

## **The Poles of the Moon and Their Significance\***

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### **Abstract**

In the past decade, the Clementine and Lunar Prospector missions have conducted global reconnaissance of the Moon. We have discovered unique properties of the polar regions that make them desirable targets for exploration and exploitation. The Moon's spin axis is perpendicular to the ecliptic plane, resulting in areas of near-permanent sunlight and definite permanent darkness at the poles. The former offers unique sites to inhabit, for such areas provide constant sunlight, enabling continual power generation and a benign thermal environment. The latter act as "cold traps" that may have accumulated water and other volatiles near both poles. Water ice likely is present as finely disseminated bodies, mixed with impact generated rock and debris. The presence of water on the Moon has the potential to completely change the space flight paradigm. Currently, our space probes must be supplied and equipped on Earth and launched complete; this limits the amount of material, and thus capability, of future space probes. In contrast, if we can use the resources of the Moon, specifically the water ice at the poles to make rocket propellant, we forever change the rules of space exploration. Use of lunar generated propellant will create an Earth-Moon transportation infrastructure, with which we can not only access any point in cislunar space, vital to national economic and security interests, but also voyage to the planets beyond.

# The Poles of the Moon and Their Significance



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# Why the Moon?

## It's close

three days away and as accessible as GEO

Alien yet familiar; Earth is visible to crew and TV audiences

Moon can be reached with existing or derived launch systems

## It's interesting

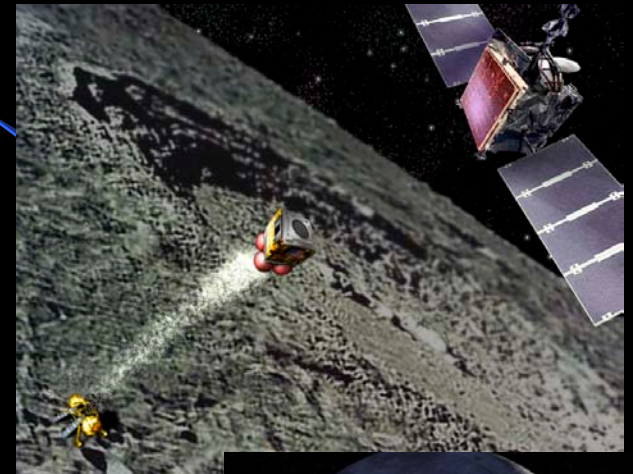
A natural laboratory for planetary science

A platform to observe the universe

## It's useful

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

Development of lunar resources could create a major logistics base in near-Earth space



# The Known Moon

## Equator and mid-latitudes

### Resources

Regolith, mean grain size  $\sim 40 \mu\text{m}$ , 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  $\sim 20\text{-}90$  ppm, C  $\sim 100\text{-}200$  ppm, N  $\sim 10\text{-}90$  ppm

### Environment

14-day diurnal sunlight and thermal cycle; possible electrostatic charging environment associated with terminator

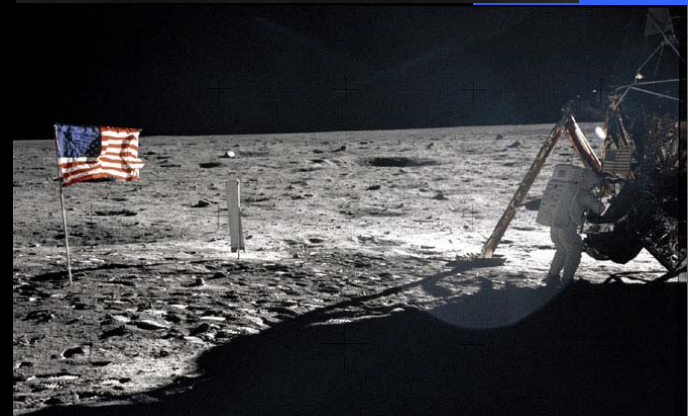
Surface temperatures  $\sim 100^\circ\text{C}$  at local noon;  $-150^\circ\text{C}$  before sunrise

High vacuum ( $10^{-12}$  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

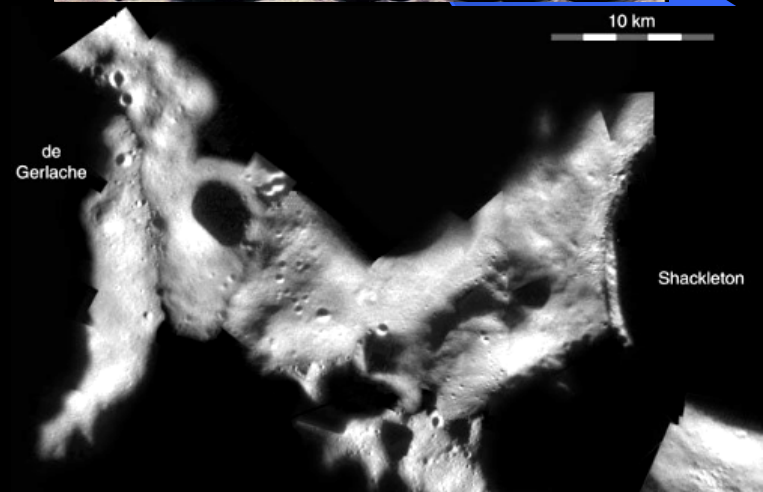
Areas of near-constant sunlight (-50 °C), constant darkness (unknown; modeled as -220 °C)

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 Permanent Darkness

- Only scattered light or starlight
- No direct solar illumination
- Very low temperatures (~50-70K)
- Serves as cold trap for volatiles

