Network Science on the Moon: Missions that also Inform Exploration

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Visions and Voyages, 2013-2022 [Page 5-24]

Priority [Lunar] mission goals include (New Frontiers):

- Sample return from the South Pole-Aitken Basin region;
- A Lunar Geophysical Network.

Other important science to be addressed by future missions include (Discovery):

- The nature of polar volatiles;
- The significance of recent lunar activity at potential surface vent sites;
- The reconstruction of both the thermal-tectonic-magmatic evolution of the Moon;
- The impact history of the inner solar system through the exploration of better characterized and newly revealed lunar terrains.

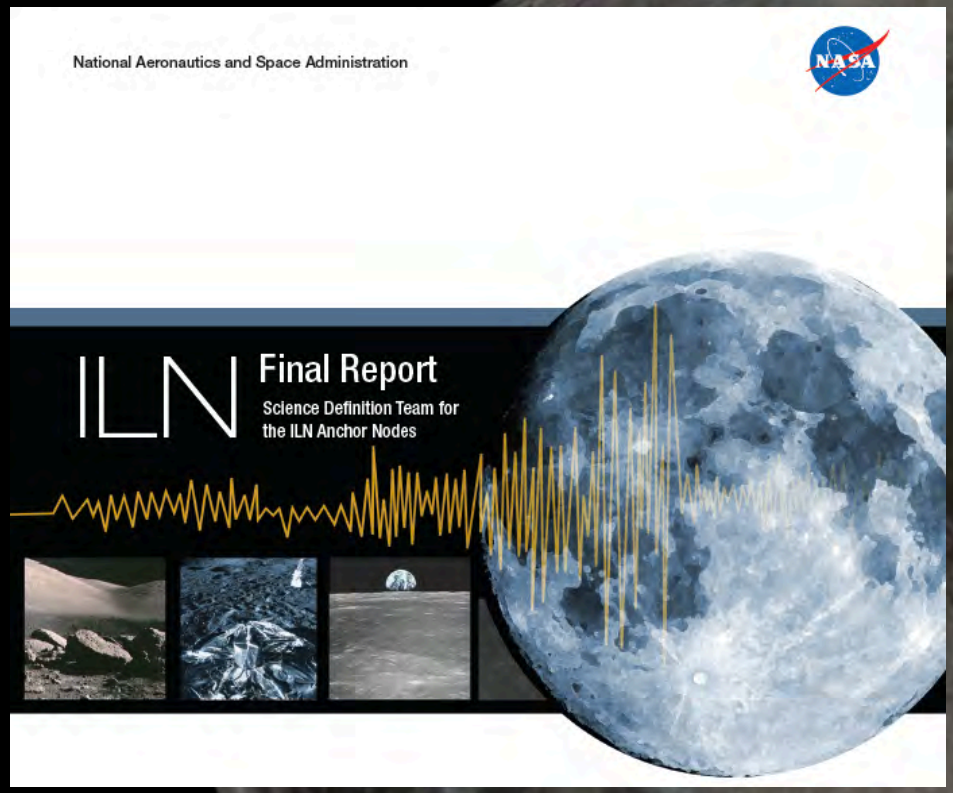
WATER IS DISCOVERED ON THE MOON.

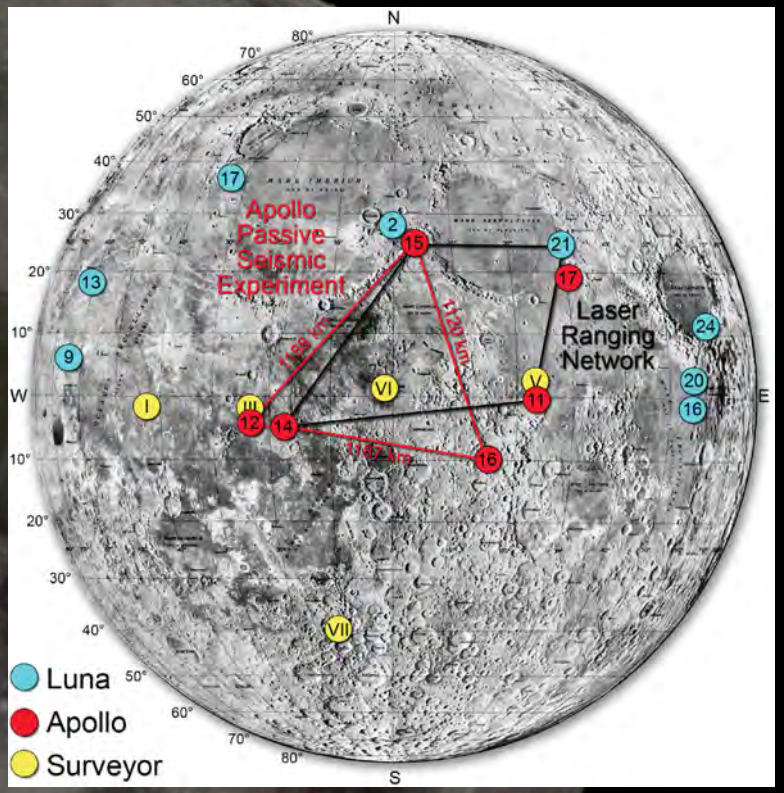
Such missions may include orbiters, landers & sample return.

Lunar Exploration Roadmap

Investigation-Sci-A-1A: Characterize the lunar exosphere and current gas/surface interactions to determine baseline lunar environment.
Investigation-Sci-A-4D: Characterize volatile concentrations and transport mechanisms.
Objective Sci-A-5: Understand lunar differentiation.
Objective Sci-A-7: Understand the impact process.
Objective Sci-A-8: Determine the stratigraphy, structure, and geological history of the Moon.
Investigation-Sci-B-2A: Characterize volatile concentrations and their variability.
Investigation-Sci-B-2D: Assess variations in cosmic radiation through time.
Investigation-Sci-C-2D: Dust-Plasma Interaction on the Surface & Exosphere of the Moon.
Investigation-Sci-C-2H: Analyze the composition of the Solar Wind.
Investigation-Sci-C-2L: Characterize Radiation Bombardment on the Lunar Surface.
Initiative-Sust-B-5B: Utilize robotic precursor missions to conduct selected lunar science investigations that focus on characterizing the pristine lunar environment and contribute to identifying lunar resource concentrations.
Initiative-Sust-B-6D: Establish global communications and navigation network.
Initiative-Sust-B-8A: Characterize aspects of the lunar environment that affect human health and safety including lunar regolith dust, radiation, temperatures, etc.

