

Lunar Objectives, Benefits, Pathways, Strategy

A crescent moon is visible in the center of the frame, set against a clear blue sky. The bottom of the image shows a dark, silhouetted horizon line, suggesting a sunset or sunrise. The overall color palette is dominated by blues and blacks.

Michael B. Duke
October 21, 2013

My Charge

- Present a balanced view of the various reasons that we might wish to return to the Moon for short, intermediate, and extended stays and their pros and cons.

Background

- National Commission on Space “Pioneering the Space Frontier” said most of this nearly 30 years ago (1985)
- Important new discoveries made in last 15 years

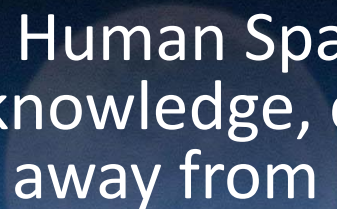
Why Have a Space Program?

- Scientific advancement; new insights
- Excitement of going new places and doing new things
- Develop new technological capabilities
- Stimulate economic development
- Contribute to national pride, prestige and security
- Encourage International cooperation
- Long-term survival of the human species

Why Have Humans in Space?

- Explore new places; communicate findings
- Learn human capabilities in new environments
- Operate space systems
- Establish and test new technological systems
- Maintain and operate industrial infrastructure
- Pioneer new niches
- Settle other places

The Principal Goal of the Human Space Flight Program should be: “Developing knowledge, capabilities and opportunities for people away from Earth”



Reasons for Lunar Exploration

- Scientific knowledge – address unsolved mysteries
- Provide a platform for increasing capabilities and reducing risk for humans in planetary surface operations
 - Reduced gravity – long-term adaptation to partial-g
 - Test habitats, life support systems, transportation systems, etc.
 - Lunar resources can reduce risk, reduce cost, and increase capability for Moon
 - Preparation for exploration and settlement of other planetary bodies
- Potential for economic development
 - Near term markets in space are accessible (e.g. LEO)
 - Propellant
 - Energy
 - Potential to “bootstrap,” utilizing local resources
 - Rare commodities may have high value (e.g. ^3He)
 - Initial stages of commercial space development are underway with access to substantial amounts of capital

The Rest of the Story

- Lunar Science and exploration
- The roles of and potential for humans
- Lunar Resources and Economic Development
- Options for Human Exploration of the Moon
- A Lunar Exploration Strategy



Lunar Science and exploration



Origin and History of the Moon

- Created in a primordial collision of a large body with the Earth
 - Composition of the Moon is rocky, like the Earth's mantle, rather than metallic, like the Earth's core
- Internally differentiated (melting and differential separation) to form core, mantle, crust – the crust formed from a “magma ocean”
- Surface history was dominated by impacts and volcanic processes
Surface has been relatively quiet for last 3 billion years
 - The small size of the Moon accounts for the absence of a significant permanent atmosphere (an “airless” body)
- The lunar axis of rotation is now nearly perpendicular to the solar system ecliptic, so areas around the poles are in continual shadow, very cold, and have trapped condensable volatile compounds, such as water



The Moon as a Touchstone for Solar System Science

APOLLO 11



APOLLO 12



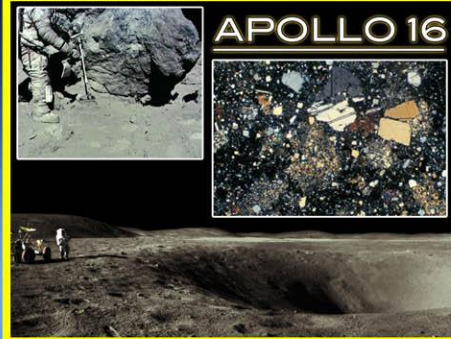
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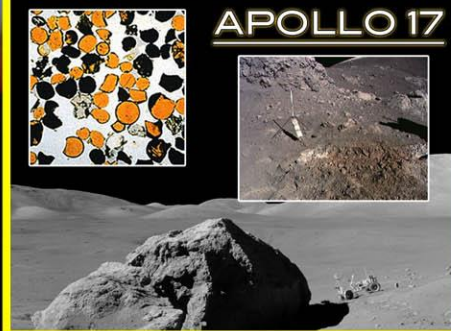
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The Legacy of Apollo:
Science *is* Exploration!

Science-Engineering-Technology Synergism!

Secrets of the Lunar Interior

- Lunar core confirmed.

