By the Light of a Watery Moon:

New Discoveries About Lunar Volatiles

Paul D. Spudis

Lunar and Planetary Institute

spudis@lpi.usra.edu
www.spudislunarresources.com

14 February, 2013

Why the Moon?

It's close

Three days away and easily accessible (as near as GEO)

Transport system to Moon can also access GEO, cislunar, Earth-Sun Lagrangians, and some asteroids

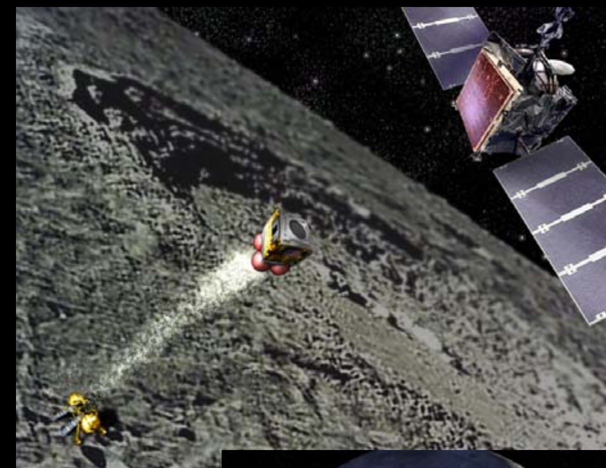
It's interesting

Moon contains a record of planetary history, evolution and processes unavailable for study on Earth or elsewhere

It's useful

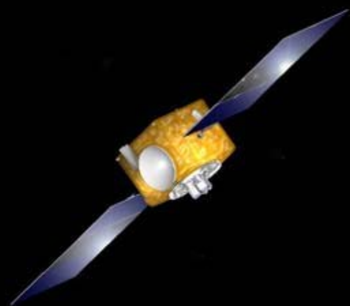
Retire risk to future planetary missions by re-acquiring experience and testing with lunar missions

Development of lunar resources has potential to be a major advancement in space logistics capability



Missions to the Moon

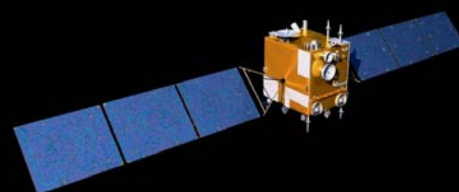
2003-2012



SMART-1
2003-2006

CHANG'E-1
2007-2009

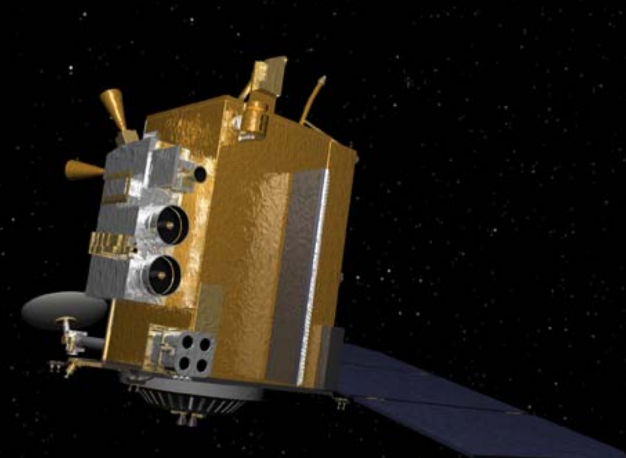
LCROSS
2009



CHANG'E-2
2010-2011

KAGUYA-SELENE
2007-2009

CHANDRAYAAN-1
2008-2009



LRO
2009-present

The Known Moon

Equator and mid-latitudes

Resources

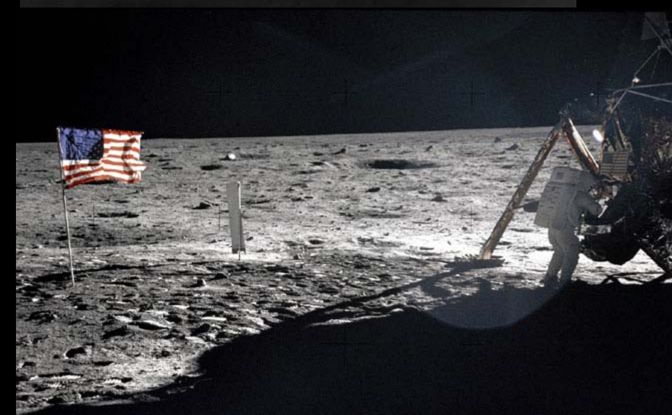
- Regolith, mean grain size ~ 40 µm, mostly mineral fragments and agglutinate glass
- Basaltic or anorthositic composition, volatile-depleted, no indigenous lunar water, < 3% meteoritic debris
- Oxygen can be extracted from regolith:
  - Break metal-oxygen bonds in silicates or oxides
  - Melt bulk soil and pass electrical current through magma, releasing oxygen
  - Both are high energy, variable output processes, but conceptually understood
- Solar wind volatiles in soil: H ~20-90 ppm, C ~100-200 ppm, N ~10-90 ppm

Environment

- 14-day diurnal sunlight and thermal cycle; possible electrostatic charging environment associated with terminator
- Surface temperatures ~100° C at local noon; -150° C before sunrise
- High vacuum (10^{-9} torr), no global magnetic field (but locally strong anomalies)
- Hard radiation environment (cosmic rays), solar wind impinges directly on surface, Moon flies through Earth’s geomagnetic tail

Operations

- Operations experience in early to mid-lunar morning; no experience at lunar noon or night



The Unknown Moon

The Polar Regions

Resources

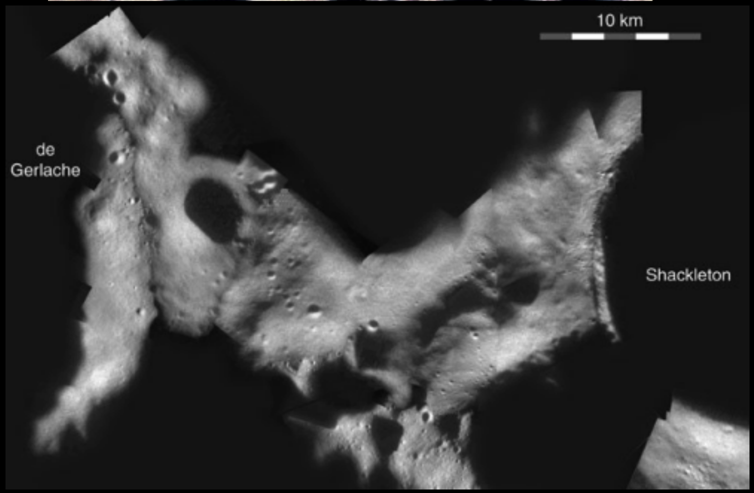
- Enhanced hydrogen content (water ice?) in polar regions; composition, physical state, and origins unknown
- Other volatiles may be present in cold traps; composition, physical state, and origins unknown
- In principle, polar regolith similar to equatorial, but cold trap material may have very different physical properties (cold+ admixed ice); details unknown

Environment

- Areas of near-constant sunlight (-50° C), constant darkness (unknown; modeled as -220° C)
- Known and constant thermal environment dependent on *location*, not time

Operations

- Sun always at or near horizon; possibly a difficult operational/working environment
- Earth “rises” and “sets” depending on state of 14-day libration cycle; need communications relay for constant Earth contact



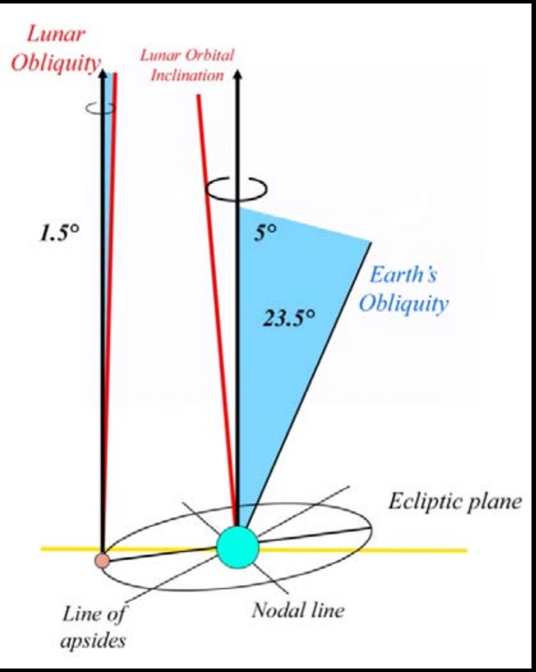
Lunar Polar Environment

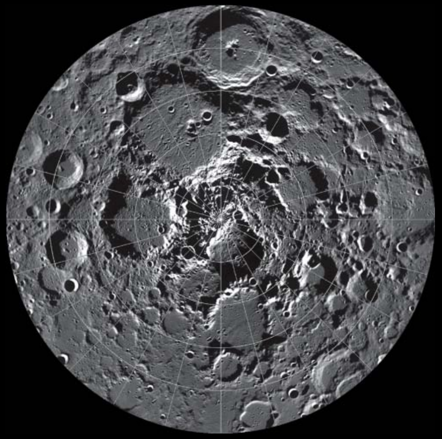
Low Lunar Obliquity (1° 32´)
- Geometry stable for ~2 billion years
- Grazing Sunlight
- Extended shadows
- Terminator always nearby

Areas of Quasi-Permanent Light
- Prominences stand above the local horizon
- Low, constant surface temperatures (~220K)
- High flux on vertical surfaces
- Serves as solar power source

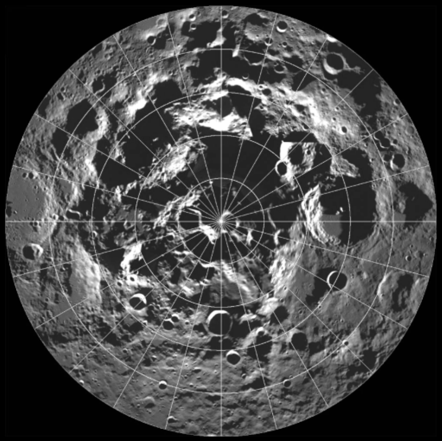
Areas of Permanent Darkness
- Only scattered light or starlight
- No direct solar illumination
- Very low temperatures (30-50K)
- Serves as cold trap for volatiles

View from the Earth
- Lighted Areas
  - Two weeks of visibility / two weeks obscured
- Shadowed Areas
  - Permanently obscured





North pole



South pole

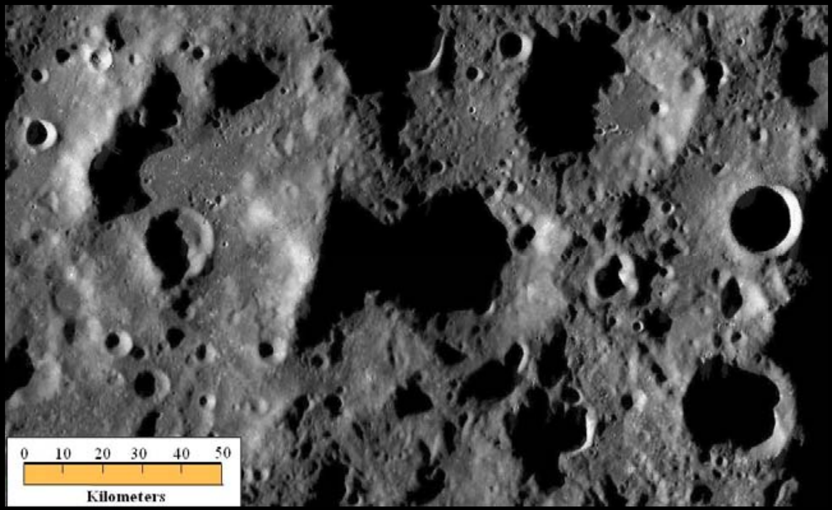
Importance of the Lunar Poles

Scientific

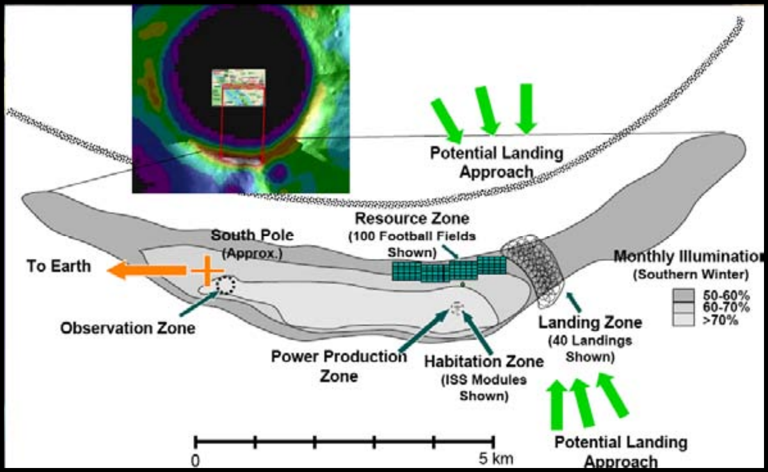
- South pole just inside the rim of largest and oldest impact feature (SPA basin) on the Moon
- Unique environment of poles may have resulted in unusual processes and history

Operational

- Need to understand geological setting to evaluate resource potential
- A likely site for future robotic and human exploration and resource use



Goldstone image, 2008



LAT, 2006

Permanent sunlight?

South Pole: Three areas identified with sunlight for more than 50% of lunar day

One zone receives 70% illumination during dead of southern winter

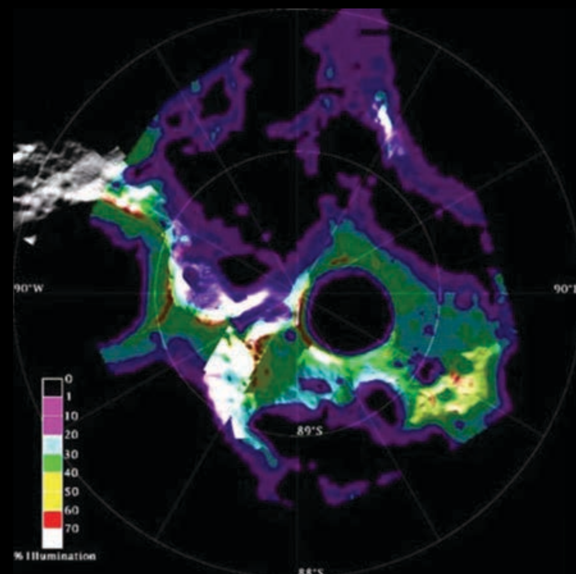
Lit areas in close proximity to permanent darkness (rim of Shackleton)

North Pole: Three areas identified with 100% sunlight

Two zones are proximate to craters in permanent shadow

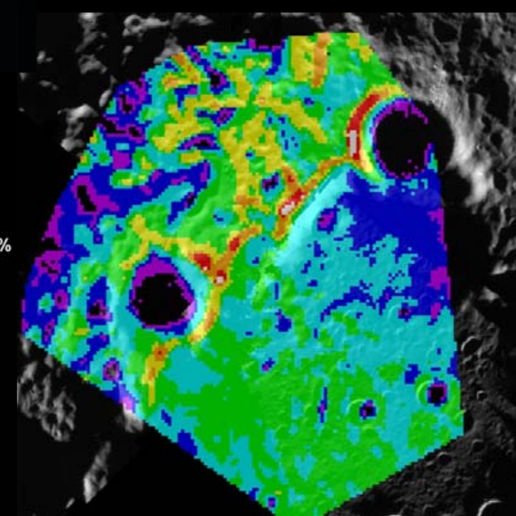
Data taken during northern summer (maximum sunlight)

South Pole



Data obtained during southern winter (maximum darkness)

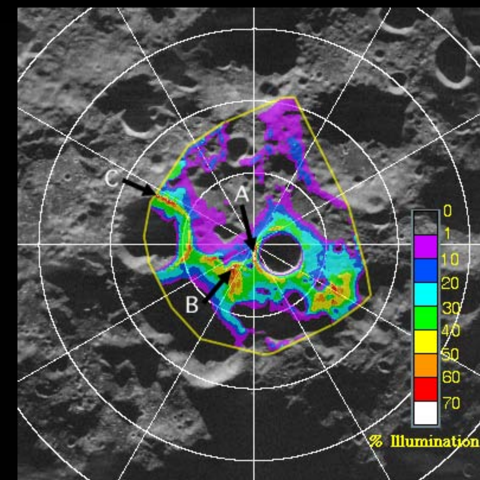
North Pole

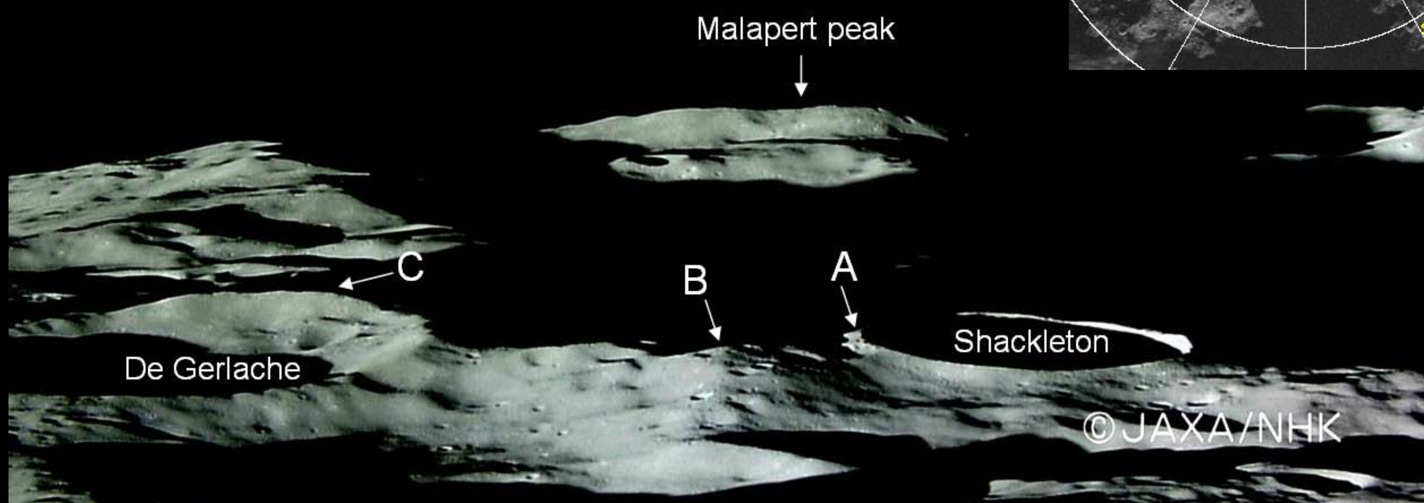


Data obtained during northern summer (maximum sunlight)