Lunar Network Science





Lunar Geophysical Network—*This mission consists of several identical landers distributed across the lunar surface, each carrying geophysical instrumentation. The primary science objectives are to characterize the Moon's internal structure, seismic activity, global heat flow budget, bulk composition, and magnetic field.* **Vision and Voyages 2013-2022**.

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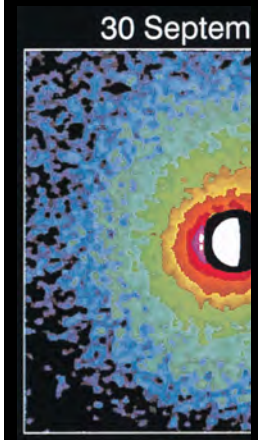
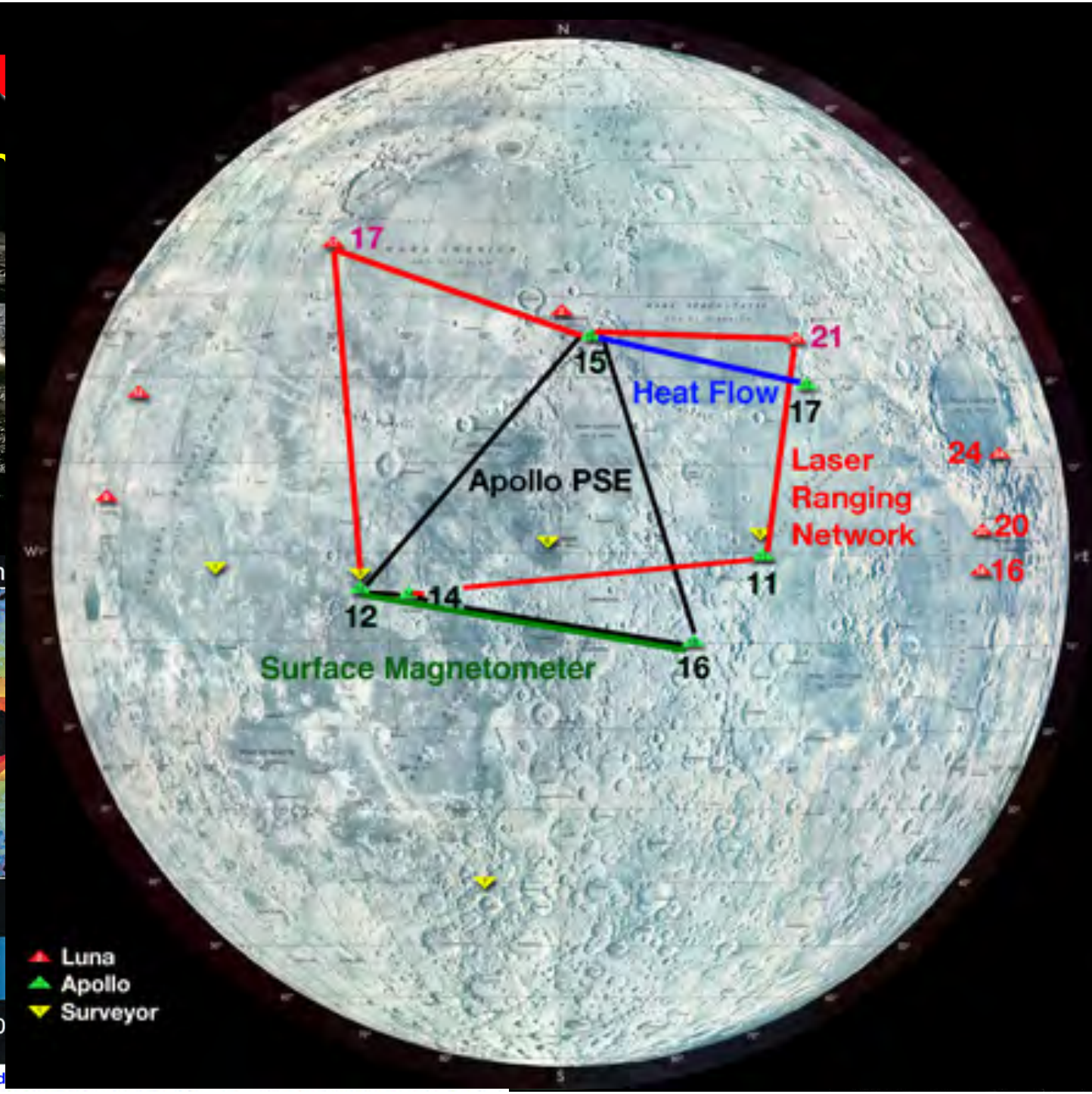
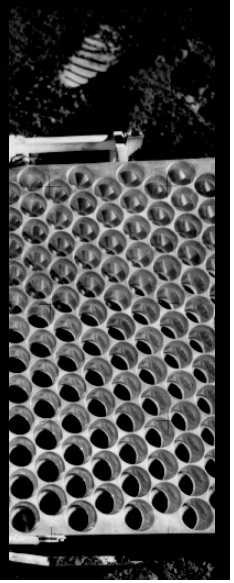