(Weber et al., 2011)



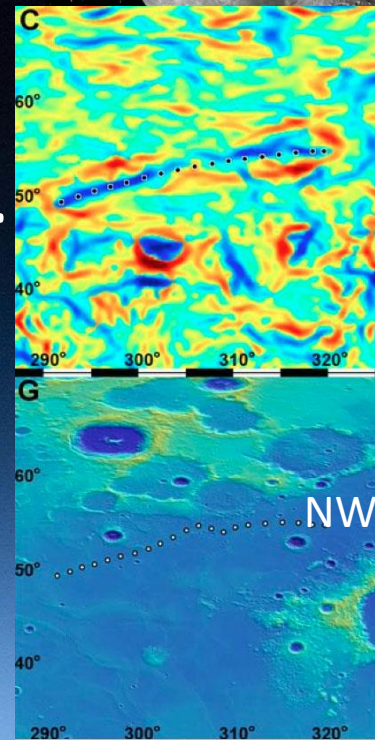
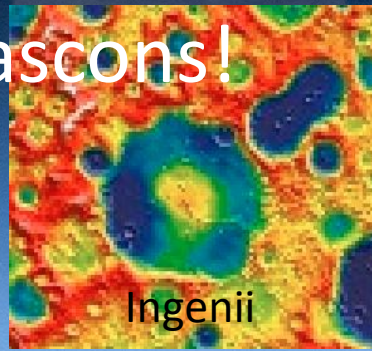
- Lunar dynamo dated (through 3.56Ga).

(Shea et al., 2012; Sauvet et al., 2013)

- Deep crustal structure detected.

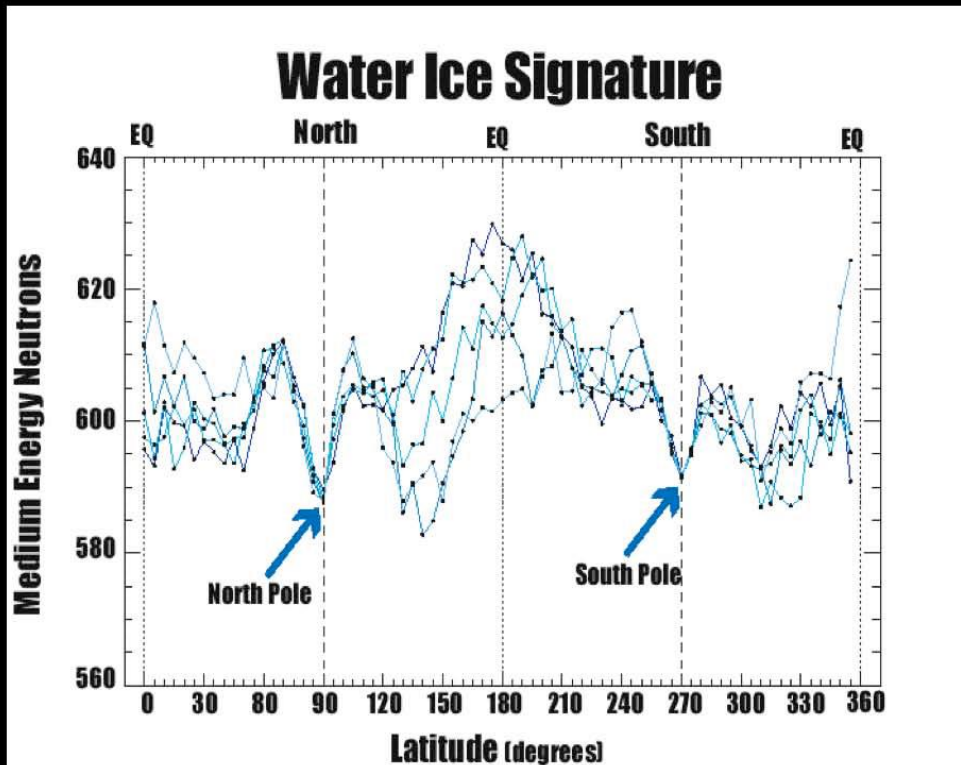
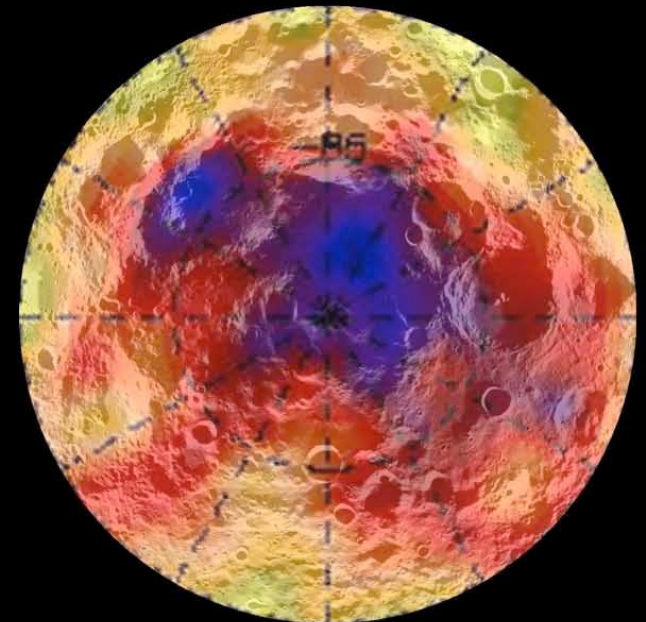
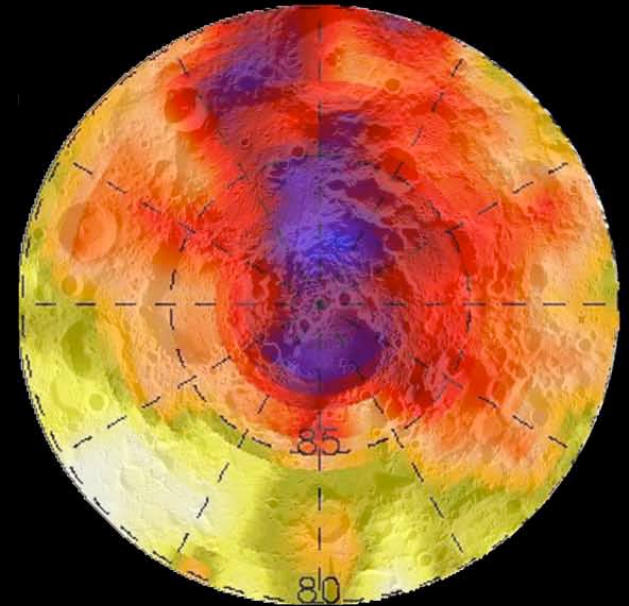
[horizontal Bouguer gradient: Andrews-Hanna et al., 2012]