New Data for the South Pole

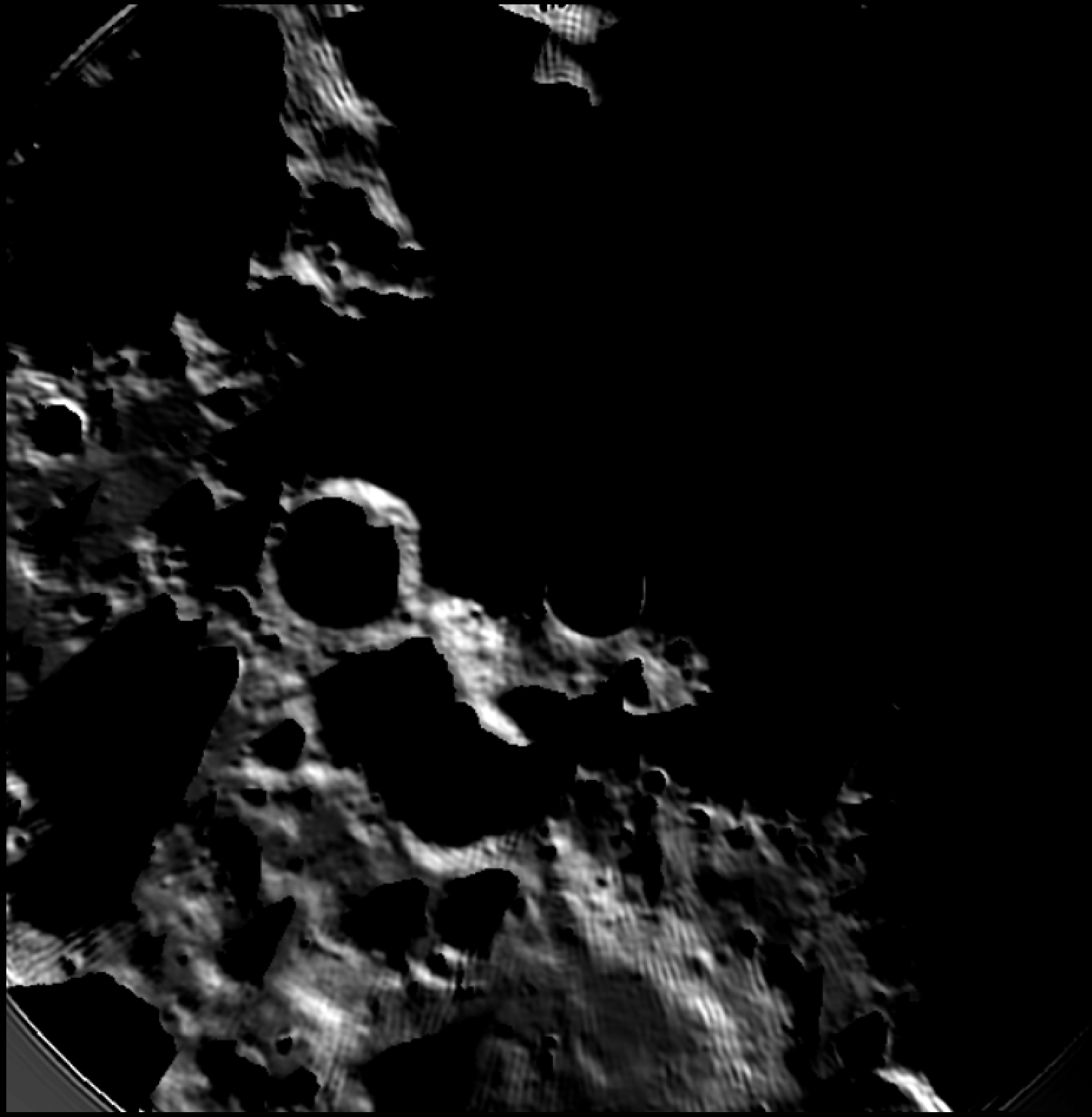
Kaguya HDTV images





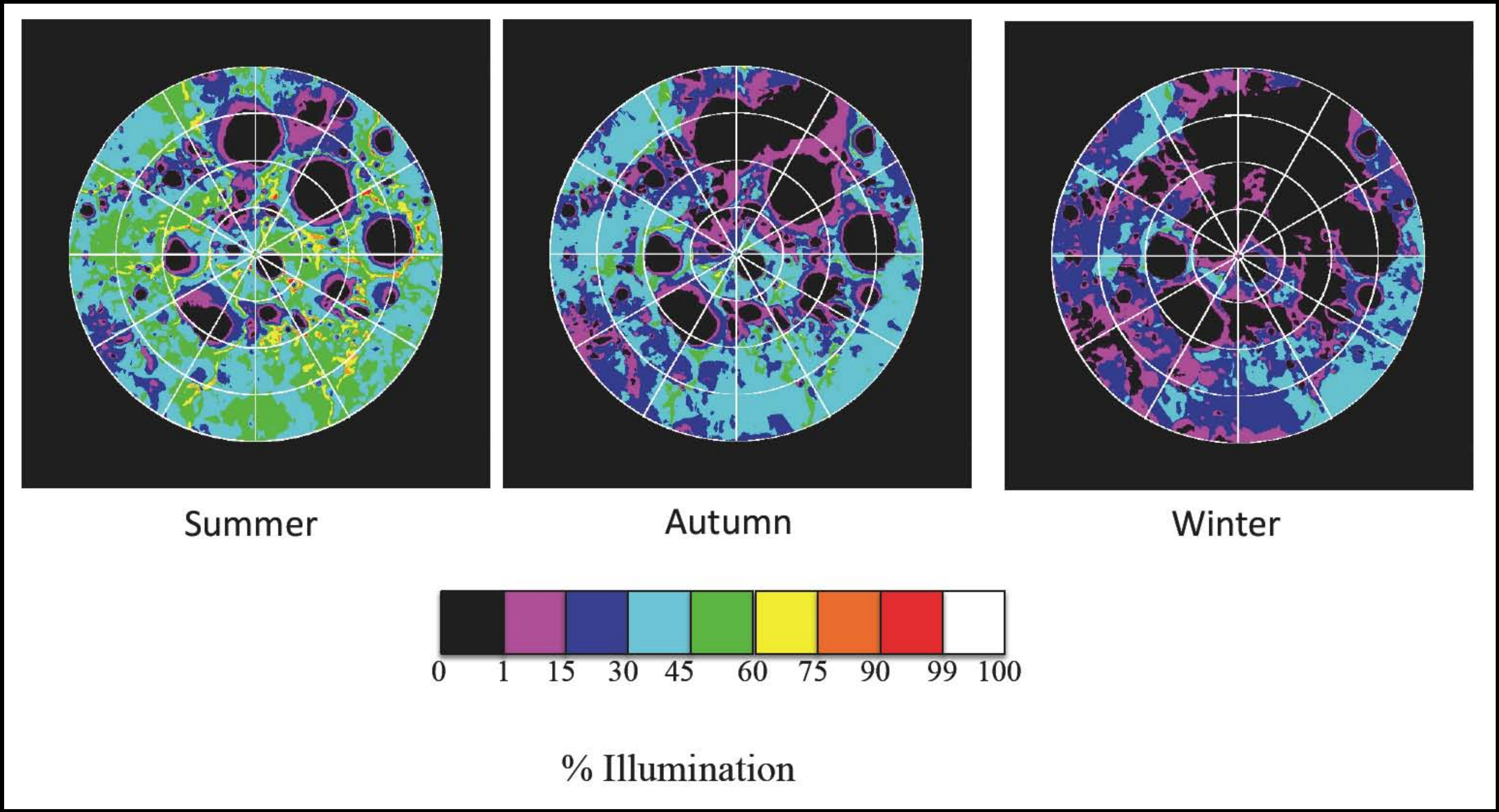
- Confirms inferences from Clementine and SMART-1 images on sunlit peaks in region
- Malapert peak appears to be in sunlight during lunar night

Polar lighting based on Kaguya altimetry



New polar lighting studies

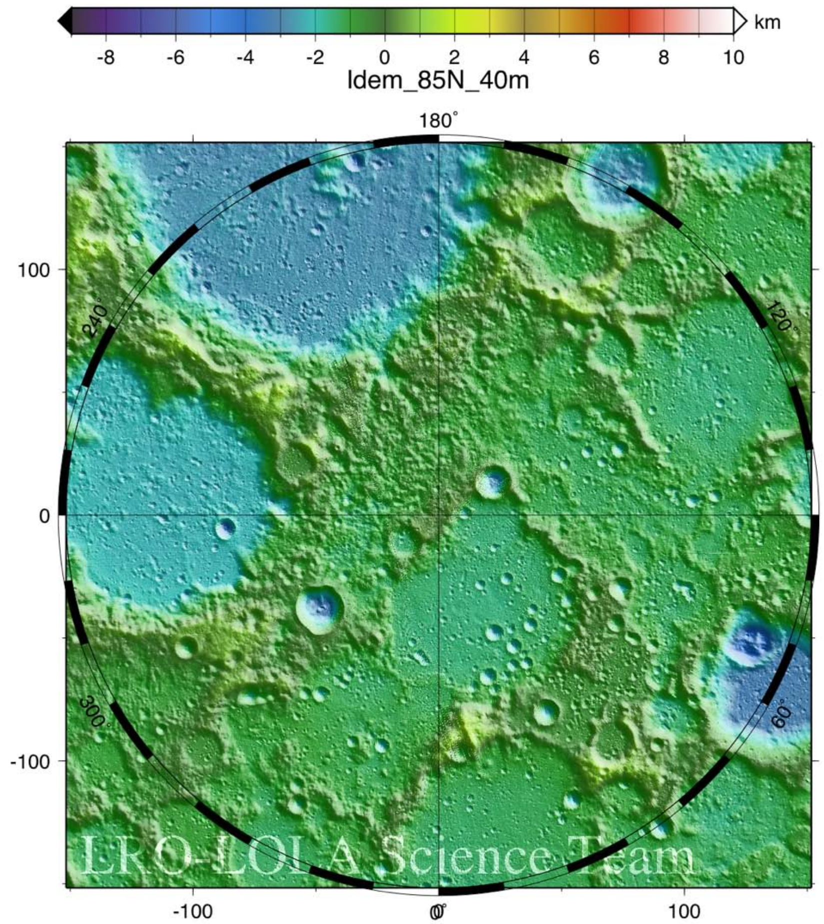
Lighting maps showing seasonal variation