Mendillo et al. (1997) Ad

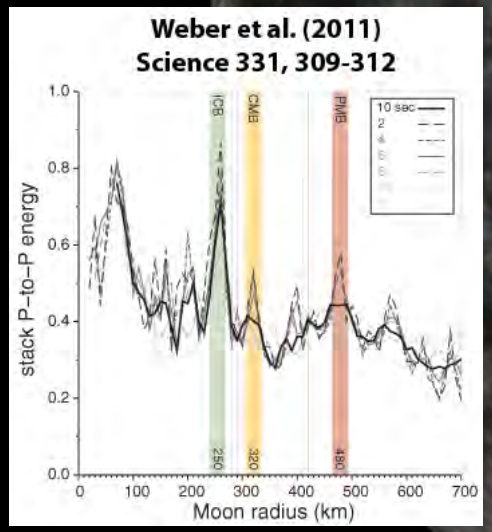


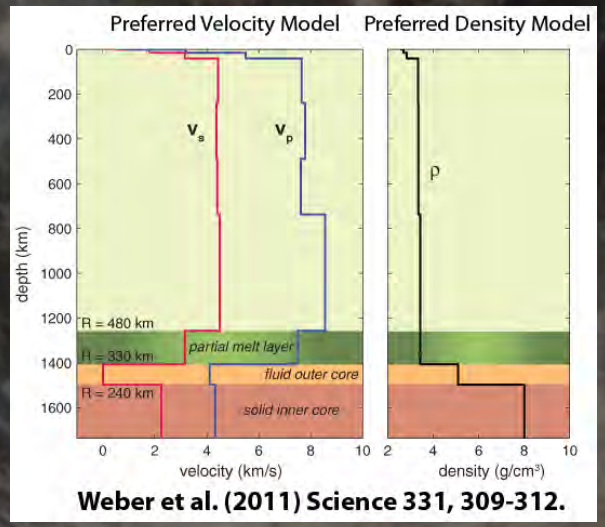


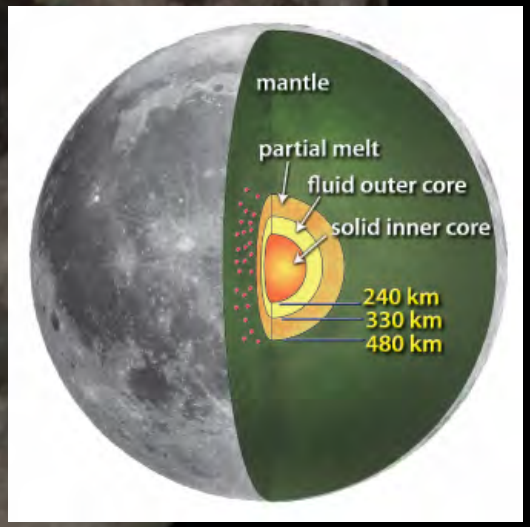
Apollo Seismics: "the gift that keeps on giving"?

Seismic Detection of the Lunar Core?

- Stacked seismograms aligned on predicted core arrival times to enhance small-amplitude arrivals.
- Searched for lunar core reflections by time-shifting the polarization-filtered deep moonquake cluster stacks to travel time predictions of reflections from specific layer depths, then summing the shifted traces.





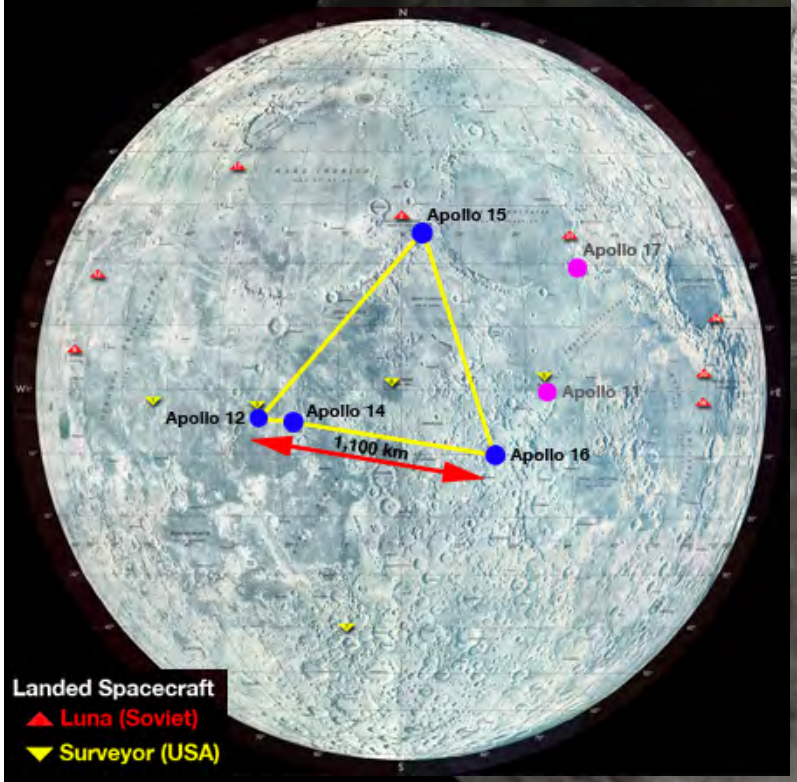


Weber et al. (2011) *Science* 331, 309-312.

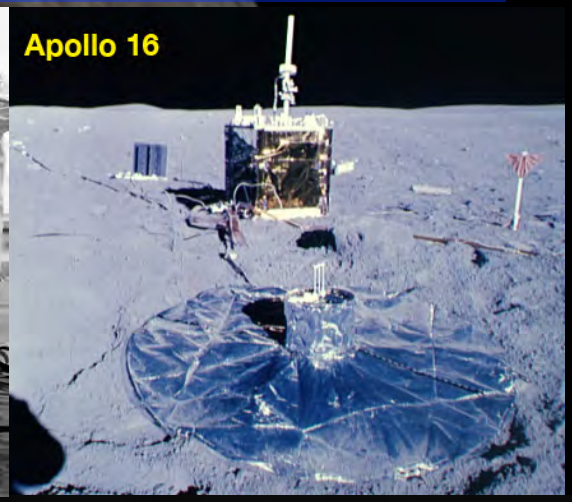
Why do we need the LGN?

