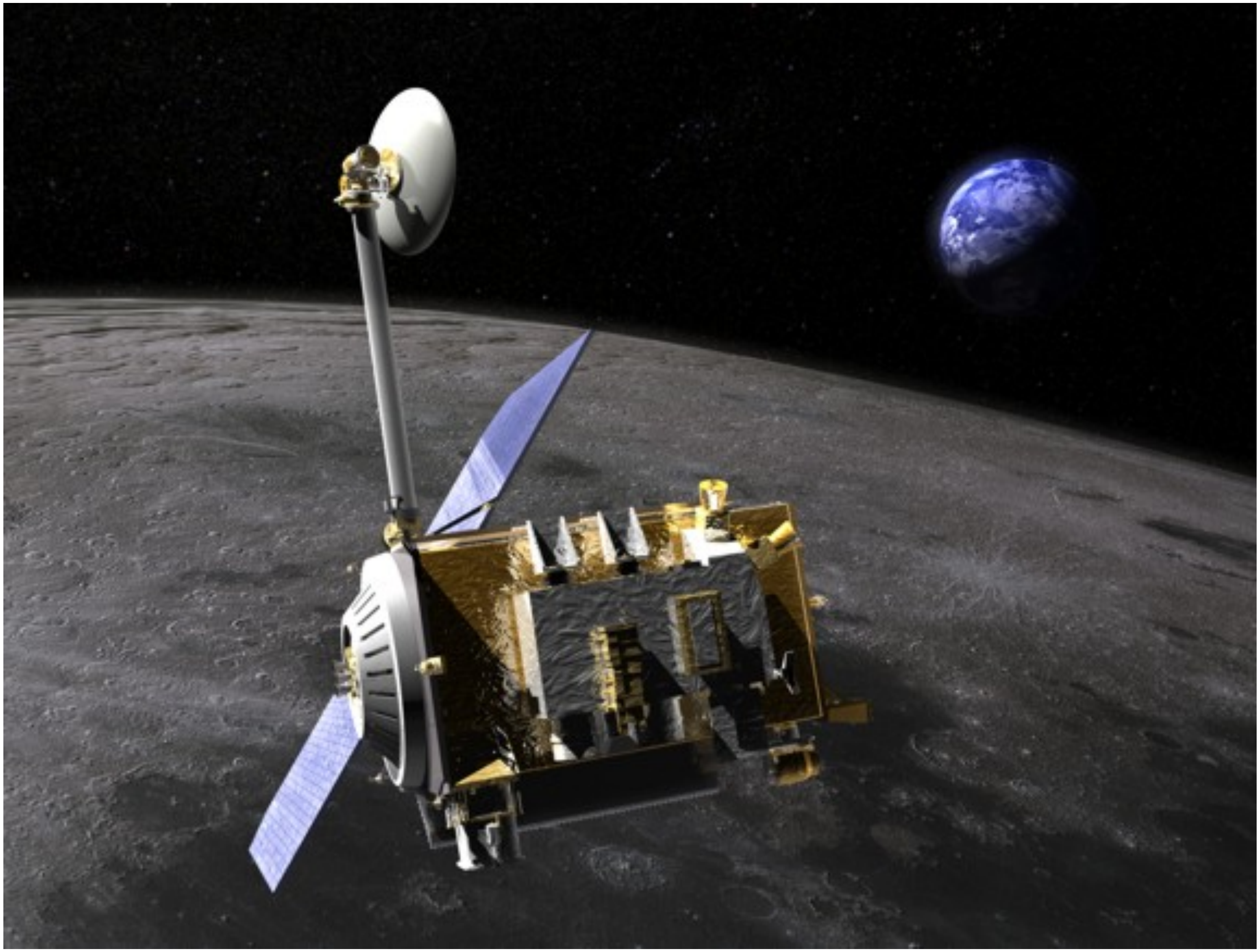
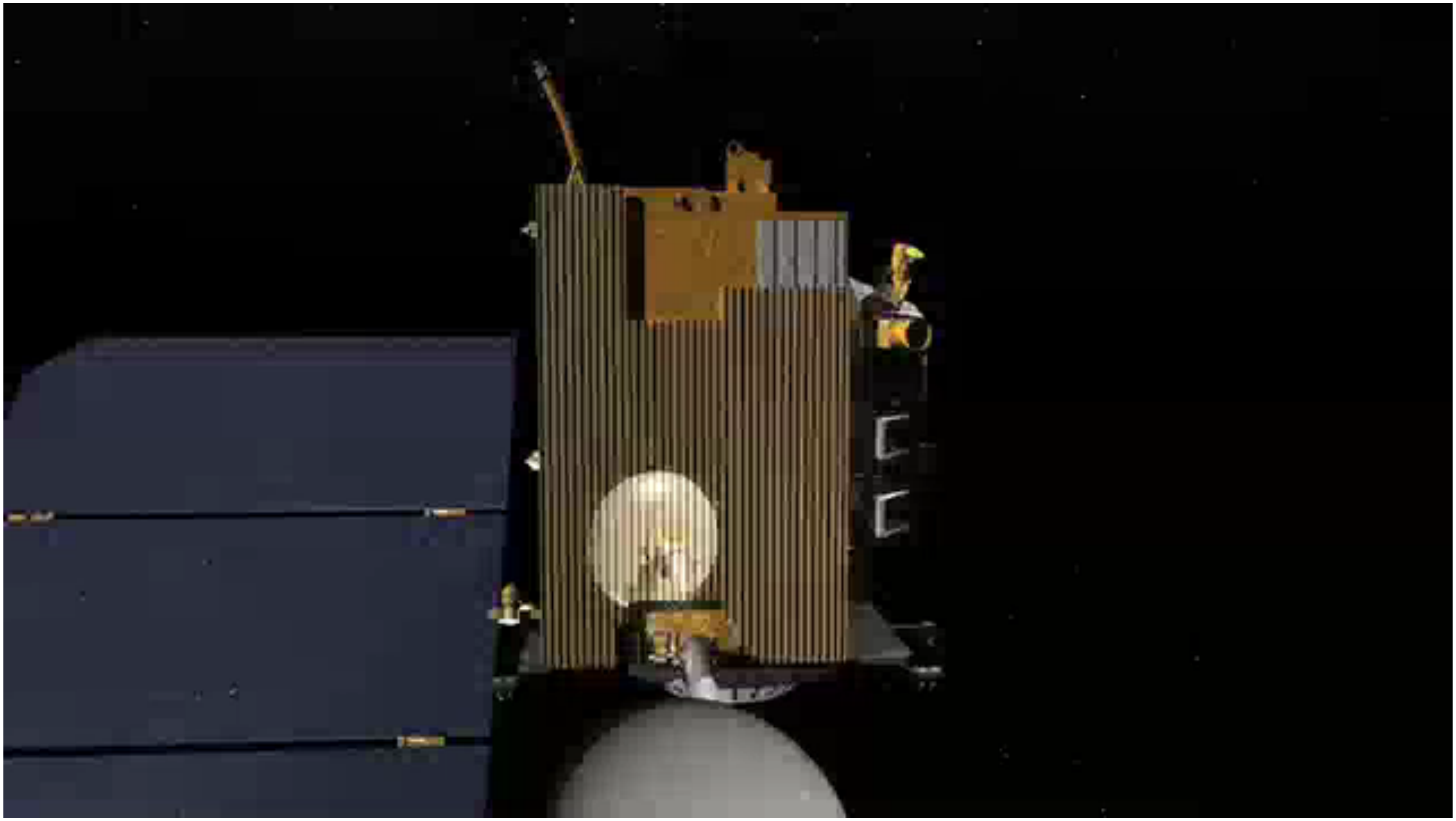
# The Lunar Reconnaissance Orbiter Mission After 6 Years



# LRO has 7 Instruments



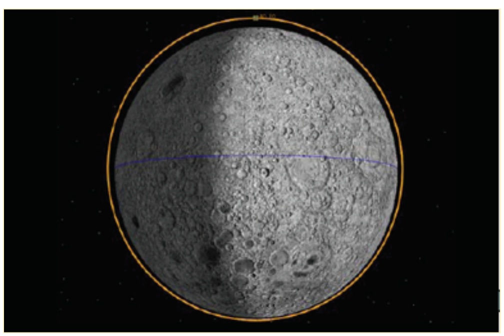
| LRO Key Dates – Six Years of Successful Operations | |
|---|---|
| First NLSI Forum | 20-Jul-08 |
| Launch | 18-Jun-09 |
| Commissioning Orbit (30 x 216 km) established | 27-Jun-09 |
| Insert into Mapping Orbit (50 ±15 km) | 16-Sep-09 |
| LCROSS Impact | 9-Oct-09 |
| First Public Release of LRO Data From Planetary Data System (total at least 500 Tbytes through May) | 3/15/2010 and every 3 months |
| Begin Science Phase | 17-Sep-10 |
| Begin First Extended Mission | 17-Sep-12 |
| Complete First Extended Science Mission | 16-Sep-14 |
| Complete proposed Second Extended Science Mission | 16-Sep-16 |

# Icarus Special Issue

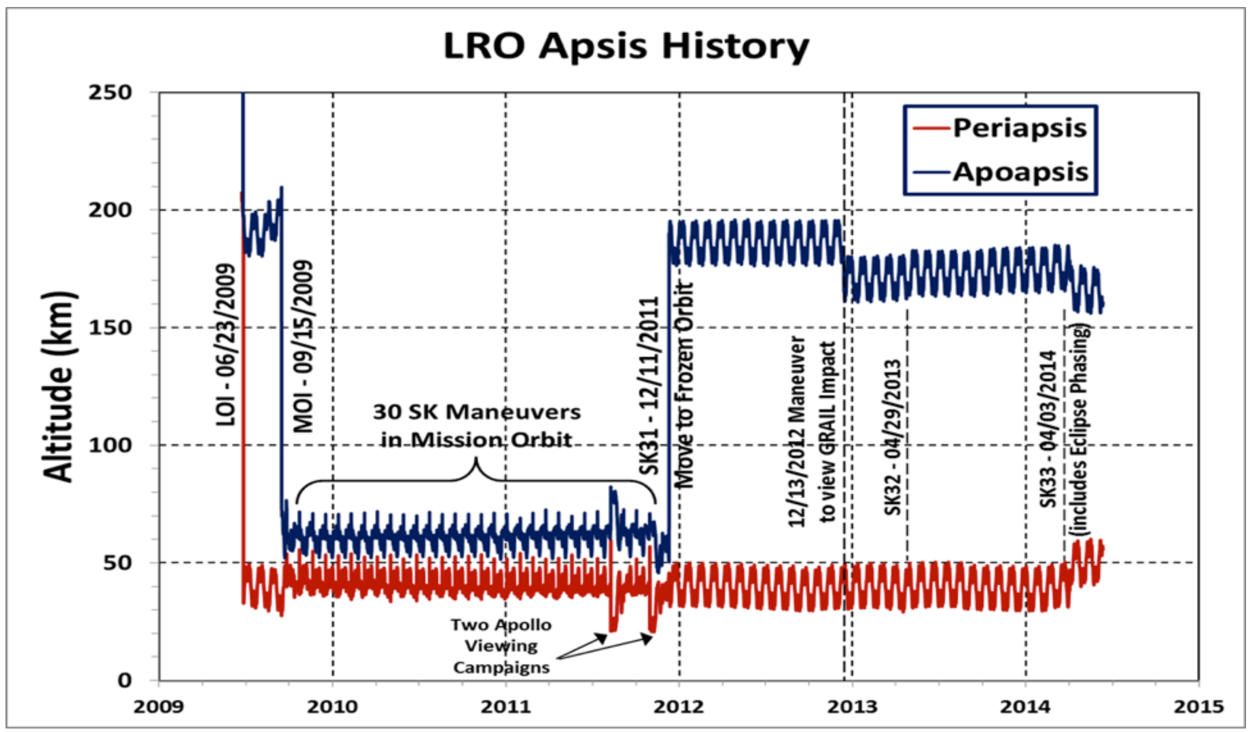
- LRO is planning a special issue of Icarus highlighting LRO results.
- Contributions from the broader community is encouraged.
- Submission deadline has past but …..
- Please consider reviewing when invited!