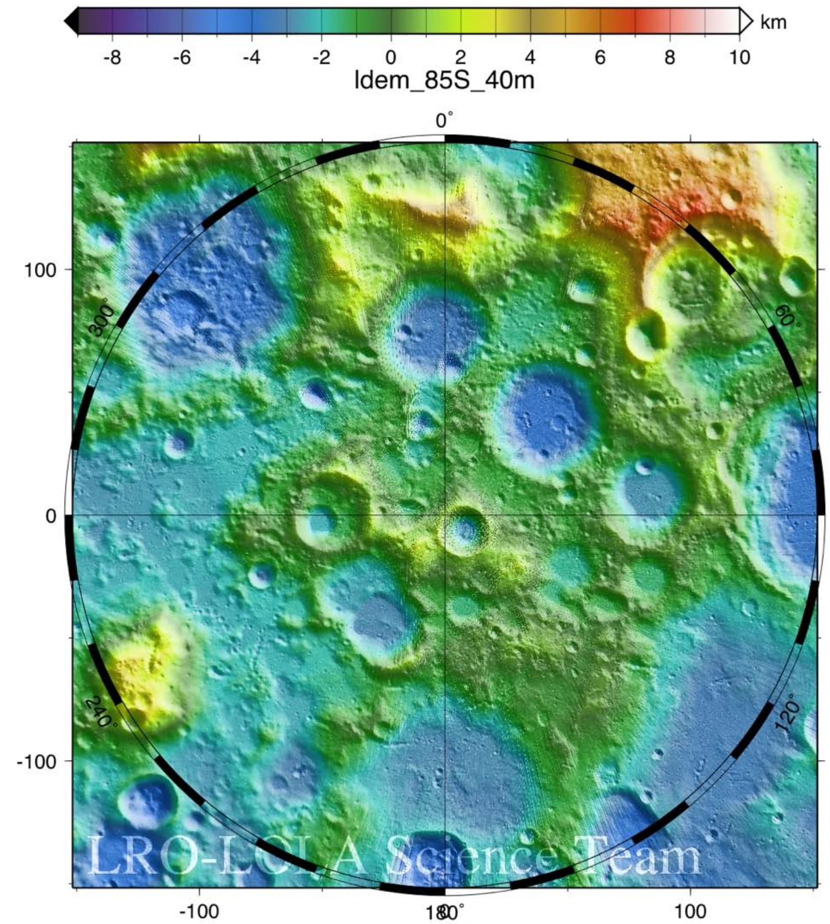
South Pole

LOLA altimetry

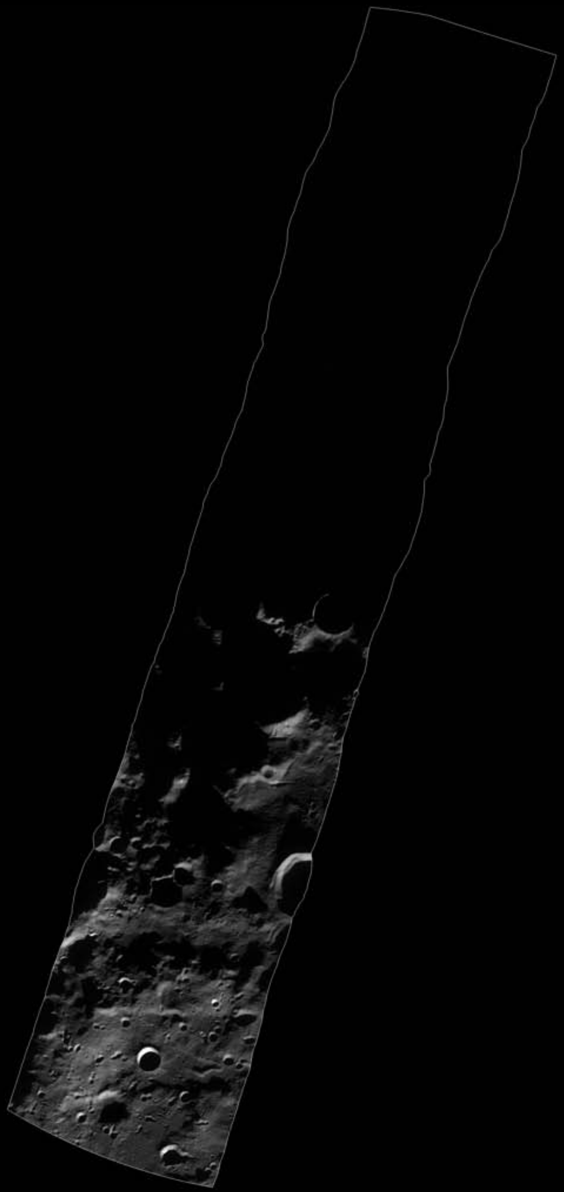
North pole



South pole

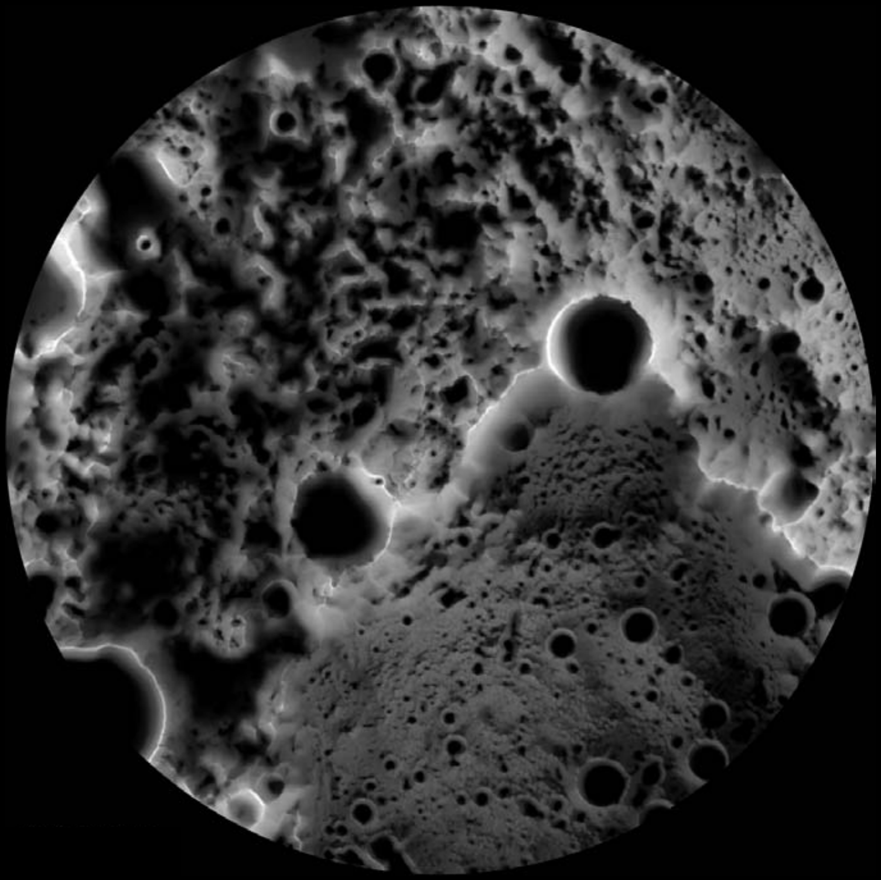


LROC WAC polar movie

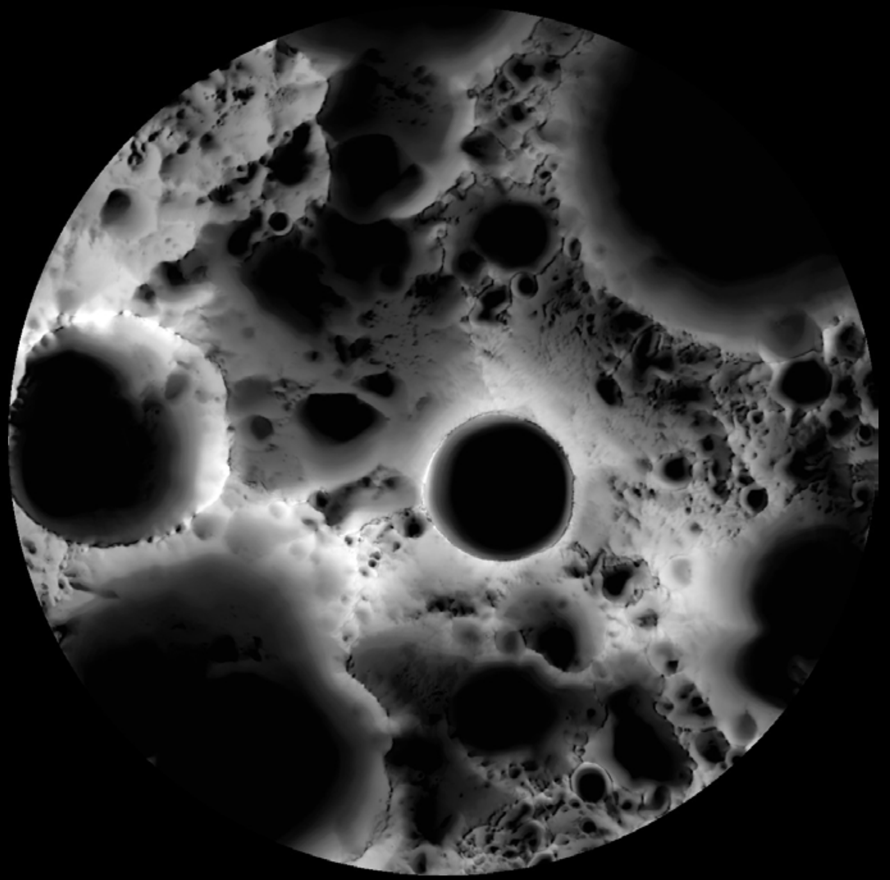


New polar lighting studies

LROC WAC composite images



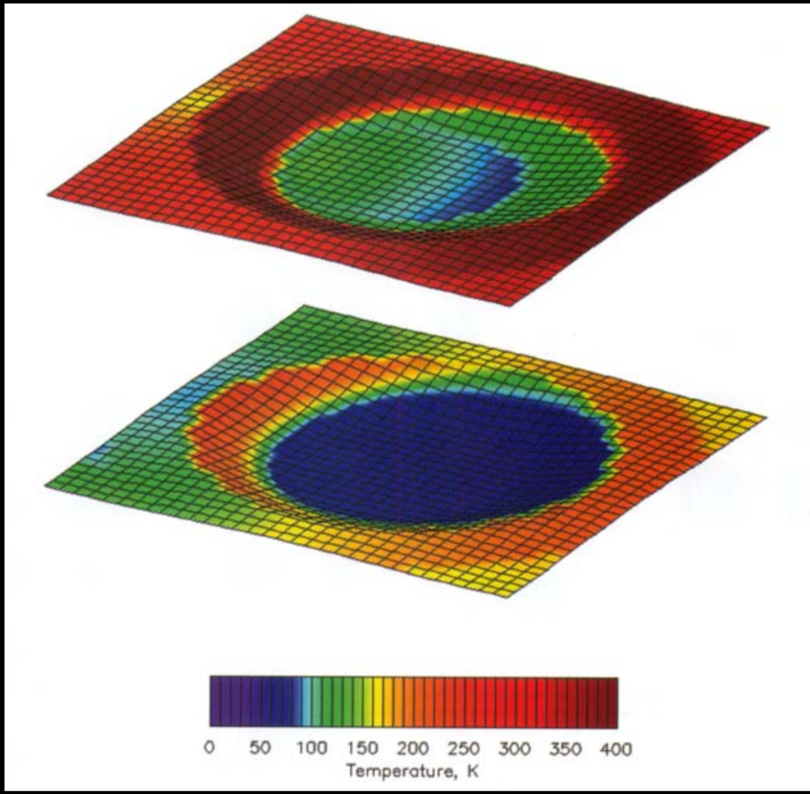
North pole



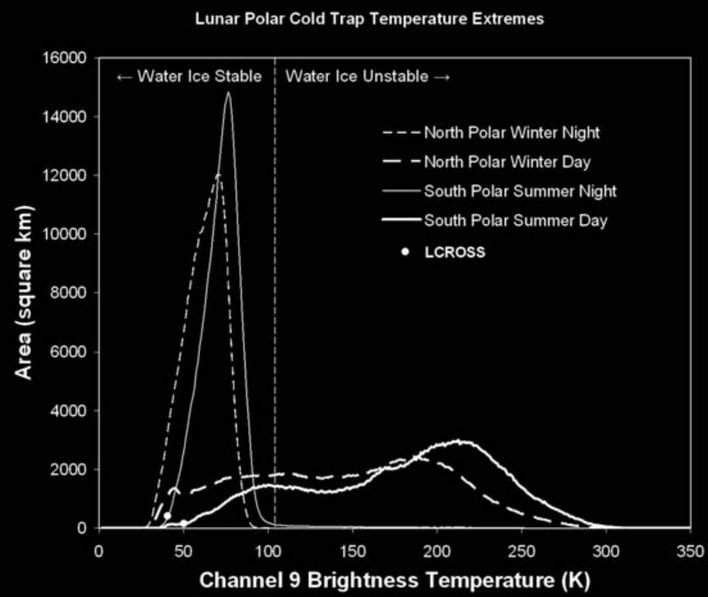
South pole

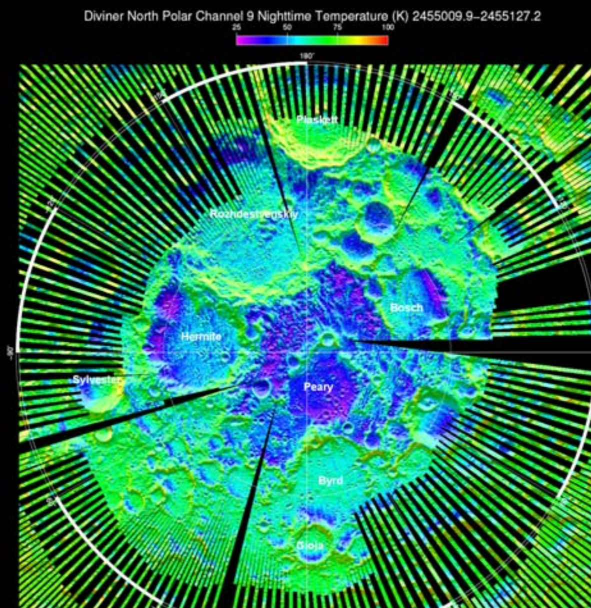
Polar Cold Trap Temperatures

- Permanently shadowed areas have very low model temperatures (~ 50-70 K) and act as cold traps (e.g., Vasavada *et al.* 1999)
- Uncertainty largely a reflection of unknown value for heat flow of Moon (14 - 22 mW m^{-2})
- Temperatures may vary substantially in the shallow subsurface
- At these temperatures, atoms and molecules of volatile species cannot escape
- New DIVINER thermal maps from LRO show that cold traps are even ***colder*** than thought! (as low as 30 K)

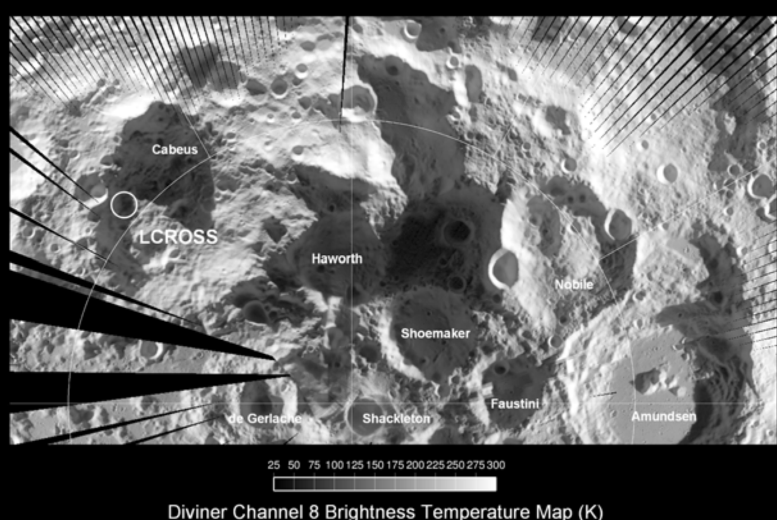


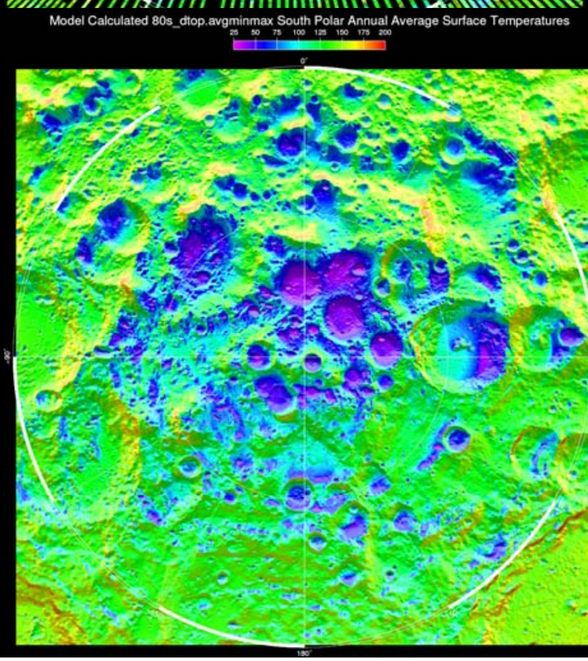
DIVINER thermal data





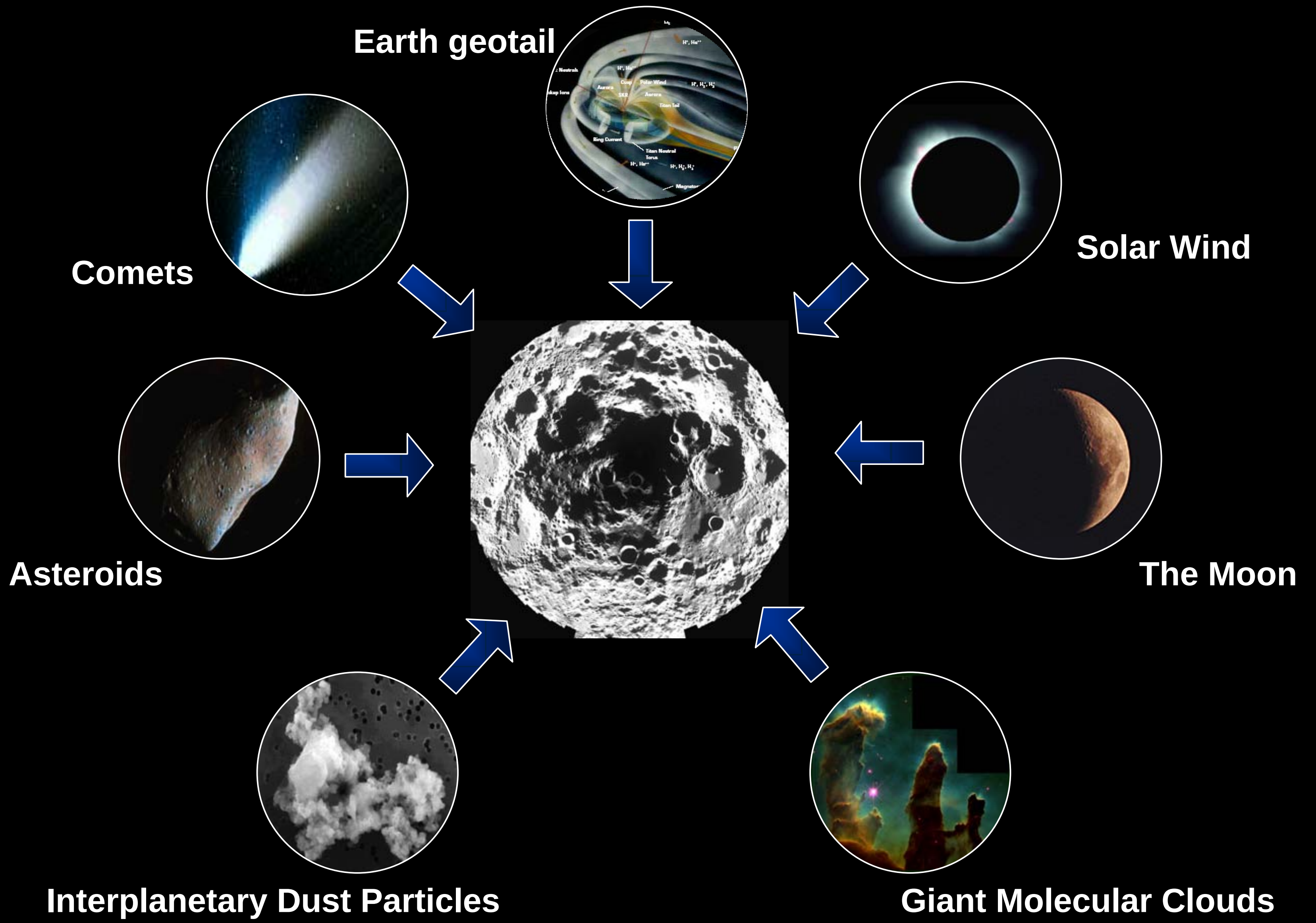
North pole





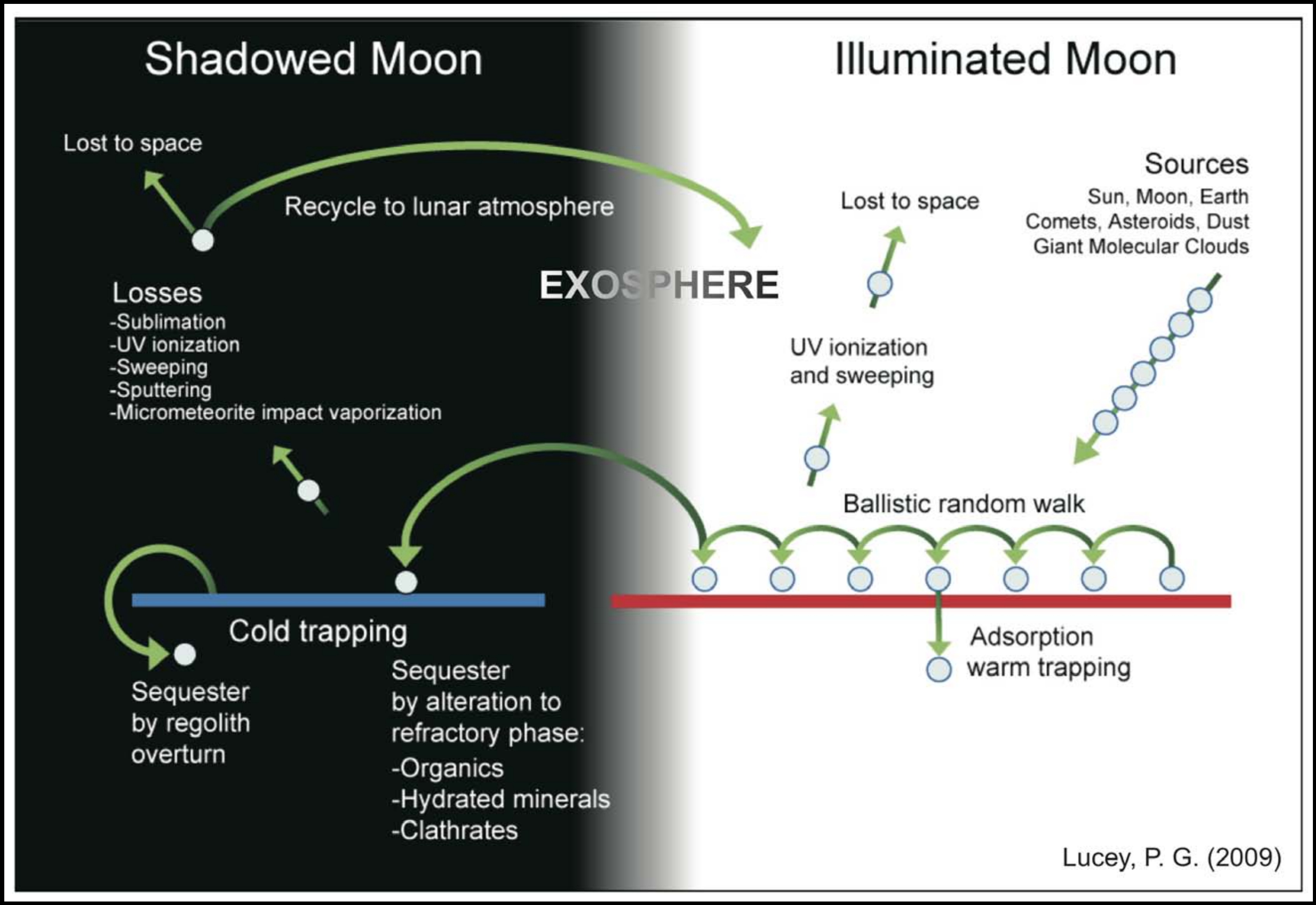
South pole

Sources of Lunar Polar Volatiles



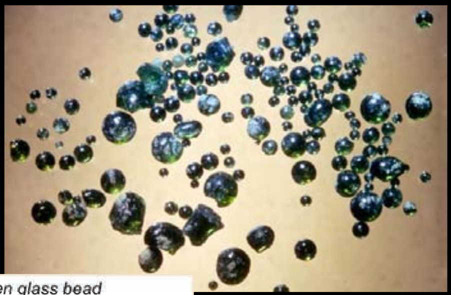
Modified from Lucey (2001)

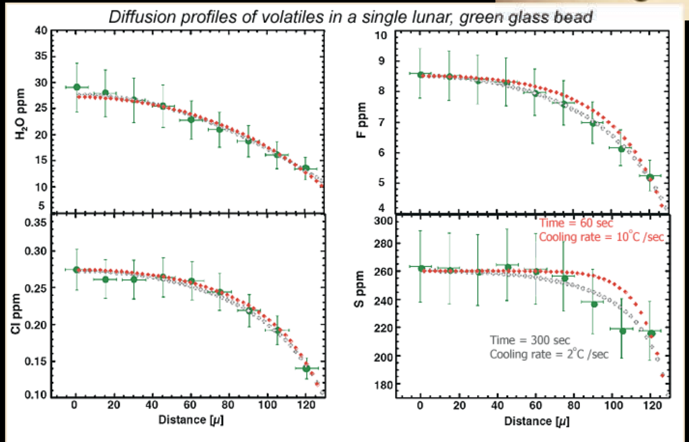
Water on the Moon



Indigenous lunar water?

- Apollo 15 green glass pyroclastics (volcanic ash) contain up to 50 ppm inside
- Diffusion profiles imply much higher magma concentrations of water
- Implies water concentrations of 260-700 ppm in mantle
- Most water in magma lost during eruption when magma was sprayed into space during “fire fountaining”
- Original Moon was not completely devolatilized; could have degassed interior water which could then be cold-trapped



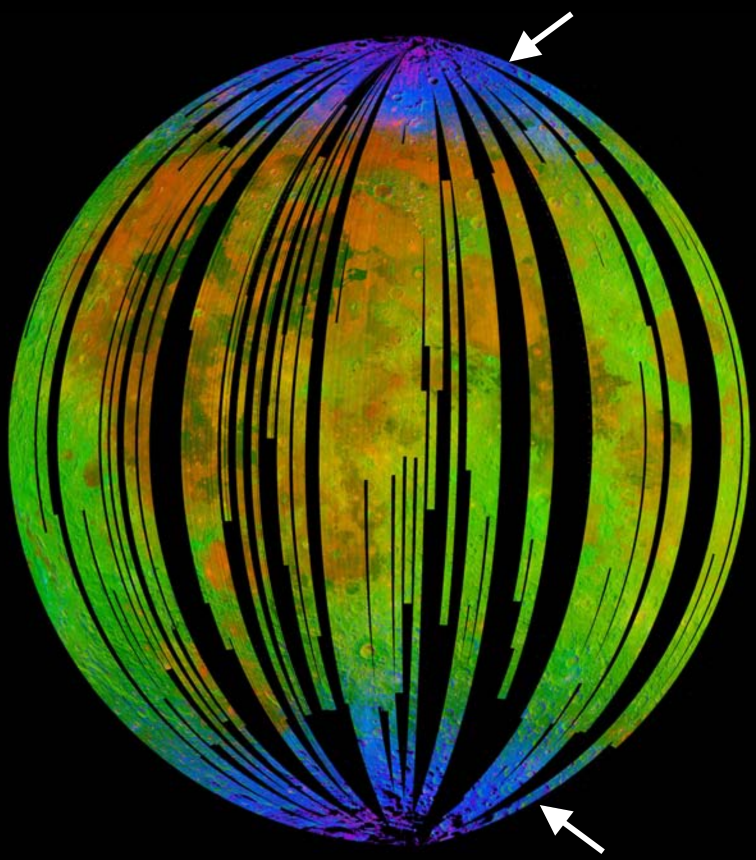


(From Saal et al., 2008, Nature, v. 454, p. 192-196. doi:10.1038/nature07047.)