Apollo Seismic Stations

The *complete* Apollo passive seismic network operated from 20 April, 1972, until 30 September, 1977.




Apollo 16 Seismometer Test




Apollo 11 Geophysics Package deployed on the Moon

Network too restricted to define global lunar structure

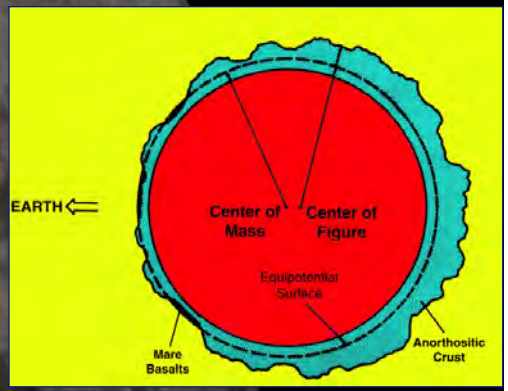
Unresolved Science Questions

The narrow extent of the Apollo Passive Seismic Network resulted in limited resolution of mantle mineralogy, little information about crustal variations, and no details about the lunar core.

[From: Taylor (1982) Planetary Science: A Lunar Perspective]

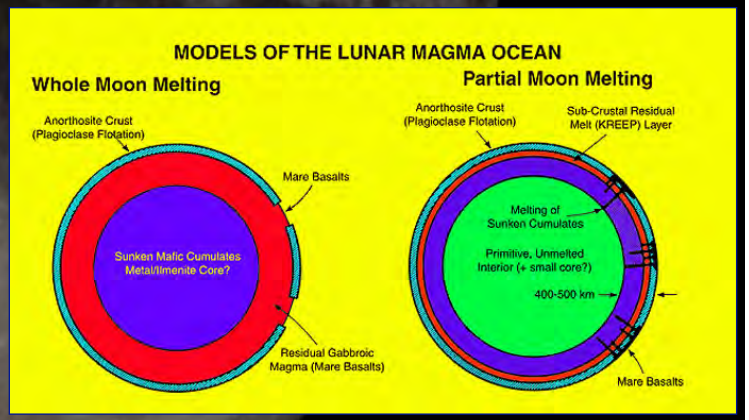
Lunar Crust

What are the structural & thickness variations in the lunar crust (nearside vs. farside)?
Are crustal structure changes gradational or are distinct domains present?
Do such (terrain) boundaries extend into the lunar mantle?



Lunar Mantle

If there was a magma ocean, how deep was it?
Is there a Moon-wide ~500 km discontinuity?
What is the nature of the deep lunar interior?
Is there garnet present?
Is the upper lunar mantle pyroxenitic?



