

The Moon: A “New” Destination For Humanity

Paul D. Spudis

*Johns Hopkins University Applied Physics Laboratory
Laurel, Maryland USA*

Space Soon Conference, 2006
London UK

9-13 September, 2006

The Vision for Space Exploration

Return Shuttle to flight

**Complete ISS assembly
and retire Shuttle**

**Build new human
spacecraft (CEV) for
transport beyond LEO**

**Return to the Moon with
people and robots to
explore and prepare for
voyages beyond**

**Human missions to Mars
and other destinations**



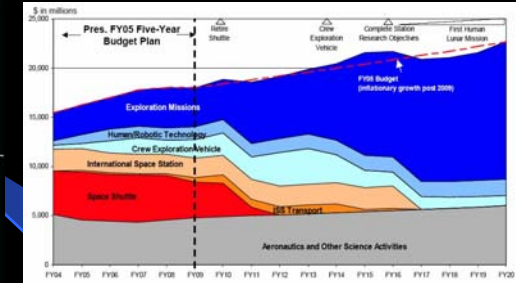
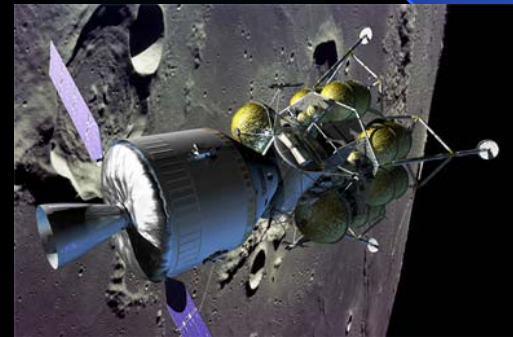
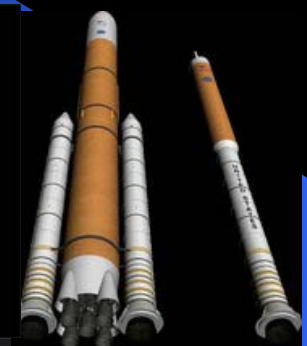
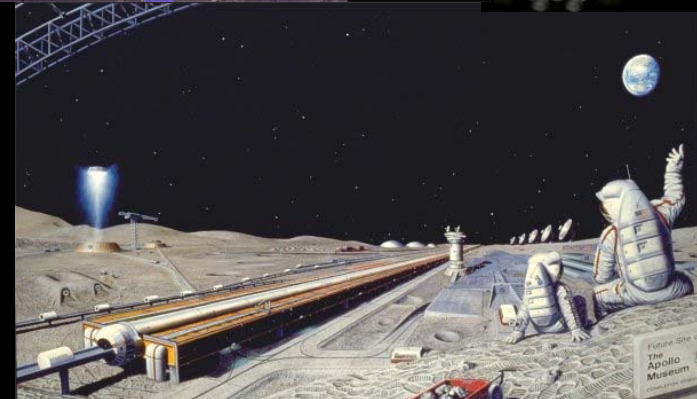
"It is time for America to take the next steps.

Today I announce a new plan to explore space and extend a human presence across our solar system. We will begin the effort quickly, using existing programs and personnel. We'll make steady progress – one mission, one voyage, one landing at a time.

President George W. Bush - January 14, 2004

What's It All About?

A journey, not a race
Incremental steps, cumulative
No turning back
Build-up space-faring
infrastructure
Robotic precursors lead the
way
Expanding sphere of human
“reach”
Human-robotic partnership
and synergy
Can humans thrive off-planet?

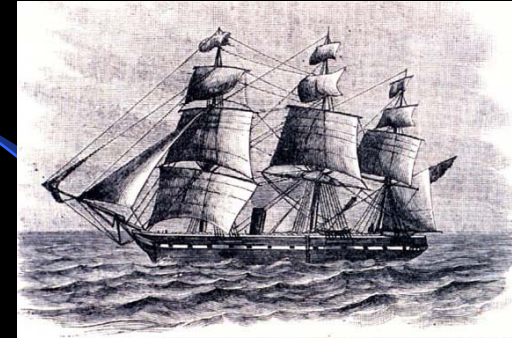


What's the value of exploration?

Humans explore because it conveys an evolutionary advantage

exploration broadens experience and imagination,
permitting better prediction of the future,
ensuring better odds for survival

curiosity and its satisfaction is intellectually and
emotionally satisfying



Exploration improves our ability to solve problems

increased imagination and knowledge base permits
recognition of innovative approaches and
solutions

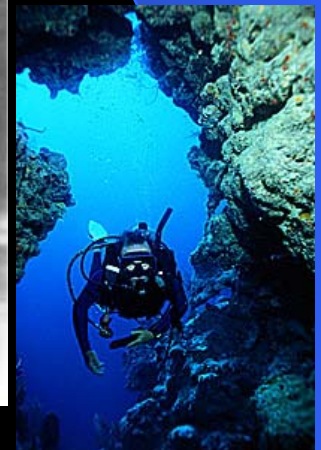
helps focus energies on posing the right questions,
or, questions that can be addressed and
answered



Exploration excites and inspires the creative, productive segments of society

permits intellectual connections and relations that
might not otherwise occur (the 'ah-ha!'
syndrome)

Frontiers are unknown, mysterious places that
stimulate imagination



Exploration ≠ Science

Exploration is going into the unknown, probing the frontier, looking over the next hill.

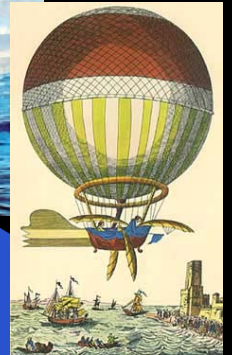
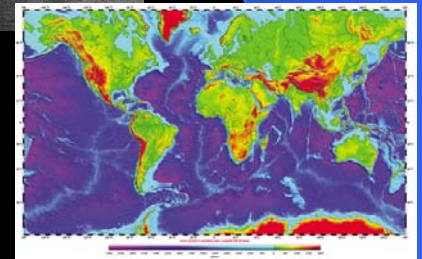
It has structure, but is not directed
Discoveries sometimes build on each other, sometimes are isolated

Science is the process by which we explain nature

It has a well-defined, directed structure (observation, hypothesis, experiment, verification)

Scientific knowledge is cumulative and self-correcting

Both are dynamic, not static. Science always follows exploration



Exploration precedes and enables science

Exploration and Science

“Exploration without science is tourism” – A NASA official

Exploration is *broader and richer* than science

Security and asset protection

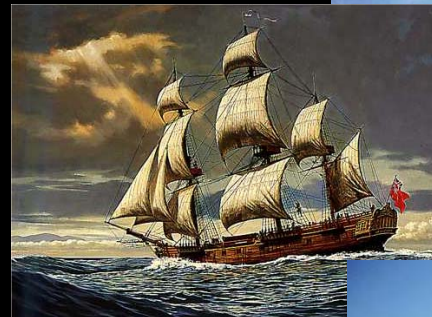
Wealth creation

Settlement and infrastructure development

Exploration *enables* science

Access to remote locales and exotic environments

Exploratory infrastructure permits scientific investigation



Why Human Spaceflight?

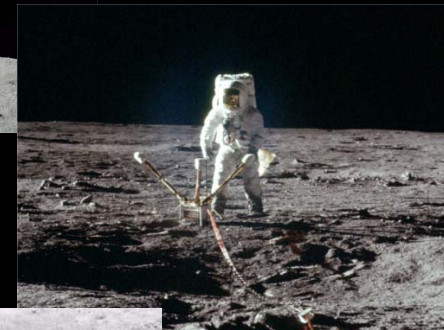
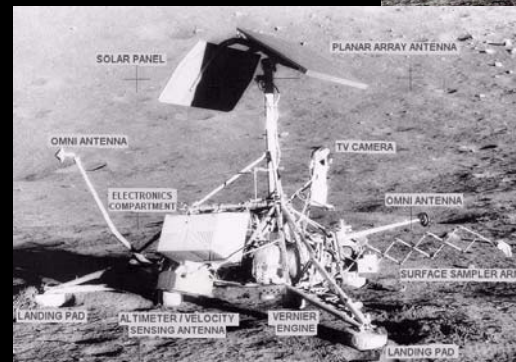
The rational dimension

People bring unique capabilities to space exploration

- Conduct field science, requiring intense interaction of human with environment
- Repair and maintain complex equipment and installations

Machines do not and will not possess intelligence of necessary magnitude to explore the solar system

- Robots are good for remote, hostile environments to provide first-order reconnaissance
- Robots can be designed to answer focused questions (hypothesis testing) or make precision measurements



But: We don't always know ahead of time what measurements are significant and which are irrelevant

Why Human Spaceflight?