## Areas of Semi-Permanent Light

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

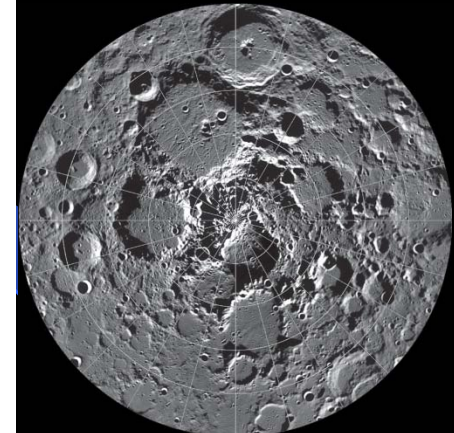
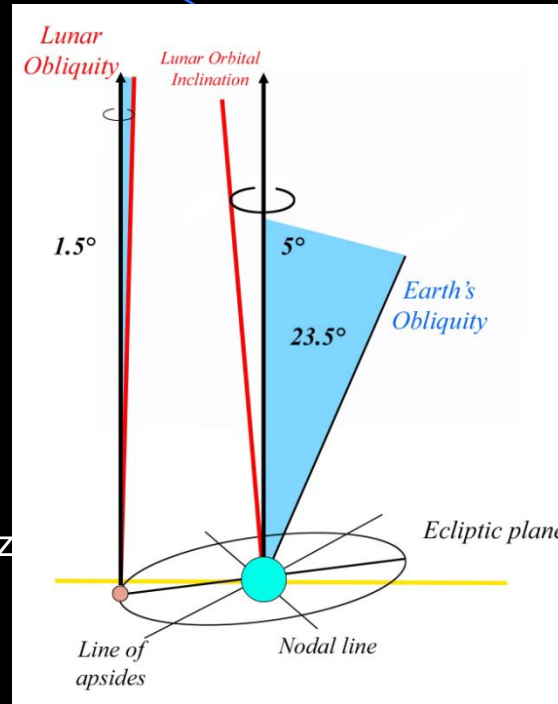
## View from the Earth

- Lighted Areas

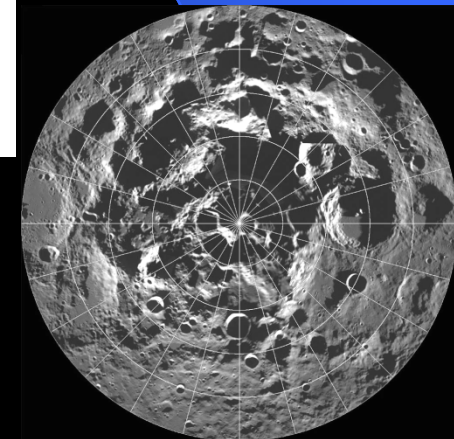
  - Two weeks of visibility / two weeks obscured

- Shadowed Areas

  - Permanently obscured



North pole



South pole

# Permanent sunlight?

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

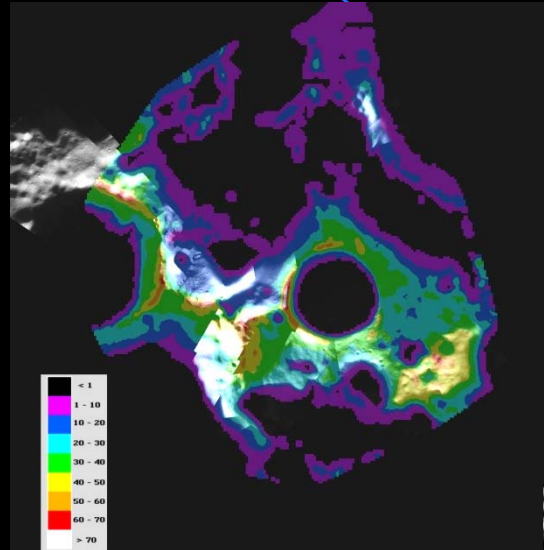
One zone receives 70% illumination during dead of southern winter

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

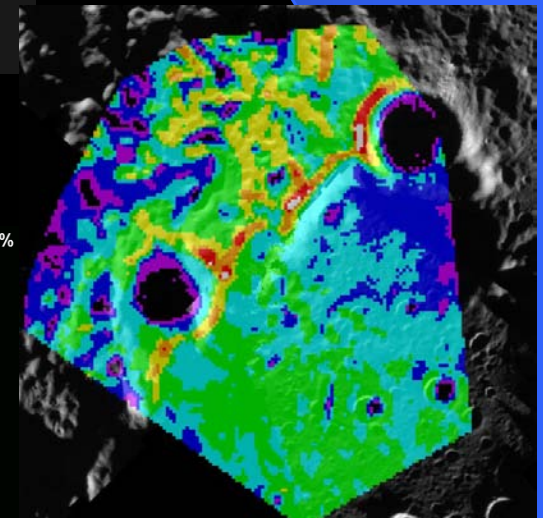
Data taken during northern summer (maximum sunlight)



Data obtained during southern winter (maximum darkness)

South Pole

North Pole



Data obtained during northern summer (maximum sunlight)

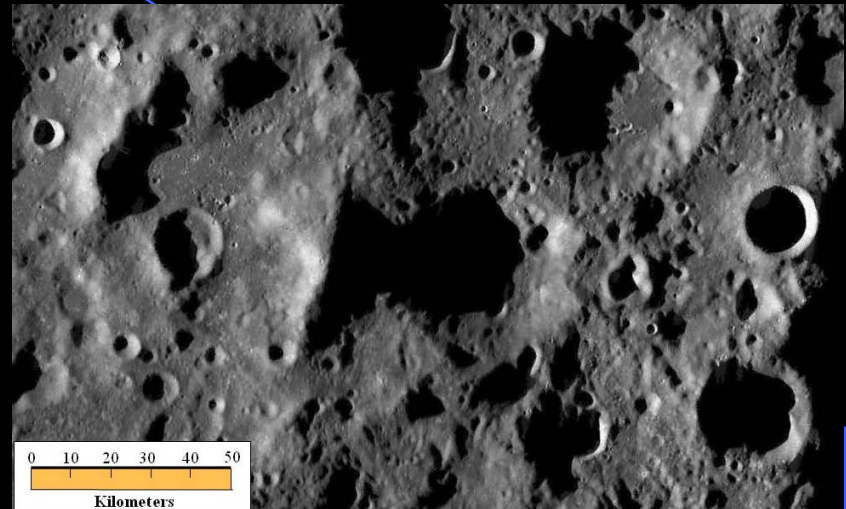
# Importance of the South Pole of the Moon