# LRO Orbits – Maximizing Science and S/C Resources

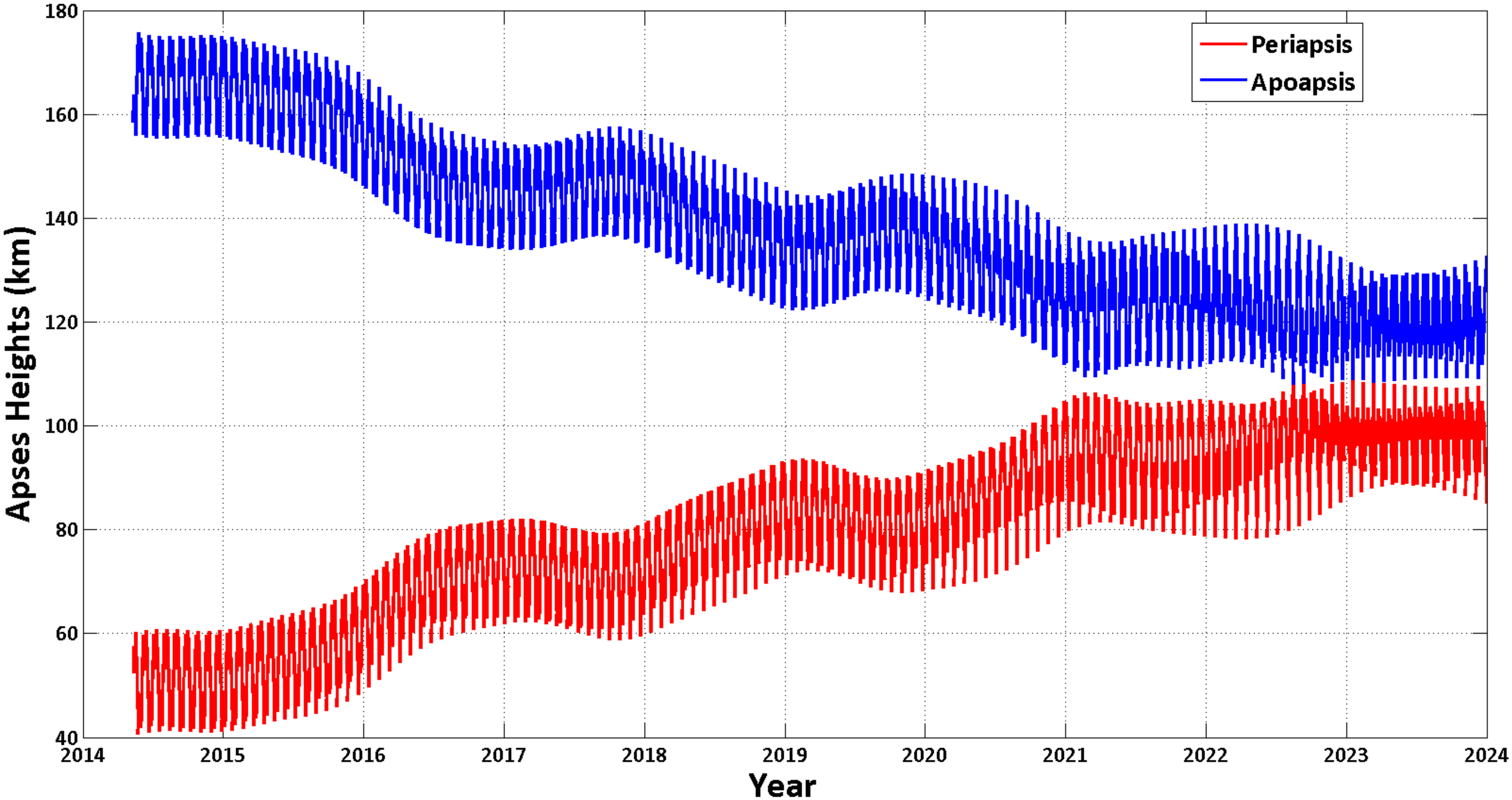
- LRO initially placed in a 30 x 216 km quasi-frozen polar orbit for commissioning
- Moved to 50 ± 15 km orbit on 9/15/09 for science mission
- Low-periapsis (21 km) orbits in August & November of 2011
- LRO returned to a quasi-frozen orbit on 12/11/11 with decreasing inclination for Extended Science Missions
- Anticipated orbital lifetime at least eight years of fuel remaining



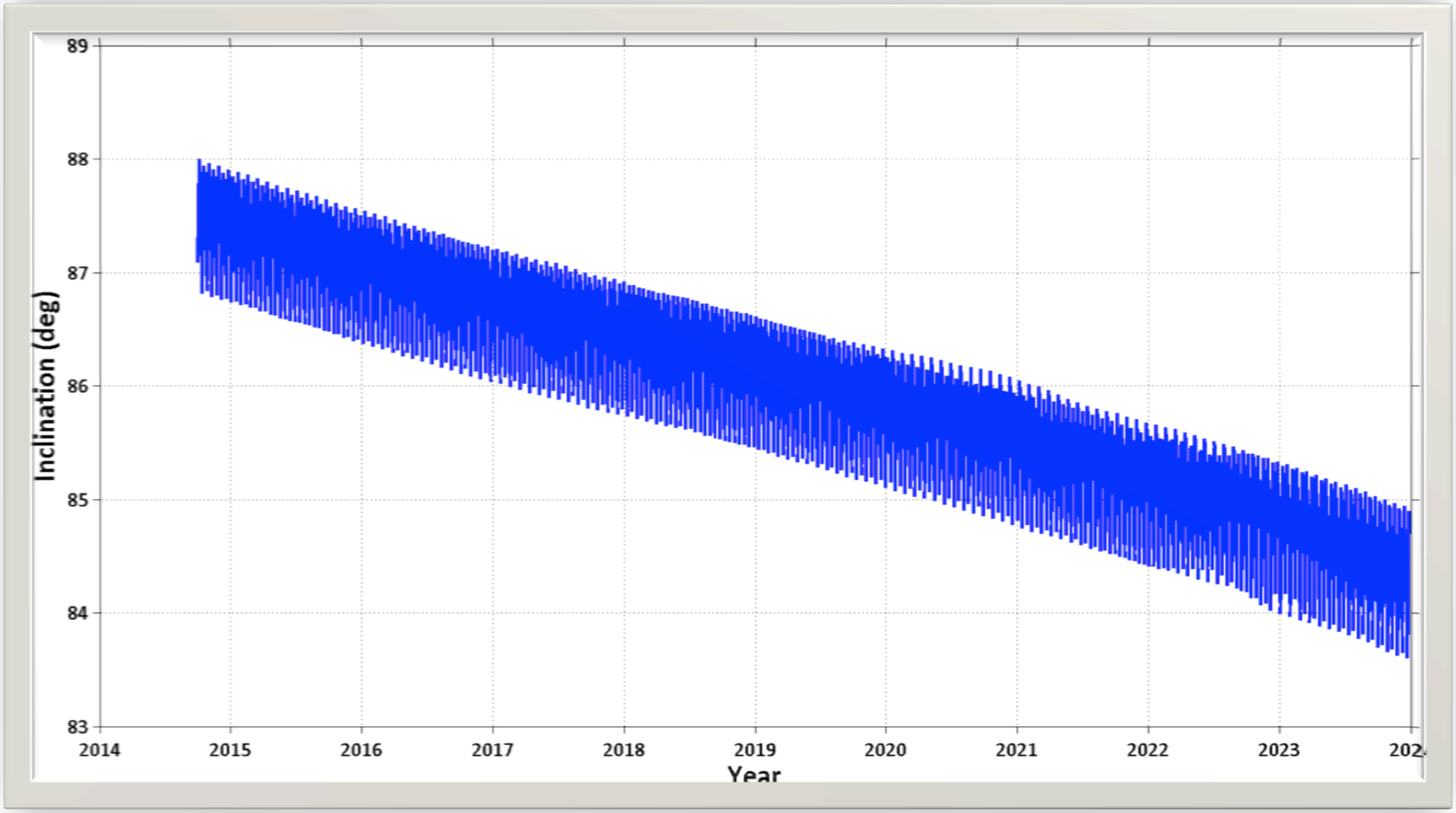
**30 x 216 km Altitude Quasi-Frozen Orbit**



# Low Passes Over the South Pole



# Low Passes Over the South Pole But not "The South Pole"

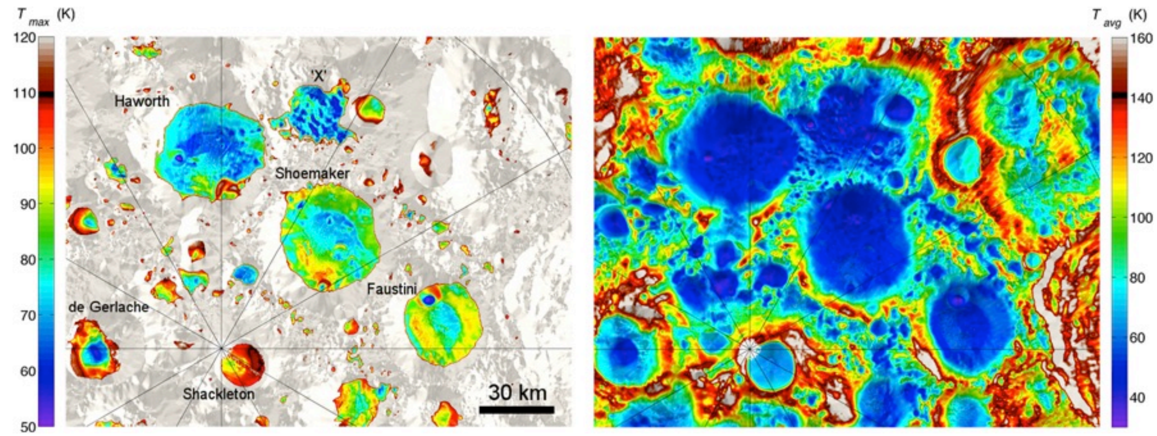


# LRO's Second Extended Mission – Five Themes

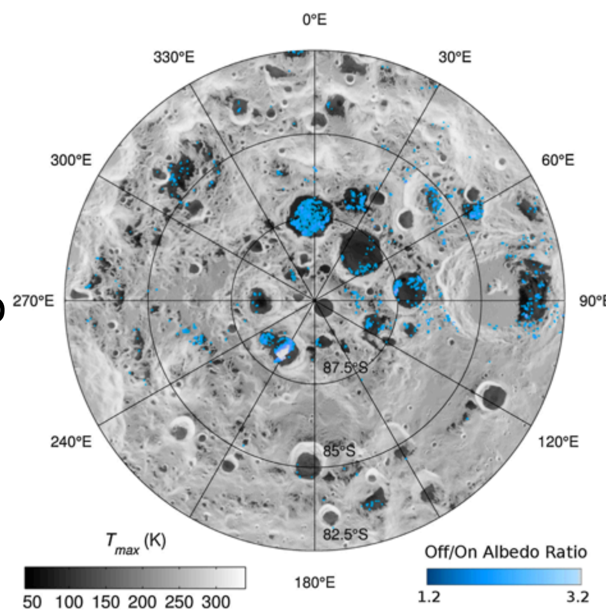
- **Transport of Volatiles**
  - How are volatile elements and compounds distributed, transported, and sequestered in near-surface environments on the surfaces of the Moon and Mercury?
- **Contemporary Surface Change**
  - What causes changes in the flux and intensities of meteoroid impacts onto terrestrial planets
- **Regolith Evolution**
  - Characterize planetary surfaces to understand how they are modified by geologic processes.
- **Probing the Interior from Observations of the Surface**
  - Characterize planetary interiors to understand how they differentiate and evolve from their initial state
- **Interactions with the Space Environment**
  - How is surface material modified exogenically?
  - How do exospheres form, evolve, and interact with the space environment?