Water on the Moon

New Evidence from Remote Sensing

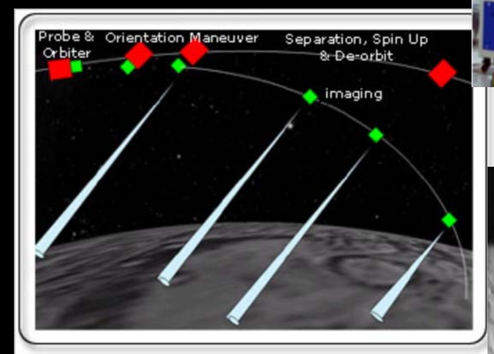
- Spectral evidence for widespread hydration (2.8 µm absorption band)
- Seems correlated with latitude (most evident at latitudes > 65°)
- Created how?
  - Solar wind reduction of oxides in rock and soil
  - Water residue from comet impacts
  - Outgassed water vapor from lunar interior
- A possible source for polar ice
  - Migration to polar cold traps by ballistic hopping

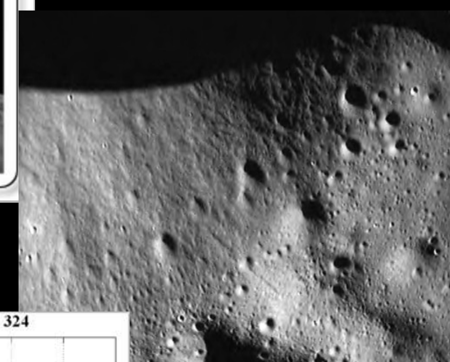


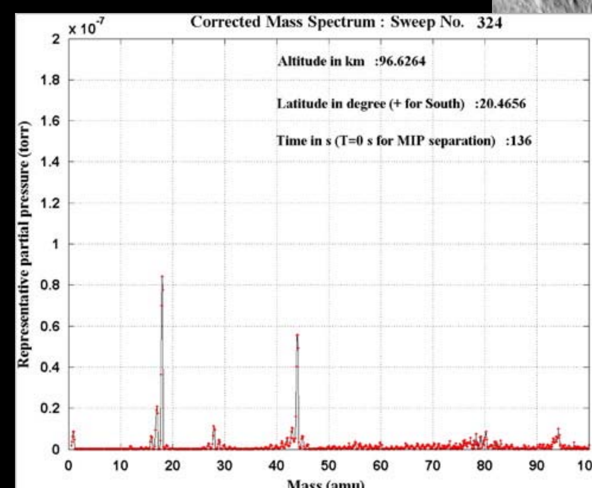
Water on the Moon

MIP results

- Impact probe released from Chandrayaan-1 orbiter
- Descended from equator to south pole of Moon
- Mass spectrometer detected water vapor in lunar "atmosphere" (exosphere) at ~10^{-7} torr ("normal" lunar daytime atmosphere pressure is ~10^{-9} torr)
- Water is probably molecules in motion from surfaces of high temperature to surfaces of lower temperatures (M3 results)







Water on the Moon

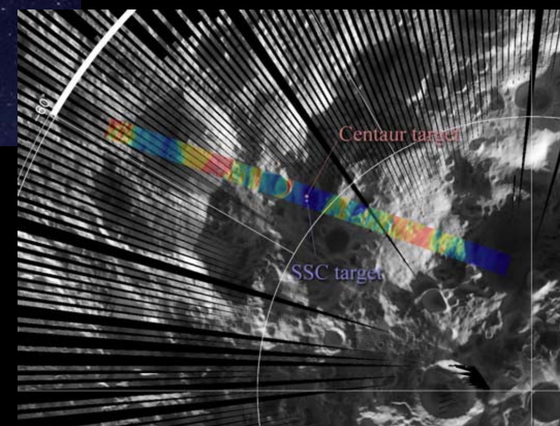
LCROSS mission

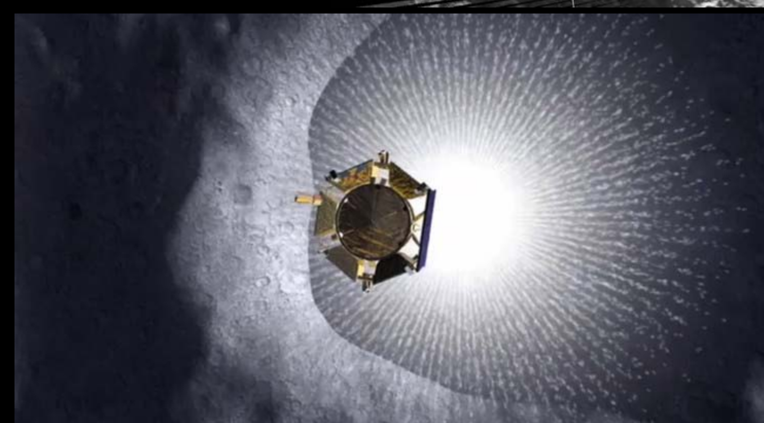
Impactor vehicle into permanently dark region near a lunar pole

Use LRO Centaur LV with “shepherding” satellite to monitor impact

Analyze composition of ejected plume, look for water vapor and ice

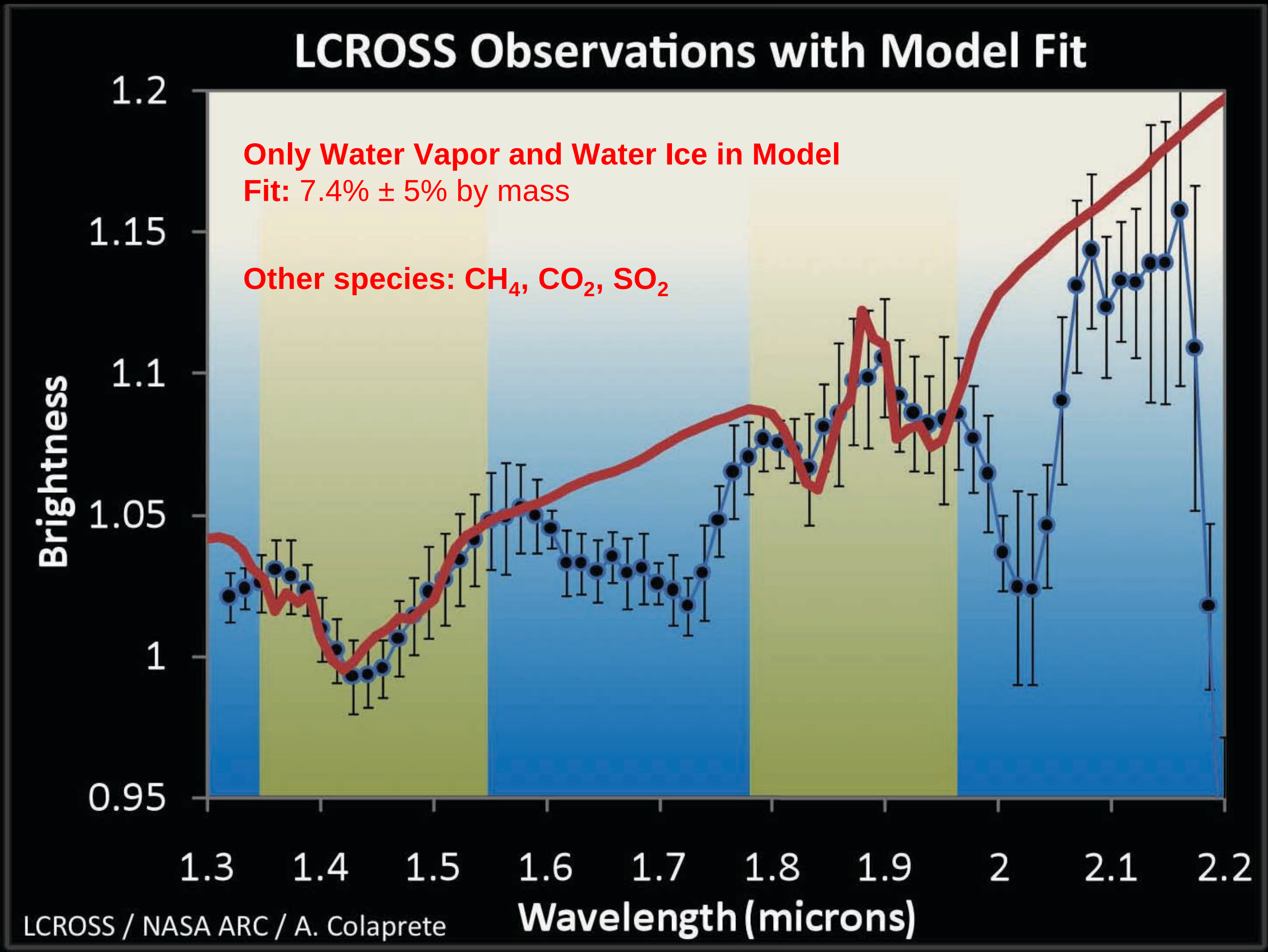
Single-shot -- if we miss it, is it not there?





Water on the Moon

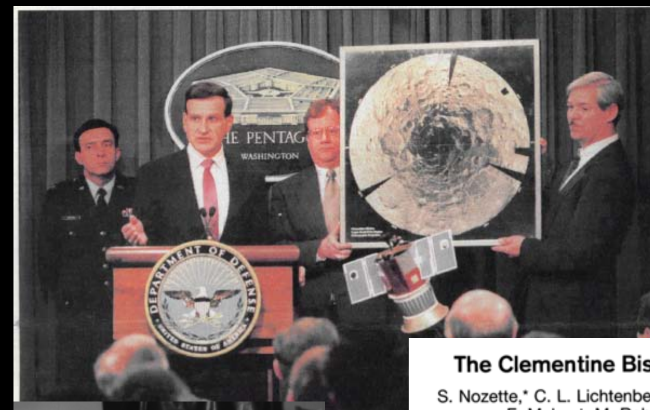
LCROSS results



The Search for Lunar Ice

"To be uncertain is uncomfortable but to be certain is ridiculous." – Goethe

- Radar has been used since 1960's to map the lunar surface
- Backscattering properties are different for normal Moon and water ice
- Long recognized that polar areas are dark and cold (Watson, Murray and Brown, 1961)
- Discovery of ice at poles of Mercury in 1992 spurred renewed interest in lunar poles
- Unfavorable viewing geometry and infrequent opportunities for observation from Earth complicated interpretation of results
- Thus, 20 years of controversy



The Clementine Bistatic Radar Experiment

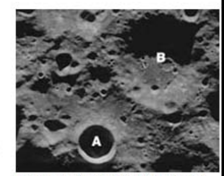
S. Nozette,* C. L. Lichtenberg, P. Spudis, R. Bonner, W. Ort, E. Malaret, M. Robinson, E. M. Shoemaker

During the Clementine 1 mission, a bistatic radar experiment measured the magnitude and polarization of the radar echo versus bistatic angle, β, for selected lunar areas. Observations of the lunar south pole yield a same-sense polarization enhancement around β = 0. Analysis shows that the observed enhancement is localized to the permanently shadowed regions of the lunar south pole. Radar observations of periodically solar-illuminated lunar surfaces, including the north pole, yielded no such enhancement. A probable explanation for these differences is the presence of low-loss volume scatterers, such as water ice, in the permanently shadowed region at the south pole.

Ice Store At Moon's South Pole Is A Myth

by Staff Writers
Paris (AFP) Oct 18, 2006

Hopes that the Moon's South Pole has a vast hoard of ice that could be used to establish a lunar colony are sadly unfounded, a new study says. In 1994, radar echoes sent back in an experiment involving a US orbiter called Clementine appeared to show that a treasure trove of frozen water lay below the dust in craters near the lunar South Pole that were permanently shaded from the Sun.



Because of the tilt of the moon's orbital plane relative to the Earth's equatorial plane, the Earth can rise much higher above the

Water on the Moon? Scientists Await Definitive Answer

By Rick Callahan
Associated Press
posted: 01:00 pm ET
12 November 2003

Circular Polarization Ratio (CPR)

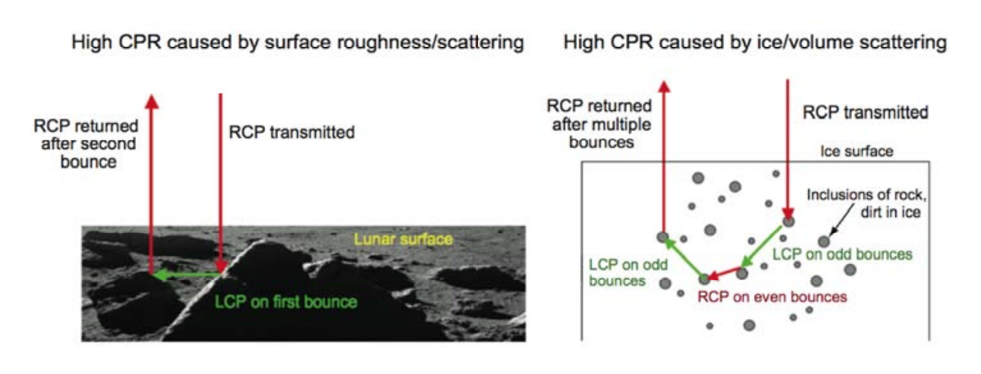
Ratio of received power in both right and left senses

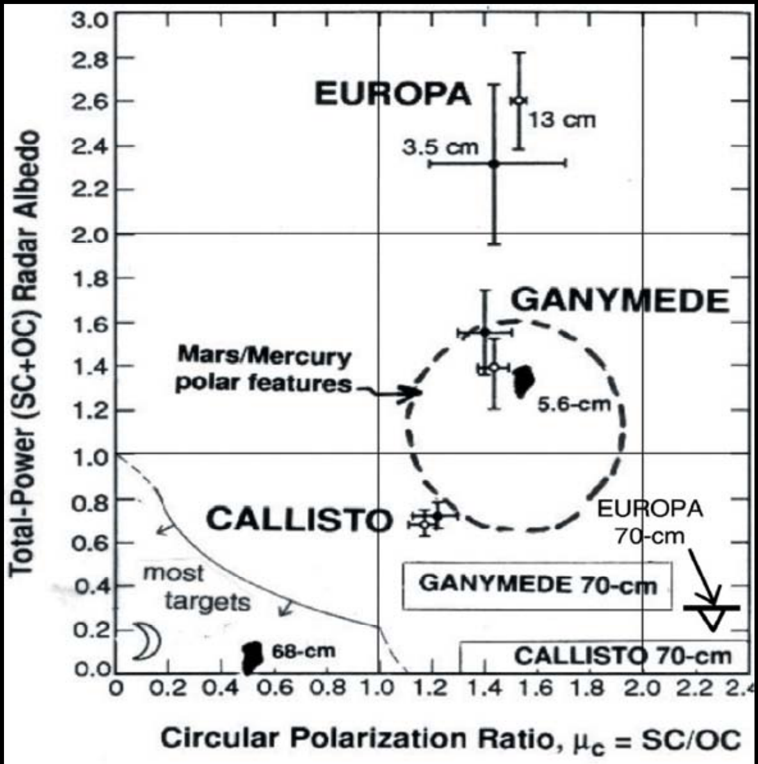
Normal rocky planet surfaces = polarization inversion (receive opposite sense from that transmitted)

"Same sense" received indicates something unusual:

- double- or even-multiple-bounce reflections
- Volume scattering and CBOE from RF-transparent material

High CPR (enhanced "same sense" reception) is common for fresh, rough (at wavelength scale) targets and water ice



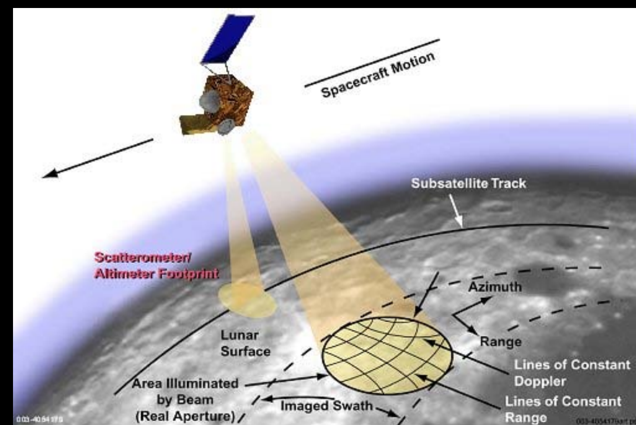


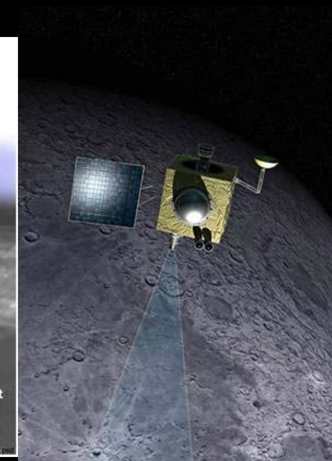
Mini-RF

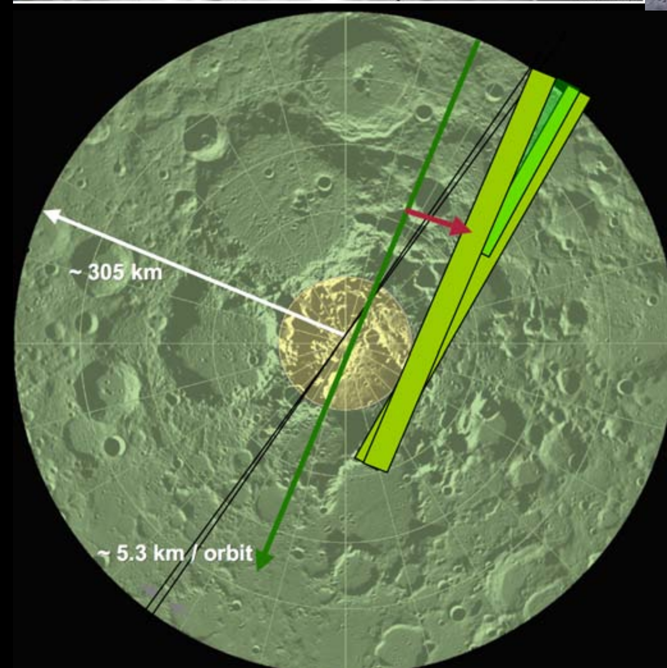
Imaging Radar on the Chandrayaan-1 and LRO spacecraft