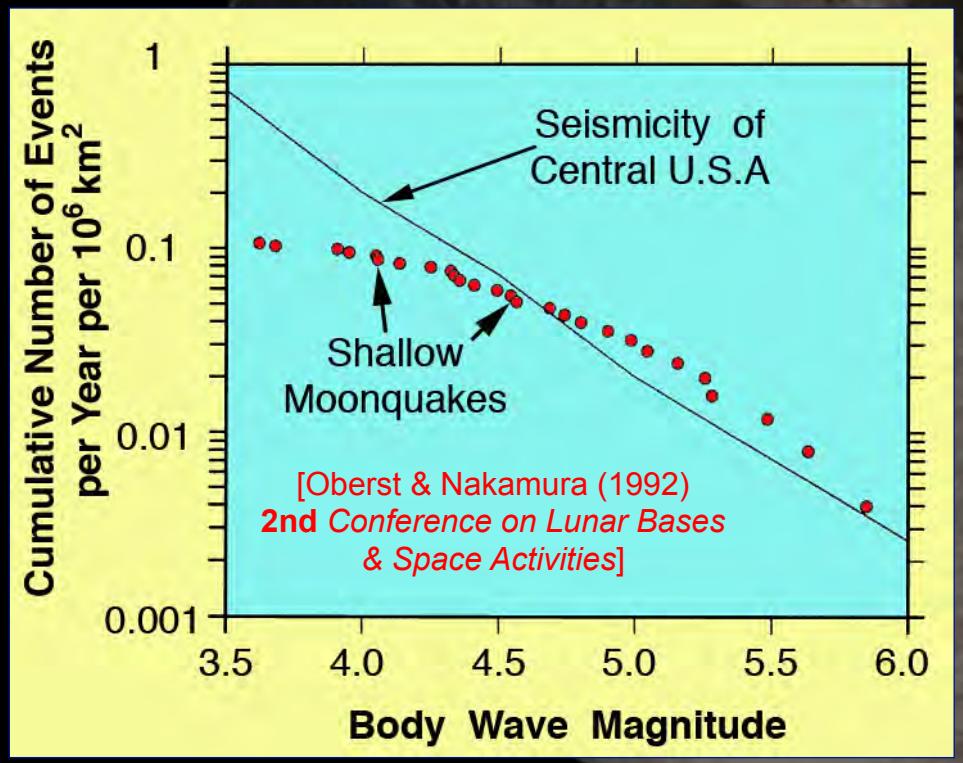
Lunar Core

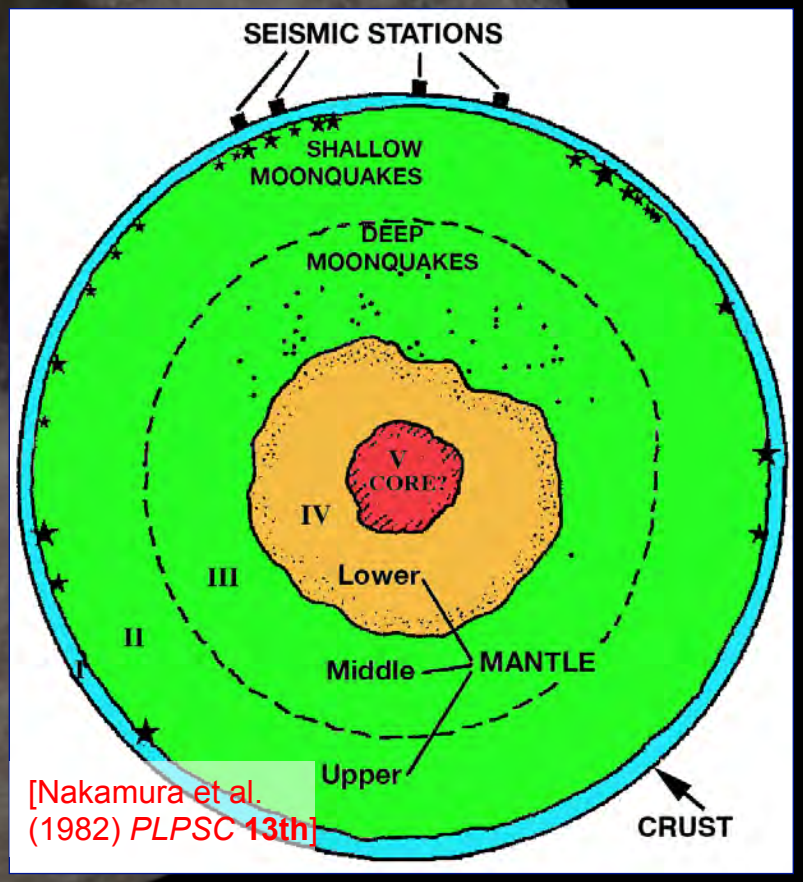
Moon has a small core ~250 - 350 km. May be Fe, FeS, but may be ilmenite ($FeTiO_3$). Current models suggest that the core would be solid if Fe metal, but could still be liquid if it was FeS.

Unresolved Science Questions

Are there DMQ seismic "nests" on the lunar farside or did plastic zones within the Moon prevent their detection?

What are the locations and origins of shallow Moonquakes, the largest lunar seismic events?





Unresolved Science Questions

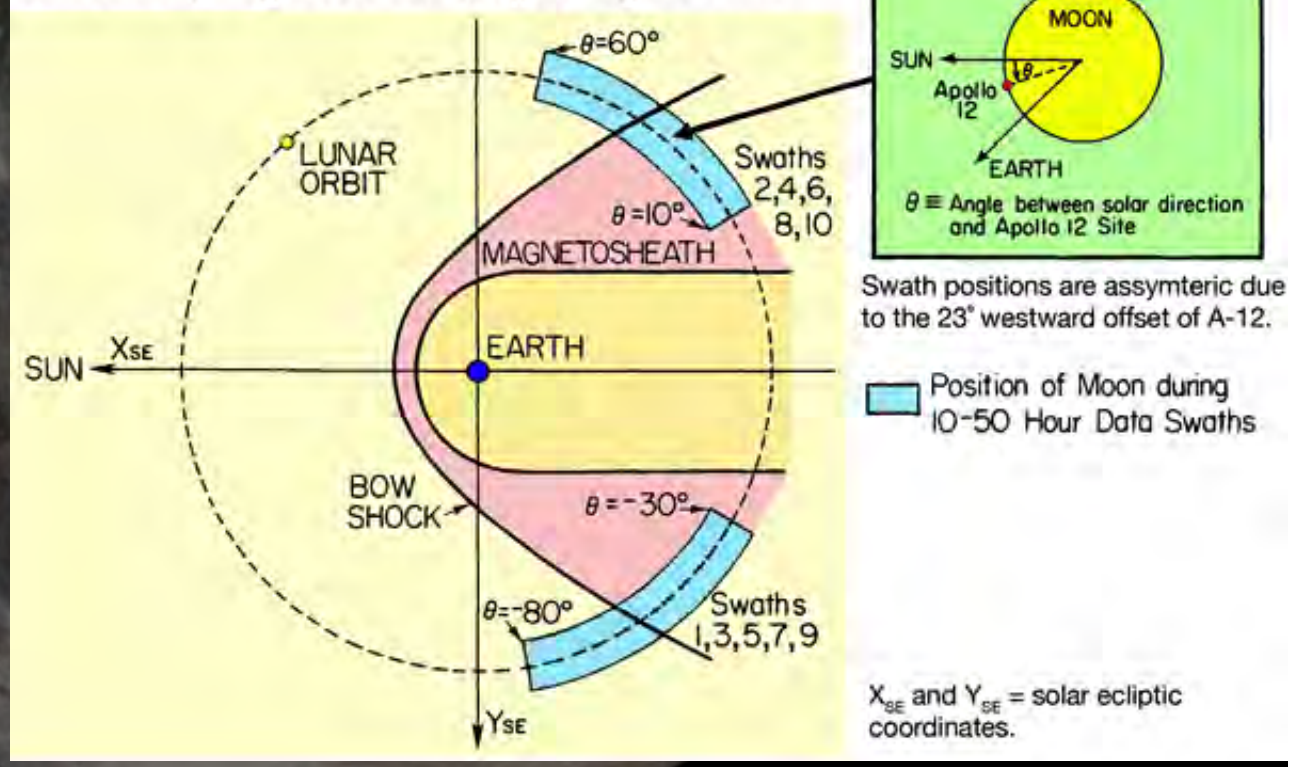
Magnetics

Origin of the magnetic anomalies in the lunar crust?

Deep magnetic sounding (possible core detection).

Analyze induced magnetic fields caused by currents generated in the deep interior in response to external magnetic field changes (define core radius).

Geometry of the Apollo 12 Magnetometer and the Explorer 35 Lunar Orbiter relative to the solar wind, bow shock, magnetosheath, & geomagnetic tail.