Just inside the rim of largest impact feature (SPA basin) on the Moon

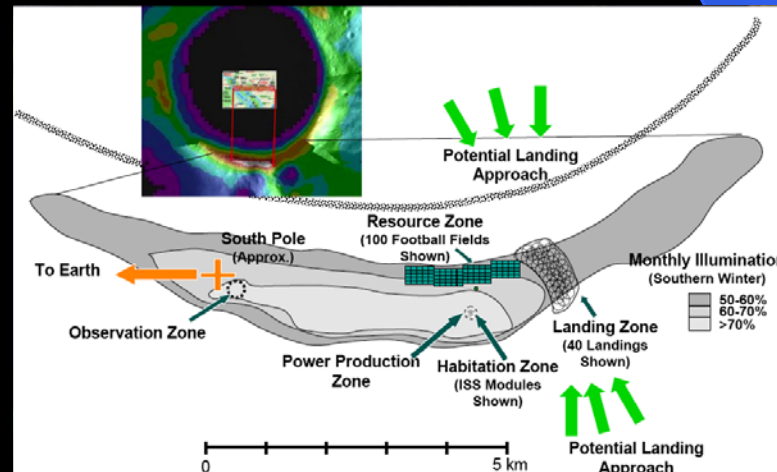
Unique environment of poles may have resulted in unusual processes and history