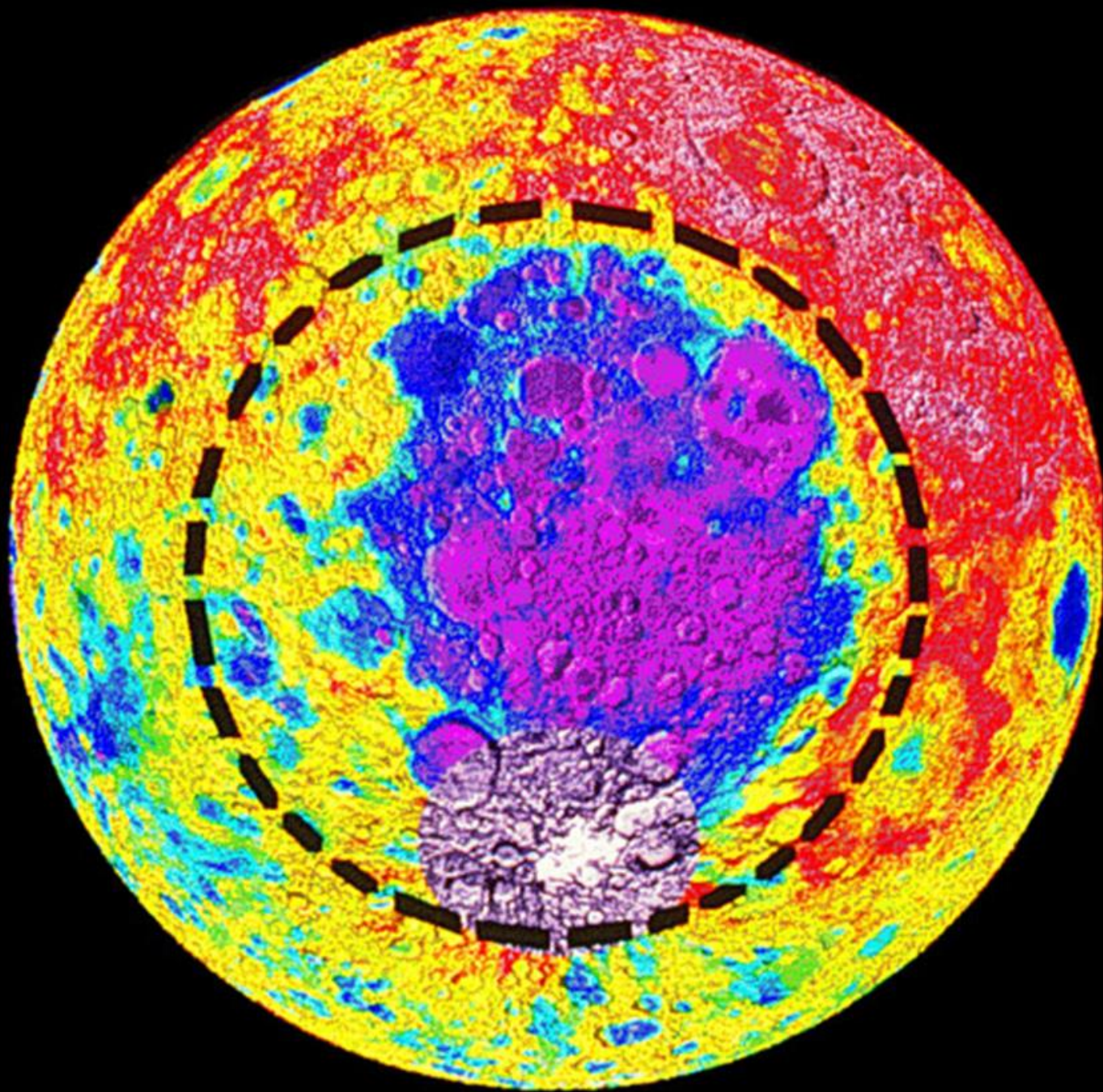
- Multiple Minor Mascons!