- Mini-RF is an S-band (λ= 12.6 cm) imaging radar with hybrid polarity architecture
- Map both polar regions at 75 m/pixel
- Transmit LCP, receive *H* and *V* linear, coherently
- Use Stokes parameters and derived "daughter" products to describe backscattered field
- Map locations and extent of anomalous radar reflectivity
- See polar dark areas (not visible from Earth)
- Cross-correlate with other data sets (topography, thermal, neutron)

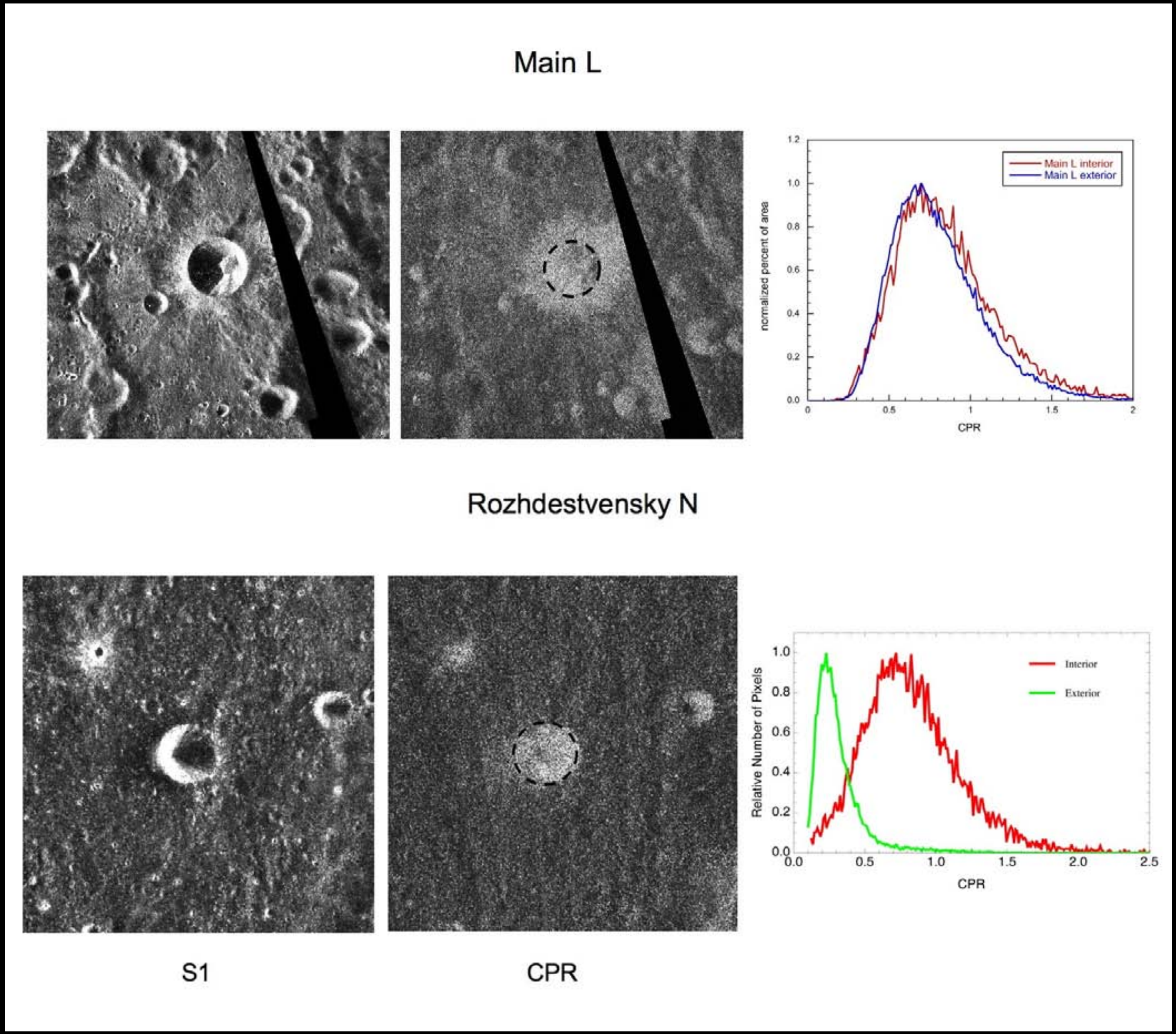
- LRO version has two bands (λ=12.6 and 5 cm), high-resolution zoom mode (15 m/pixel)