# LRO Finds Broadly Distributed Water Frost Near The South Pole

- LRO Diviner temperature data are used to constrain locations near the South Pole where water frost is stable at the surface (top)
- LRO LAMP data show that areas where the surface remains cold throughout the lunar year have spectral signatures consistent with water frost (bottom)
- LAMP data constrains the abundance of ice from ~0.1-2.0% by mass if mixed with the regolith, could be up to 10% if is pure water ice
- The synergy of the two datasets suggests that the distribution of water ices is controlled by temperature

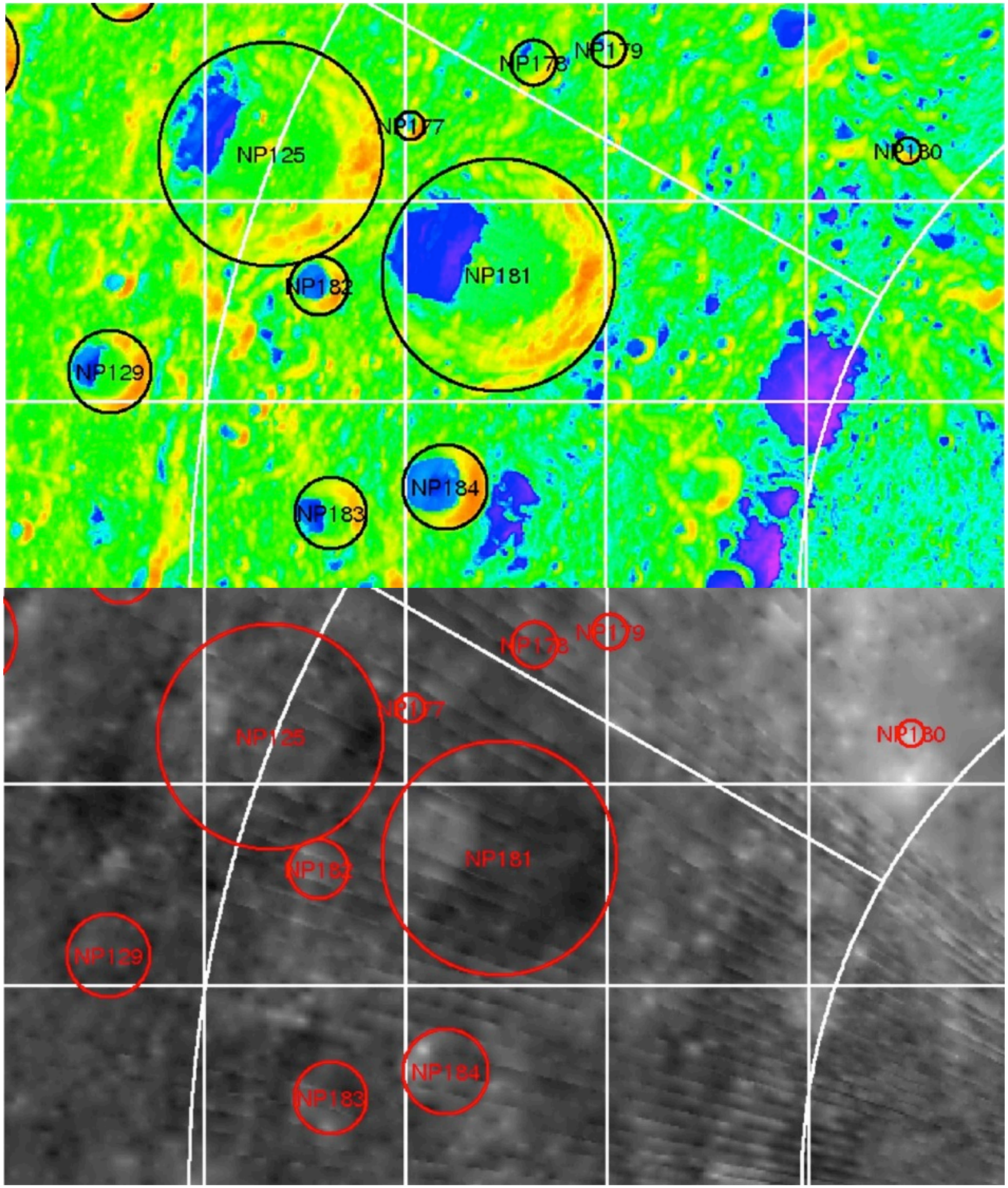



Diviner derived maximum surface temperature (left) for area near the South Pole, temperatures below 110K are stable for surface ice. The map of average annual temperature (right) show where temperatures below 140K can support subsurface ice.




Locations of anomalous UV albedo consistent with water ice as determined by LAMP data. A ratio of two bands in the UV in the range 1.2–4.0 are consistent with water ice concentrations of 0.1–2.0% by mass. If patchy exposures of pure water ice are mixed by area with dry regolith, the abundance could be up to 10%.


Hayne, P. O. et al. Evidence for exposed water ice in the Moon's south polar regions from Lunar Reconnaissance Orbiter ultraviolet albedo and temperature measurements. *Icarus*. 255 doi: j.icarus. 2015.03.032 (2015).




# LOLA/Diviner Identifications of Surface Frost

Lucey et al., 2013
Submitted to *Icarus*

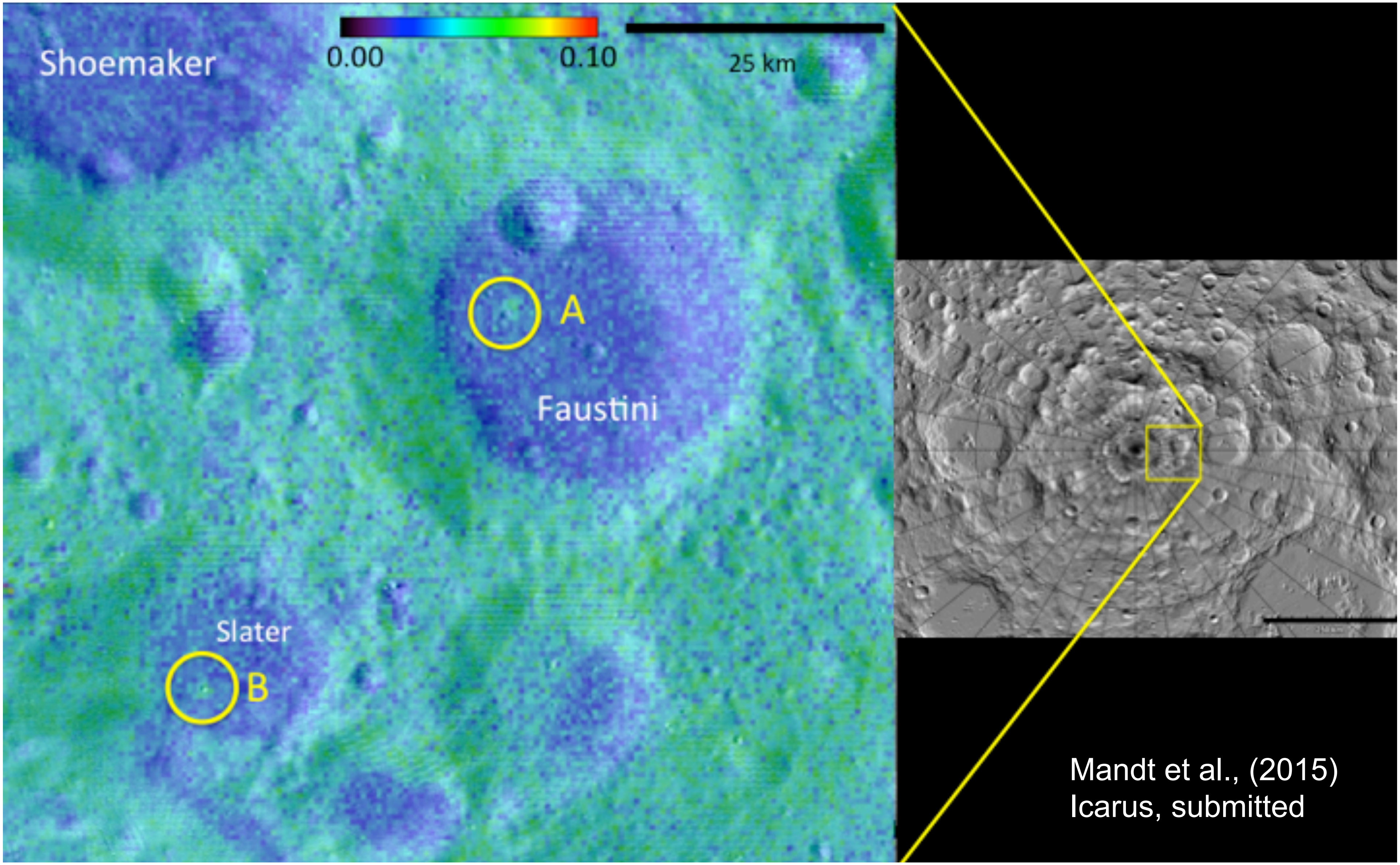
Bottom Line Results:

- LOLA reflectance increases with decreasing temperature
- Surface water ice suspected

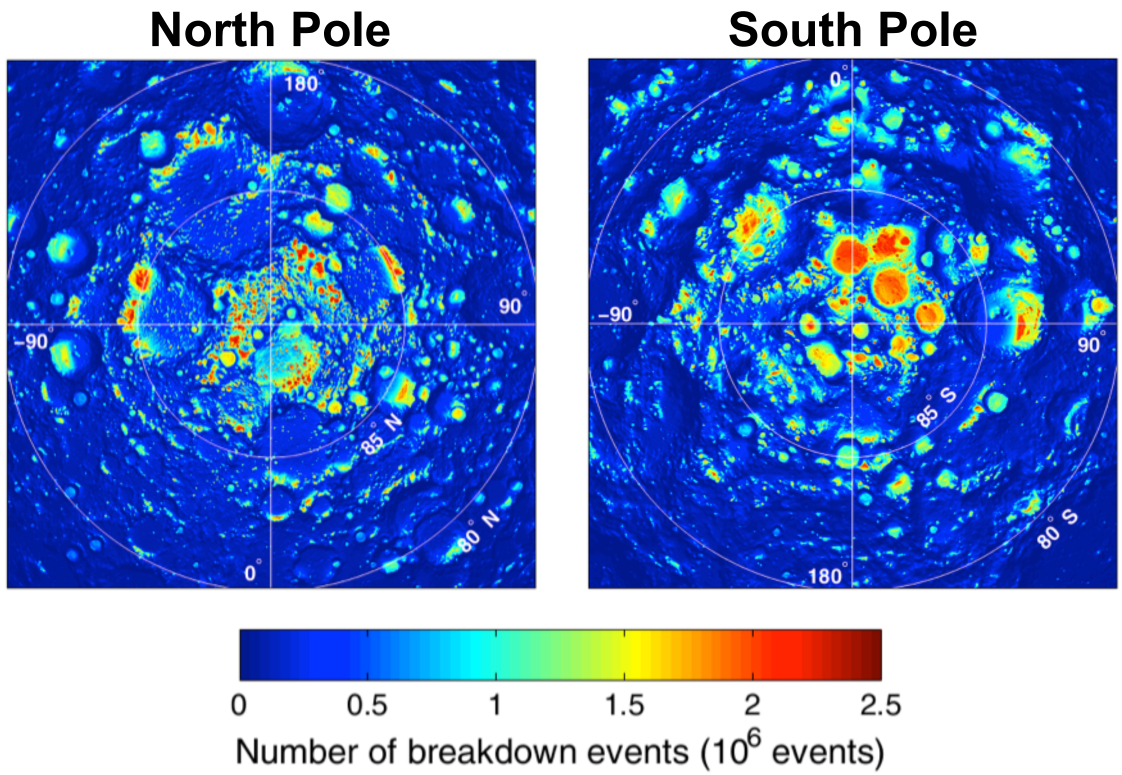
Next Steps:

- Reanalysis using updated LOLA calibration
- Reanalysis using crater interiors to reduce “geologic noise”

# Lamp Detection of a Geologically Young Crater Within the Faustini PSR



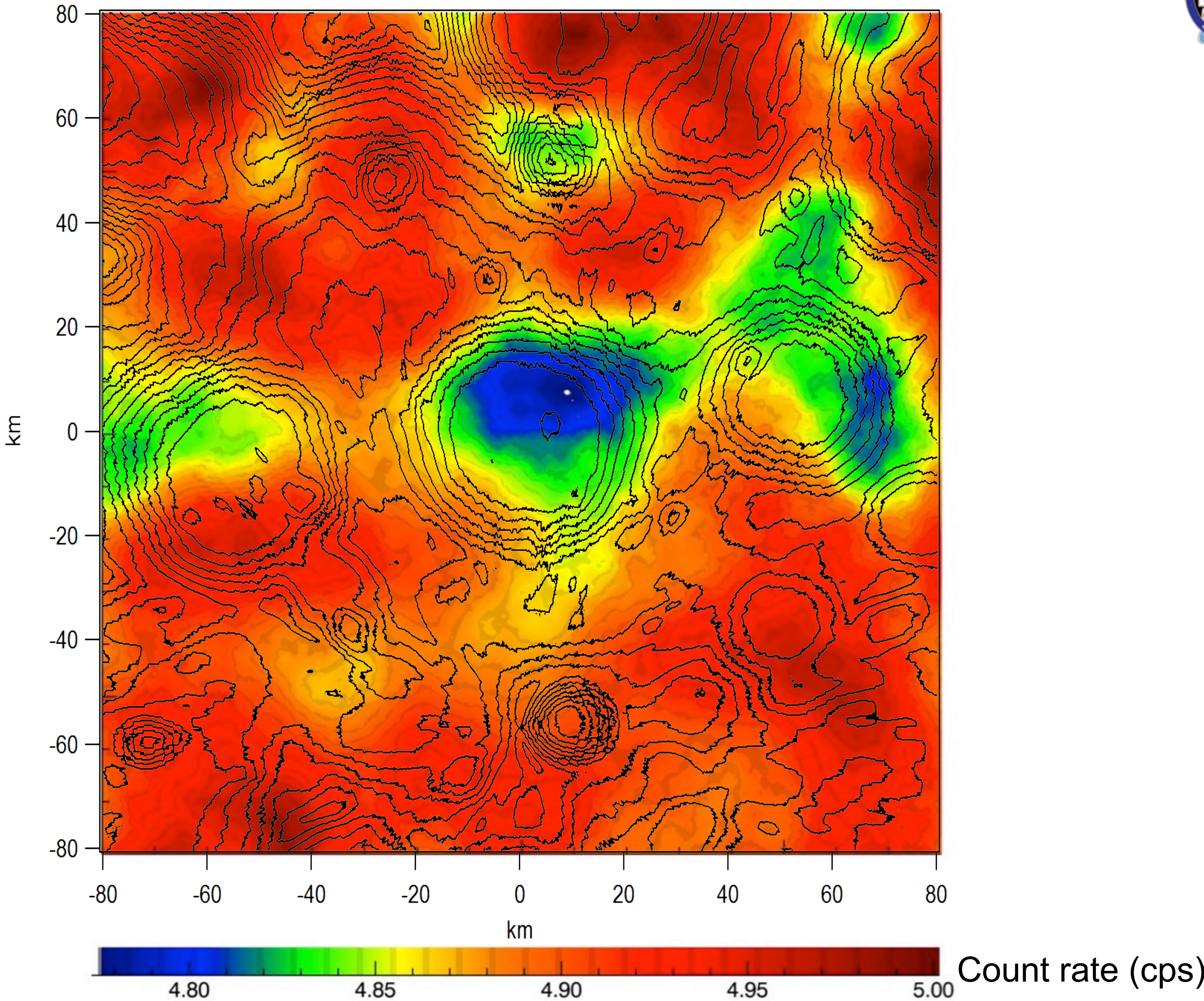
# Breakdown weathering may be comparable to meteoritic weathering