Need to understand geological setting to evaluate resource potential

A likely site for future robotic and human exploration and use



Goldstone image, 2008



LAT, 2006



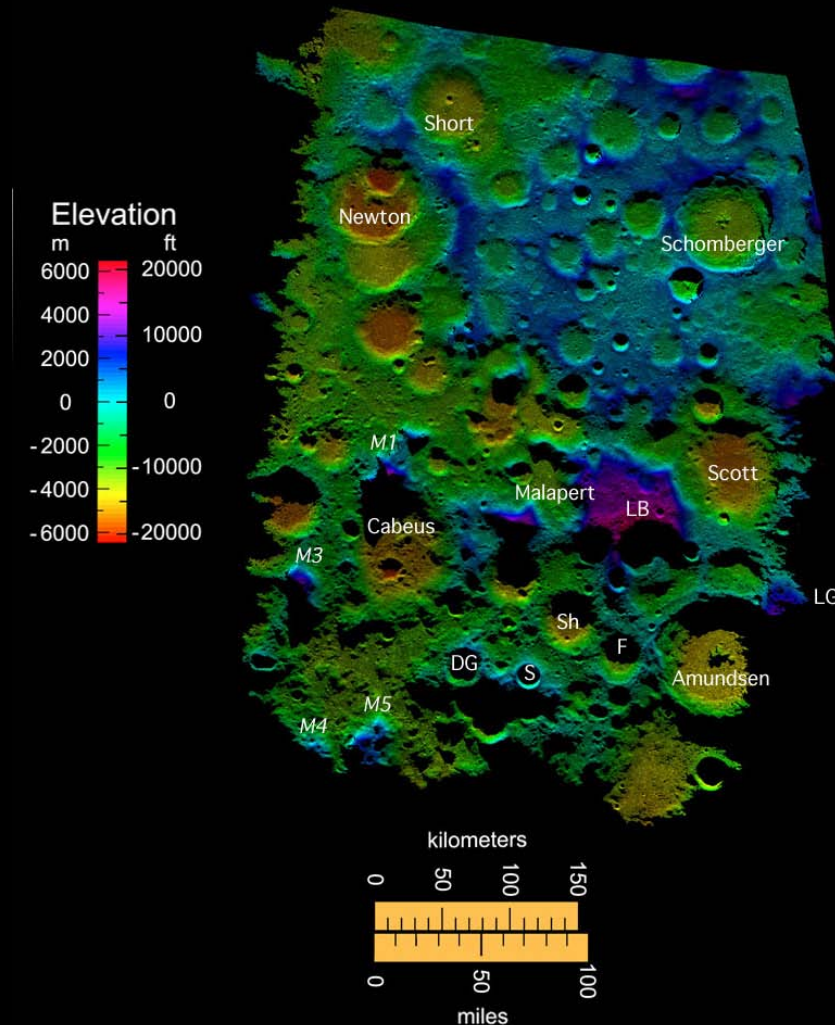
# New Data for the South Pole

## 1. Goldstone radar topography

New radar  
topography  
shows extreme  
terrain of SPA  
basin rim

Range from +6 to  
minus 5 km over  
100 km

Confirms Malapert  
peak should be in  
near-constant  
sunlight



# New Data for the South Pole

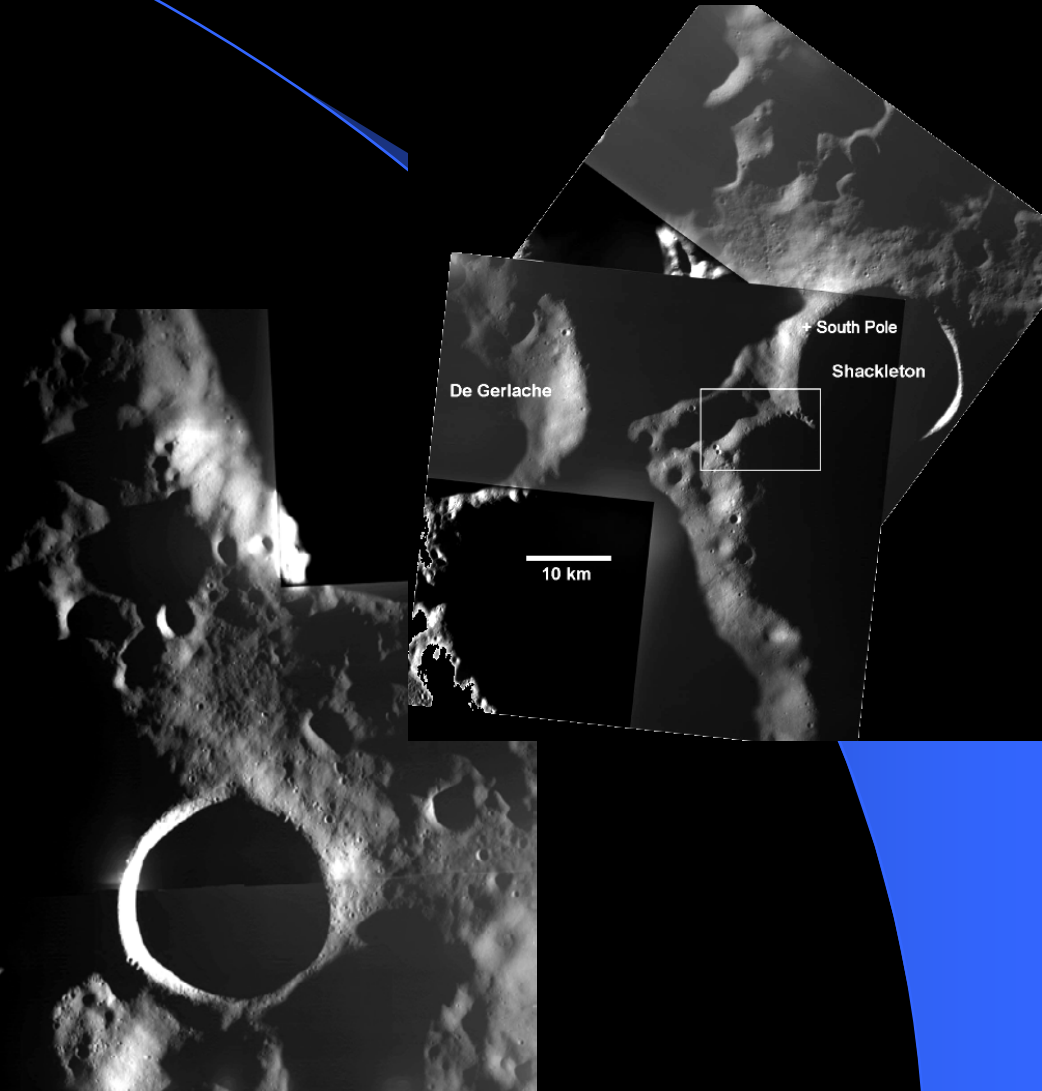
## 2. SMART-1 images during southern summer

Seasonal coverage  
complements  
Clementine winter  
images

Point B is in sunlight 100%  
of lunar day in summer

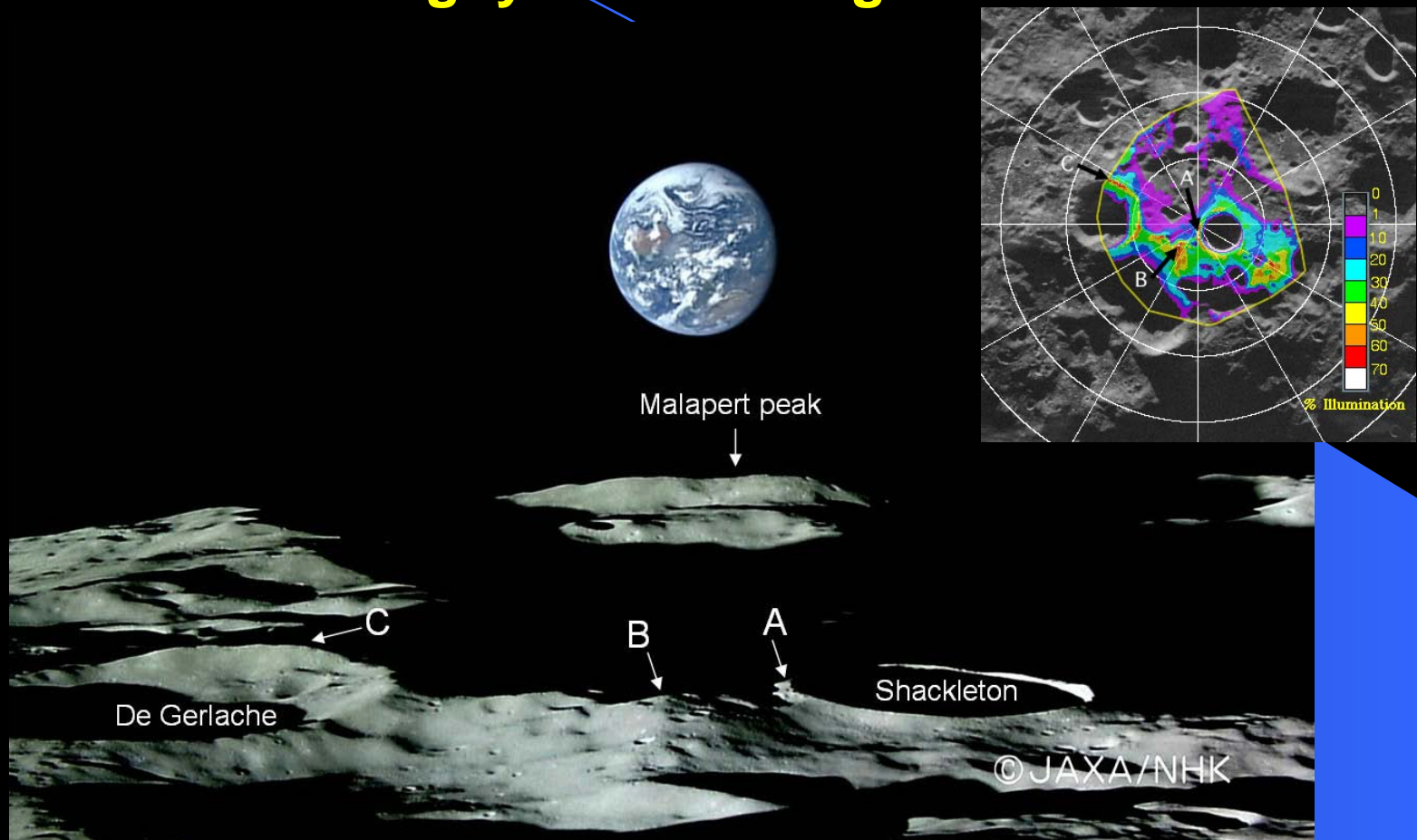
Shackleton located on  
side of SPA interior  
basin mountain