Wiskerchen & Sonett (1977) PLSC 8th 515-535

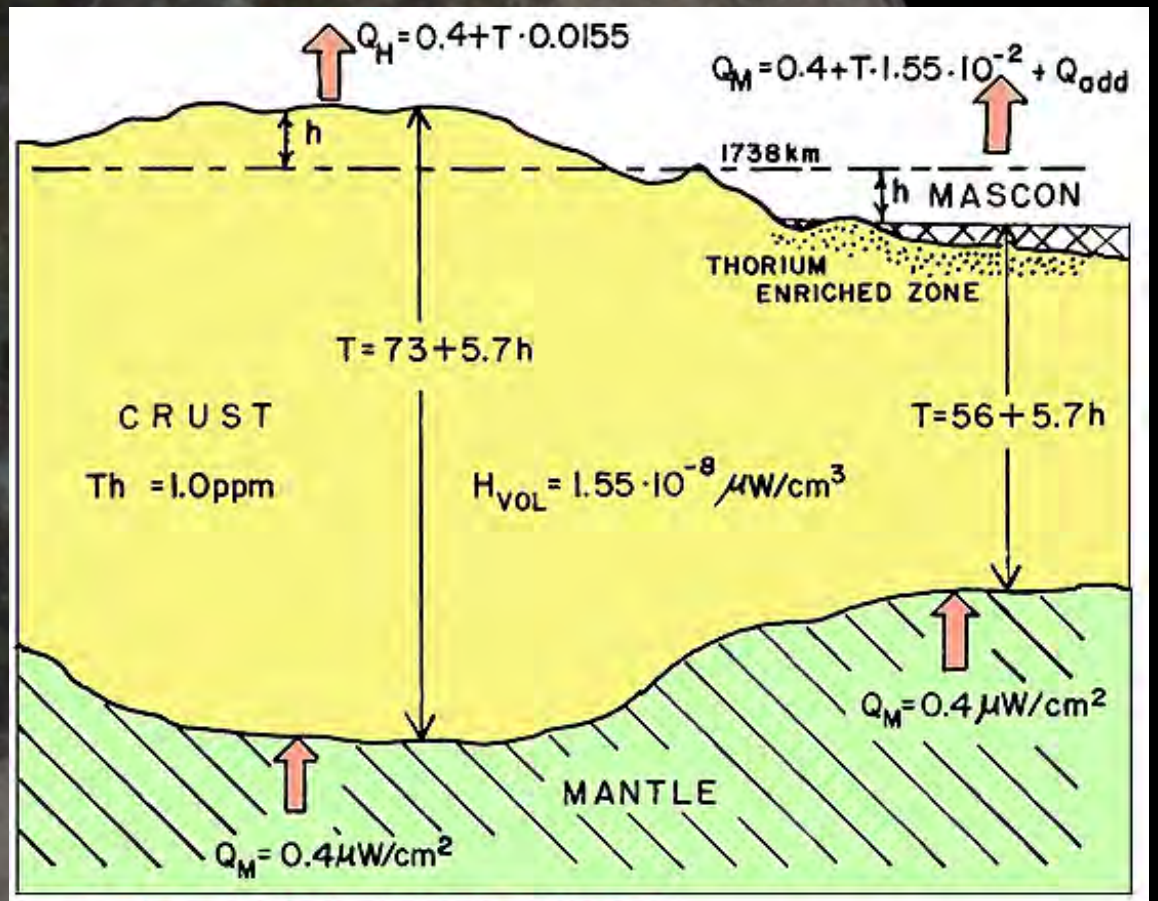
Unresolved Science Questions

Heat Flow

Implications for lunar bulk composition, thermal models, and distribution of heat-producing elements.

Only Apollo 15 and Apollo 17 measured heat flow.

Need data from a broader distribution of sites around the Moon, especially with the heterogeneous nature of the regolith.



Langseth et al. (1976) PLSC 7th, 3143-3171.

Lunar Seismology: A Lunar Base Context

Shallow Moonquakes and **Meteoroid Impacts** present significant risks to any proposed lunar outpost.
[see Oberst & Nakamura (1991) *Icarus* **91**, 315-325; Oberst & Nakamura, 1992, Lunar Base Workshop, LPI]

Meteoroid Impact: > 1,700 impacts of mass > 0.1 kg recorded by Apollo seismometers. ***Need better location data for meteorite impacts.***

Shallow Moonquakes: more energy at higher frequencies than equivalent earthquakes. Although regolith will scatter surface waves, seismic waves are much less attenuated on the Moon relative to Earth - effects felt much further than an earthquake of comparable magnitude and for much longer.

Lunar Geophysical Network – Solar System Science

Planetary Evolution:

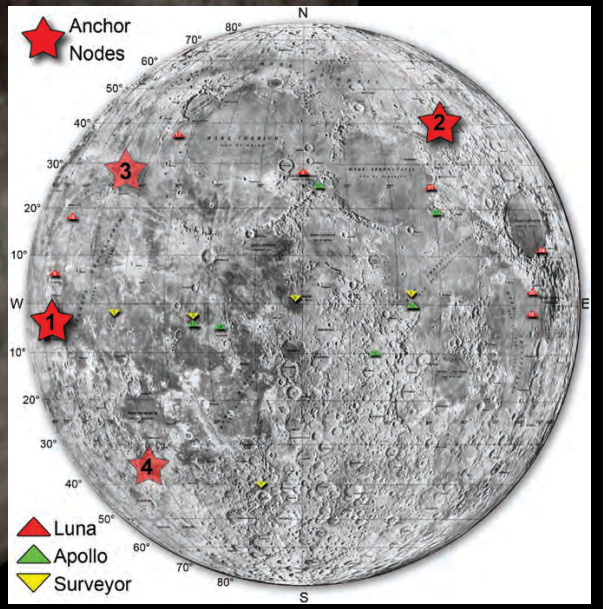
- The Moon is the small end-member of terrestrial planet evolution and the larger end-member in small body evolution (adding to the understanding of the evolution of asteroids and other stony moons);
- Its small size suggests that thermal-tectonic-magmatic evolution occurred early in Solar System history;
- This preserves a stage that has since been obliterated in the larger terrestrial planets.