(Jordan et al., 2015)

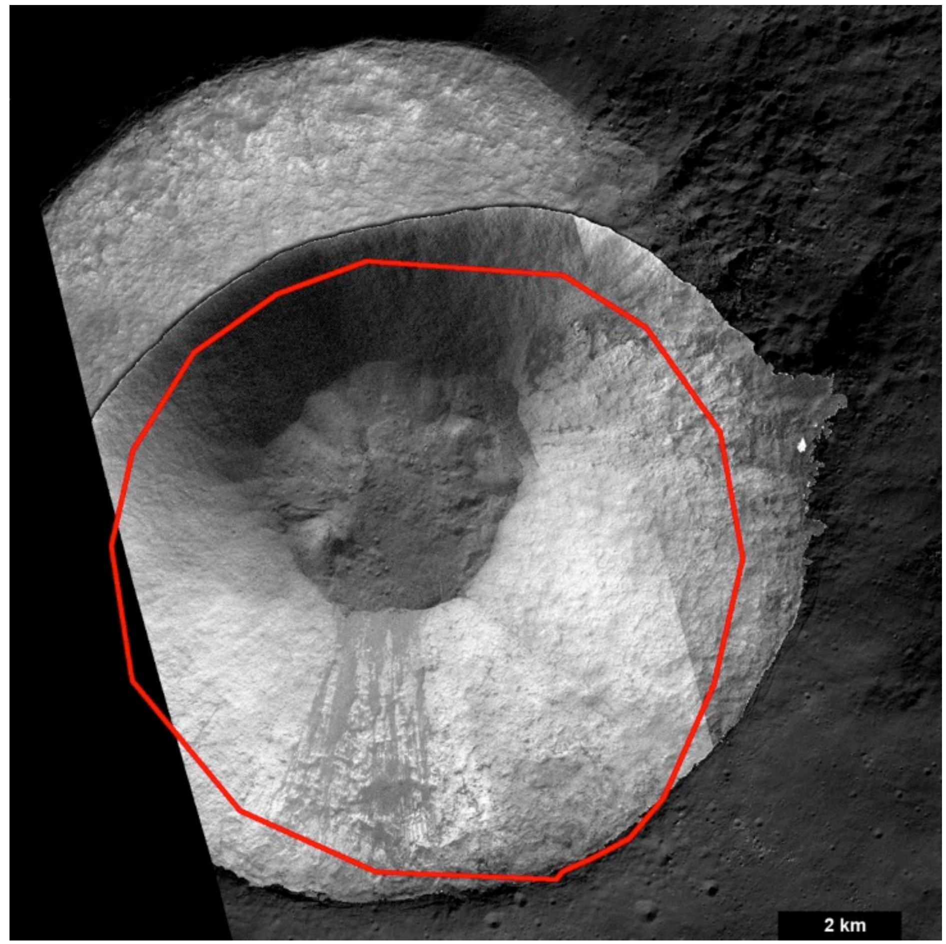
| Weathering process | Energy flux (J $m^{-2}$ $yr^{-1}$) | Vapor + melt production (kg $m^{-2}$ $yr^{-1}$) | % Gardened soil melted or vaporized |
|---|---|---|---|
| **Meteorites** | 12 | $1.8 \times 10^{-7}$ | ~10% |
| **Breakdown** | 0.88 | $1.8 – 3.4 \times 10^{-7}$ | ~10-25% |

# LEND Shoemaker Crater with LOLA Topography



# PSR Imaging

- Long exposure times allow NAC imaging in many PSRs
- Search for albedo boundaries, distinctive morpholgies (ice-rich regolith)
- Only negative results so far, 60% complete
- Why are the mercurian PSRs so different than the lunar examples? Key aspect(s) of sequestration remain unknown?




NAC imaging PSR
Main L (D: 14 km, 81.4°N, 22.8° E)

# LROC Temporal Imaging

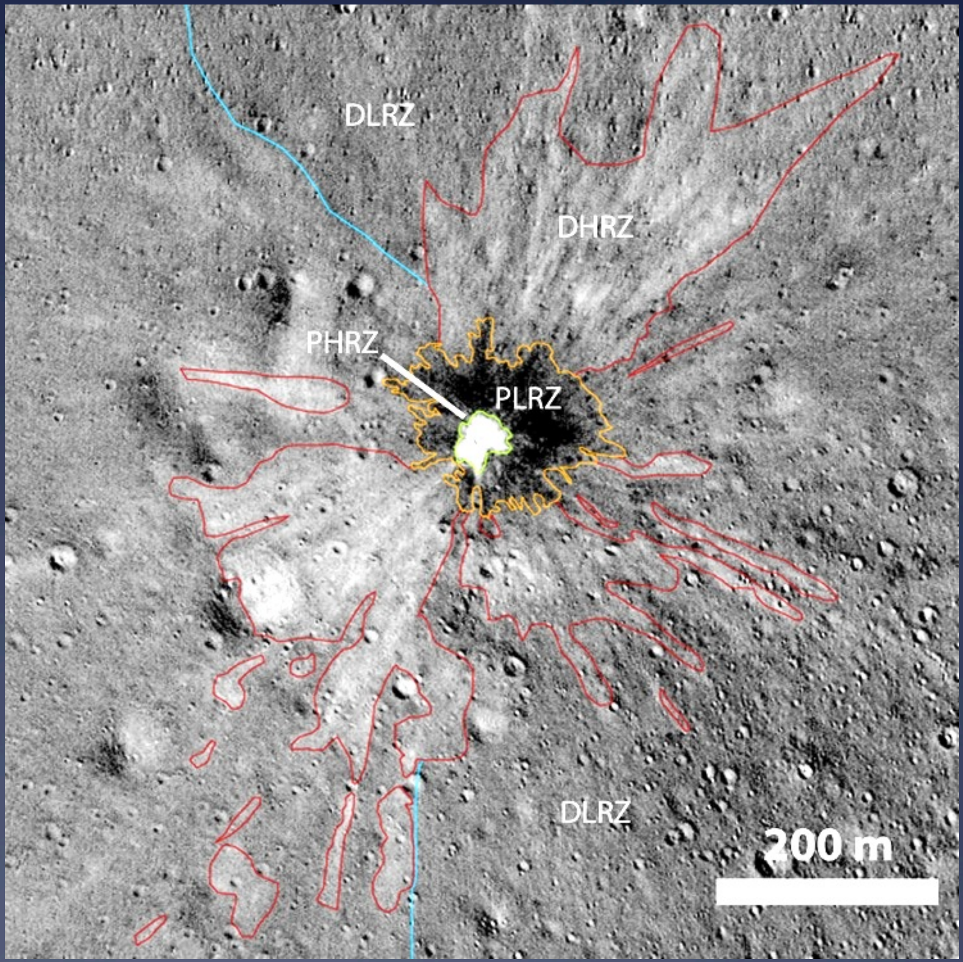
ESM2 Theme: Contemporary Surface Change

- Discovered hundreds of impact related changes since start of mission (NAC Before/After pairs)
- Significance
  - Refine flux of >0.5 m bolides inner Solar System
  - Seeing new complex ejecta patterns
  - Secondaries from small craters are extensive
  - Engineering constraints for future long lived assets


17 March 2013 impact, 18 m crater, secondaries found >30 km distant

# 17 March Crater: Ejecta

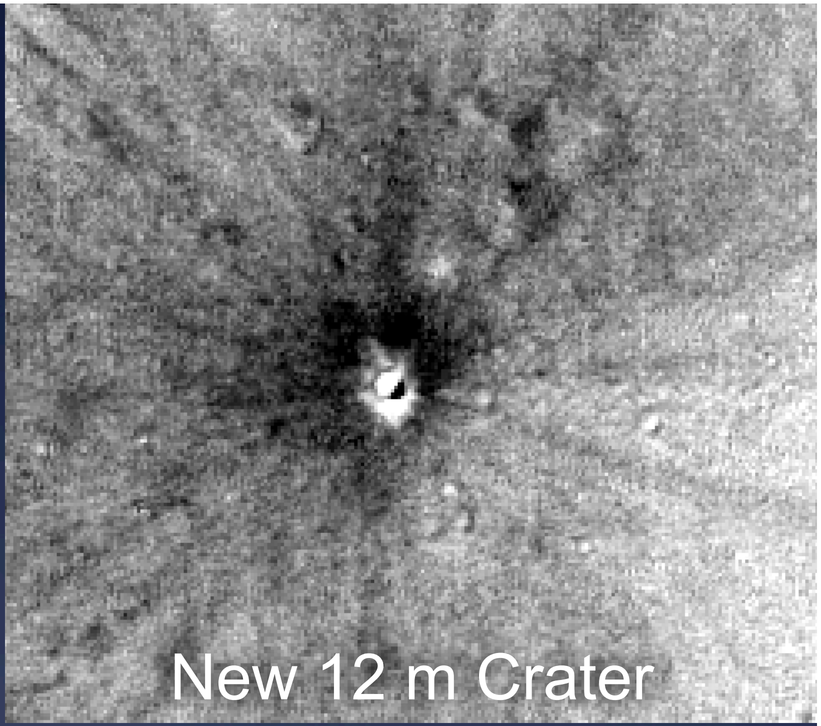
- Four Distinct Zones
  - Proximal high reflectance (+25 to +50%)
  - Proximal low reflectance (-5% to -10%)
  - Distal high reflectance (+3% to +5%)
  - Distal low reflectance (-3%)
- Abundant splotches out to 30 km distant

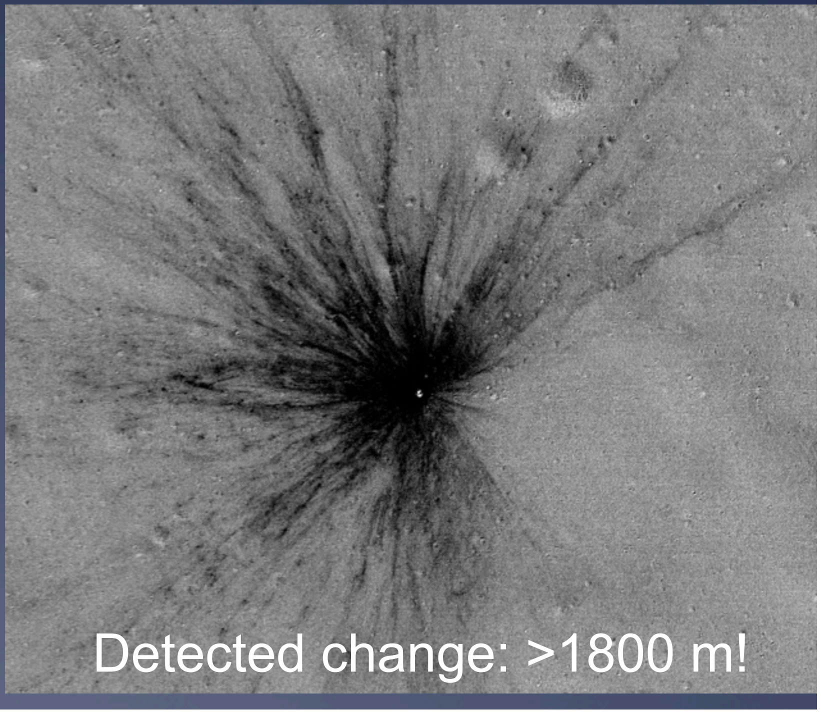


# New Impact Craters!

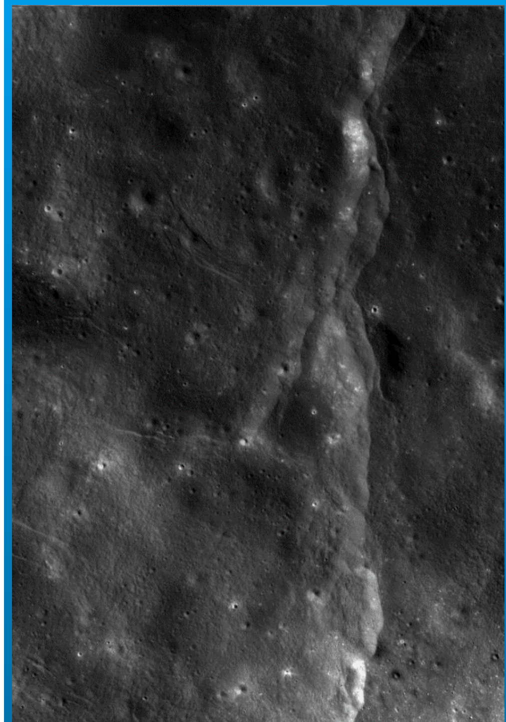
Identified 139 resolved impact craters that formed since orbit insertion (1.5 m to 43 m diam)