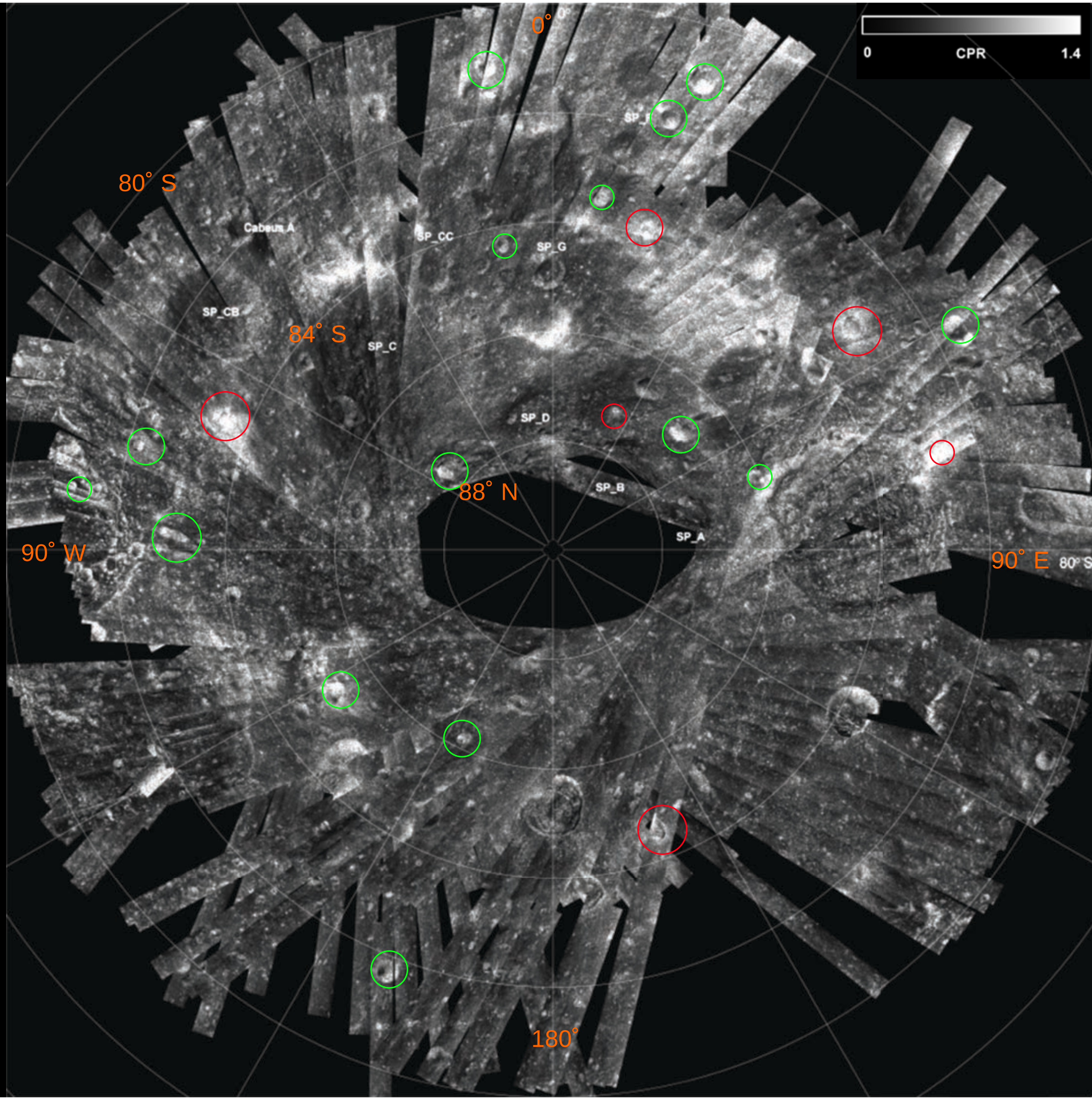
Normal and "anomalous" polar craters



LUNAR AND PLANETARY INSTITUTE

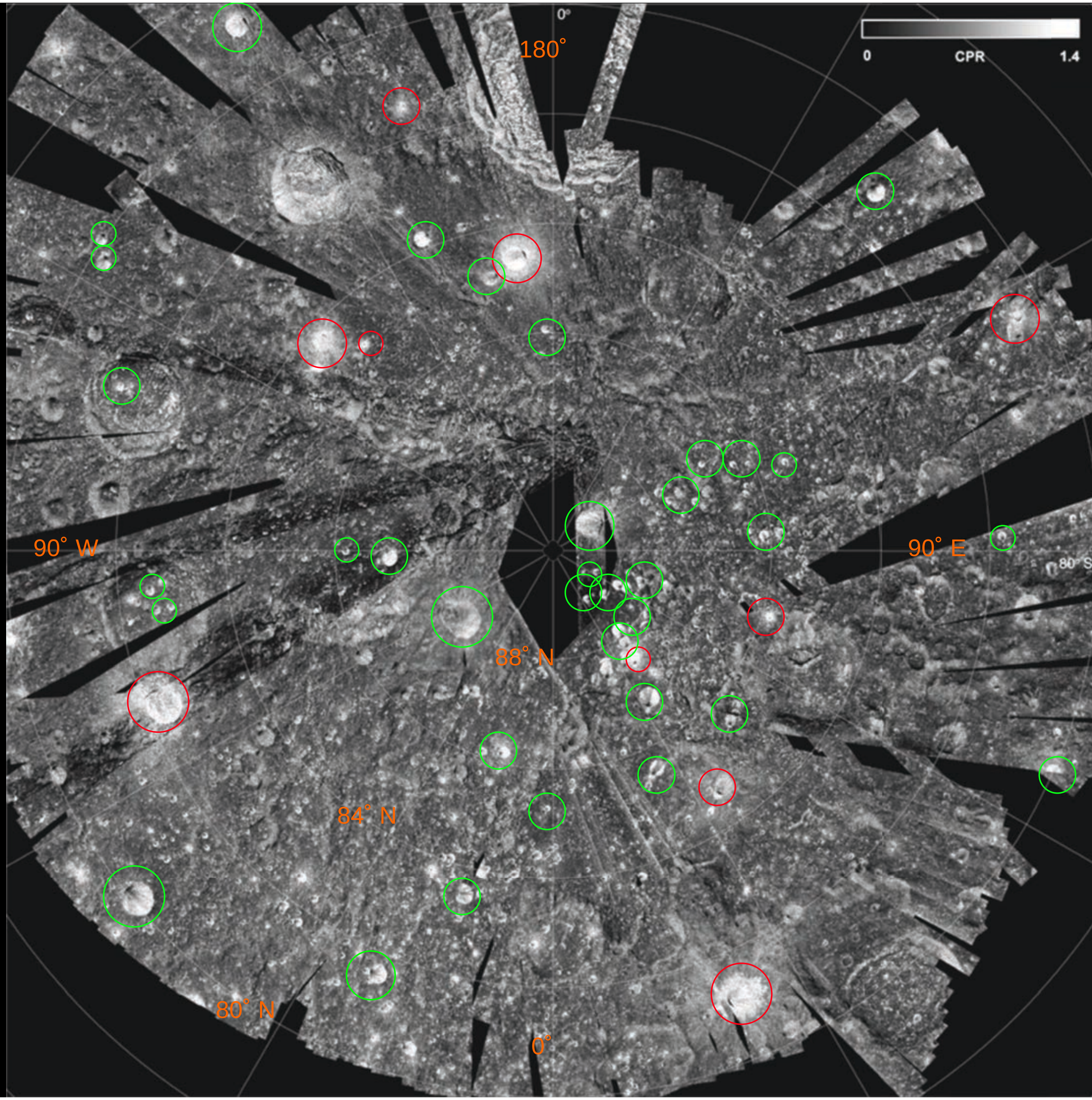
Fresh craters

Anomalous craters



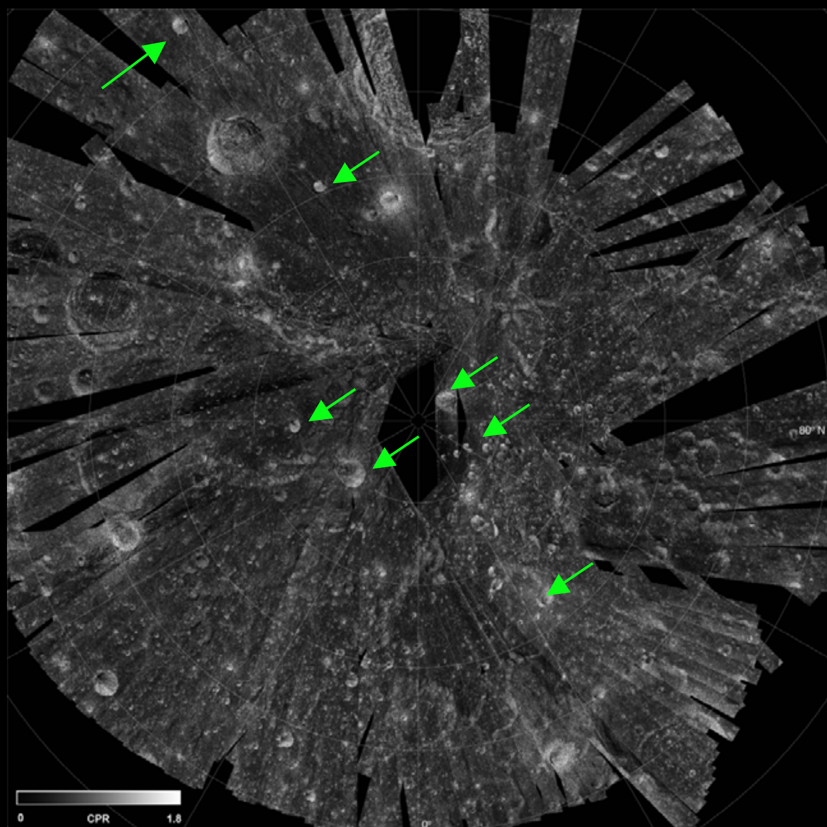
Fresh craters

Anomalous craters

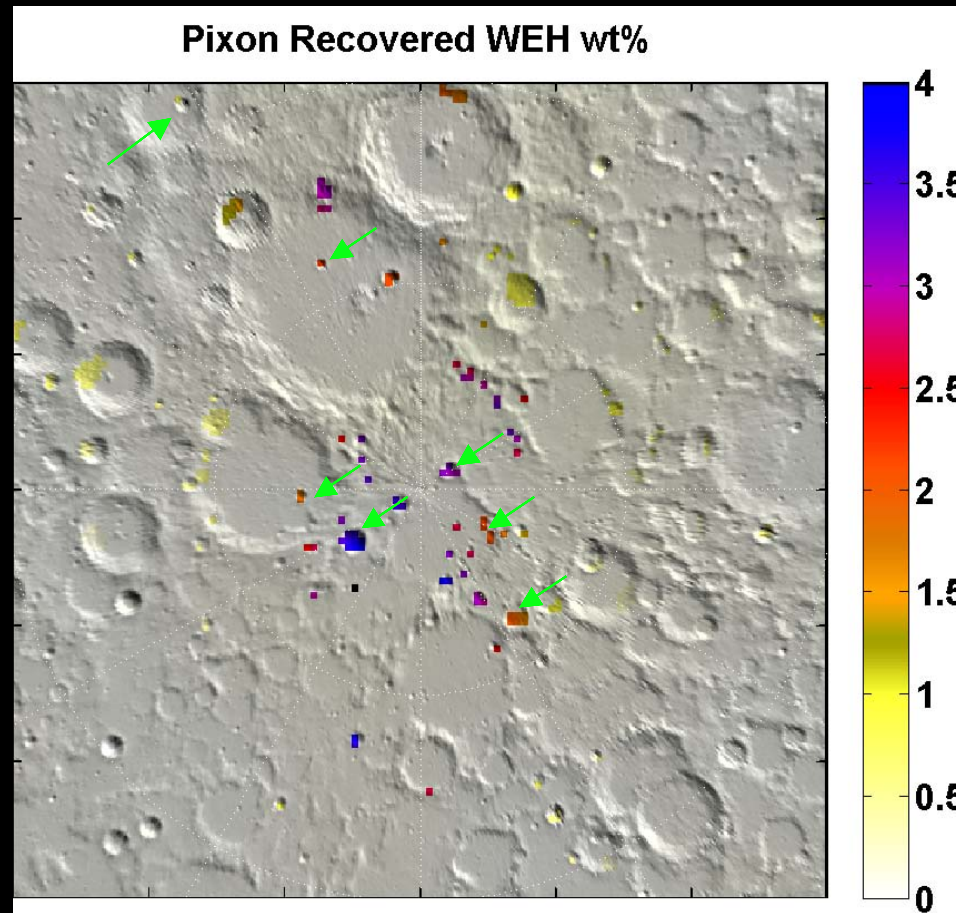


LUNAR AND PLANETARY INSTITUTE

CPR v. LP neutron data

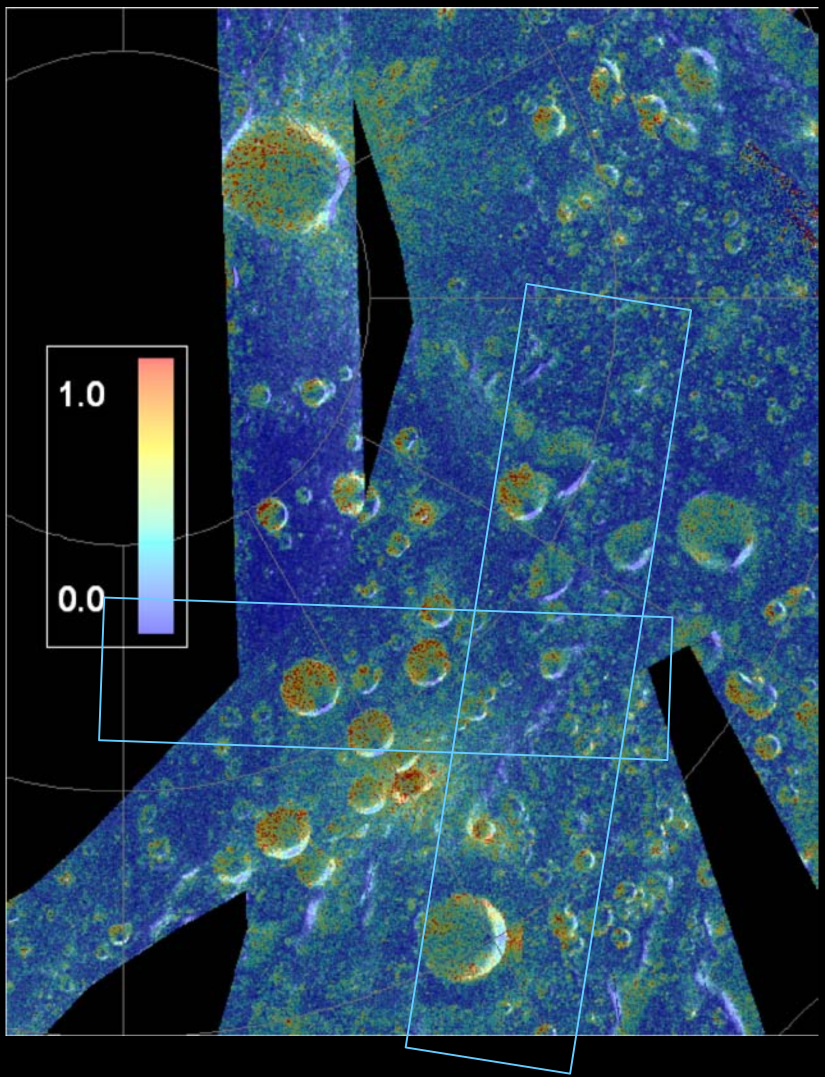


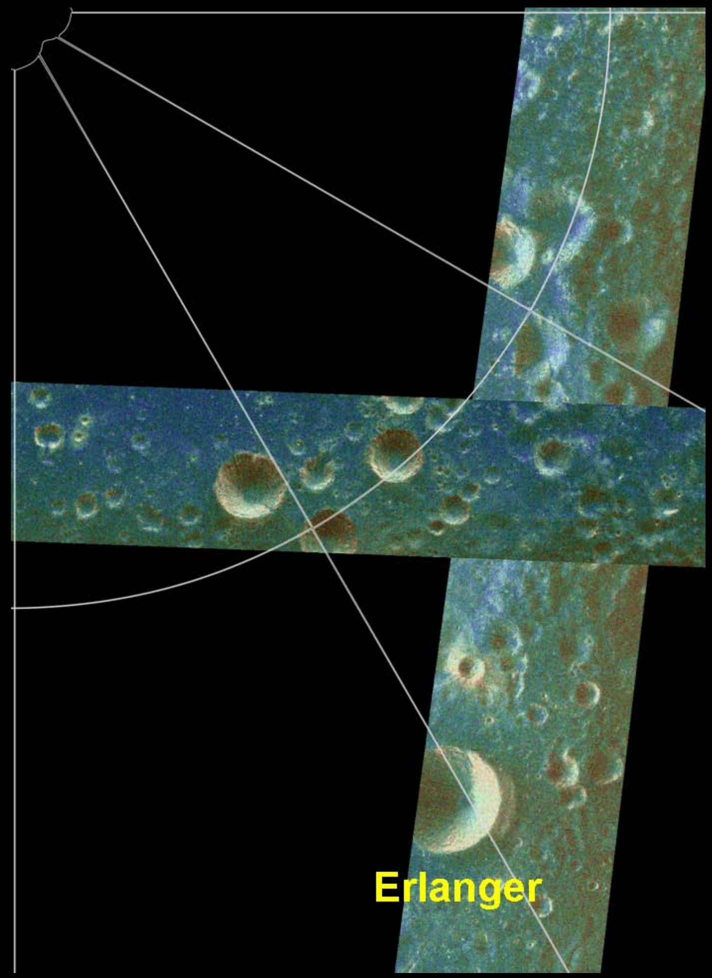
Mini-SAR CPR