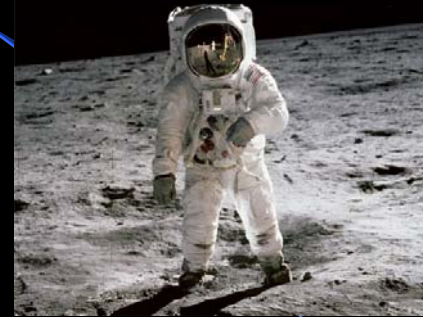
The emotional dimension

Inspiration

People in space are our surrogates; vicarious exploration

Cathedral building; scale is too big for one generation

A human window onto the universe



Drama

Marked upsurge of public interest during crises (e.g., Apollo 13)

Emotion and curiosity (about past and future)

A modern gladiatorial contest, without the gore



Spectacle

A reincarnation of our pioneer/frontier origins

Encourages a communal perspective

Belief in something bigger than ourselves



Why the Moon Next?

It's close (3 days) and accessible (as near as GEO)

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

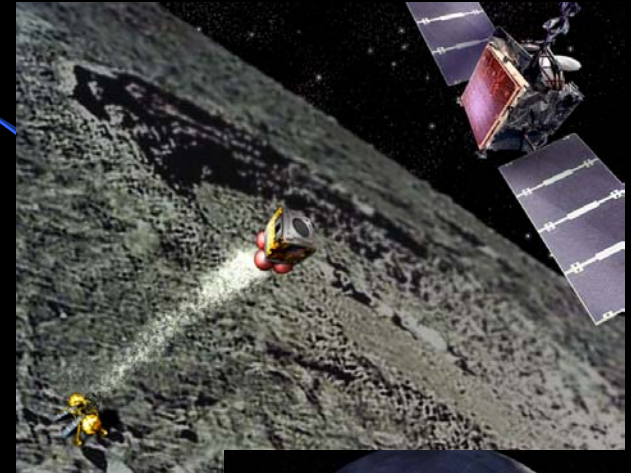
Moon can be reached with existing or derived launch systems

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

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

Advance science, improve engineering state-of-the-art, inspire country



What good is the Moon?

Science

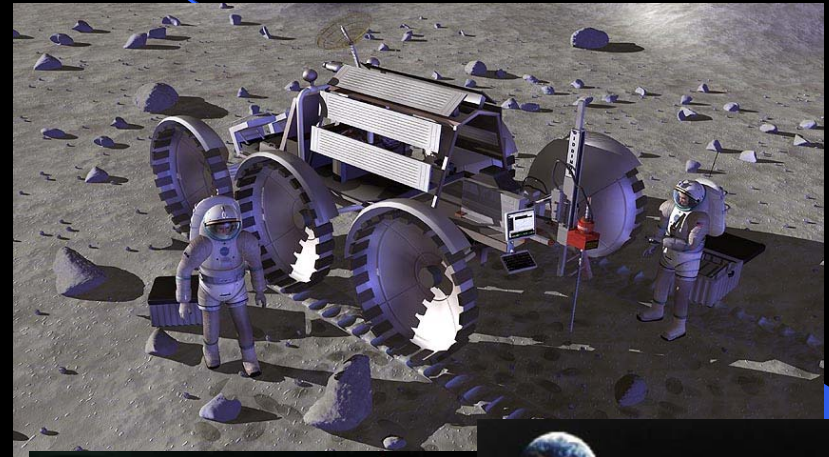
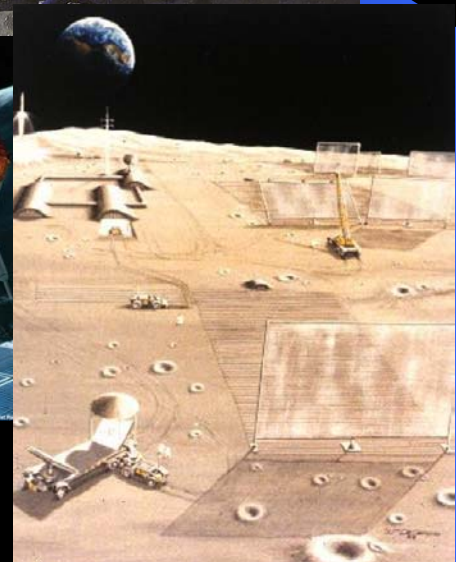
A natural laboratory of planetary processes and history and a platform to observe the universe

Inspiration

A place to learn to live and work in space

Resources

A source of materials and energy



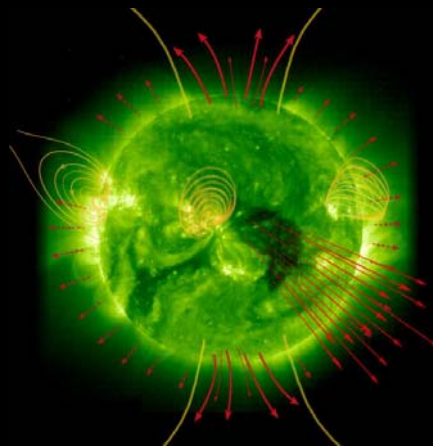
Science

Learning about the Moon and the universe

The Moon records the history of the sun and galaxy

The Moon records the history of the Earth-Moon system

The Moon: A miniature museum of planetary processes



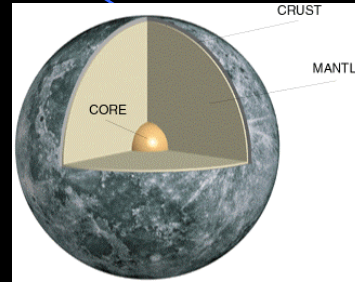
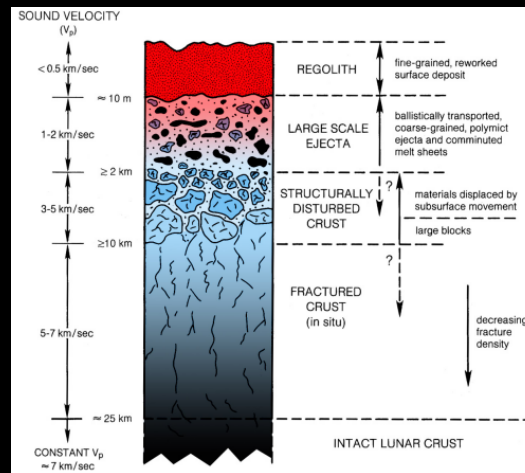
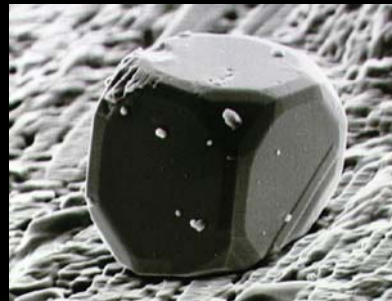
The nature of the Moon

A rocky planetary object, differentiated into crust, mantle, and core

Heavily cratered surface; partly flooded by lava flows over 3 billion years ago

Since then, only impacts by comets and asteroids, grinding up surface into chaotic upper layer of debris (regolith)

Regolith is easily accessed and processed; likely feedstock for resource extraction



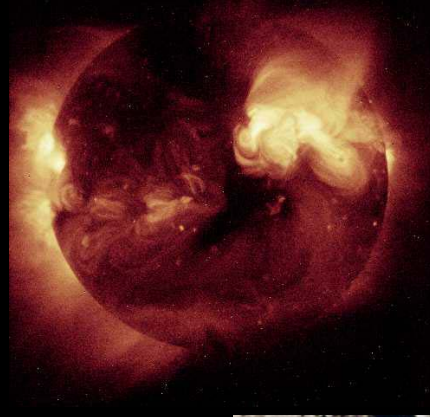
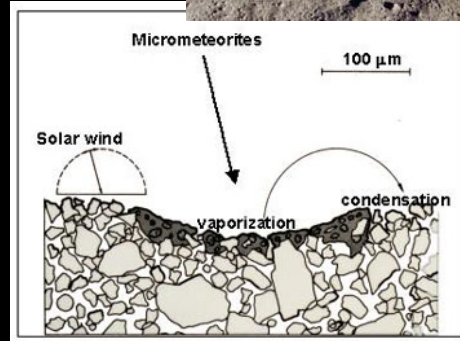
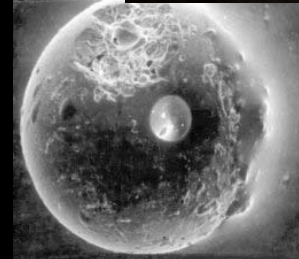
A record of the ancient Sun

