Water Ice Detection Technique

- Apollo era lab measurements of water frost reflectance shows a distinct, broad UV absorption band near 160 nm (Wagner et al. 1987)
- More recent lab measured water frost reflectances (by Jay Goguen) shows a distinct broad UV absorption band or “cut off” in reflectivity at ~160-180 nm
- Search for this spectral signature of water ice in PSR albedo measurements
- We generally observe lower albedos in the coldest, most volatile rich regions, not higher
  - More lab investigation essential
LURE - Lunar Ultraviolet Reflectance Experiment

UV Ice and Lunar Simulant Reflectance Measurements

Lunar Soil Simulants

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Recent LAMP Maps
PSRs are darker than surrounding areas in the Far-UV. We’re still improving the instrument calibration and characterizing artifacts (e.g., the stripes).

Poleward of 80° shown here.

Lyman-α relative blackness indicates higher porosity surface (“fluffier regolith”).
Some crater rims are brighter, consistent with their surfaces being affected by sunlight and solarwind particles.

Good agreement with coldest areas measured with LRO’s Diviner radiometer instrument.
PSRs are not all the same! (e.g., Shackleton is relatively bright)

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Upturn in **PSR albedo** at longer wavelengths consistent with presence of volatiles. But is it $\text{H}_2\text{O}$? Possibly $\sim 1\%$ surface water ice by area. Other PSRs show this too.
LAMP’s nightside Lyman-α maps of the lunar poles show lower albedos (dark blue) in the PSRs, which is consistent with higher porosity surfaces in these regions. Comparisons of star-illuminated surfaces on-band and off-band the diagnostic water spectral signature near 160 nm (inset) include PSRs such as Haworth crater that are best explained by 1-2% abundances of water frost right at the surface.
L crossover impact

LRO.Web MPEG
LRO - LCROSS Coordination

• LRO observed LCROSS’s:
  – Impact site before, during, and after impacts
  – **Ejecta cloud**/curtain
  – Crater thermal response
  – **Searched for Lunar atmosphere response**

Lab simulations
LRO Close Approach at 11:32:30 UTC
60 seconds after Centaur Impact

Animation by M. Mesarch, GSFC
LAMP L CROSS Plume Data

- LAMP’s L CROSS light curves are a rich data set for constraining detailed plume models
Detection of LCROSS Plume Atmosphere

- LAMP Detected Five Gaseous Species
  - $\text{H}_2$ & CO fluorescence emissions from 105-165 nm ($T=1000$ K)
  - Neutral atomic Hg at 185 nm (with contributions from Ca and Mg)
We’ve learned that water is just one of many interesting volatile species collecting in the PSRs, and they’re surprisingly abundant.
Summary

• LAMP is mapping out the Far-UV reflectance of the lunar poles and is searching for exposed water ice in permanently shadowed regions

• LAMP uses a spectral “fingerprint” for water ice that can identify exposed water ice on the surface

• LAMP-observed low FUV albedos suggests high porosities (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 detected LCROSS impact plume gas identified as H₂ and CO molecules, and Hg, Mg, and Ca atoms

• LRO has an exciting extended mission planned to study how water and other volatiles are transported through the lunar exosphere

http://www.boulder.swri.edu/lamp/
http://twitter.com/lrolamp
http://lro.gsfc.nasa.gov/