GRAIL
NW Procellarum

Lunar Prospector





Examples of Significant Questions

- What is the impact history of the inner solar system –what is the age of the South Pole – Aitken Basin? **Sample Return**
- What is the internal structure of the Moon and what planetary processes created them? When? **Sample Return-South Pole – Aitken Basin, special sites, Human exploration**
- Where are volatiles concentrated on the Moon? What is their abundance? What is their origin? Are they renewable? **Soft Landers, Robotic Sample Return, Human exploration of polar regions**
- Many other more detailed questions can be addressed, primarily with sample return

International Lunar Exploration Continues

Recent Missions

- Kaguya 2007
- Chang'e 1 2007
- Chandrayaan-1 2008
- LRO 2009 (continuing)
- LCROSS 2009
- Chang'e 2 2010
- ARTEMIS 2010
- GRAIL 2011
- LADEE 2013

Planned Missions

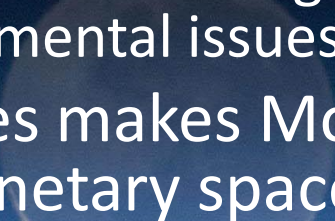
- Chang'e 3 2013
- X Prize
- Luna 25 2015
- Chang'e 4 2015
- Chandrayaan-2 2015?
- Luna 26 2016
- Luna 27 2017
- Chang'e 5 2017

Orbiter Hard Lander Soft Lander Sample Return

The roles of and potential for humans



The Moon Remains a Good Place for Human Capability Development

- Significant benefit to being close to Earth
 - Rapid feedback from surface exploration; easy communication
 - Quick trip times; many launch opportunities; many types of abort possibilities
 - Close to early in-space markets (low Earth orbit, GEO)
 - Surface environment is generally well-known and benign
 - Thermal extremes, intermittent lighting and radiation cause biggest environmental issues, but are understood
 - Availability of resources makes Moon qualitatively different than interplanetary space
- 

Humans in Space Exploration

- Humans are observers, reporters, experimenters – can use tools sent from Earth or devised on-site
- Humans are most effective explorers for complex environments (e.g. Mars surface, lunar poles)
- Humans will install, operate and maintain complex surface systems
- Humans may become pioneers and settlers

Objectives for Humans on the Moon

- Understand human adaptation to reduced-g ($1/6g$) – will it be a problem for Mars?
- Develop means of counteracting radiation environment and protecting humans (including warning systems)
- Develop systems for human habitation and work areas
- Develop systems for human surface mobility (pressurized and unpressurized)
- Develop skills in maintaining complex surface systems, especially resource processing
- Develop understanding of what long-duration planetary surface activities require

All of these will increase human effectiveness and safety for exploration beyond the Moon as well as make long-term stays possible on the Moon

System Development Requirements for Human Lunar Exploration

- Surface habitation modules
 - Standalone and connectable; Protected from solar and cosmic radiation; Hybrid systems utilizing indigenous resources
- Energy systems
 - Solar photovoltaic; Energy storage (e.g. fuel cells); Nuclear power sources; Energy transmission; Systems utilizing indigenous resources
- Surface transportation systems
 - Pressurized and unpressurized rovers; Surface hoppers
- Life support systems
 - Atmosphere handling and storage; Water handling and storage; On-site food production; Waste disposal
- Highly-reusable space suits
- Lunar resource mining, extraction, storage, delivery and fabrication technologies
 - On-site workshops and fabrication capabilities
- Teleoperated tools for difficult environments and repetitive tasks
- Communications and surface navigation technologies

Lunar Resources and Economic Development



Benefits of a Lunar Propellant Capability

- Propellants do not have to be brought from Earth – the Earth-to-Moon transportation system is much smaller (escape velocity from Moon is much smaller than that from Earth, so much smaller space vehicles will do)
- Reusable space systems are enabled – lunar lander and ascent vehicle; lunar orbit – Earth orbit
- Space vehicles can be more robust (e.g. more engines) because transportation costs are much-reduced
- Life support consumables are a byproduct – enables consumable caches at outposts, reducing risk
- Reactants for fuel cells can be produced locally
- Surface-to-surface “hoppers” enabled
- Development could lead to commercial investment in resource production

“Bootstrapping”

Interesting “rule of thumb:” To land a vehicle on the lunar surface or ascend into orbit takes about the same mass of propellant as the vehicle itself

Robotic

1-MT robotic lander

- Robotic sample return spacecraft
- Robotic site exploration rovers
- Surface excavation and extraction systems
- 10-MT / year propellant production module

10-MT robotic lander

- Propellant storage, transfer and delivery system
- Lunar manned ascent vehicle - dry
- Power system
- 100 MT/year propellant production system
- + Propellant storage, transfer and delivery system emplaced in L1