Moon's surface is
bathed in solar wind,
cosmic rays

Dust grains retain
these particles

Regolith retains
historical record of
these fluxes

Detailed study by
humans can retrieve
this record



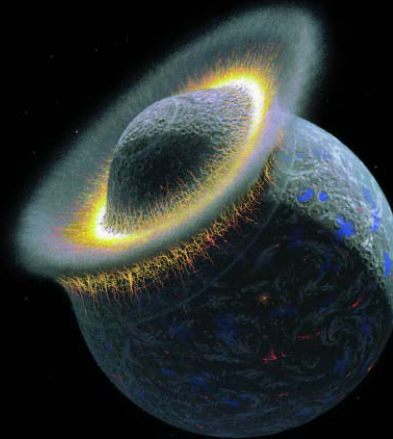
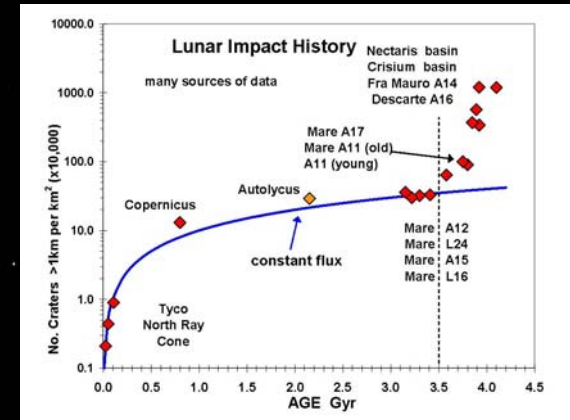
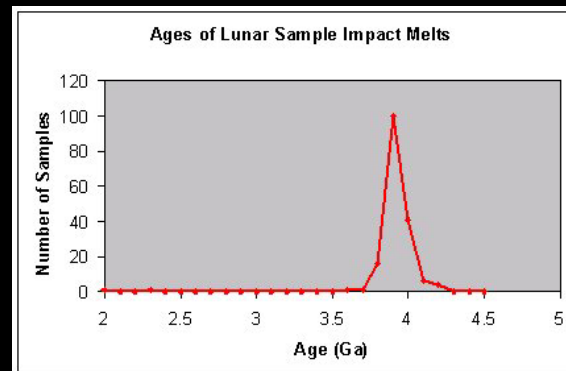
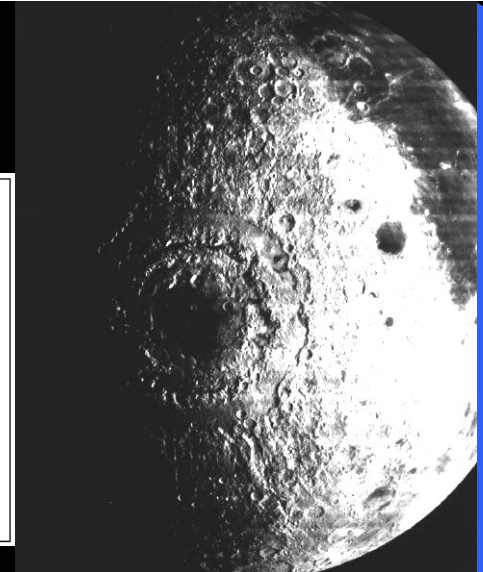
The impact history of the Earth-Moon system

Craters are erased on the dynamic, eroded surface of Earth

The Moon retains this record

Both bodies reside at 1 AU, recording the impact flux in this part of the solar system

The Moon's impact record can be recovered and interpreted in terms of Earth-Moon history



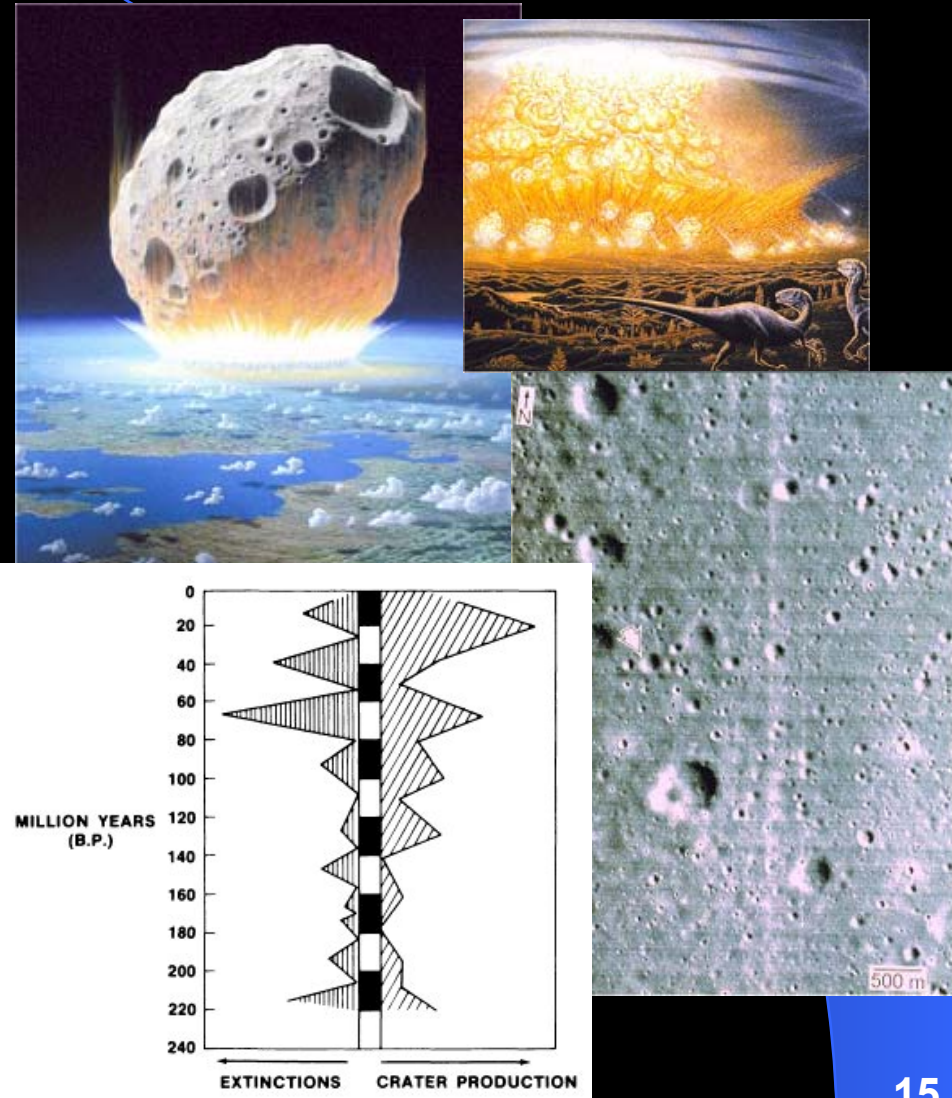
Impact episodicity?