Important implications for  
geology of potential  
outpost site



# New Data for the South Pole

## 3. 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

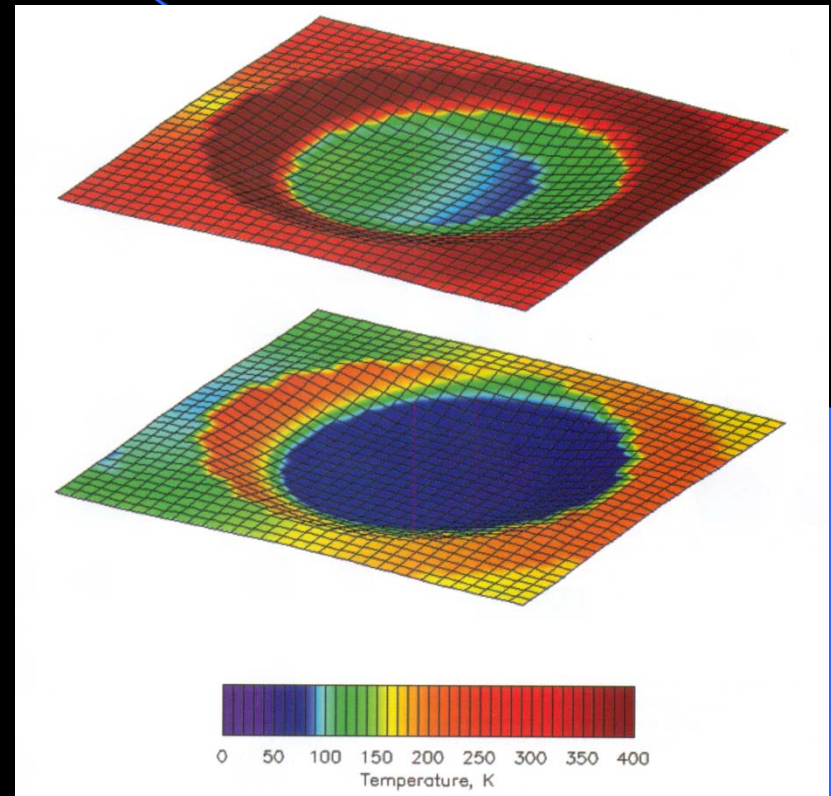
# Polar Cold Trap Temperatures

Permanently shadowed areas have very low model temperatures ( $\sim 50\text{-}70\text{ K}$ ) and act as cold traps (e.g., Vasavada *et al.* 1999)

Uncertainty largely a reflection of unknown value for heat flow of Moon ( $2.2 - 3.1\ \mu\text{W cm}^{-2}$ )

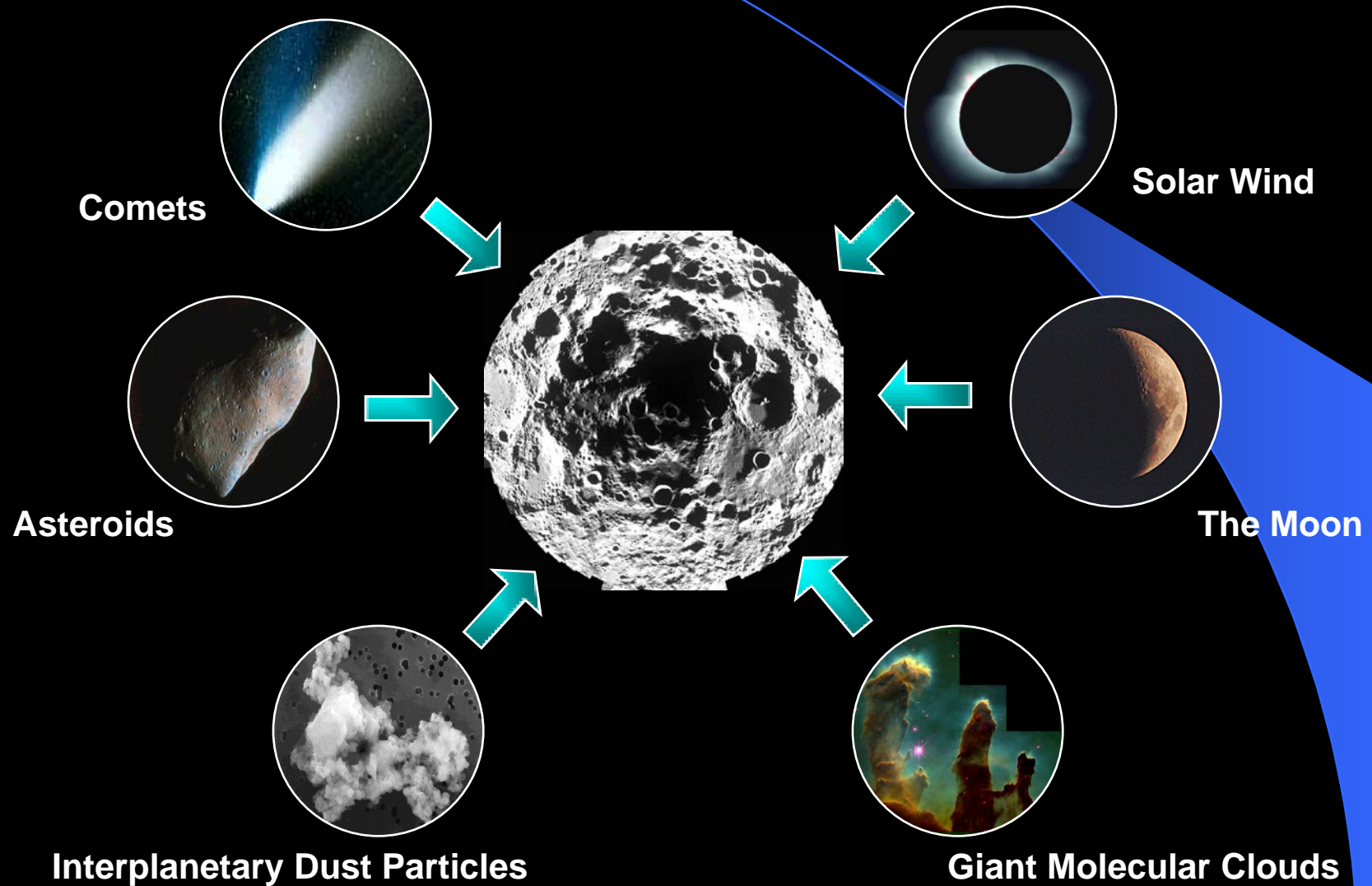
Temperatures may vary substantially in the shallow subsurface