Human

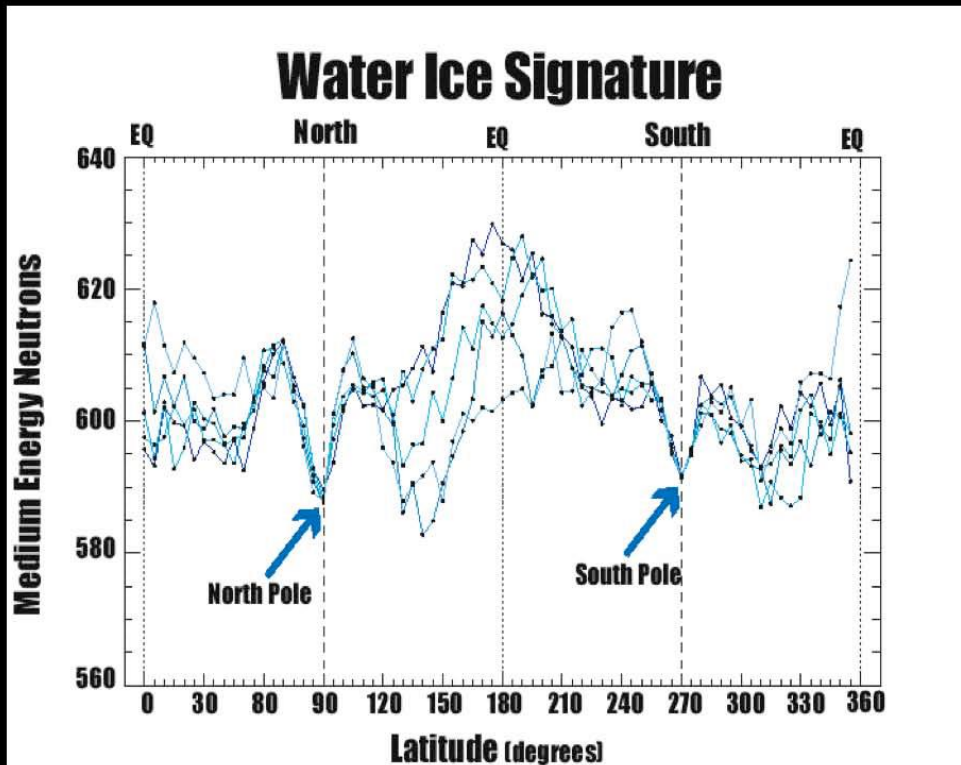
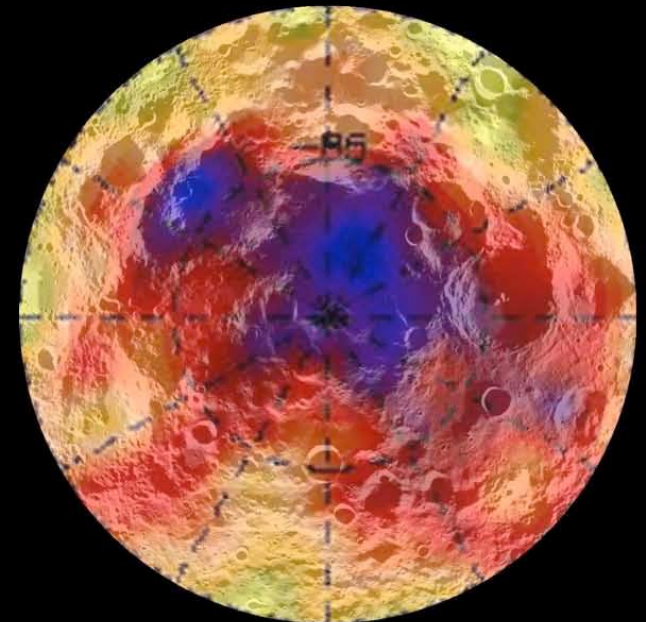
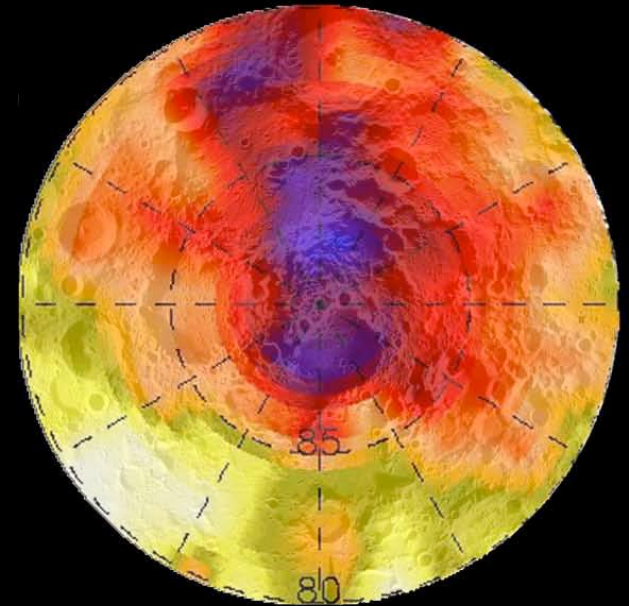
Human Landing