- Total excludes craters located with recorded flashes (n=2)
- 11 of these craters have a diameter greater than 10 m (>30% more than the Neukum production function estimates).
- Witnessed complex ejecta patterns and regolith disturbances that extend well beyond 1.5 crater diameters

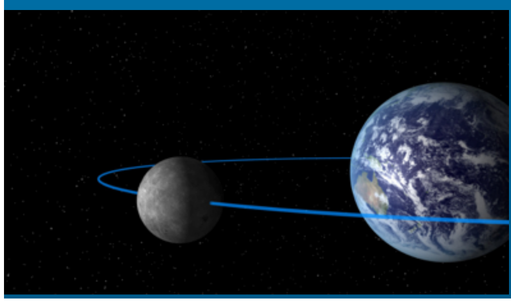


# Global thrust faulting on the Moon and the influence of tidal stresses



Lobate thrust fault scarp  in the Vitello cluster



## Radial contraction from interior cooling

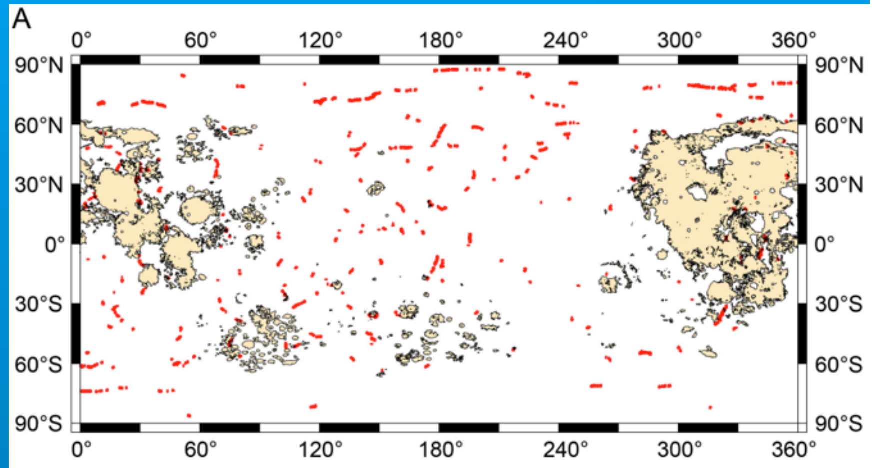
- Produces a isotropic compressional stress field
- Random distribution of orientations predicted

## Non-random orientations of faults indicates other influences

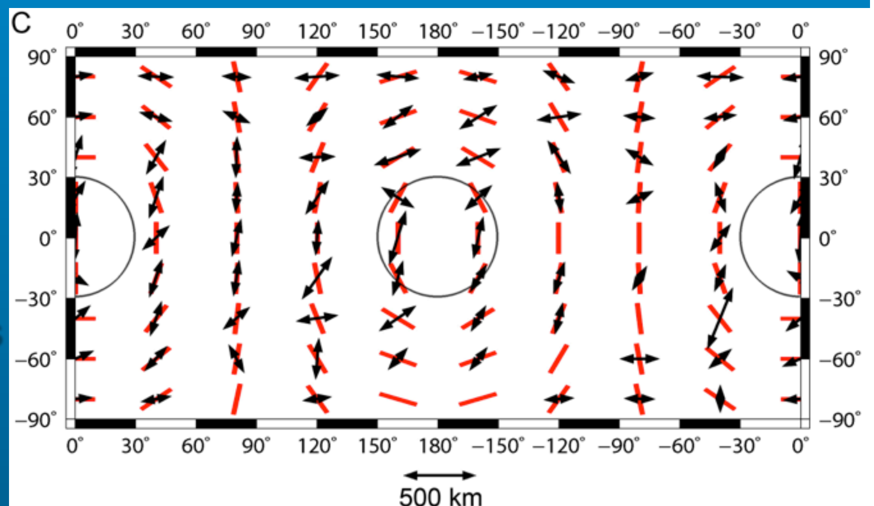
## Two sources of tidal stress acting on the Moon today are

- Orbital recession ($\sigma_r$)
- Earth-raised diurnal tidal stress ($\sigma_t$)

## Superimposed tidal stresses on global contraction ($\sigma_c$) result in a net non-isotropic compressional stress field ($\sigma_c >> \sigma_r > \sigma_t$) and faults with preferred orientations




Digitized locations of over 3, 200 young lobate thrust fault scarps on the Moon.

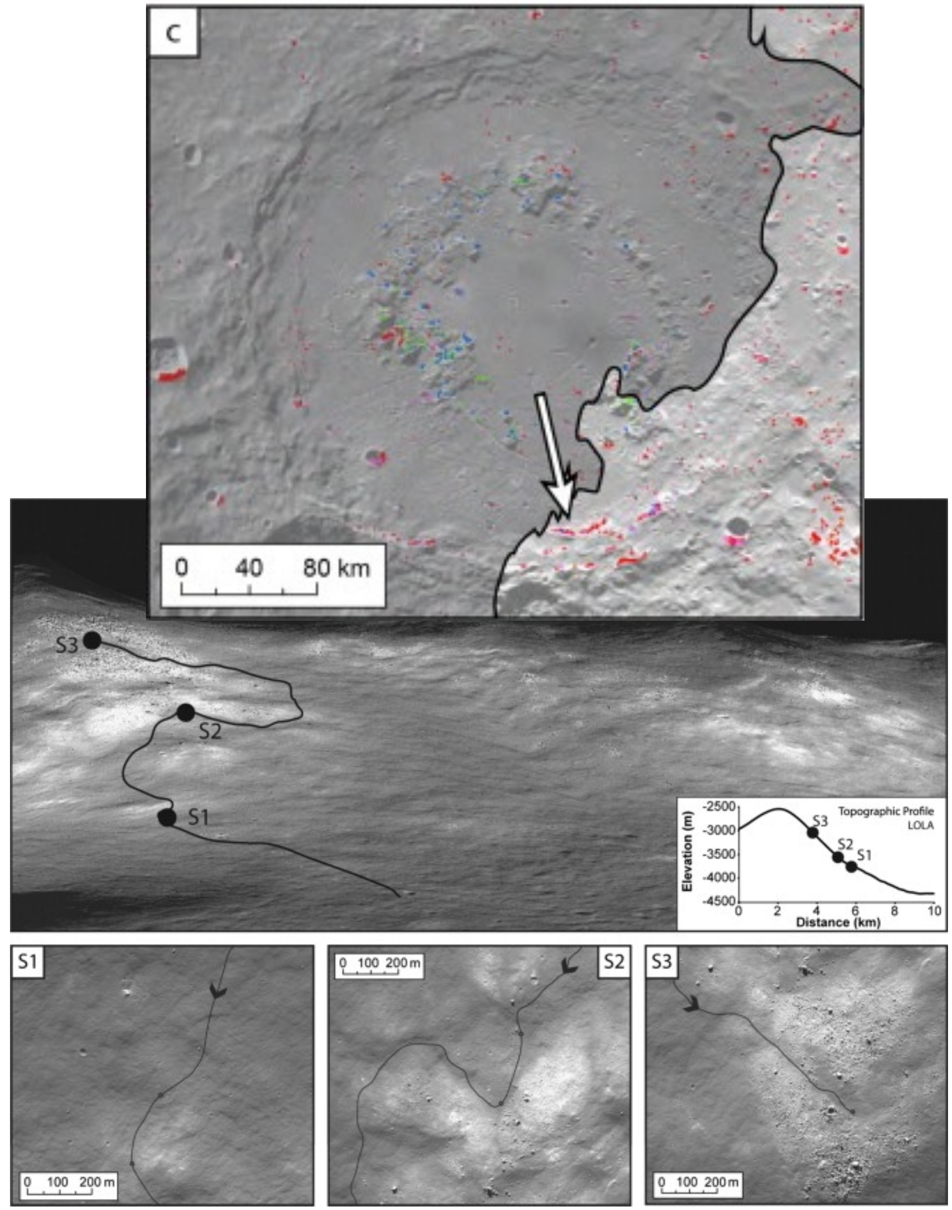



Orientations of predicted faults (red lines) due to the combination of stresses from orbital recession, diurnal tidal stresses at apogee, and global contraction plotted with the orientation vectors of the lobate scarps.

# CLSE: LRO Data – Identifying Sample Sites within SPA

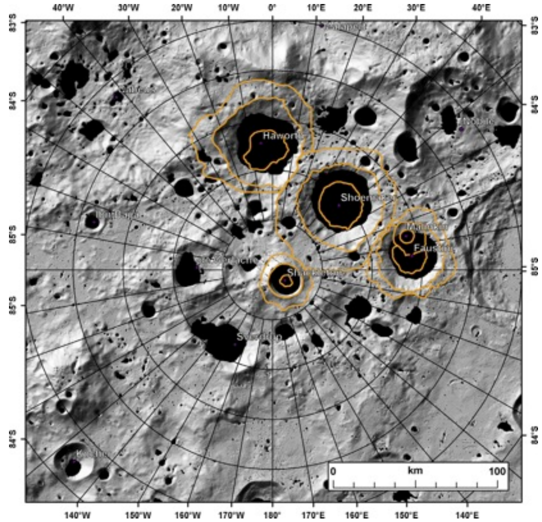
Hurwitz and Kring (2015, EPSL) use LRO data to identify sampling sites within Schrödinger Basin. Such sites contain material that can be used to determine the age of SPA.

High-resolution images coupled with topographic data enable detailed traverse planning and the identification of specific outcrops or boulders to sample.



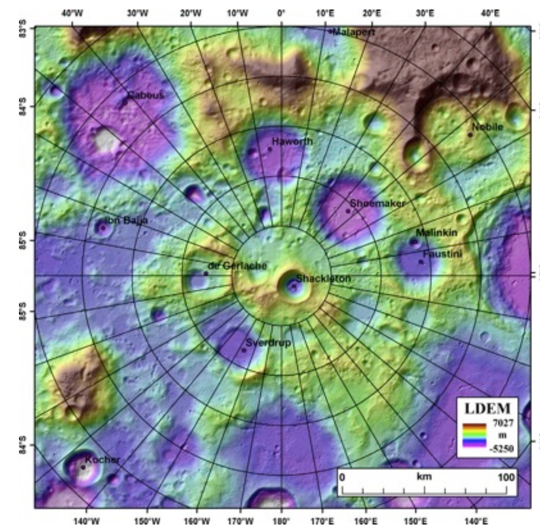
# SEEED: LRO Data Used To Estimate the Age of South Polar Craters and Implications for Volatile Sequestration

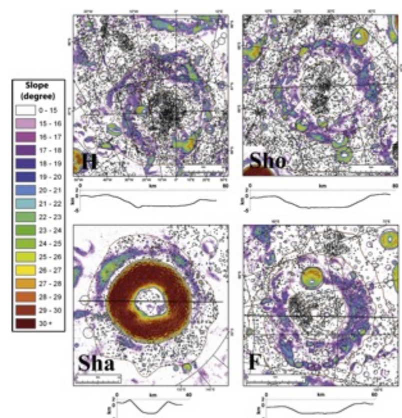
- Areas in permanent shadow near the lunar poles present challenges in determining the ages of surfaces (top left figure)
- LRO LOLA data (right) allows for small craters in permanent shadow to be identified for the first time and used to constrain the age of larger features
- Prior age inferences for the ages of the craters was based on images and under-estimated the ages of the craters
- The largest craters are estimated to be ~4.1-4.2 Ga old, while Shackleton is 3.15 Ga
- These ages constrain when surface volatiles were emplaced, likely in the last 3.5 Ga, such emplacement have not significantly modified the surface




(Left) View of the lunar South Pole showing the location of areas in permanent shadow (in black). Four large craters were assessed in the study, Haworth, Shoemaker, Faustini, and Shackleton.