At these temperatures, atoms and molecules of volatile species cannot escape





# Possible Sources of Lunar Polar Volatiles

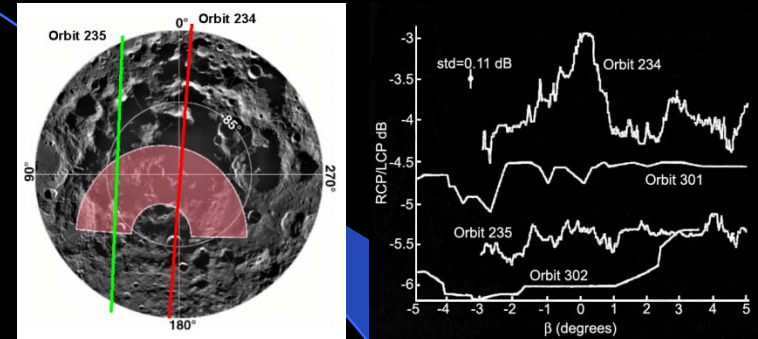


# Does ice exist on the Moon?

## Clementine

Found evidence on one orbit (234) for high same-sense backscatter (high CPR; CBOE?) over dark areas near poles

Other orbits (e.g., 235; over sunlit areas) show no enhancement

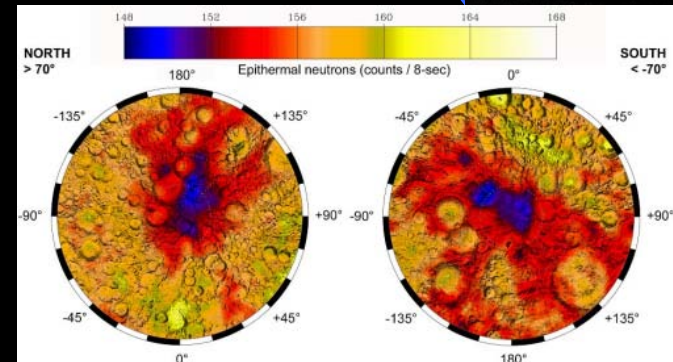


## Lunar Prospector

Neutron spectrometer detects “excess” hydrogen, but not phase state

Enhanced  $H_2$  over poles; consistent with ~ 2 % polar ice or solar wind

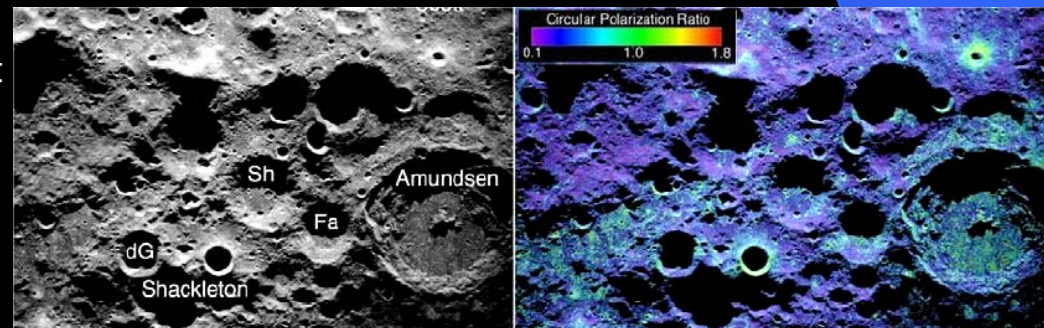
No fast neutron signal; upper 10 cm of surface desiccated



## Earth-based radar

Patchy, high CPR found in both sunlight and polar darkness

Surface roughness or two different scattering mechanisms?