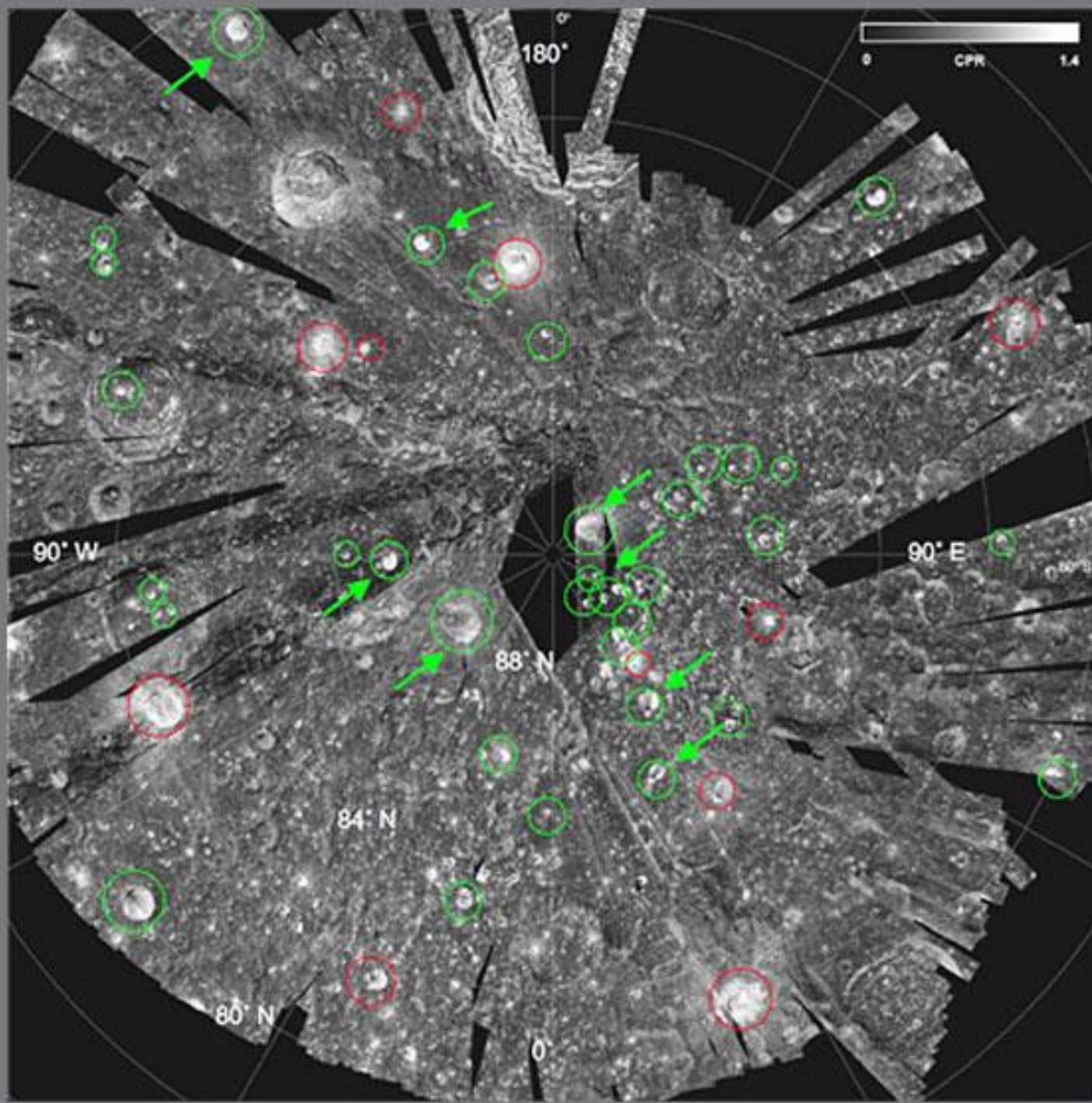
- Lunar lander/ascent vehicle delivered to Moon (empty, dry), fueled on Moon
- Lunar crew arrives in second lander/ascent vehicle
- Crew leaves Moon in first lander/ascent vehicle
- L1 propellant depot provides propellant for lunar landers

Polar Lunar Resources May Be Key for Long Term Stays

- After a series of robotic missions (Clementine, Lunar Prospector, LRO and LCROSS, Chandrayaan) we can confidently expect substantial quantities of water and other volatiles (C, N compounds) near lunar poles
- Water can be electrolyzed and stored as liquid hydrogen and liquid oxygen for rocket propulsion
 - Rocket propellant can be transported to space (e.g. Earth-Moon L1) using reusable lander technology. Moon is a few days from L1, so a propellant infrastructure with continual supply can be envisioned
- Other polar volatiles, such as CO₂, could broaden choice of propellants

Lunar Prospector





We Still Need More Information

- What is the form, concentration, and distribution of volatile deposits?
 - Requires surface exploration
 - Can places be found where long-term immersion in sub-100K temperature regime is not needed for extraction of volatiles?
- What is the nature of the surface materials – how easy or difficult will it be to extract the volatiles?
- What kinds of filtration/purification systems will be needed?

New Technologies Will Be Required for the Poles

- Working at very low temperature
- Dealing with unique illumination and solar energy conditions near poles (nuclear power would be very useful)
- Extraction, purification, analysis, storage and transfer for propellants, water, etc.
- Most of these can be demonstrated rapidly using robotic systems

What if Polar Volatiles Cannot Be Mined

- Oxygen can be produced by hydrogen reduction of lunar oxides and iron-bearing glasses
- Hydrogen and carbon are present at levels of 50-100ppm (up to 0.1% water equivalent) in lunar surface fines – can be extracted by heating
- Technologies are under development for oxygen extraction



Is Lunar Resource Development Feasible?