(Right) LOLA derived topography at 20m per pixel of the South Pole region showing the interiors of areas in permanent shadow.




(Right) Maps of the four craters with identified craters shown and LOLA-derived surface slopes mapped in color.


Tye, A. R. et al. The age of lunar south circumpolar craters Haworth, Shoemaker, Faustini, and Shackleton: Implications for regional geology, surface processes, and volatile sequestration. *Icarus*. 255 doi: j.icarus.2015.03.016 (2015).

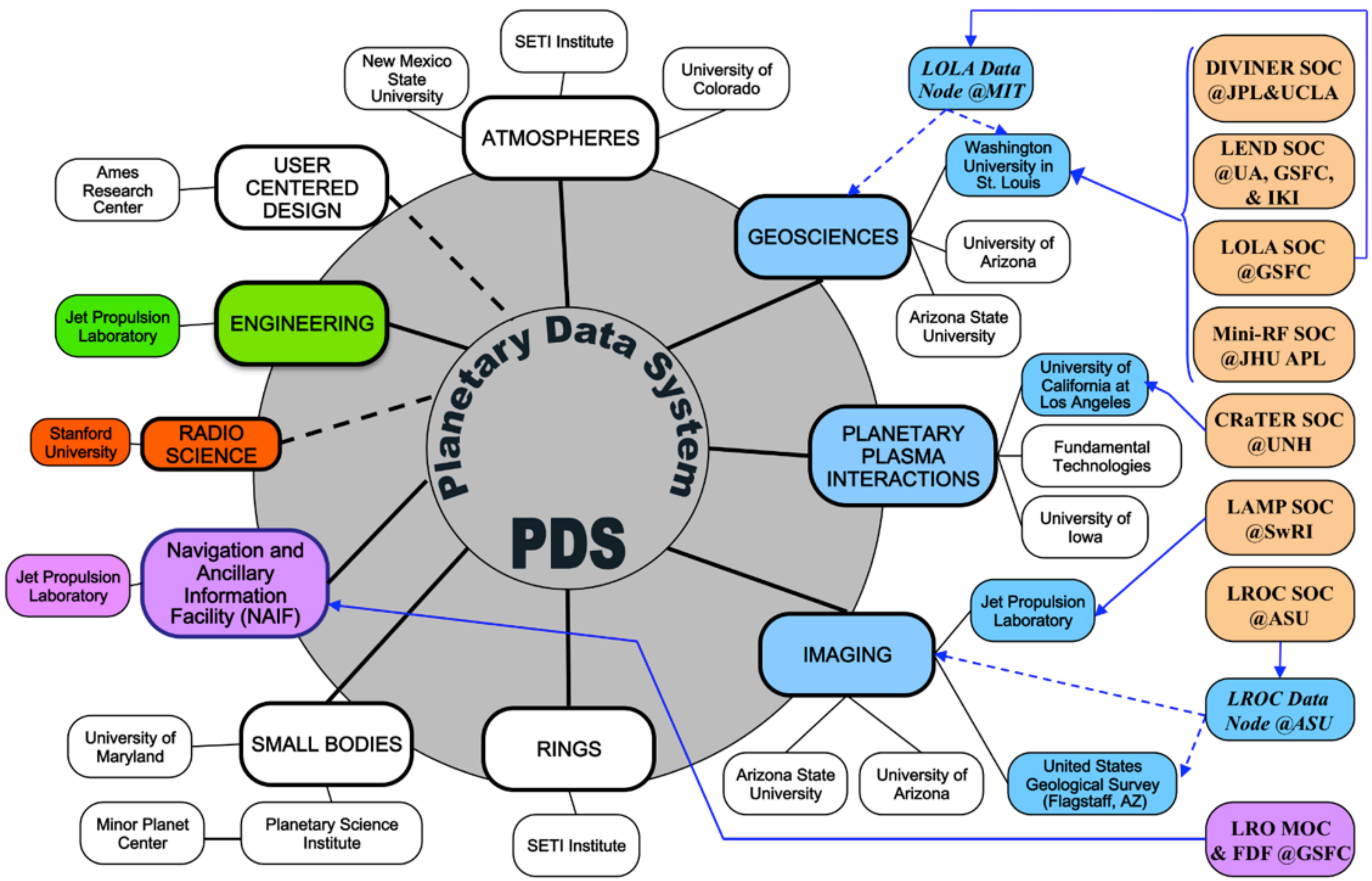
# Lunar Data Analysis Program

Step 1 due 08/28/15
Step 2 due 10/30/15

**LDAP supports scientific investigations of the Moon using publicly available (released) data. These include the following missions:**

**Lunar Crater Observation and Sensing Satellite (LCROSS),**
**Moon Mineralogy Mapper (M3),**
**Lunar Reconnaissance Orbiter (LRO)**
**Gravity Recovery and Interior Laboratory (GRAIL),**
**Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moonâ€™s Interaction with the Sun (ARTEMIS),**
**Lunar Atmosphere and Dust Environment Explorer (LADEE),**
**Non-U.S. missions: Kaguya, Changâ€™e 1, Changâ€™e 2, Chandrayaan-1, Changâ€™e 3.**

# LRO SOCs & PDS Support

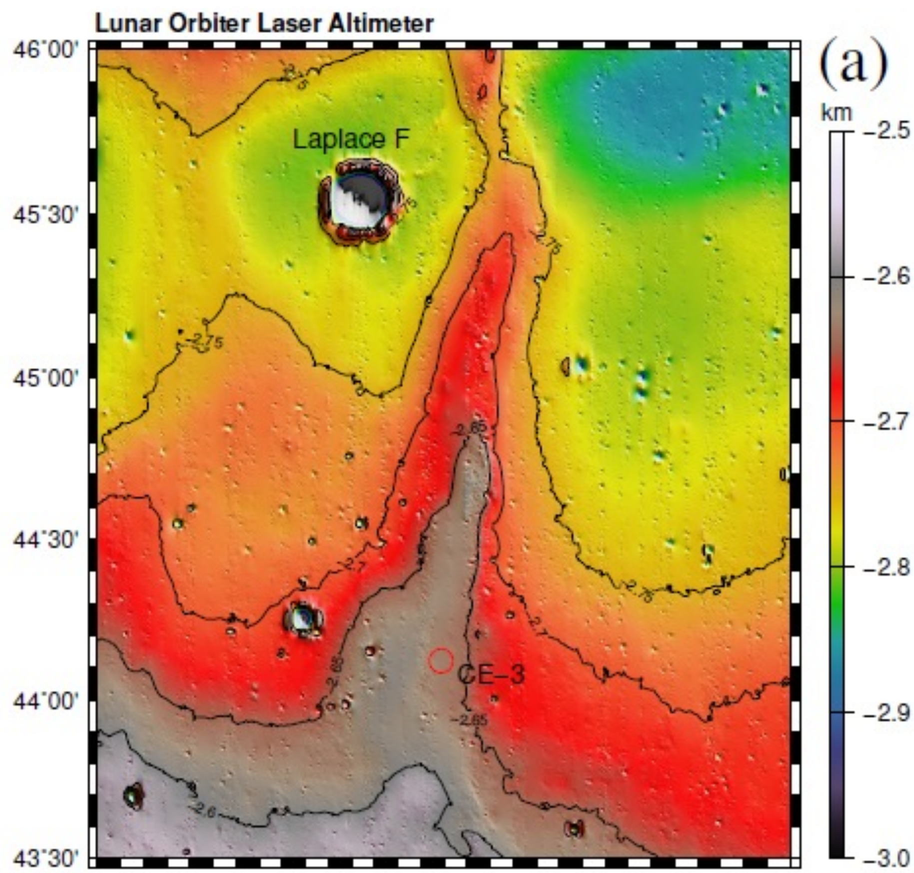



**Color and font scheme (PDS elements in white do not support LRO):**
**Tan:** LRO Science Operations Center (SOC);
**Blue:** LRO data archive sites- PDS Node & Data Node; ***Blue & Italics:*** LRO Data Node;
**Green:** PDS system-wide engineering; **Purple:** LRO SPICE data origin & archive sites; **Orange:** PDS Function with LRO advisory role

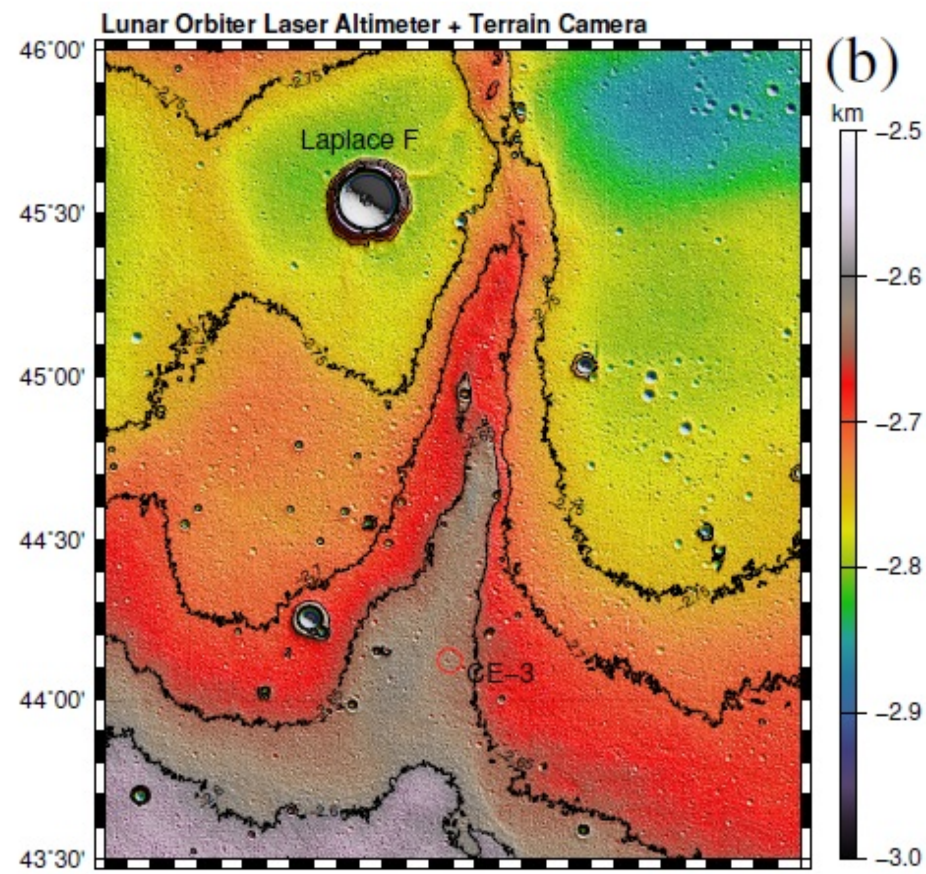
Stan Scott 2010-08-27

# SLDEM 2015: A new lunar digital elevation model from the Lunar Orbiter Laser Altimeter and SELENE Terrain Camera

Barker, M. K. et al.(2015) Icarus, in press. See poster #59




LOLA




LOLA + TC

# Backups

# LRO Data is Widely Used.

Contents lists available at ScienceDirect

ELSEVIER

Icarus

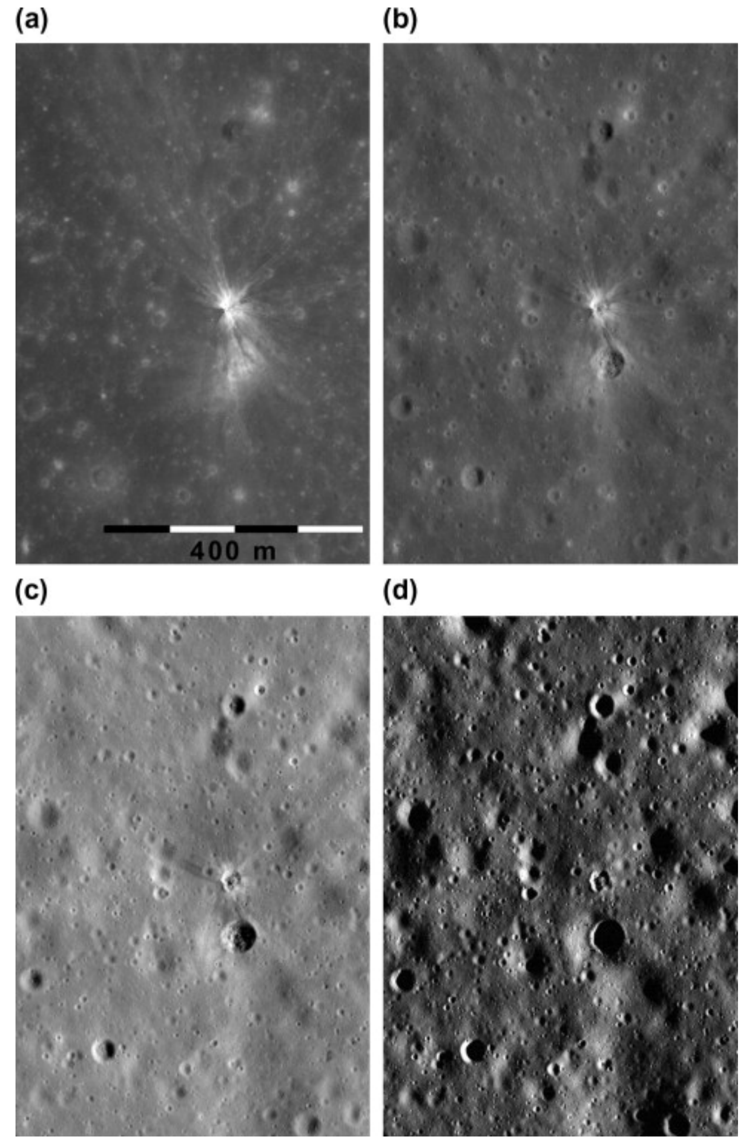
journal homepage: www.elsevier.com/locate/icarus