# Synthesis: Best Guess for Polar Volatiles

**Ice exists in dark areas, but its origin and the processes associated with it are unclear**

Could be of cometary, meteoritic, or solar wind origin

Rates of deposition, and implications for its physical nature, are unknown

**Ice deposits cover a minority of the terrain and their concentrations could vary widely leading to a very heterogeneous deposit**

Suggested by distribution of high CPR spots

Ice concentration unknown, but if heterogeneous, deposits could cover 10-50% of dark area

Volume scattering at S-band suggests ice bodies of decimeter to decameter scale

**Uppermost surface is desiccated; ice occurs at depths between 10 cm and 2-3 m**

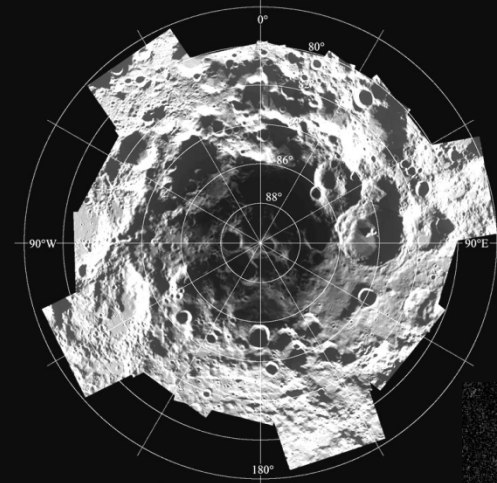
From neutron and radar data

**Ice is probably not “pure” but contains regolith contaminants of varying concentration**

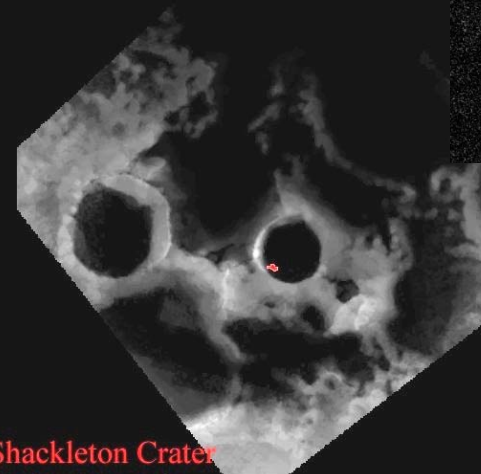
From current knowledge of regolith formation, evolution, and overturn

**Although water ice is expected to dominate, other minor species of cometary origin could be present in useful quantities (e.g.,  $\text{CH}_4$ ,  $\text{NH}_3$ )**

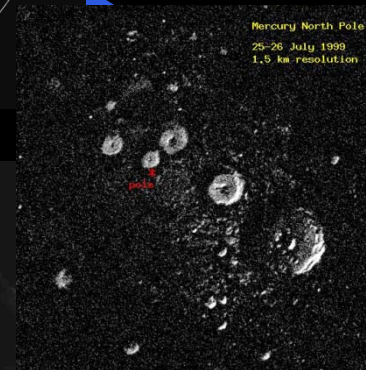
From astronomical observations of comets



Clementine Illumination Map



Shackleton Crater  
Radar Anomaly





# Information Needed on Lunar Polar Volatiles

Inventory of trapped ice

Composition of ice

Variability in ice composition

State of volatiles (ices,  
amorphous compounds,  
separate phases, clathrates)

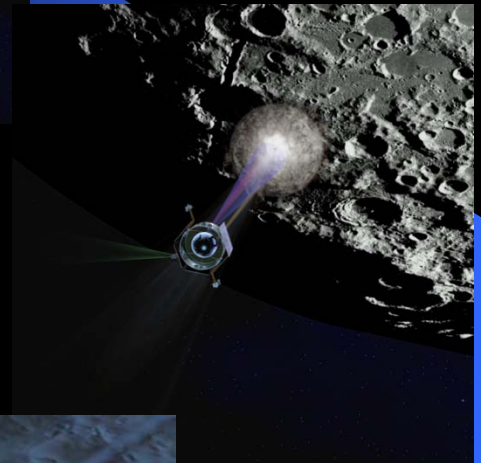
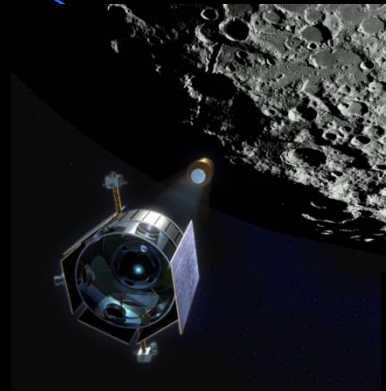
Distribution with depth