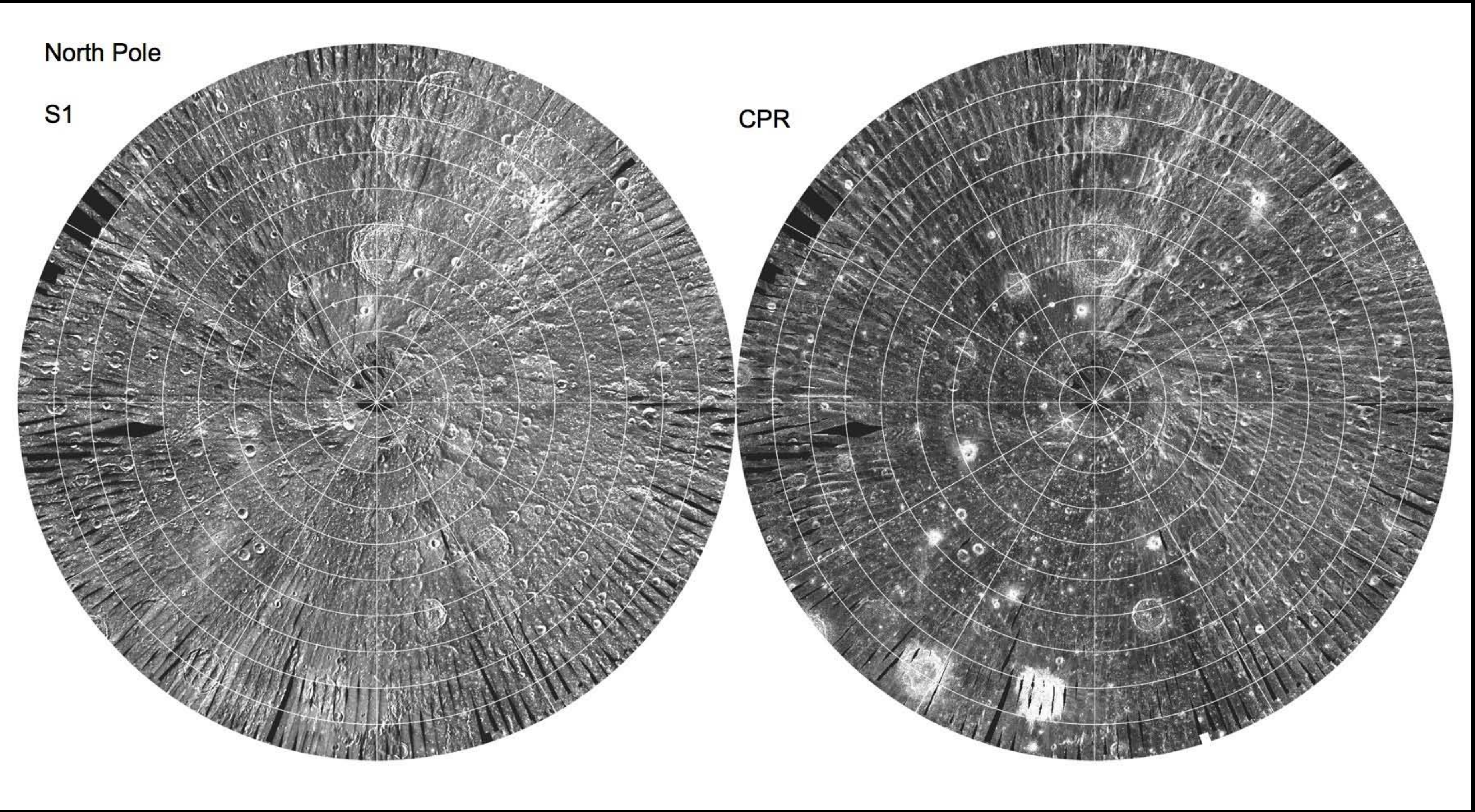
LP Neutron Pixon Model

Mini-RF high resolution SAR of polar areas

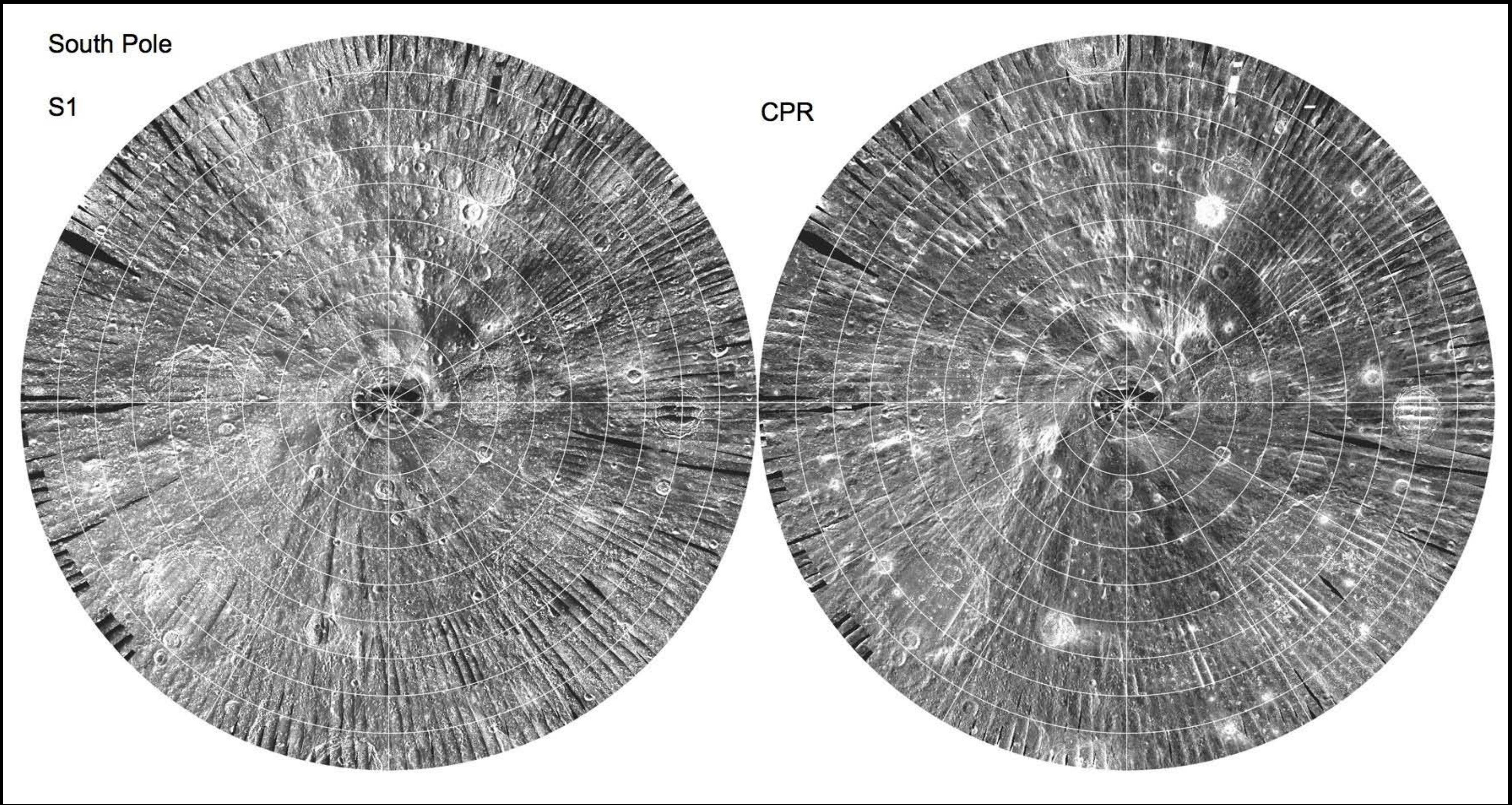




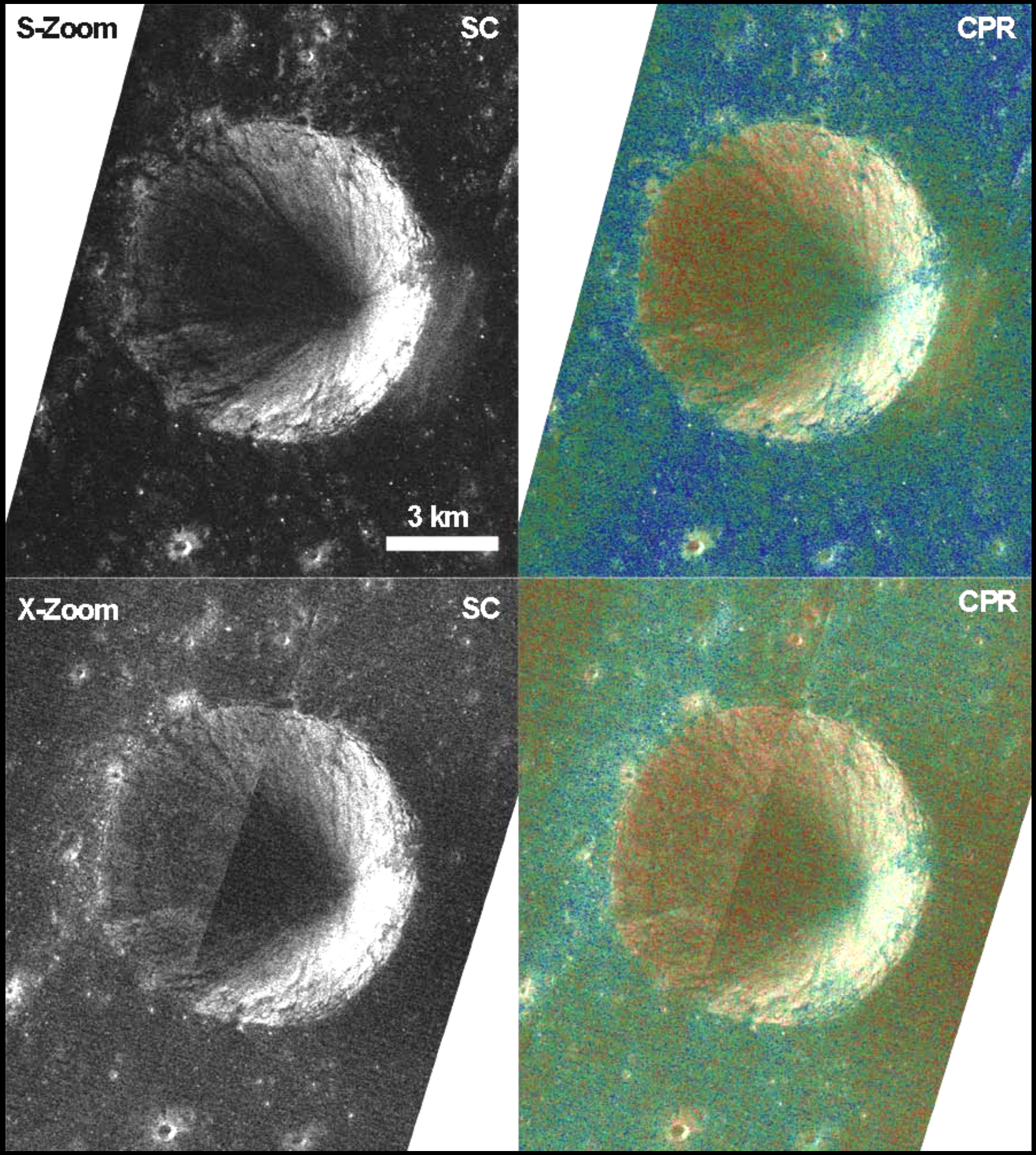
Mini-RF Polar Maps



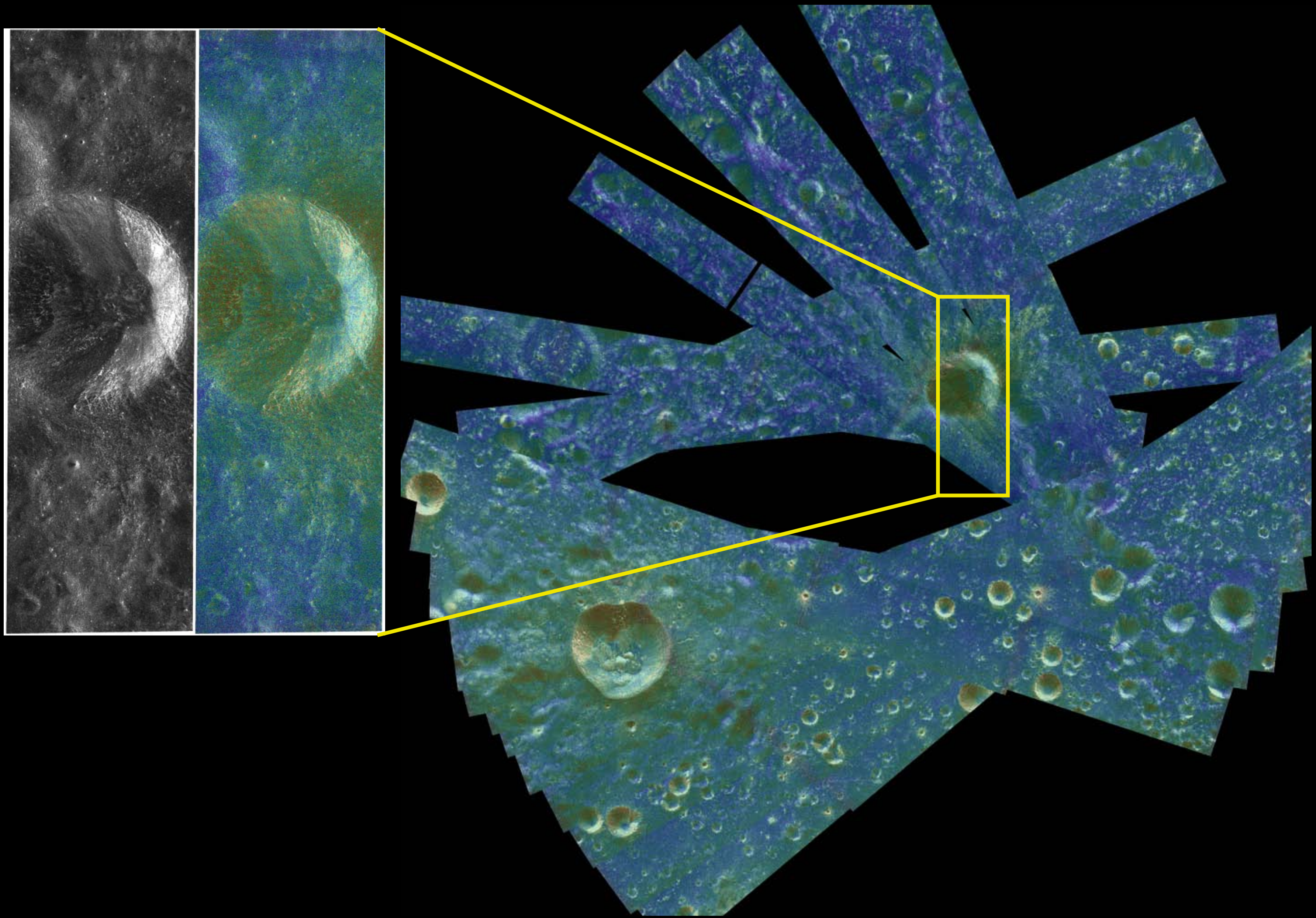
Mini-RF Polar Maps



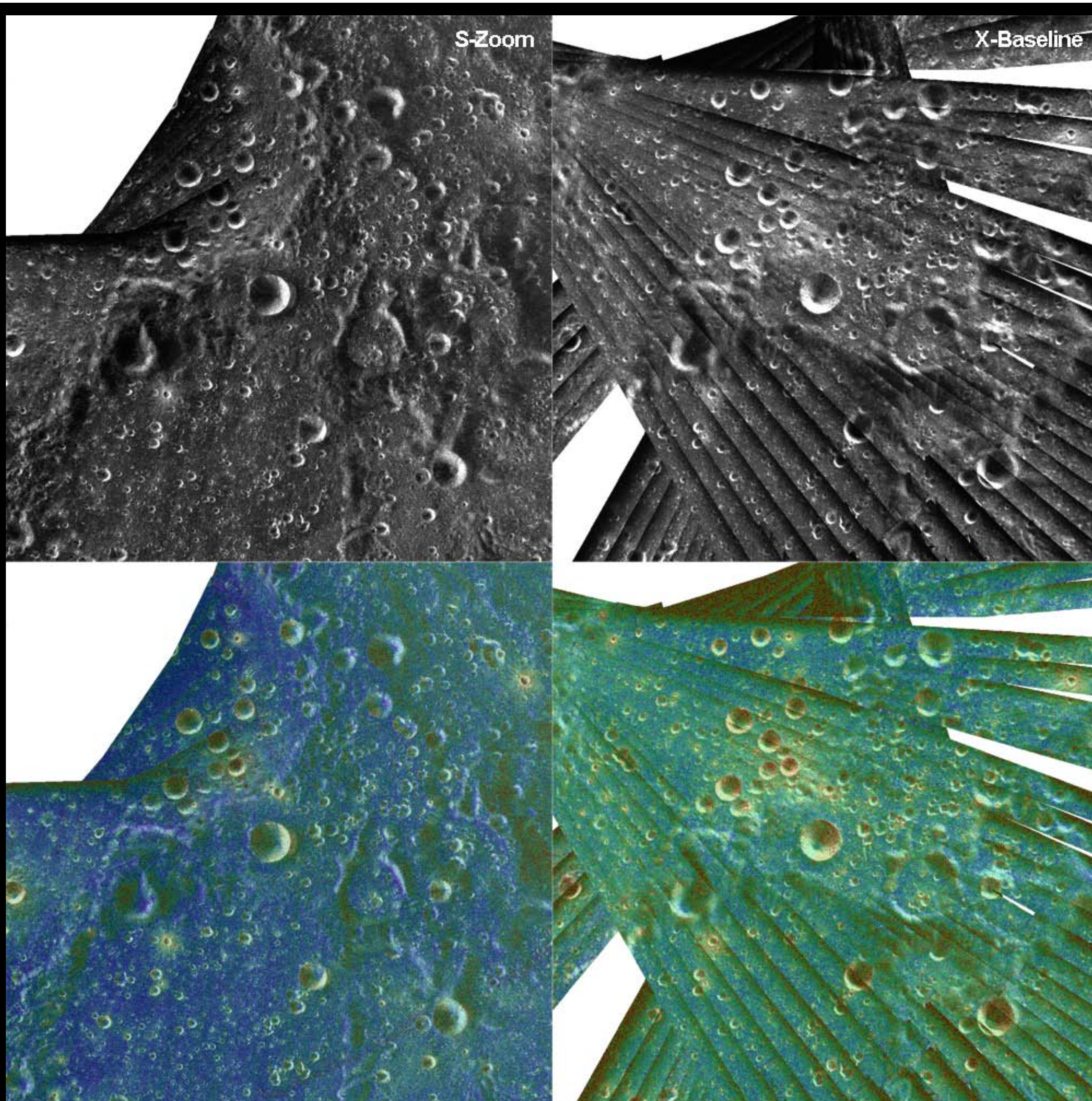
Mini-RF high resolution SAR of polar areas



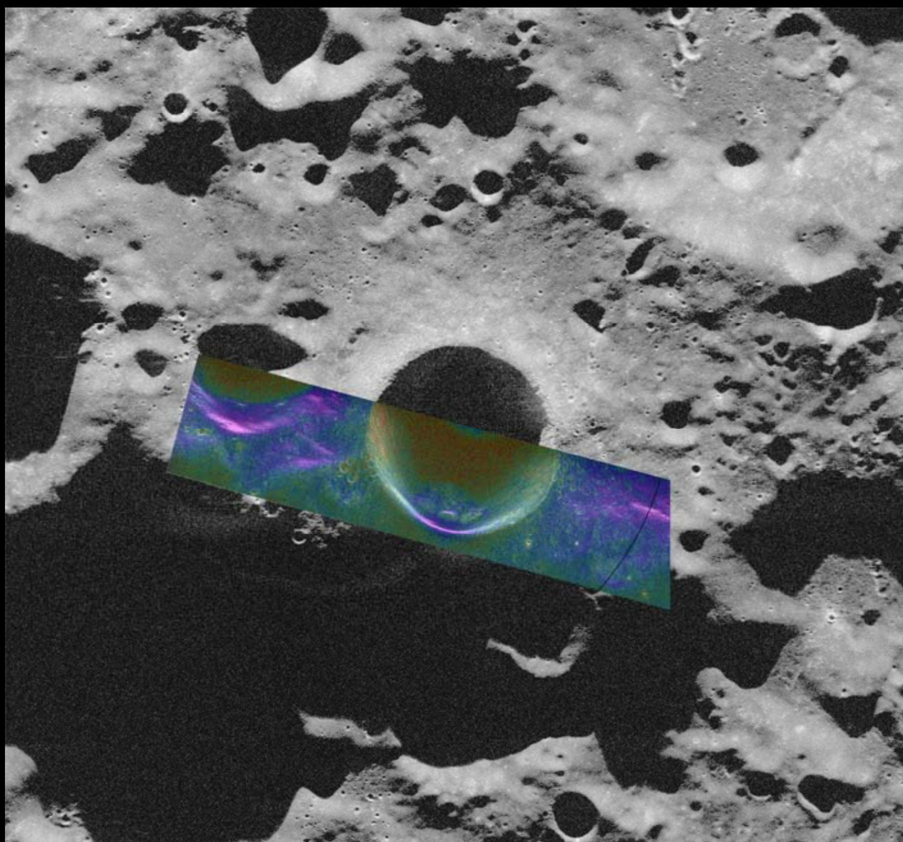
Mini-RF high resolution SAR of polar areas