KT impact 65 my ago
wiped out 85% of all
fossil species

Incomplete statistics
suggest such impacts
may occur
periodically

Earth geological record
too incomplete to
assess the effect

Moon retains impact
record of Earth-Moon
system



A museum of planetary processes

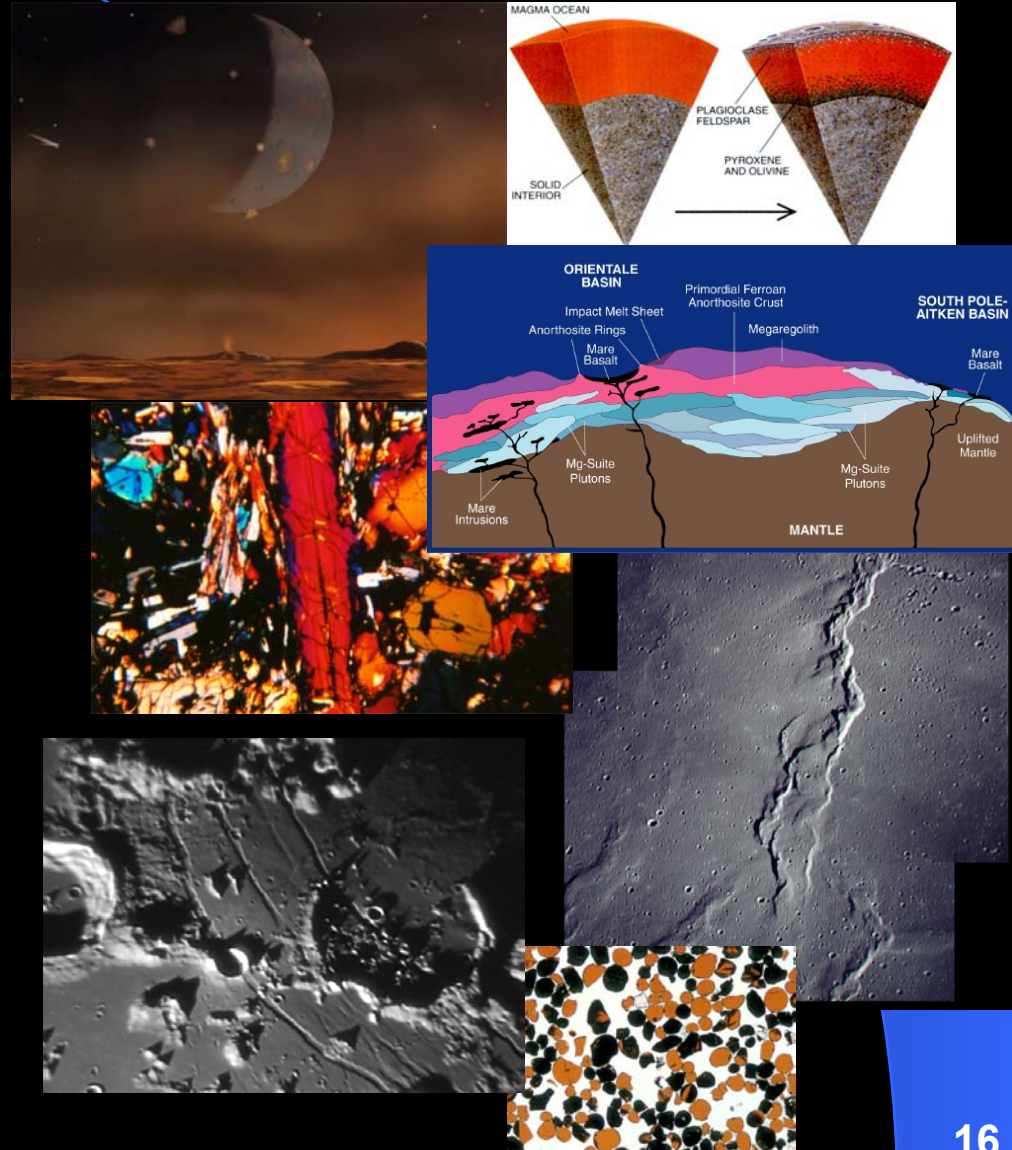
Differentiation - magma oceans, crust and mantle

Impact - basins and craters, mixing of the crust

Volcanism - partial melting, eruptions, flow sequence and compositions

Tectonism - deformation of the crust and thermal history

Volatiles - history, production and escape mechanisms

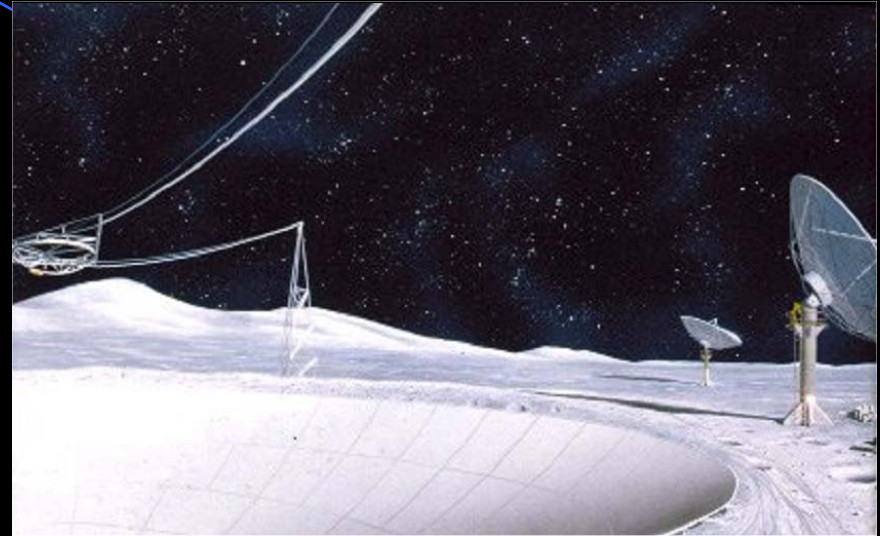


A Platform to Observe the Universe

No atmosphere; full spectrum from DC to gamma-rays visible from lunar surface

Far side of Moon only known place in universe permanently shielded from Earth's radio noise

Stable platform permits extremely sensitive instruments to be built and operated



Dark areas near poles a natural resource for cooled IR detectors

Natural topography can be used to construct large dish antennas

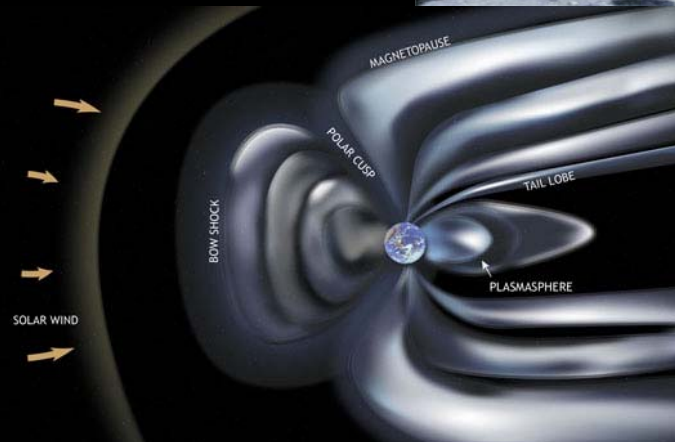
Cold, dark sky; two weeks of night time (permanent at poles)

A Condominium of Observatories

Moon's stable platform permit extensive use of distributed aperture systems at a variety of wavelengths

Moon's proximity to Earth makes it valuable to apply this technique to Earth observations

Unique investigations are possible (e.g., whole magnetosphere imaging)



Inspiration

A Place to Live and Work in Space

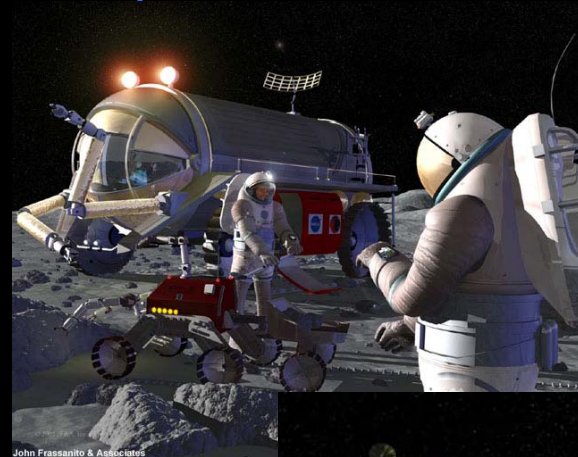
**A natural Space Station,
already in Earth orbit, ready
to inhabit**

**Learn the skills we need to
live off-planet**

**Learn how to explore
planetary surfaces (the
roles of humans and
machines)**

**Societal and psychological
impacts of human space
communities**

**Opportunities for exploration
and discovery**



John Frassanito & Associates



Becoming a Space-faring Species

A school for exploration

How do we best explore planetary surfaces?

Field science and reconnaissance

Humans and robots

Telepresence: The solution?