Dark halos and rays of young lunar craters: A new insight into interpretation

Vadym Kaydash[a], Yuriy Shkuratov[a], Gorden Videen[b,*]

[a] Astronomical Institute of Kharkov V.N. Karazin National University, Sumskaya 35, Kharkov 61022, Ukraine
[b] Space Science Institute, 4750 Walnut St. Suite 205, Boulder, CO 80301, USA

- Extensive LROC data set enables phase angle analysis to draw conclusions on the properties of the regolith
- In ESM2 the full photometric function (variable incident and emission angle) will be extended to higher latitudes. Variable emission angle measurements will be made in the IR (Diviner).



# LRO Data also serving the SSERVI Teams

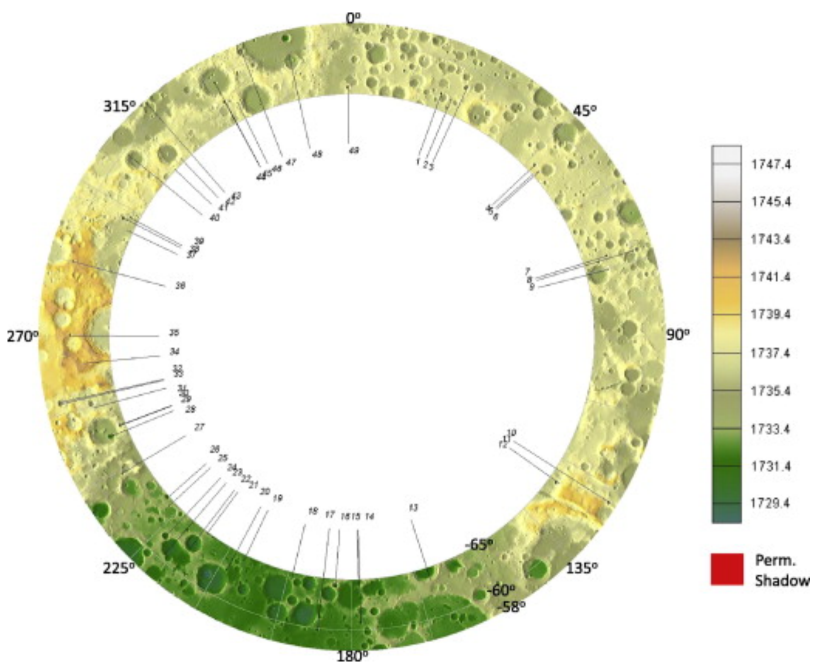

ELSEVIER

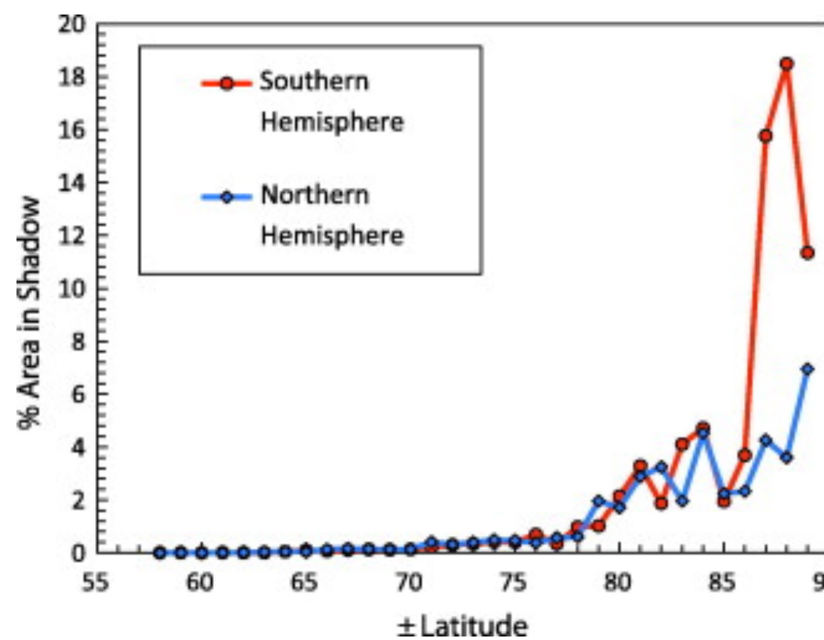
Icarus

Volume 223, Issue 1, March 2013, Pages 566–581


## Mapping and characterization of non-polar permanent shadows on the lunar surface


J. Andrew McGovern[a], D. Benjamin Bussey[a], Benjamin T. Greenhagen[b], David A. Paige[c], Joshua T.S. Cahill[a], Paul D. Spudis[d]

# LRO Data also serving the SSERVI Teams

Contents lists available at SciVerse ScienceDirect

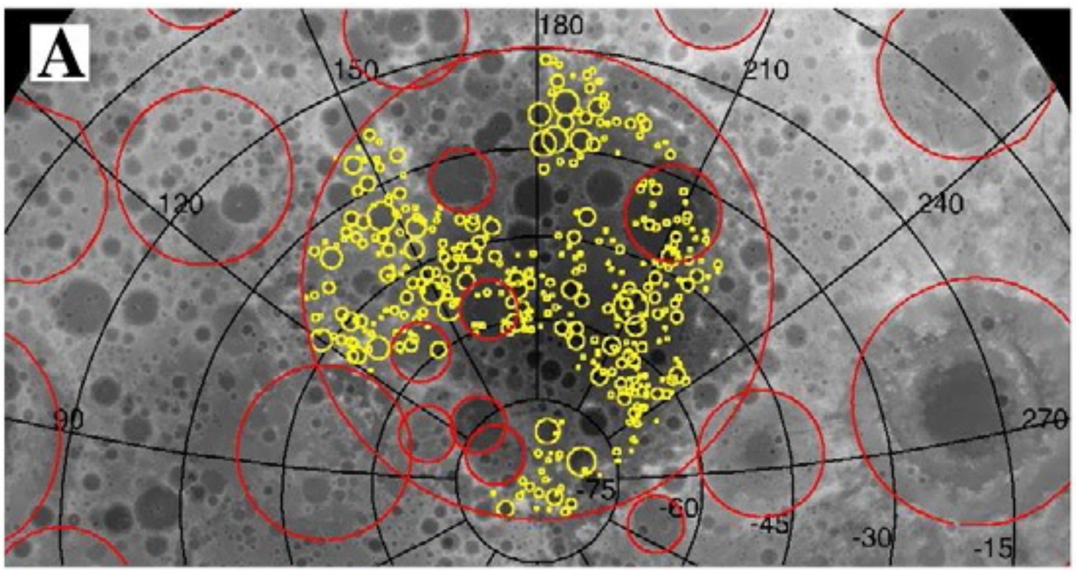
Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

The onset of the lunar cataclysm as recorded in its ancient crater populations

Simone Marchi [a,b,c,*], William F. Bottke [b], David A. Kring [c], Alessandro Morbidelli [a]

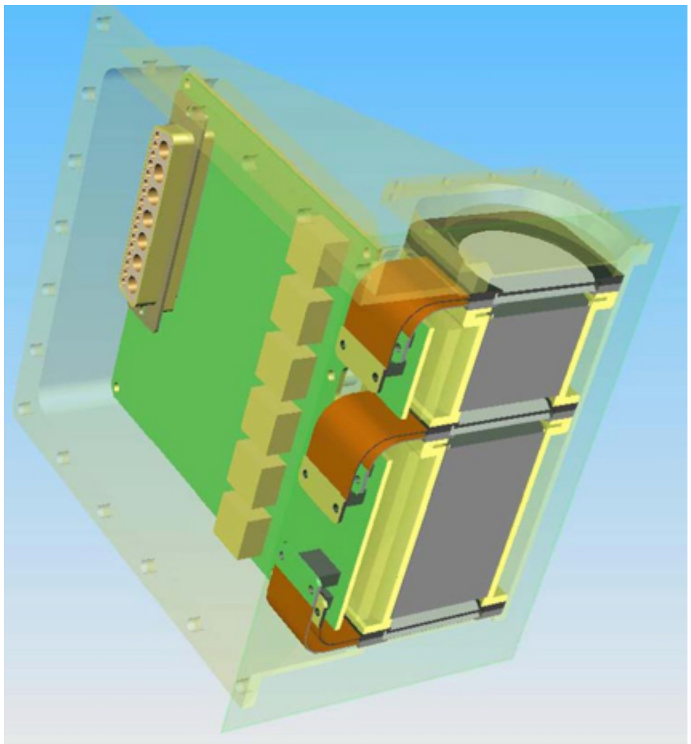
[a] Laboratoire Lagrange, Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, France
[b] Center for Lunar Origin & Evolution, SwRI, Boulder, CO, USA
[c] Center for Lunar Science & Exploration, USRA — Lunar and Planetary Institute, Houston, TX, USA