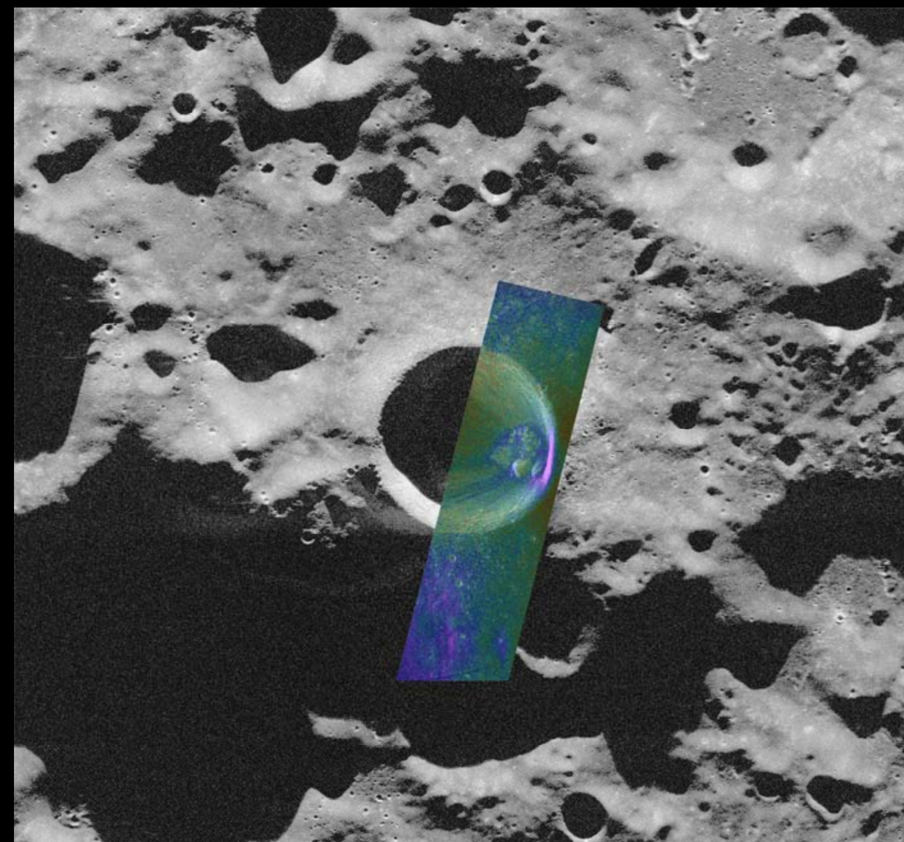


LUNAR AND PLANETARY INSTITUTE

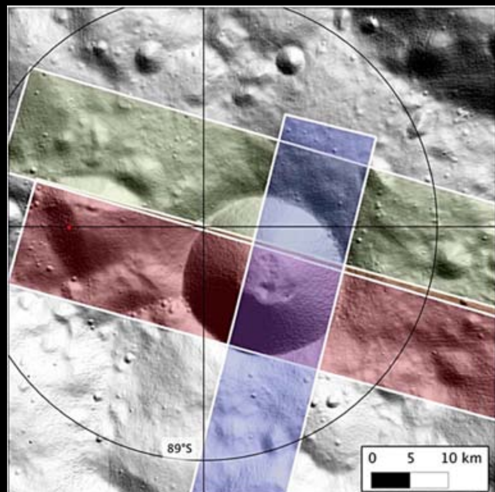


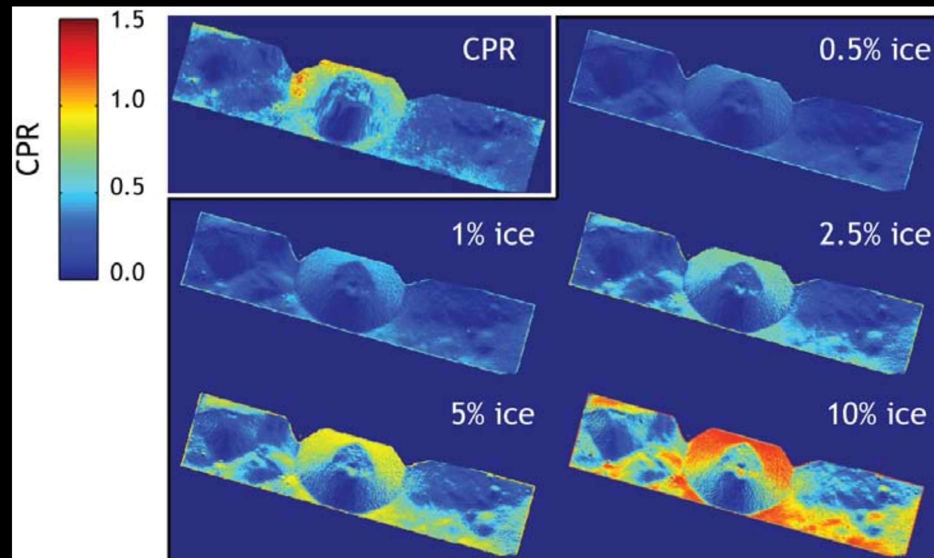
Shackleton crater - Mini-RF data

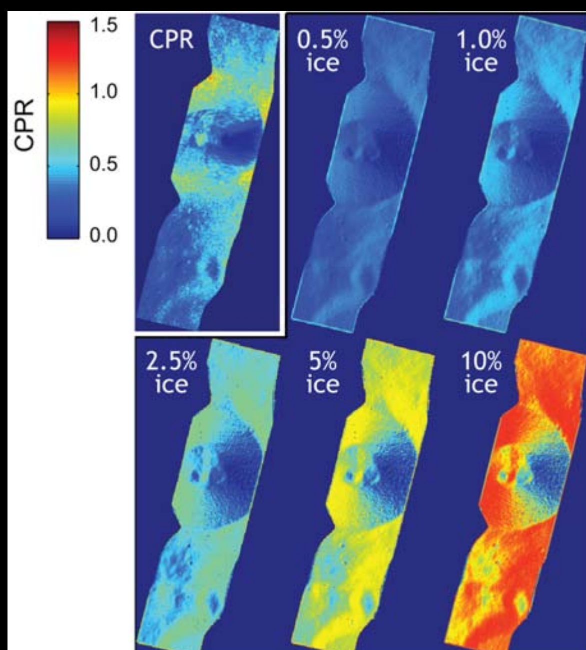


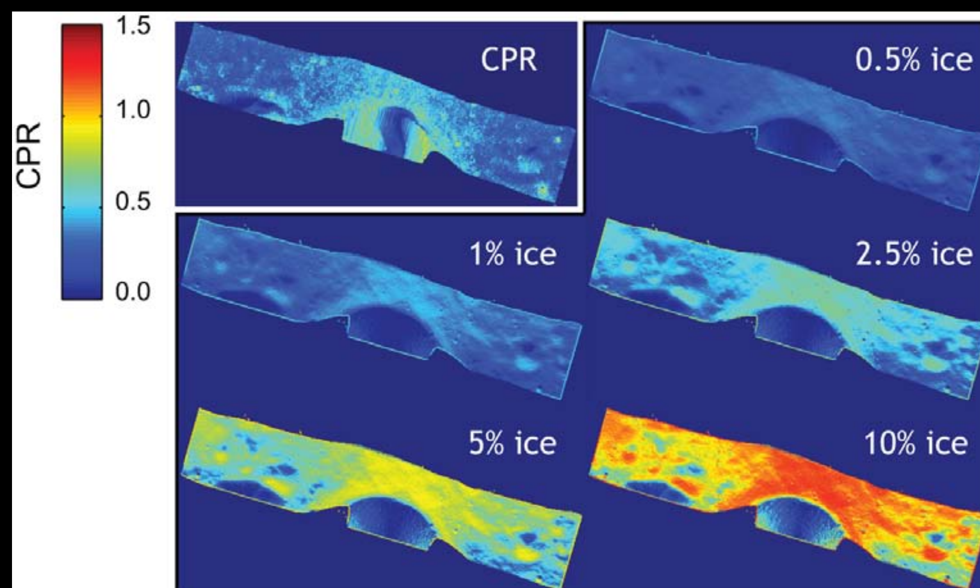


Shackleton crater - Mini-RF data

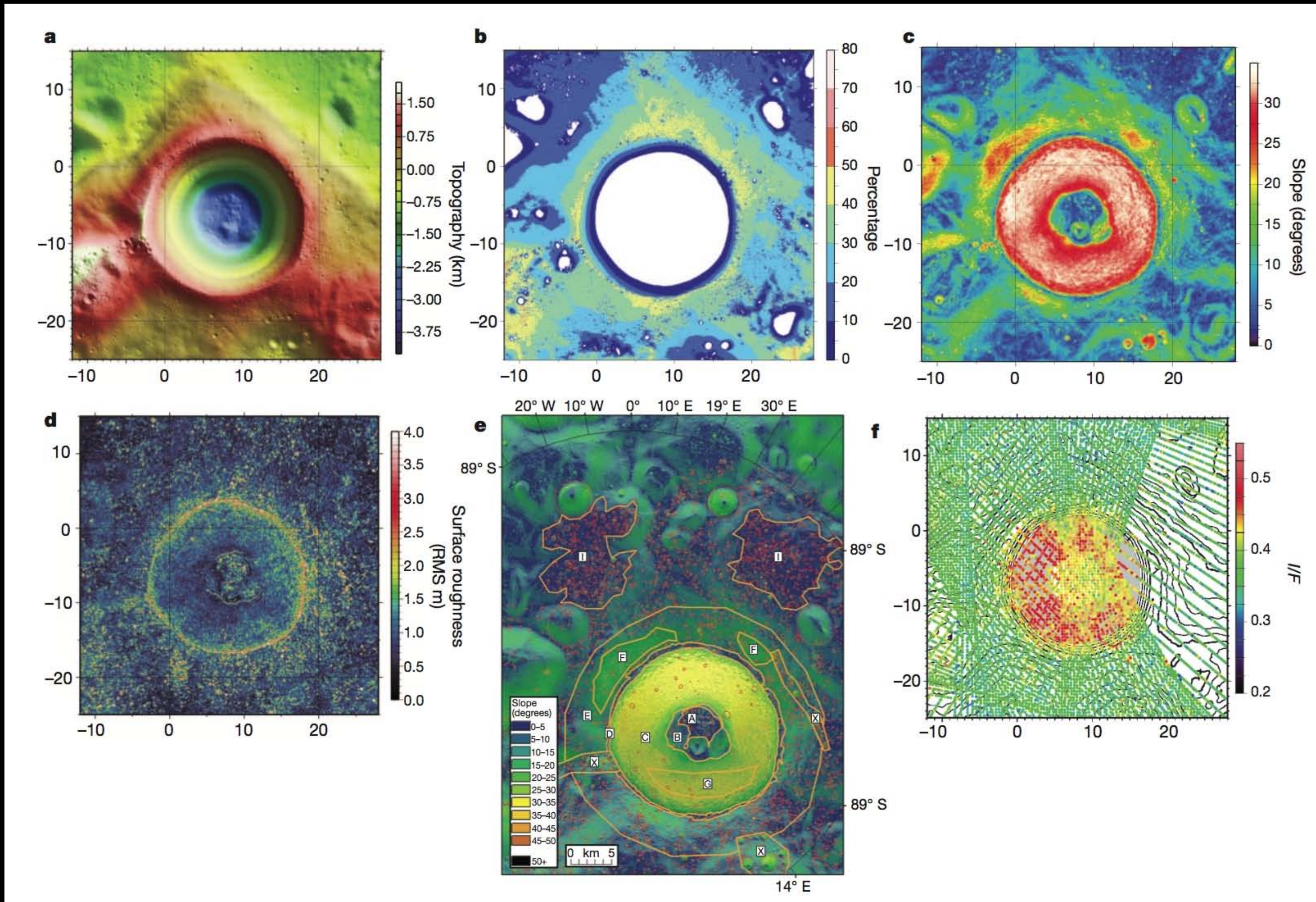




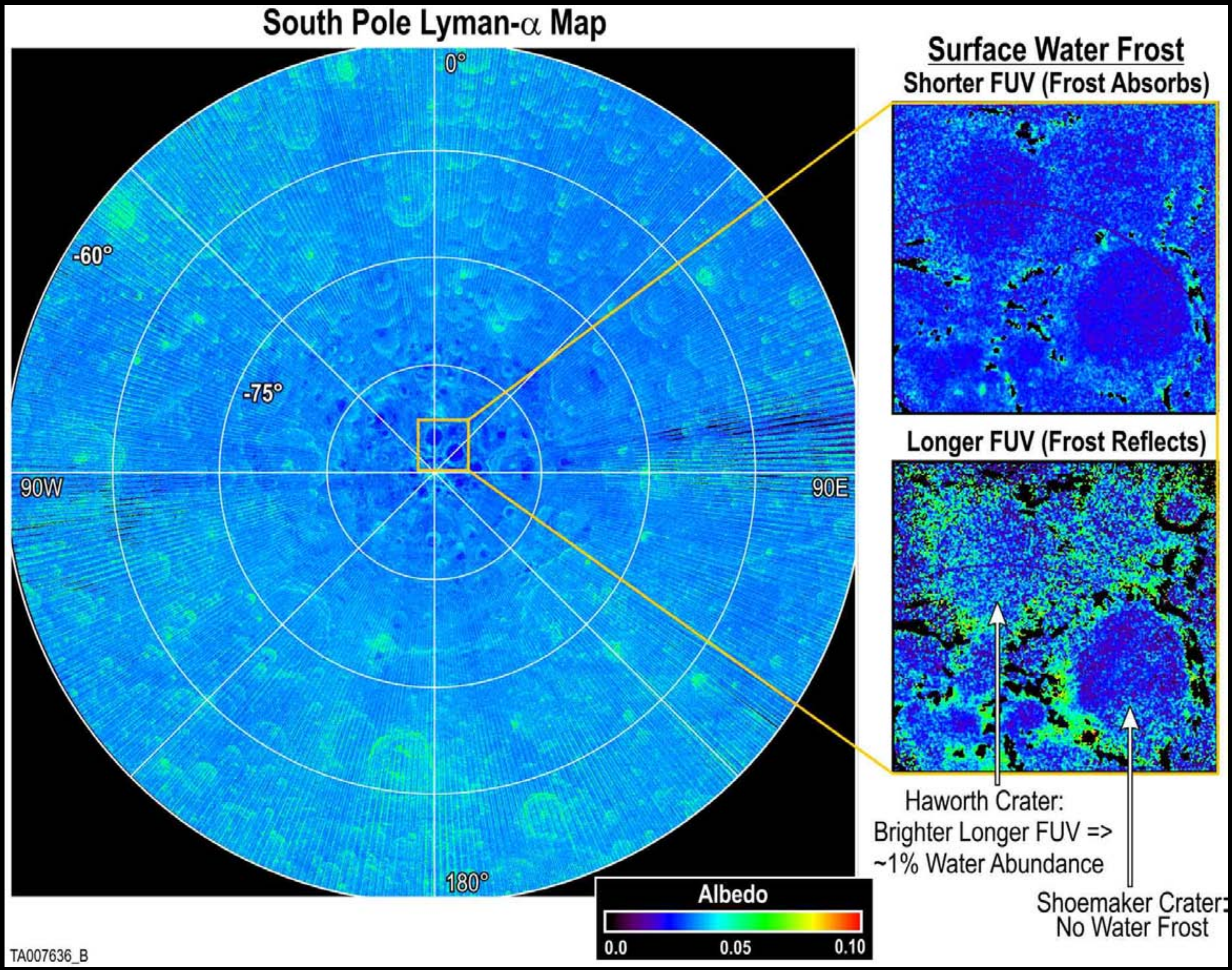




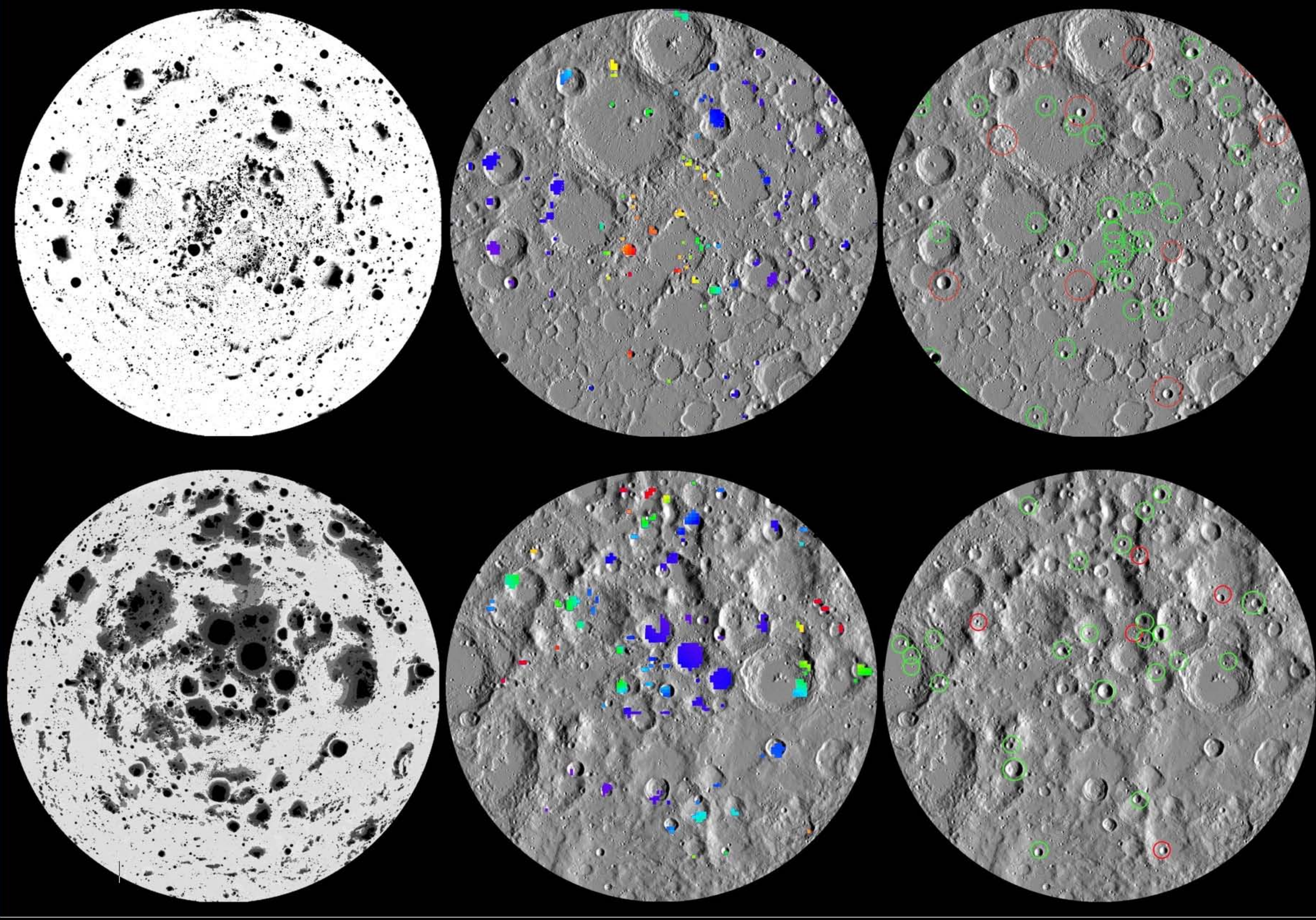
Shackleton crater - LOLA data



LAMP data (UV images)



Polar Lighting, Neutron, Radar data



The Lunar Hydrosphere

The Five Flavors of Lunar Water

Water is or was in the lunar interior (as a *minor* component; 250-700 ppm)

- Water from deep mantle (> 400 km depth) component of volatiles driving lunar pyroclastic eruptions

Water and OH molecules on surface at latitudes > 65° at both poles

- Present as adsorbed monolayer and/or bound in mineral structures
- Increasing concentration with increasing latitude (~800 ppm and *greater*)
- Temporally variable; preferentially located in cooler locales (it's moving)

Exospheric water observed in space above the south pole

- MIP mass spectrometer measured ~ 10^{-7} torr partial pressure H_2O

Water ice is admixed into regolith in polar regions

- LCROSS site (floor of Cabaeus) is 5-10 wt.% water; both ice particles and water vapor ejected during impact
- Other cometary volatiles are present (e.g., carbon dioxide, methane, sulfur dioxide, methanol, ethanol)
- Concentrations vary laterally, vertically; "fluffy" physical nature

Thick (~2 m), "pure" water ice is found in some permanently shadowed craters near the poles

- High CPR materials in over 40 craters (3-12 km dia.) near north pole
- Suggest over 600 million metric tonnes of "pure" water ice; reserves of ice mixed with dirt are much greater

The Value of Lunar Polar Ice

A concentrated, easily usable form of H_2, a rare lunar element

Two orders of magnitude *less* energy to extract H_2 from icy regolith than from dry regolith

A source of life support consumables

Reactants for fuel cell electrical power

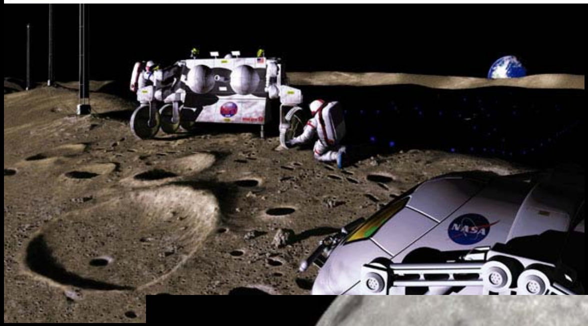
Shielding for lunar surface habitats

Propellant for the cislunar transportation system

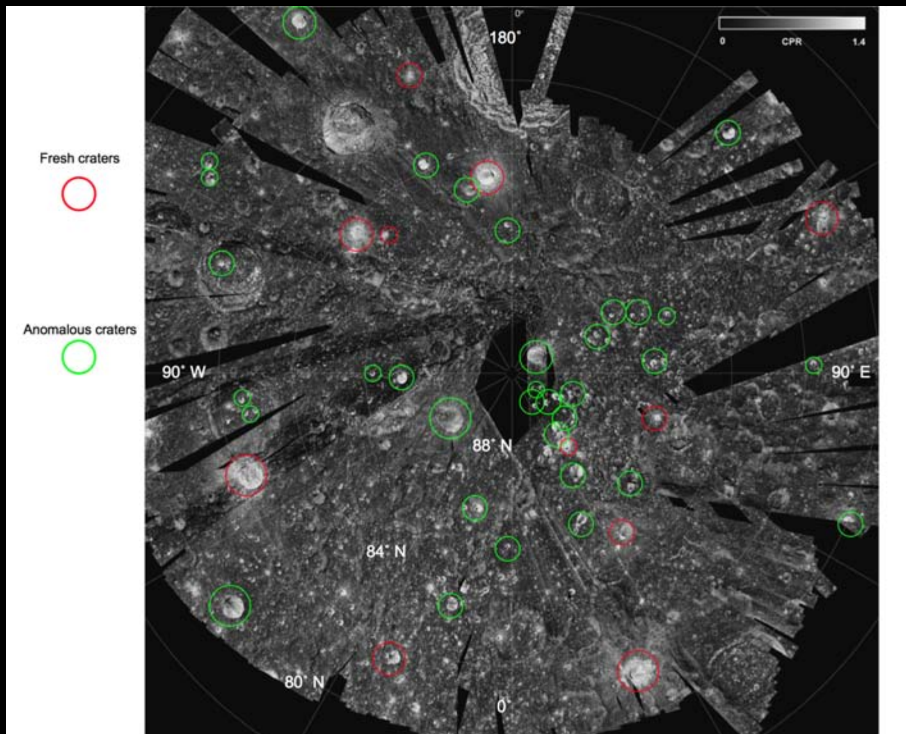
Table 1. Energies required for selected lunar resource processes

Operation	Specific Energy
Equatorial Moon	
Excavation of regolith	0.01 kWh/kg regolith (electric)
Reduction of SiO_2 to Si + O_2	10.4 kWh/kg O_2 (electric)
Extraction of hydrogen from dry regolith[1]	2250 kWh/kg H_2 (thermal)
Polar regions	
Excavation of regolith	0.01 kWh/kg regolith (electric)
Extraction of water from icy regolith[2]	2.8 kWh/kg H_2O (thermal)
Electrolysis of water	4.7 kWh/kg O_2 (electric)
Electrolysis of water	48 kWh/kg H_2 (electric)

1. Assumes 100 ppm H_2, heated 800° C above ambient 2. Assumes 1% ice, heated 100° C above ambient



How Much Ice?



1	D (km)	A (km^2)	V (m^3)/m (mT)
2	12	113.04	24000000
3	8	50.24	16000000
4	7	38.465	14000000
5	5	19.625	10000000
6	6	28.26	12000000
7	8	50.24	16000000
8	3	7.065	6000000
9	5	19.625	10000000
10	4	12.56	8000000
11	4	12.56	8000000
12	8	50.24	16000000
13	21	346.185	42000000
14	18	254.34	36000000
15	7	38.465	14000000
16	12	113.04	24000000
17	3	7.065	6000000
18	8	50.24	16000000
19	6	28.26	12000000
20	11	94.985	22000000
21	6	28.26	12000000
22	4	12.56	8000000
23	5	19.625	10000000
24	4	12.56	8000000
25	6	28.26	12000000
26	4	12.56	8000000
27	3	7.065	6000000
28	3	7.065	6000000
29	8	50.24	16000000
30	17	226.865	34000000
31	4	12.56	8000000
32	34	907.46	68000000
33	4	12.56	8000000
34	6	28.26	12000000
35	5	19.625	10000000
36	4	12.56	8000000
37	4	12.56	8000000
38	3	7.065	6000000
39	8	50.24	16000000
40	5	19.625	10000000
41	11	94.985	22000000
42			
43	Total ice (m^3)		608000000
44			
45	Total reg (m^3)		5.652E+11
46			
47	Concentration		0.001075725

Observed high CPR area in shadowed craters x 10(λ) thickness
Total N. Polar ice ~ 6 x 10^8 m^3 = 600 million mT
Average fuel mass in Shuttle ET = 735 mT (735,000 kg)
Enough LH_2/LO_2 for one Shuttle launch equivalent *per day* for more than 2200 years

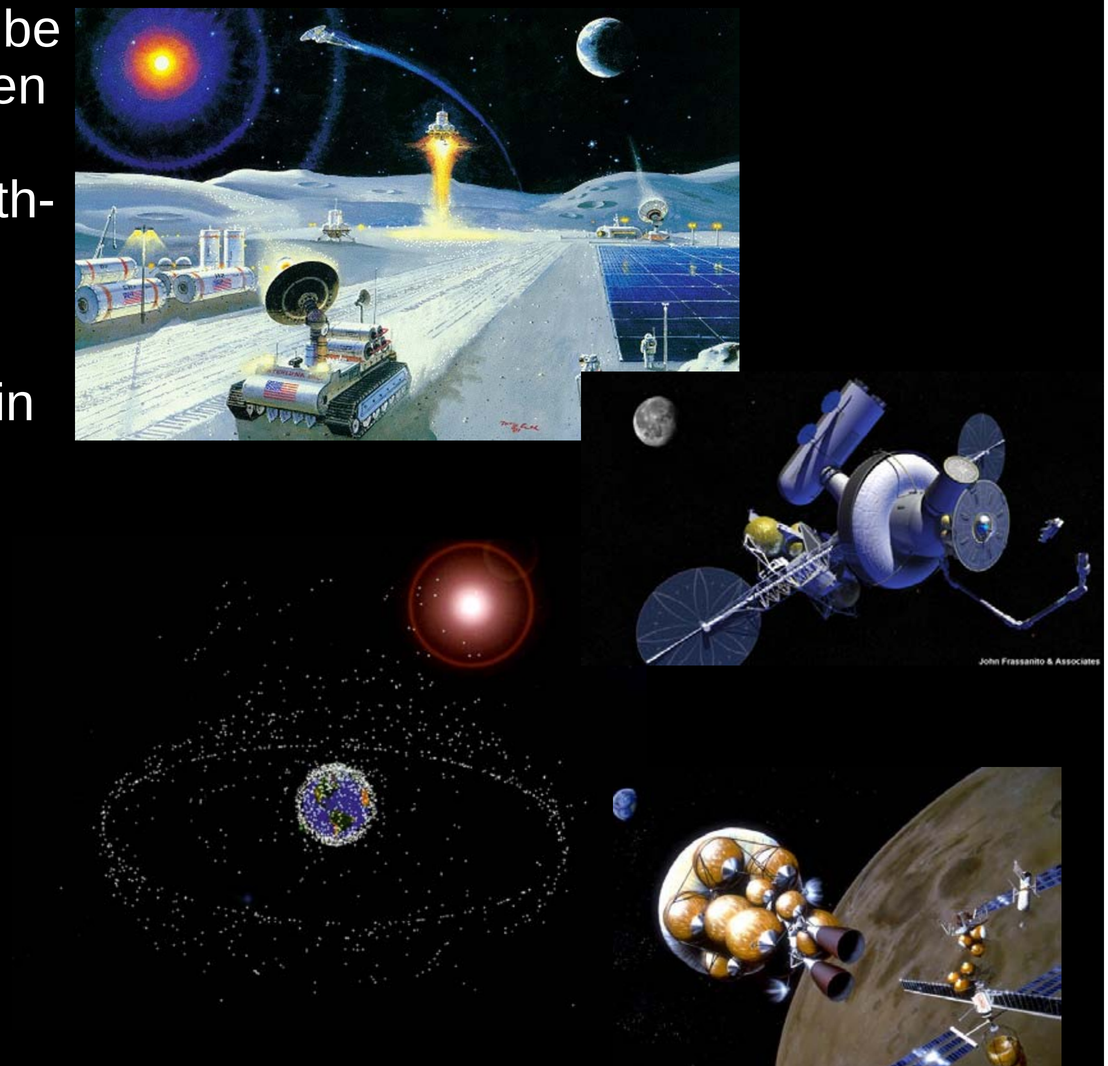
The Value of Lunar Resources

Materials on the Moon can be processed to make hydrogen and oxygen for use on the Moon and for export to Earth-Moon (cislunar) space

Propellant produced on the Moon can make travel within and through cislunar space routine

This eventuality will completely change the spaceflight paradigm

Routine access to cislunar space has important economic and strategic implications



The Moon – Gateway to the universe

"If God wanted man to become a space-faring species, He would have given man a Moon." – Krafft Ehricke

Learn about the Moon, the Earth-Moon system, the solar system, and the universe by scientifically exploring the Moon

Acquire the skills and develop the systems on the Moon that we need to become a multi-planet species

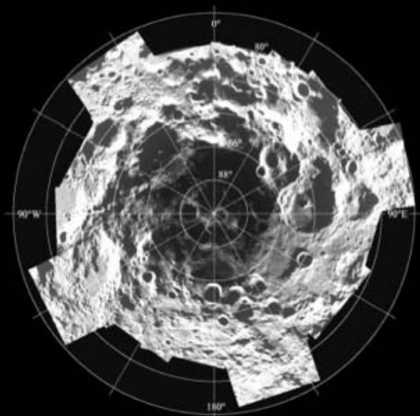
Develop and use the material and energy resources of the Moon to create new space-faring capability

For More Information:

Spudis Lunar Resources

Using the Moon to learn how to live and work productively in space

What's this web site all about?



Paul D. Spudis, Ph.D.

spudis@lpi.usra.edu

The Moon: Port of Entry to Cislunar Space (April 2010)

The New Space Race (SpaceRef, Feb. 2010)

Moonwake - Two Novels for Young Adults Free Downloads

Home Resume Bibliography Opinion/Editorial Papers Moon 101 Images/Maps Links Blogs

http://www.spudislunarresources.com