A place to live and work off-planet

Learn the skills to survive and thrive

Efficiency and synergy with other space activities

Cislunar commercial zone

Lunar industrialization

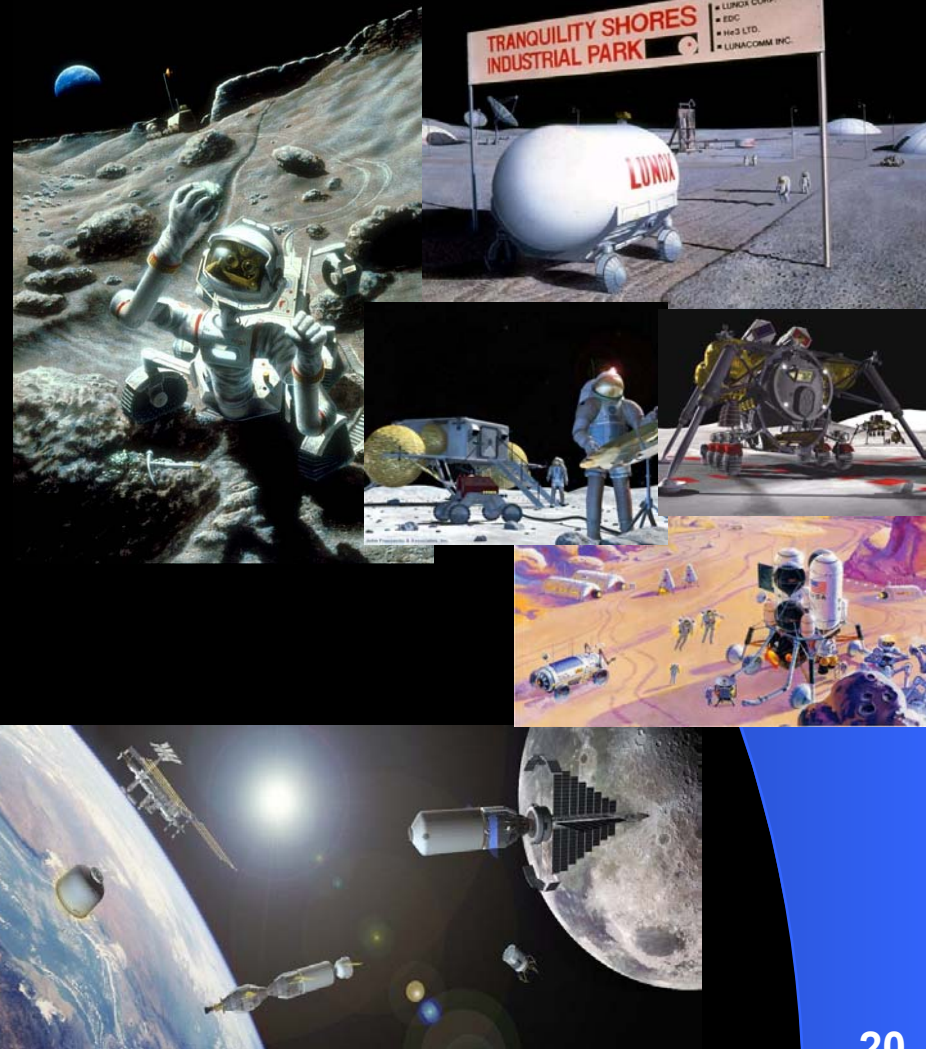
A stepping stone to the Solar System

Testing ground for systems, procedures, strategies

Reusability and reliability

Off-planet repair and modification of systems

Planetary mission rehearsal and simulation



Resources

Materials and Energy for Space and Earth

Water ice in shadowed regions of both poles

Extract oxygen, metals from lunar materials for construction, propellant

Retrieve solar-wind gases (e.g., hydrogen and other volatiles) implanted on lunar dust grains

Collect solar energy with photoelectric arrays built from lunar materials and beam energy to Earth or cislunar space



Resources of the Moon

Materials

Bulk regolith (soil) has many uses as a building material

Rocks and soils have common compositions; basaltic (Fe-rich; maria) and feldspathic (Al-rich; highlands)

Solar wind gases implanted onto dust grains; typical H_2 concentration ~ 50-100 ppm

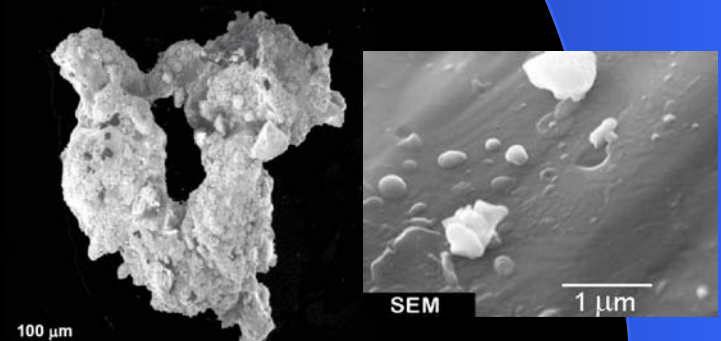
Apollo 15, 16, and 17 drill cores suggest these concentrations hold to depths of 2 m or more



Energy

Solar illumination lasts 14 days at lunar equator; extended Sun visibility near poles

Solar ^3He also implanted on dust grains at <20 ppb concentrations; may ultimately be used as fusion energy source



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

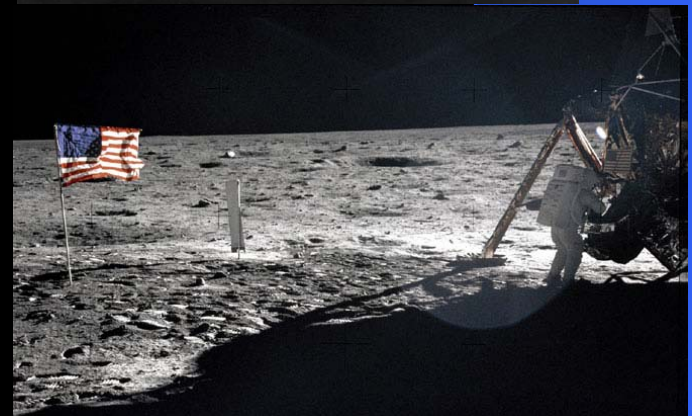
Surface temperatures $\sim 100^\circ\text{C}$ at local noon; -150°C before sunrise

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

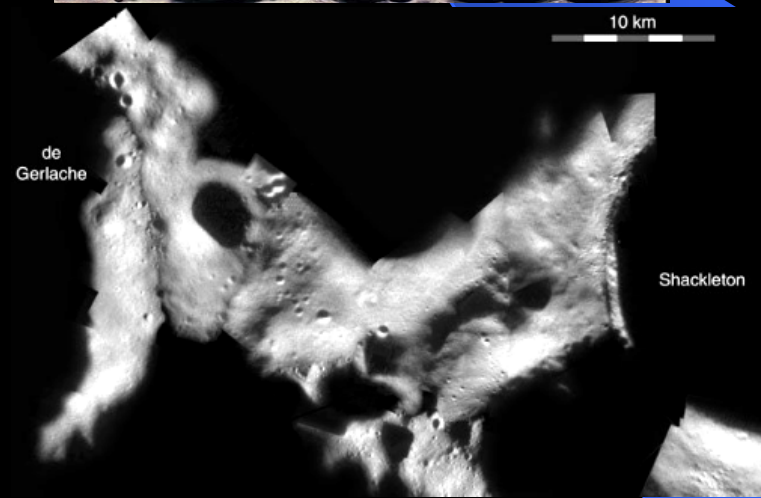
Areas of near-constant sunlight (-50°C), constant darkness (unknown; modeled as -220°C)

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 ($1^{\circ} 32'$)

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

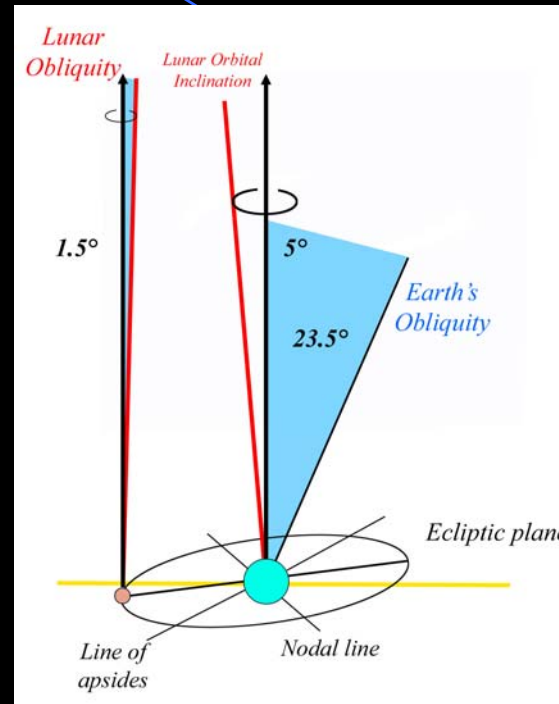
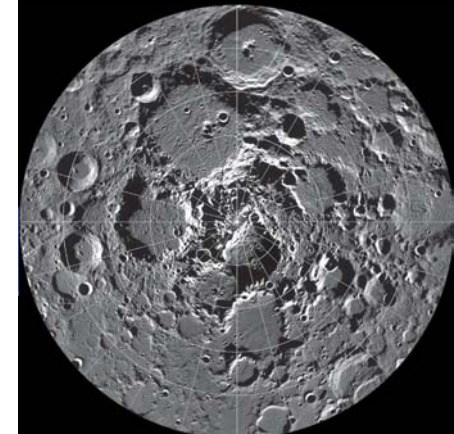
View from the Earth