How ice binds soil grains

Whether ice reacts with soil grains

Geotechnical properties of ice-  
bearing regolith

Physical environment of polar  
regions





# Mini-SAR: An Imaging Radar on the Chandrayaan 1 Mission

India polar orbiting lunar mission;  
two year duration

Mini-SAR is an imaging radar using  
hybrid polarity architecture

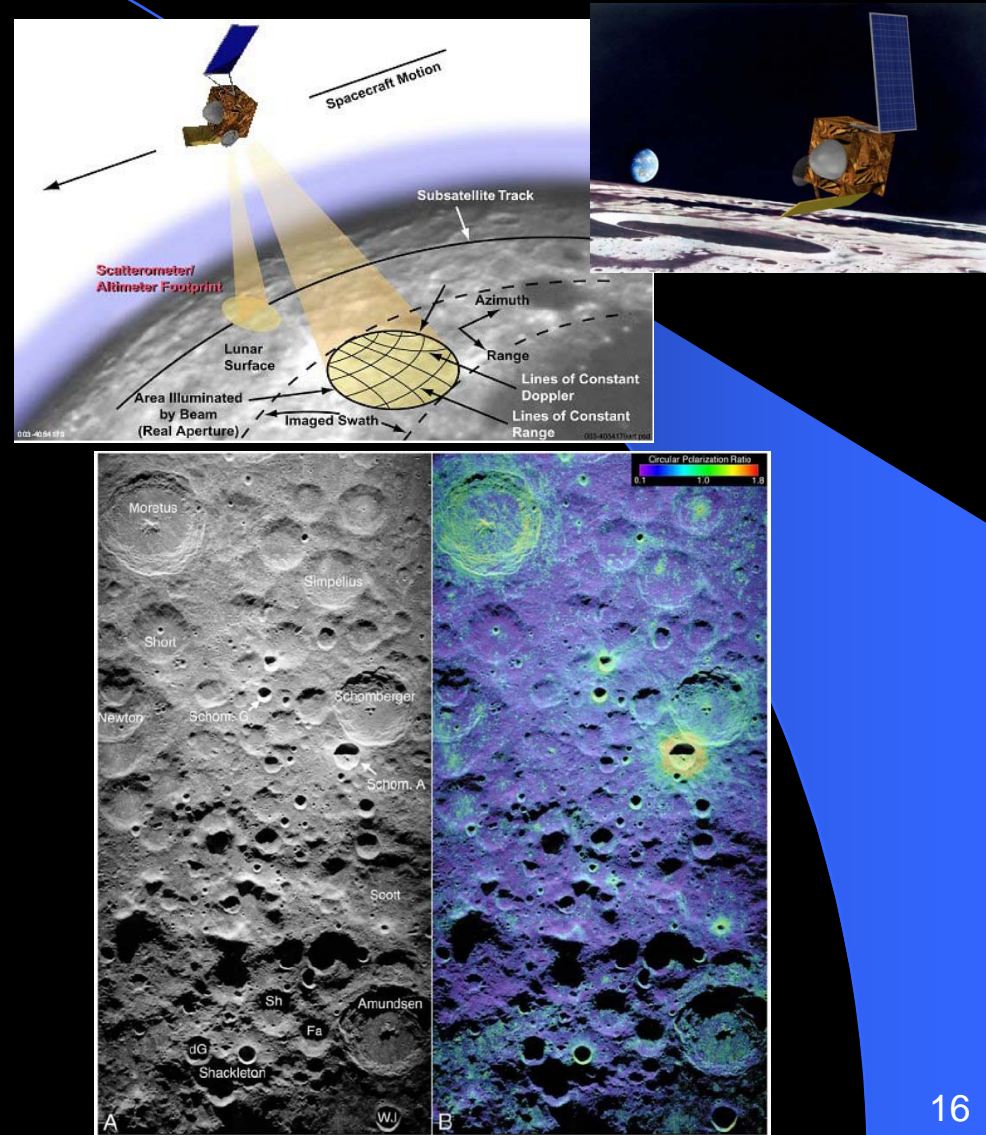
Map both polar regions at 75 m/pixel

Determine complete Stokes matrix  
to describe backscattered field

Map locations of anomalous radar  
reflectivity

See all of polar dark areas (not  
completely visible from Earth)

Cross-correlate with other data  
(topography, thermal, neutron)



# The Value of Lunar Polar Ice

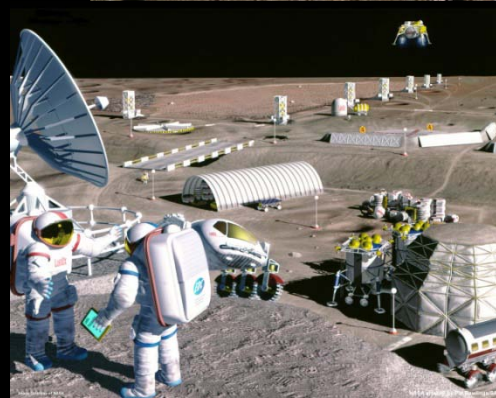
A concentrated, easily convertible source of hydrogen (a rare element on the Moon)

A source of life support consumables

Reactants for fuel cell electrical power

Shielding for lunar surface habitats

Propellant for a cislunar transportation system



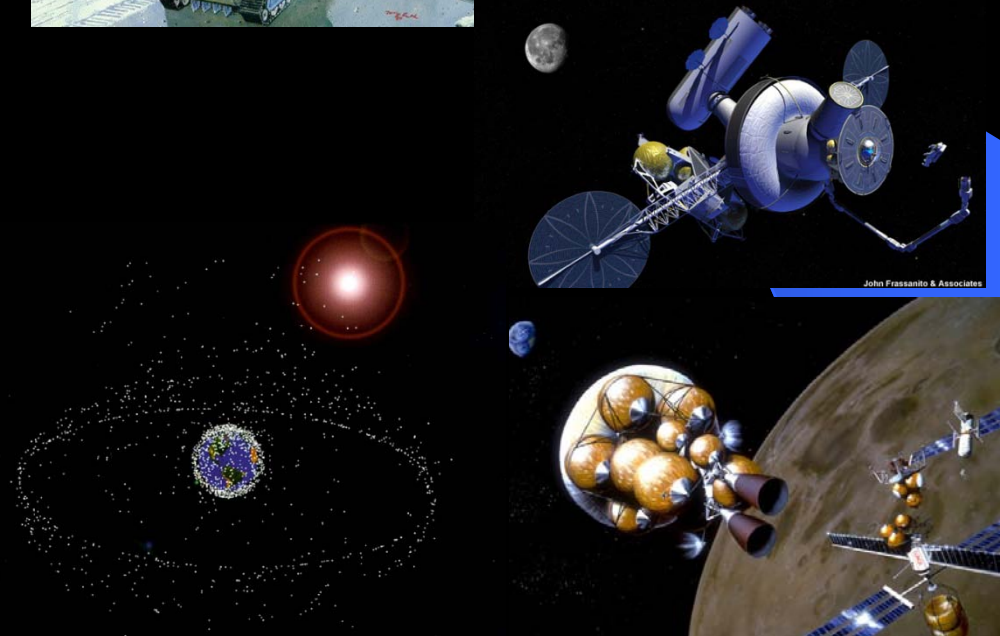
# The Value of Lunar Resources

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 build 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





# Space – A New Rationale

*Explore* to broaden our knowledge and imagination base

*Prosper* by using the unlimited energy and materials of space to increase our wealth

*Secure* the world by using the assets of space to protect the planet and ourselves



## References

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Lucey, Paul G.G., Jeffrey Taylor, and Erick Malaret, 2001, Abundance and distribution of iron on the Moon: *Science*, v. 268, no. 5214, p. 1150-1153.

Vasavada, A.R., D.A. Paige, and S.E. Wood, 1999, Near-surface temperatures on Mercury and the Moon and the stability of polar ice deposits, *Icarus*, v. 141, p. 179-193.