Lunar Geophysical Network Mission

Is this the "International Lunar Network"?

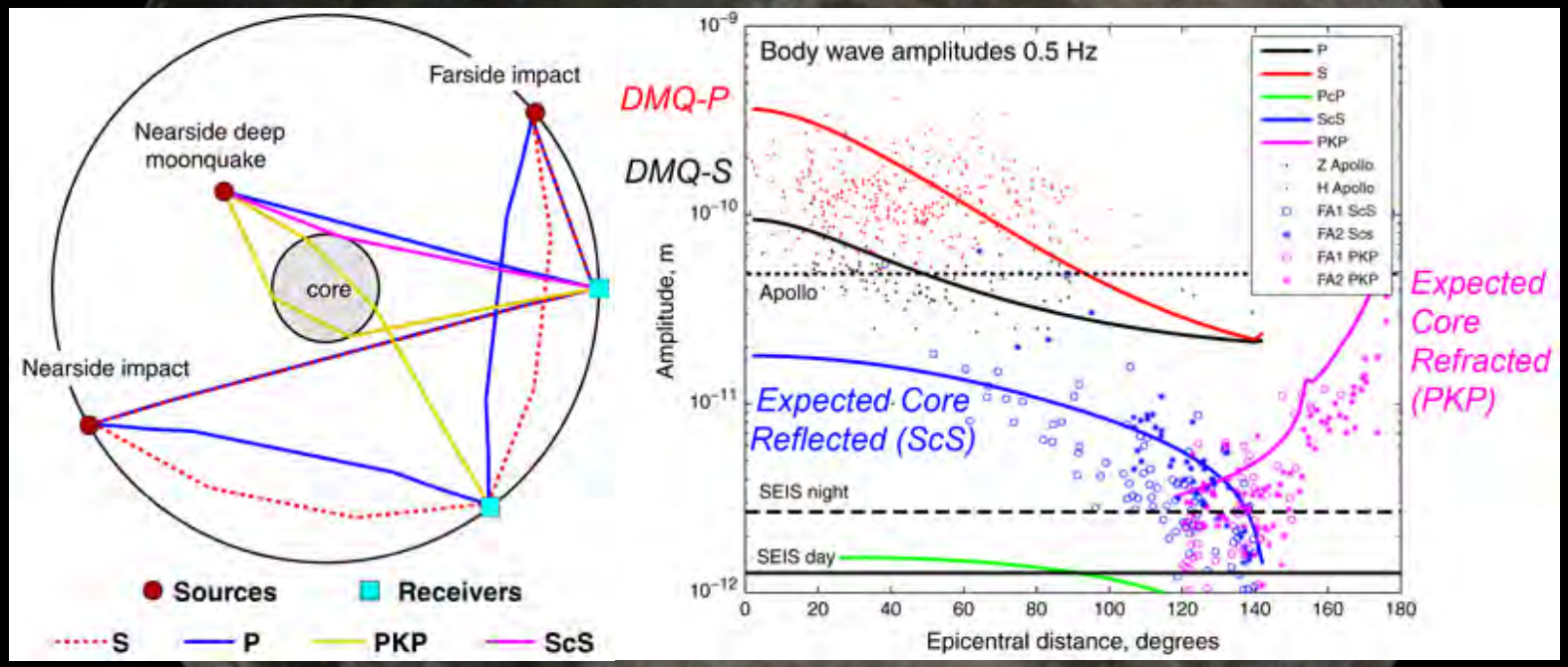
Seismometer.
Magnetomers/EM Sounding.
LRR (nearside).
Heat Flow Probes.
Other?

"Inclusion of laser retroreflectors (LRRs) on the nearside will leverage from the existing and still used Apollo LRR network. It will provide detailed information on the lunar interior and also the best constraints on General Relativity and non-metric models of gravity as accuracies of the next generation of LRRs are expected to approach 10 microns."



Lunar Geophysical Network Mission

Must be better than Apollo, but must build upon Apollo knowledge.



Network must be broader (farside stations) and instruments more sensitive. Penetrators cannot deliver seismometers of the necessary sensitivity.

Lunar Network Science

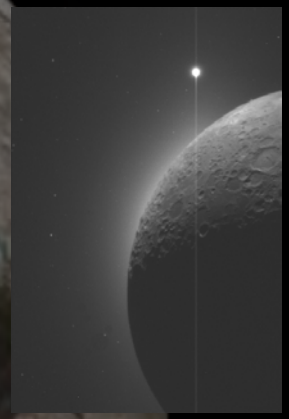
Long-Lived Exosphere/Space Environment Network

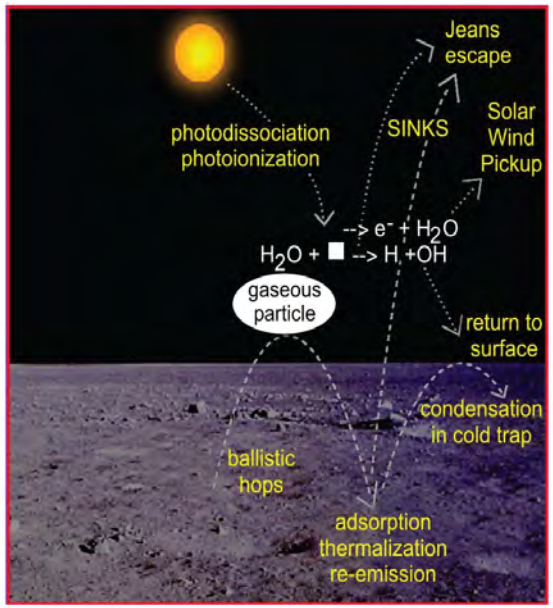
Measurement of elemental/ionic species at the surface;