Lighted Areas

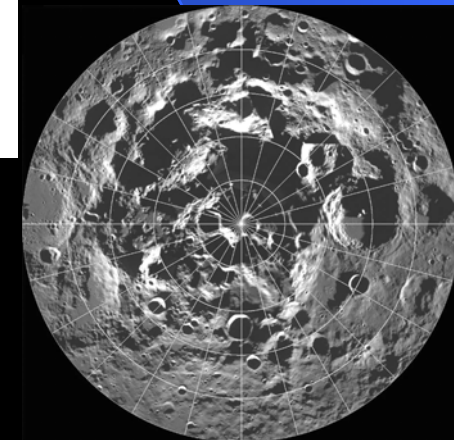
Two weeks of visibility / two weeks obscured

Shadowed Areas

Permanently obscured



North pole



South pole

Permanent sunlight?

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

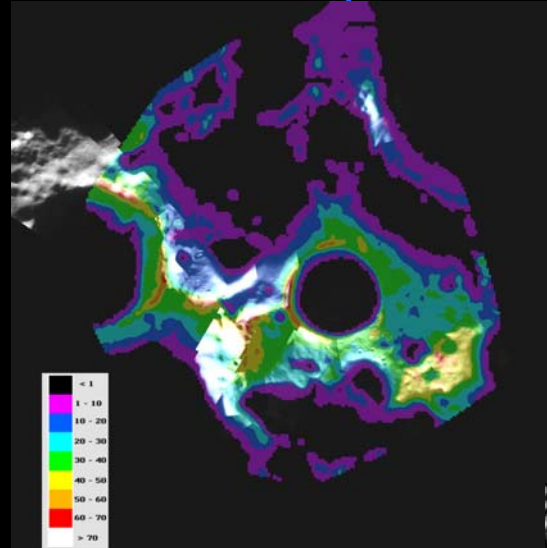
One zone receives 70% illumination during dead of southern winter

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

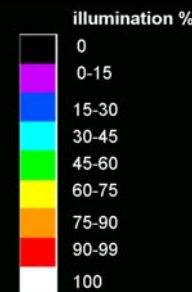
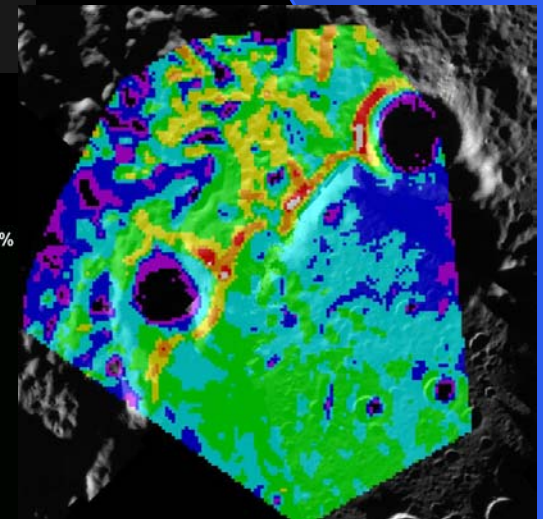
Data taken during northern summer (maximum sunlight)



Data obtained during southern winter (maximum darkness)

South Pole

North Pole



Data obtained during northern summer (maximum sunlight)

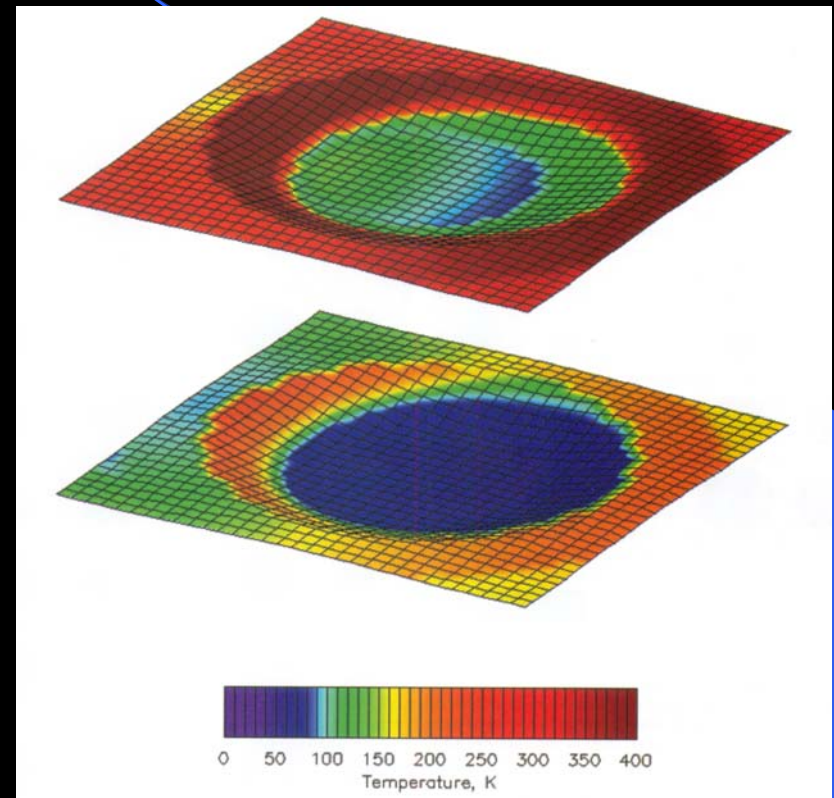
Polar Cold Trap Temperatures

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)

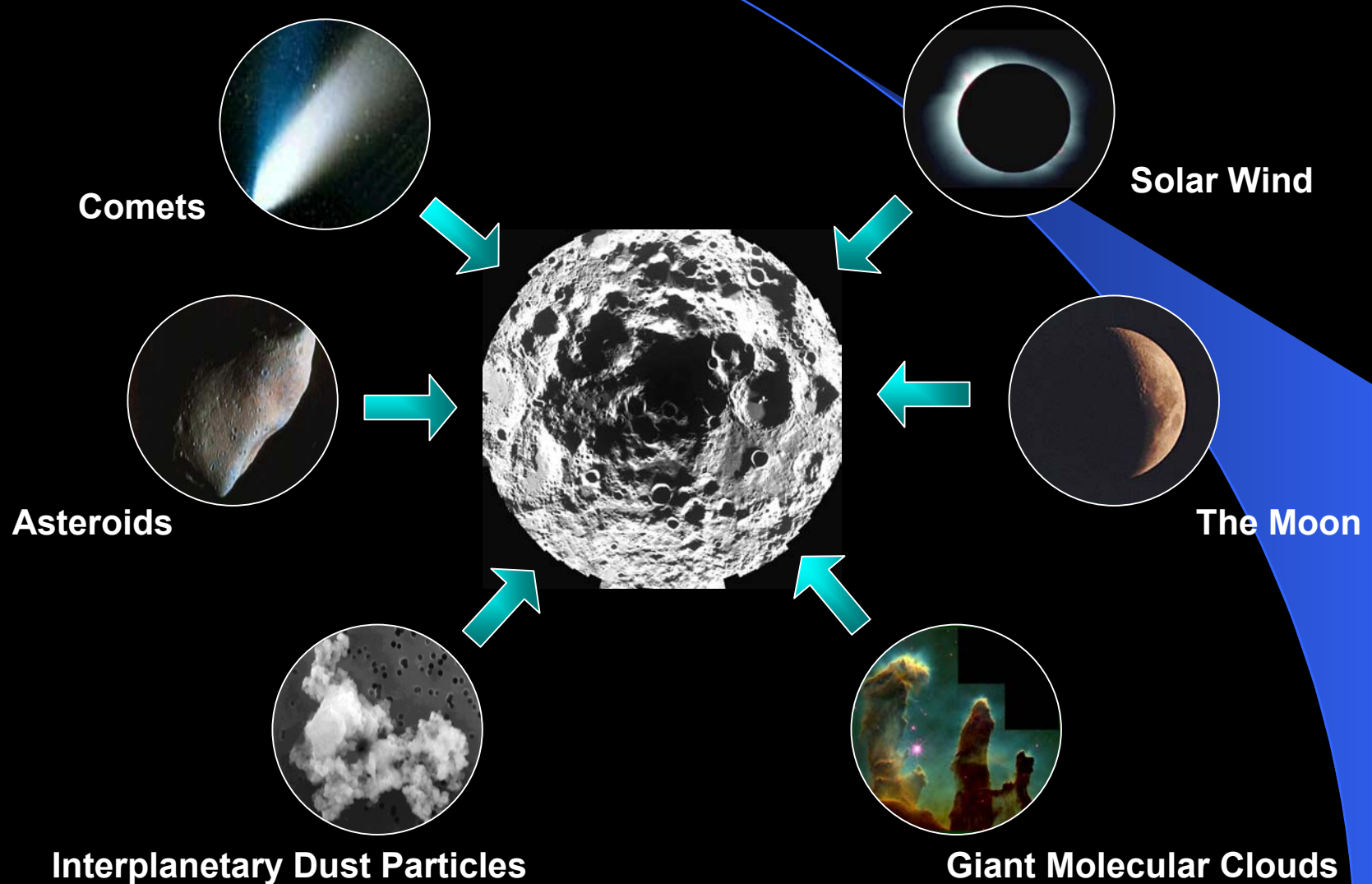
Uncertainty largely a reflection of unknown value for heat flow of Moon ($2.2 - 3.1\ \mu\text{W cm}^{-2}$)