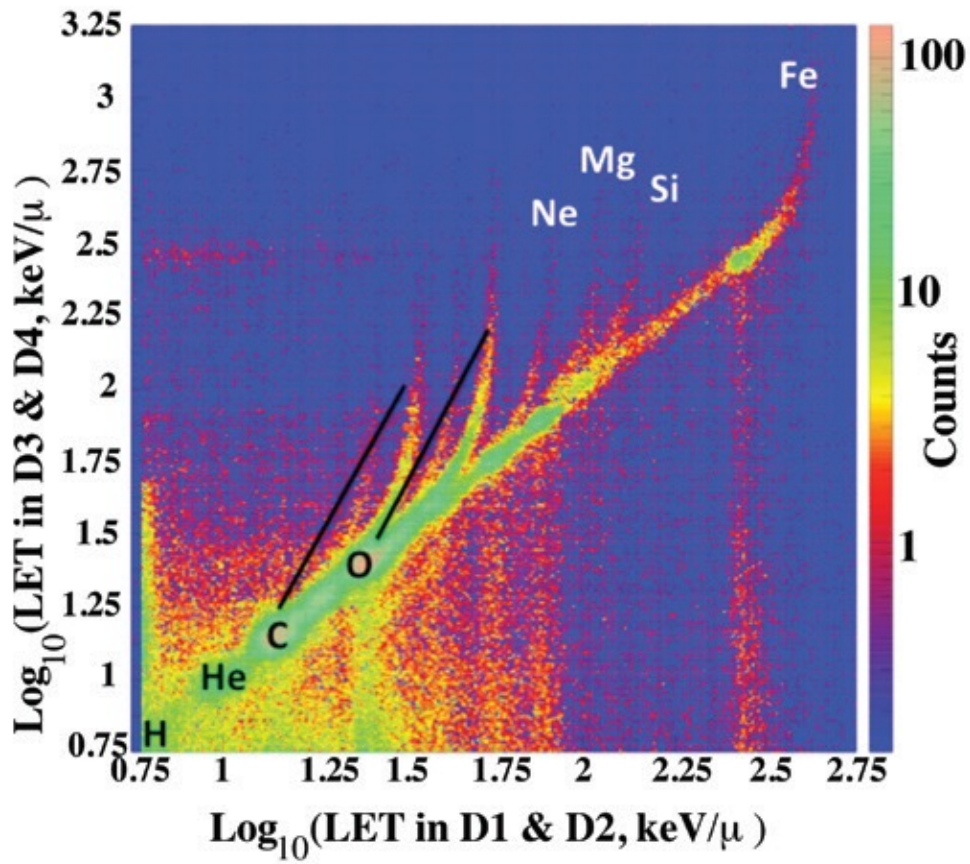



Analysis of LRO (and other) data led to these conclusions

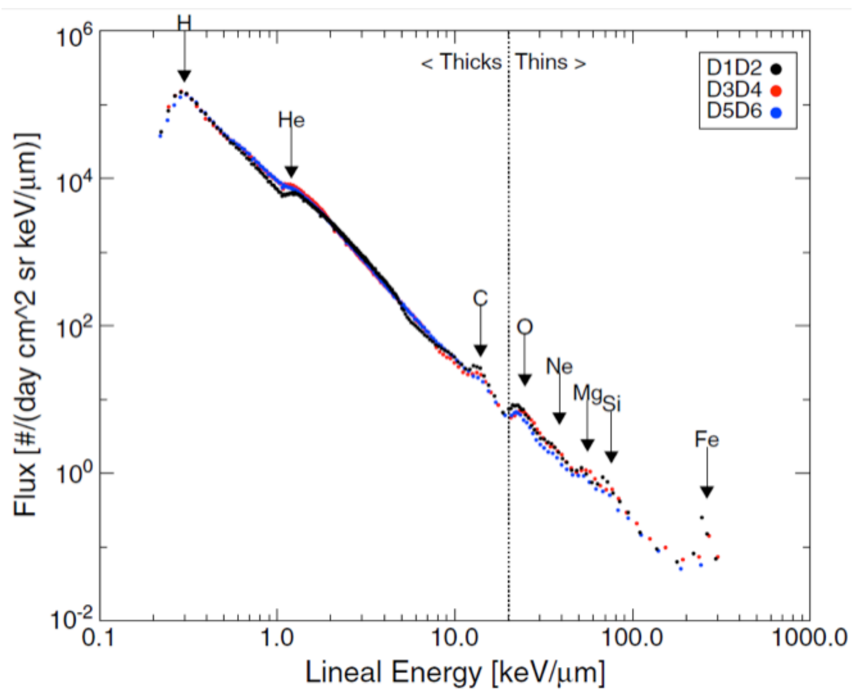
- The existence of distinct low and high impact velocity (impact crater) populations supports the existence of a lunar cataclysm.
- …interpretation that the cataclysm started near the formation time of Nectaris basin also implies that the ancient SPA basin did not form during the LC but instead was derived from an earlier phase of lunar history.

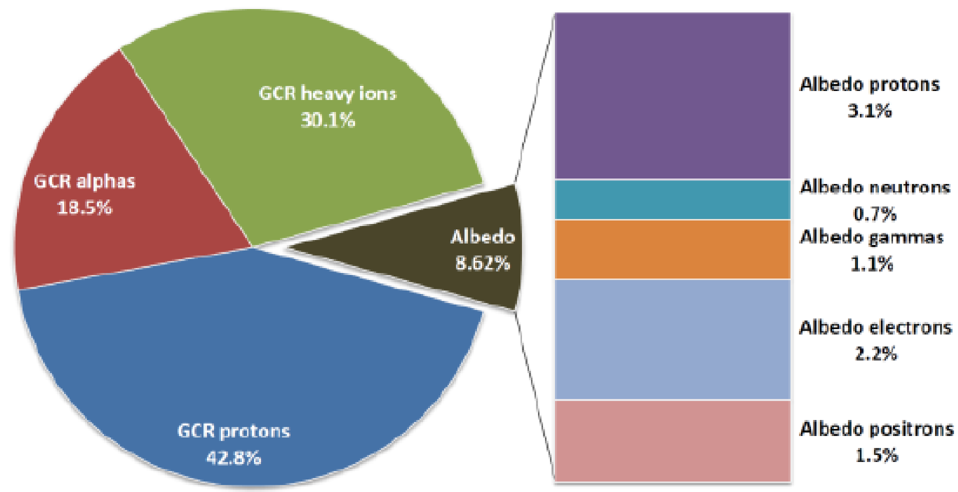
# CRaTER: Heavy Atom Cosmic Rays

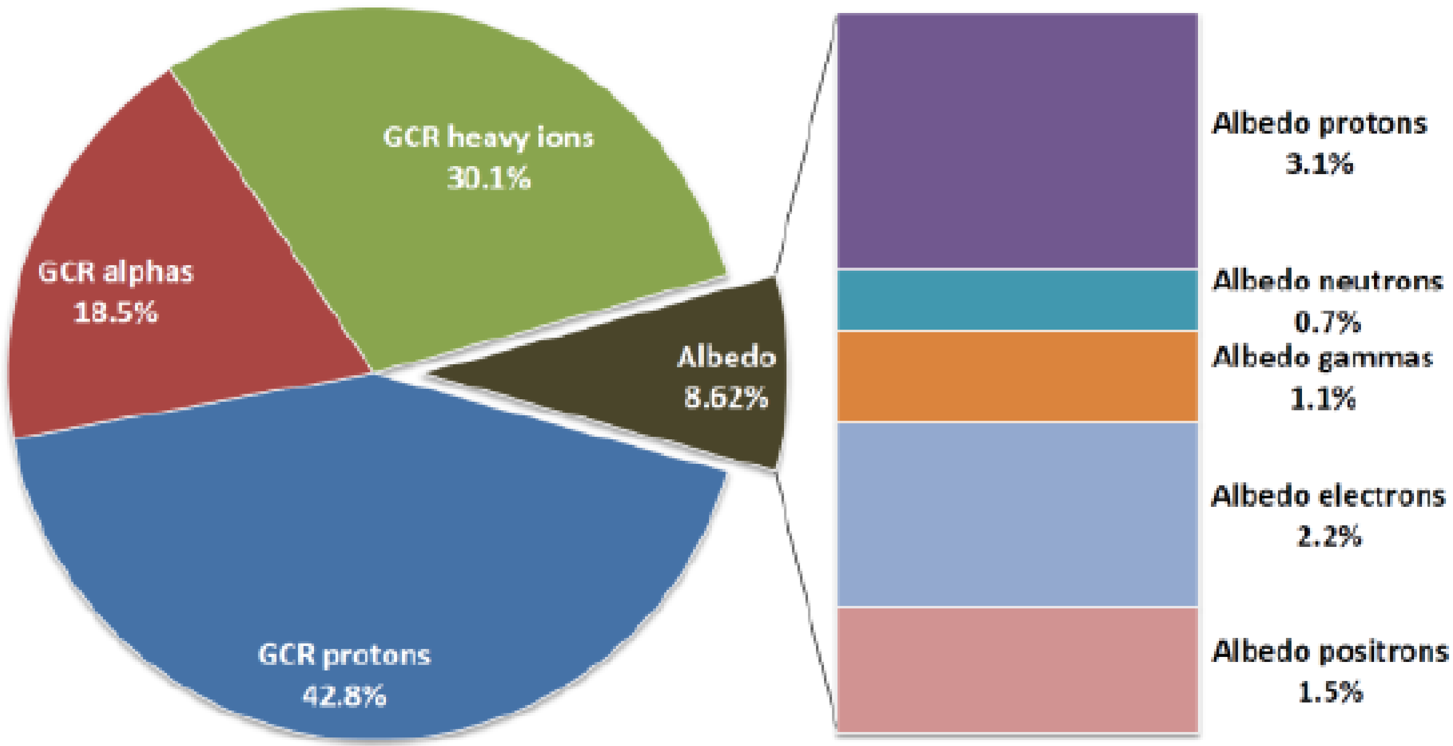




# CRaTER: Heavy Atom Cosmic Rays

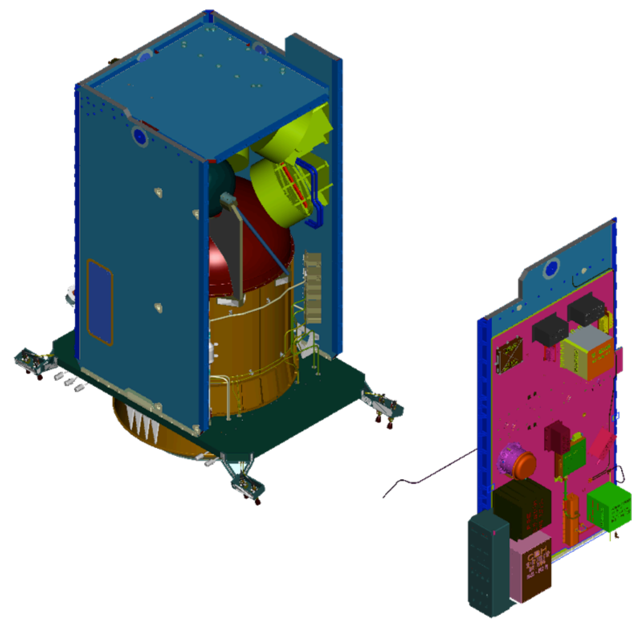



GCR heavy ions
30.1%
GCR alphas
18.5%
Albedo
8.62%
GCR protons
42.8%
Albedo protons
3.1%
Albedo neutrons
0.7%
Albedo gammas
1.1%
Albedo electrons
2.2%
Albedo positrons
1.5%

# Half of LRO Mass is Propellant
# LRO's Data Volume is Enormous

| LRO Orbiter Characteristics | | |
|---|---|---|
| Launch Mass | 1916 kg | Dry: 1018 kg, Fuel: 898 kg (1313 m/sec) |
| Orbit Average Power | 681 W (2 kW array) | |
| Data Volume, Max Downlink rate | 459 Gigabits/day, 100 Megabits/sec | |
| Pointing Accuracy, Knowledge | 60 arc-sec, 30 arc-sec | |



# Lunar Reconnaissance Orbiter (LRO)

**Seven instrument payload**

Cosmic Ray Telescope for the Effects of Radiation (CRaTER)
Lunar Orbiter Laser Altimeter (LOLA)
LRO Camera (LROC)
Lyman-alpha Mapping Project (LAMP)
Diviner Lunar Radiometer Experiment (DLRE)
Lunar Exploration Neutron Detector (LEND)
Miniature Radio Frequency System (Mini-RF)

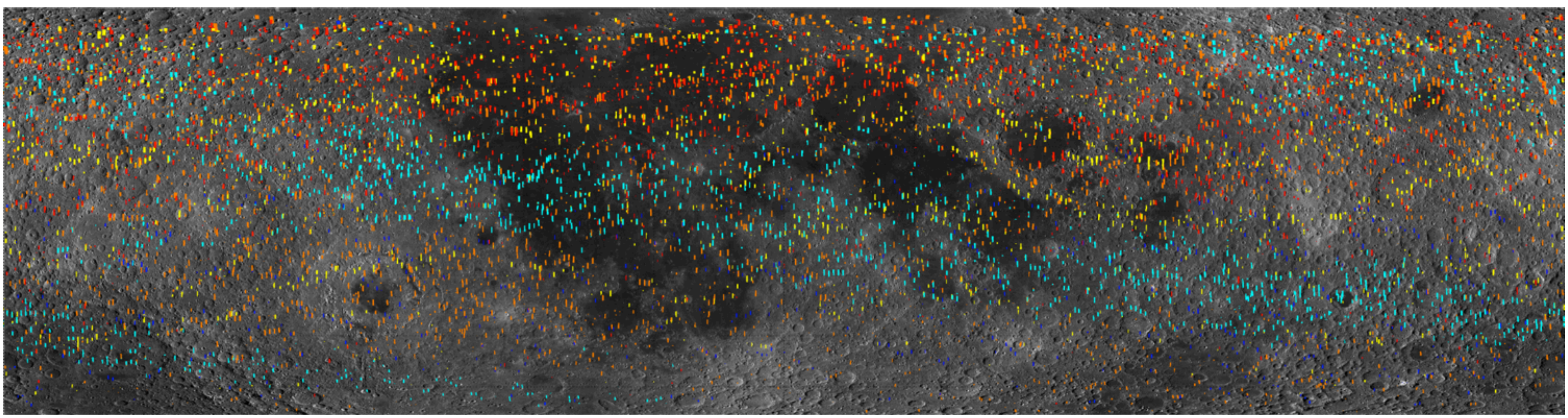
**LRO is returning**

- Global day/night temperature maps (Diviner)
- Global high accuracy geodetic grid (LOLA)
- High resolution monochrome imaging (LROC)
- High resolution local topography (LOLA, LROC)
- Global far ultraviolet albedo map (LAMP)
- Polar observations both in shadowed and illuminated areas (LEND, LROC, LOLA, DLRE, Mini-RF, LAMP)
- Ionizing radiation measurements in the form of energetic charged particles and neutrons (CRaTER, LEND)

*LRO was launched June 18, 2009 and entered mapping orbit September 15, 2009*

# Status: NAC Temporal Pairs

*Map of 10,400 NAC Temporal Pairs Searched and Cataloged*



177 days    354 days    531 days    709 days    >886 days