- Principal characteristic of Lunar ISRU is that small systems, working over long times, can develop many times their own mass per year in usable product
 - Experimental systems emplaced robotically can be pilot-scale for human support
- Significant research has been performed on extraction technology
 - Excavation systems
 - Water and oxygen extraction
 - Material handling
- Concepts are available for early experimental robotic missions
- Commercial investment can bring significant benefits



RESOLVE (Regolith & Environment Science and Oxygen and Lunar Volatile Extraction)



Sample Acquisition –

Auger/Core Drill [CSA provided]

- Complete core down to 1 m; Auger to 0.5 m
- Minimal/no volatile loss
- Low mass/power (<25 kg)
- Wide variation in regolith/rock/ice characteristics for penetration and sample collection
- Wide temperature variation from surface to depth (300K to <100K)

Sample Evaluation –

Near Infrared Spectrometer (NIR)

- Low mass/low power for flight
- Mineral characterization and ice/water detection before volatile processing
- Controlled illumination source

Resource Localization –

Neutron Spectrometer (NS)

- Low mass/low power for flight
- Water-equivalent hydrogen ≥ 0.5 wt% down to 1 meter depth at 0.1 m/s roving speed

Volatile Content/Oxygen Extraction –

Oxygen & Volatile Extraction Node (OVEN)

- Temperature range of <100K to 900K
- 50 operations nominal
- Fast operations for short duration missions
- Process 30 to 60 gm of sample per operation (Order of magnitude greater than TEGA & SAM)

Volatile Content Evaluation –

Lunar Advanced Volatile Analysis (LAVA)

- Fast analysis, complete GC-MS analysis in under 2 minutes
- Measure water content of regolith at 0.5% (weight) or greater
- Characterize volatiles of interest below 70 AMU

Operation Control –

Flight Avionics [CSA/NASA]

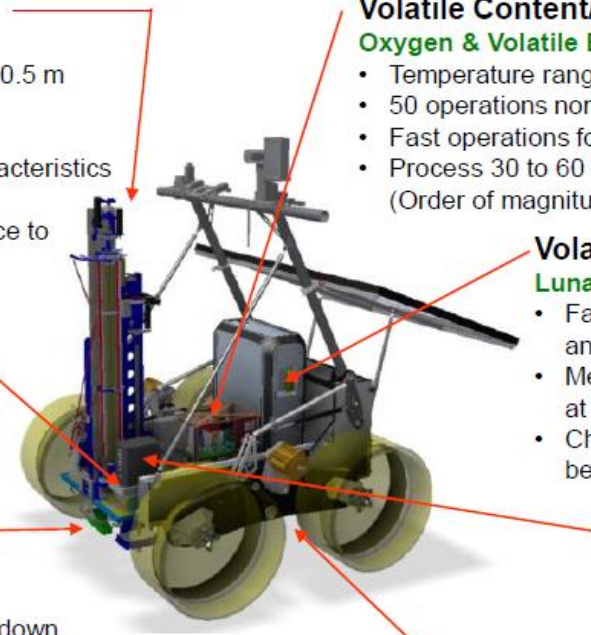
- Space-rated microprocessor

Surface Mobility/Operation

[CSA mobility platform]

Rover nicknamed “Artemis Jr.”

- Low mass/large payload capability
- Driving and situation awareness, stereo-cameras
- Autonomous navigation using stereo-cameras and sensors
- NASA contributions likely for communications and thermal management



RESOLVE Instrument Suite Specifications

- Nom. Mission Life = 10+ Cores, 12+ days
- Mass = 60-70 kg
- Dimensions = w/o rover: 68.5 x 112 x 1200 cm
- Ave. Power; 200 W

Other Resources Can Increase Returns from the Moon

- Energy

- Production of silicon photovoltaic cells from lunar silicon on glass substrates has been demonstrated in the laboratory (Freundlich and Ignatiev)
 - Growth of lunar electric power capacity can largely be decoupled from Earth
 - Adds to robustness of lunar outpost, reduced risk for humans
 - Potential for commercial involvement
- Solar concentrators made of aluminized lunar glass

- Materials

- Lunar minerals are like the starting materials for many ceramics and glasses on Earth
 - Construction using these materials on the Moon can further increase the robustness of lunar operations

A Mature Lunar Resource Base Could Support Quest for Earth's Future Energy Sources

- Construct large power systems on Moon or in Space
 - Moon provides most elements needed for a Lunar Power System (Criswell) that can transmit energy to Earth
 - Alternatively, use lunar materials and low-cost space transportation to construct solar power satellites in Earth orbit
- Lunar ^3He has been widely cited as a future fuel for nuclear fusion reactors on Earth and in Space (nuclear fusion propulsion)(Kulcinski, Schmitt)
 - ^3He may not be abundant near lunar poles, but lunar polar development would be a good start on extraction techniques
 - Requires large-scale mining capabilities
 - Likely to be a commercial enterprise if it proves to be feasible