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



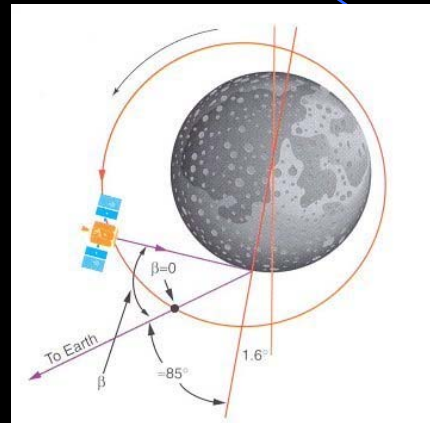
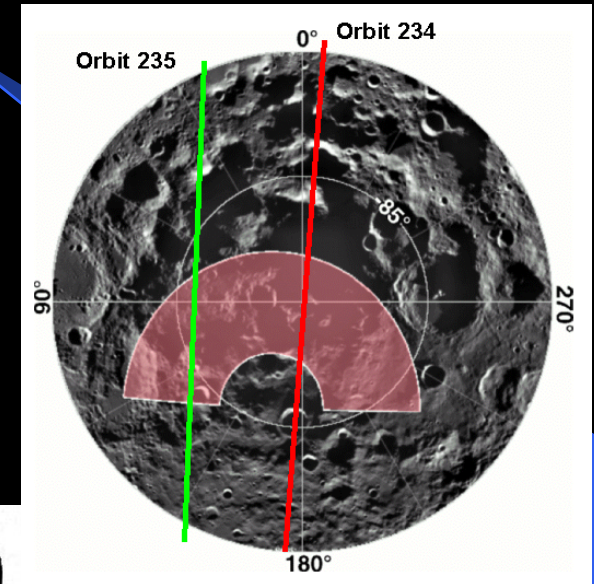
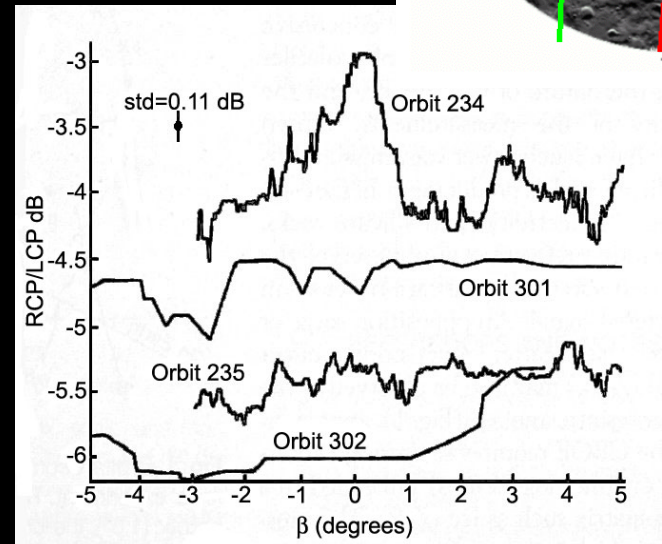
Clementine Bistatic Radar Experiment

Use RF transmitter of s/c as source of RCP CW radio; stare at pole continuously

Listen to echoes on DSN in RCP and LCP; observe reflection behavior through phase angle (β)

Orbit 235 ground track passed through sunlit area; orbit 234 directly across dark areas near pole

Orbit 234 shows CPR enhancement (~ 1 dB) around and through $\beta = 0$, consistent with CBOE from water ice



Lunar Prospector Neutron Spectrometer

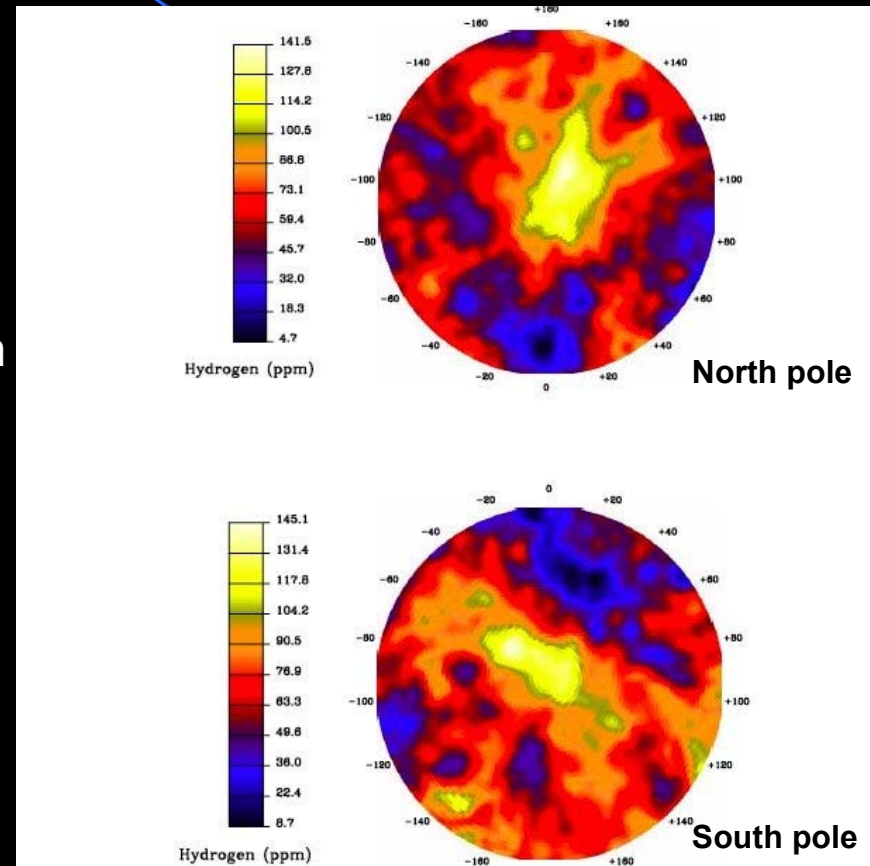
Low flux of epithermal neutrons indicate enhanced content of hydrogen in upper 40 cm of Moon at both poles (Feldman *et al.*, 2000)

Resolution ~30 km pixels (Both dark and lit areas are included in each 900 km² pixel)

Average H content over polar regions 150-200 ppm (compared with ~50 ppm equatorial average)

