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 ~ 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^{-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
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)
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
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
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 (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

- Comets
- Solar Wind
- Asteroids
- The Moon
- Interplanetary Dust Particles
- Giant Molecular Clouds

From P. Lucey, 2001
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\textsubscript{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., CH₄, NH₃)
From astronomical observations of comets
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 cis-lunar transportation system
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