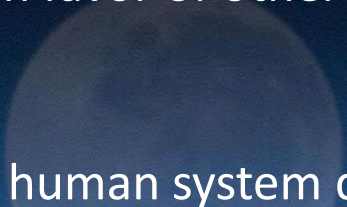
Should the Government support Lunar Resource Development

- Government is probably the only entity that can support demonstration of principle technology development and test in the lunar environment
 - May be the Chinese government
- Many of the sub-technologies needed for resource development are similar to those that will be needed for other purposes, such as:
 - Regenerable fuel cells
 - CO₂ and H₂O electrolysis
- Government may be required to be the first customer for lunar resources – e.g. first used in human exploration mission
 - Transfer technologies to private enterprise at earliest feasible time

Options for Human Exploration of the Moon



Options for Human Lunar Activities -1

- Short stays – e.g. Apollo – a few days
 - Scientific exploration of relatively simple sites
 - Re-establish lunar seismic network
 - Reconnaissance of lunar outpost or complex sites (e.g. lunar poles)
 - Resource extraction experiments
 - Test transportation and surface systems
 - Pros
 - Know how to do it (also a con)
 - Access diverse sites
 - Can abandon at any time in favor of other exploration
 - Cons
 - Expensive
 - Little opportunity for new human system development
- 

Options for Human Lunar Activities-2

- Intermediate duration stays (stay through lunar night)
 - Significant tests of human support capabilities
 - Extended surface exploration (pressurized or unpressurized rovers)
 - Complex surface science and resource extraction experiments
- Pros
 - Significant human support capability development for planetary surface missions
 - Explore human adaptation to lunar surface gravity
 - Demonstrate improved effectiveness and reliability of technical systems for longer surface stays
 - Range and depth of investigations increases rapidly with return visits
 - Compatible with development of lunar resources and use in subsequent visits
 - Develop capabilities for human support on Mars
- Cons
 - More capabilities, therefore more expensive at first (cost might be ameliorated by lunar resource development)
 - Probably limited to a single site



Options for Human Lunar Activities-3

- Long stays (including permanent outpost)
 - Develop capability for long-duration human support(years) off-Earth
 - Establish closed life support system, including food
 - Develop and utilize lunar resources
 - Understand polar resources
 - Propellants, water, gases, energy collection and storage, replacement and expansion parts and systems
 - Conduct long range surface exploration
- Pros
 - Can be demonstrated in a robotic program
 - Fully consistent with theme of humans expanding into space – develops broad range of new human activities
 - Many opportunities for international participation
 - Opens new avenues for commercial development on Moon and in space
 - Effective use of infrastructure brought from Earth and systems developed on Moon
 - Off-ramps to Mars exploration at appropriate times
- Cons
 - Long-term commitment needed (International cooperation a la ISS?)
 - Most complex and expensive, but greatly improved achievement/cost

A Lunar Exploration Strategy



Space Exploration: Revolution or Evolution?

- Space exploration had unlimited funds when the objective was international competition (Cold War)
- U. S. space science has grown steadily in a program that is basically evolutionary with few really big lifts (Hubble Space Telescope), but which regularly return exciting data
- U. S. human exploration program has used the Apollo approach – large projects, which have terminated or will terminate without a programmatic legacy
 - A constituency (NASA, Industry) has been conditioned to accept such programs
 - Human exploration of Mars and (perhaps) an asteroid have these characteristics
- The lunar exploration program can be evolutionary
 - Early investments in needed technology
 - Robotic missions to conduct experiments and build initial infrastructure
 - Bootstrapping
 - Human exploration of the Moon and beyond

Public Interest

- Migrating space program from one that goes places to one that does new things frequently should be very attractive to the public
- The concept of “Pioneering the Space Frontier” offers many opportunities for laypeople to understand the challenges of leaving Earth by watching the trials and triumphs of lunar crews
- The development of industrial capability and “profits” from space will promote involvement of more people in the program

Lunar Exploration Strategy

- Near term (5-10 years)
 - Scientific exploration with robotic systems
 - First robotic missions to surface in polar regions
 - Demonstrate capabilities for in-situ propellants
- Establish foothold for humans (10-20 years)
 - Develop production class in-situ propellant systems on lunar surface (possibly cache products for use by first human missions)
 - Establish and occupy first elements of human outpost
 - Intensive development of human support systems eventually to be used for Mars exploration
 - Develop reusable space vehicles and in-space propellant receipt, storage and delivery systems
 - Off-Earth industry begins
- Production facilities on Moon (20-30 years)
 - Begin growth phase for lunar industrial capability
 - Potential for beneficial interaction with asteroid resource scenarios
 - Support Mars missions

Summary

- Significant solar system science remains to be done on the Moon
- Moon can be a stepping stone for human exploration (cost, risk-reduction, human capability development)
- Development of lunar propellant enables reusable space system architectures while reducing exploration costs; opens commercial opportunities

“Developing knowledge, capabilities and opportunities for people away from Earth”