Average water equivalent content ~ 1.5 wt.%

Upper 5-10 cm desiccated; NS samples down to ~40 cm



Earth-Based Radar Imaging

Difficult to image lunar polar dark areas because of grazing incidence angles

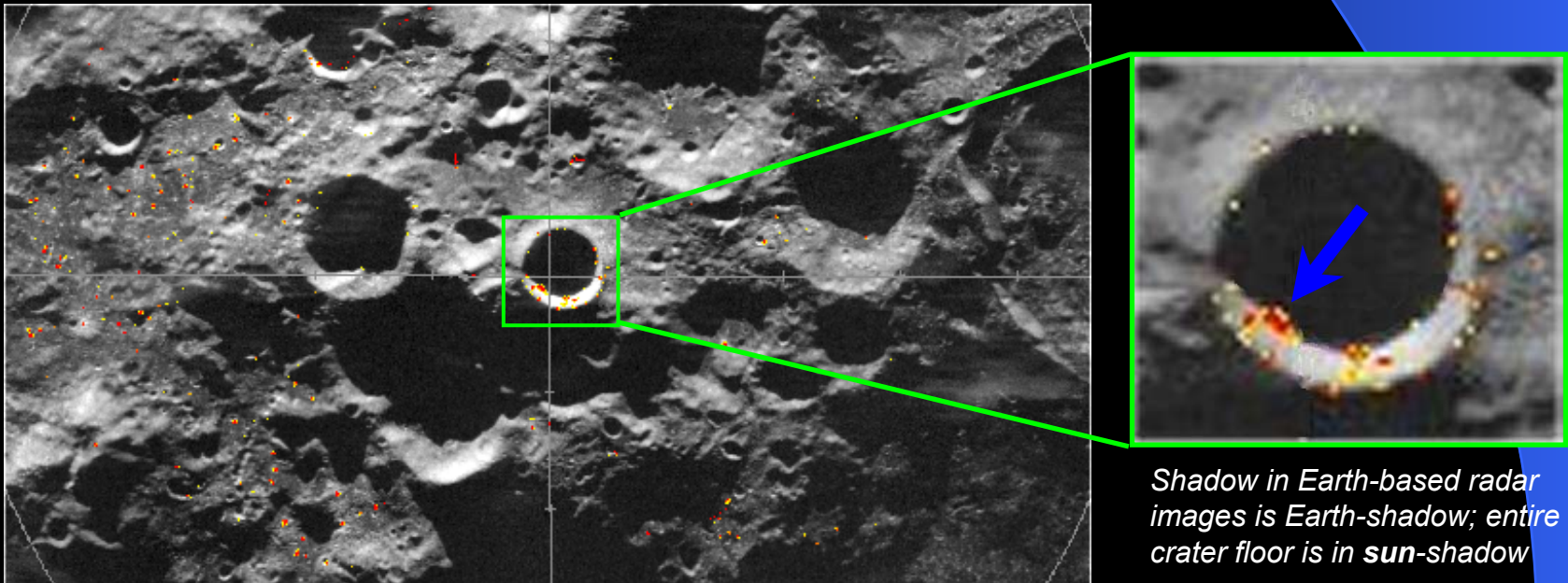
Lunar incidence is $\leq 5.5^\circ$; Mercury is twice that at $\sim 11^\circ$

Radar images show “speckles” of high CPR (same sense enhancement) consistent with either surface roughness or ice in permanently dark areas (Stacy, 1993)

S-band and X-band (5 cm); resolution ~ 50 -100 m

Largest contiguous high CPR anomaly in Shackleton (arrow) is $>10 \text{ km}^2$ and directly under the Clementine orbit 234 ground track

If ice, could partly explain Clementine bistatic result (Nozette *et al.*, 2001)



Shadow in Earth-based radar images is Earth-shadow; entire crater floor is in **sun**-shadow

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

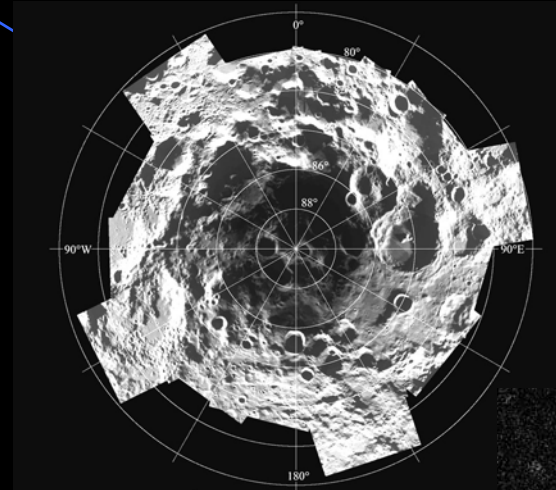
From neutron and radar data

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

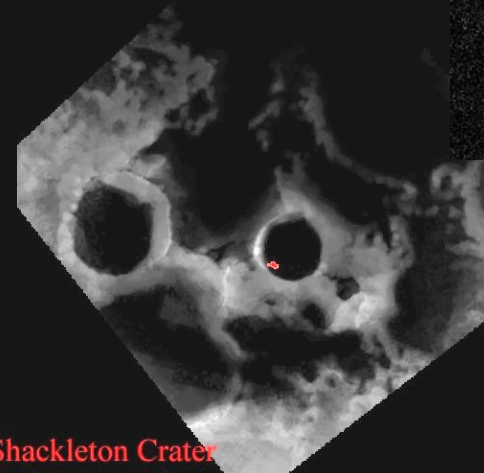
From current knowledge of regolith formation, evolution, and overturn

Although water ice is expected to dominate, other minor species of cometary origin could be present in useful quantities (e.g., CH_4 , NH_3)

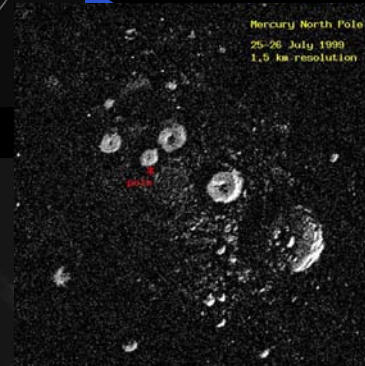
From astronomical observations of comets



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)

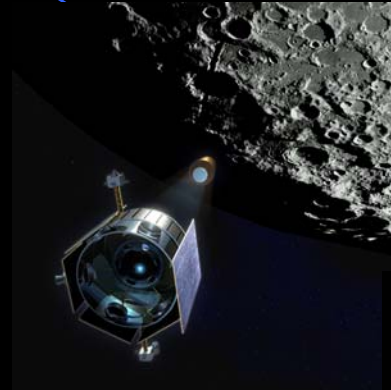
Distribution with depth

How ice binds soil grains

Whether ice reacts with soil grains

Geotechnical properties of ice-bearing regolith

Physical environment of polar regions



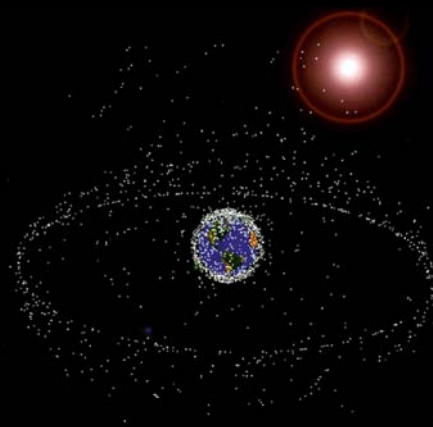
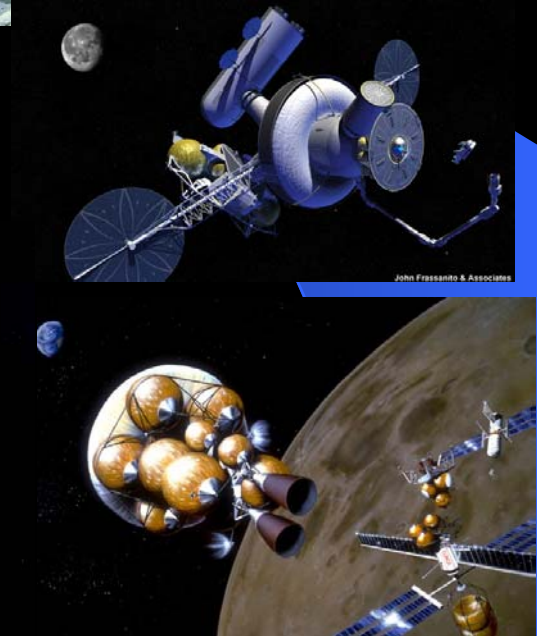
The Value of Lunar Resources

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