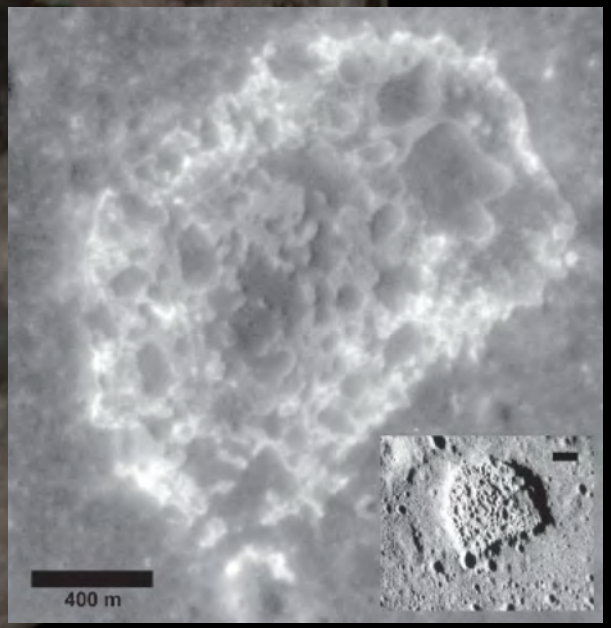
Evolution of the exosphere;

Volcanic species (active venting).

Volatile transport.







Schultz et al. (2006)
Nature 444, 184-186

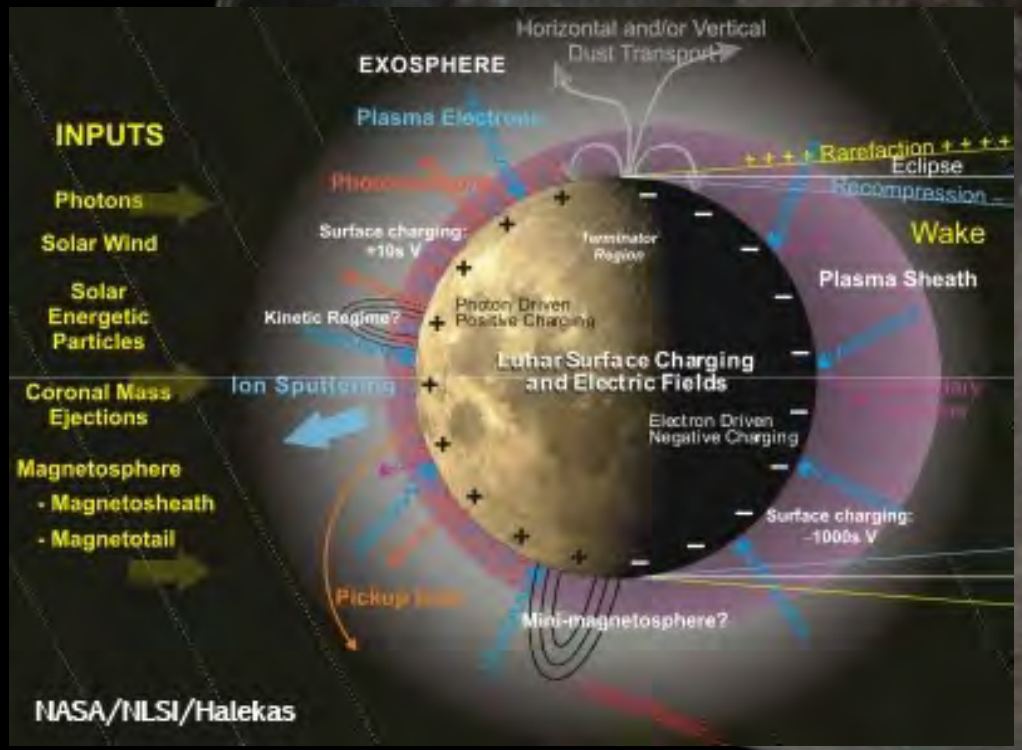
Lunar Network Science

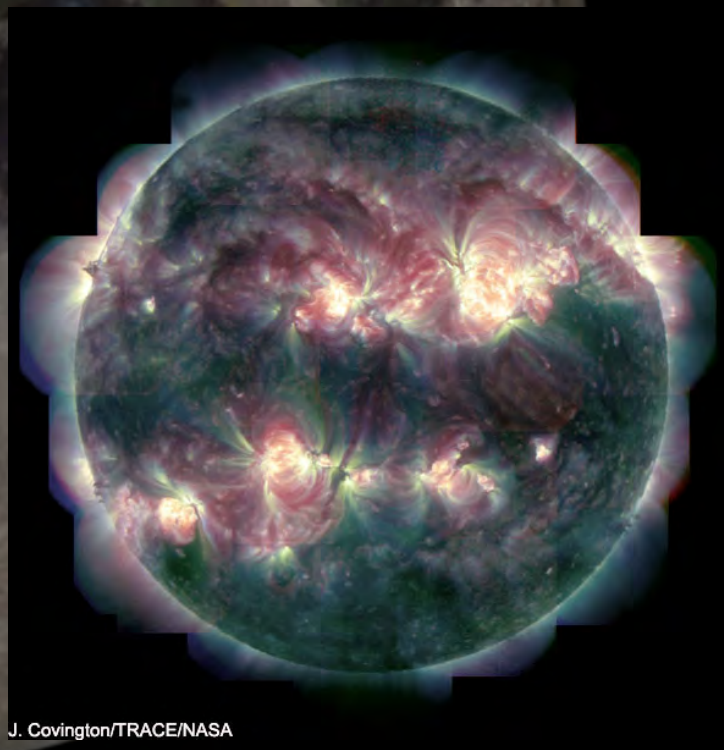
Long-Lived Exosphere/Space Environment Network

Measurement of radiation at the surface;

Evolution of space weathering agents;

Space weather monitoring – data needed for space weather forecasts (see Spence et al. 2012 poster, this meeting).

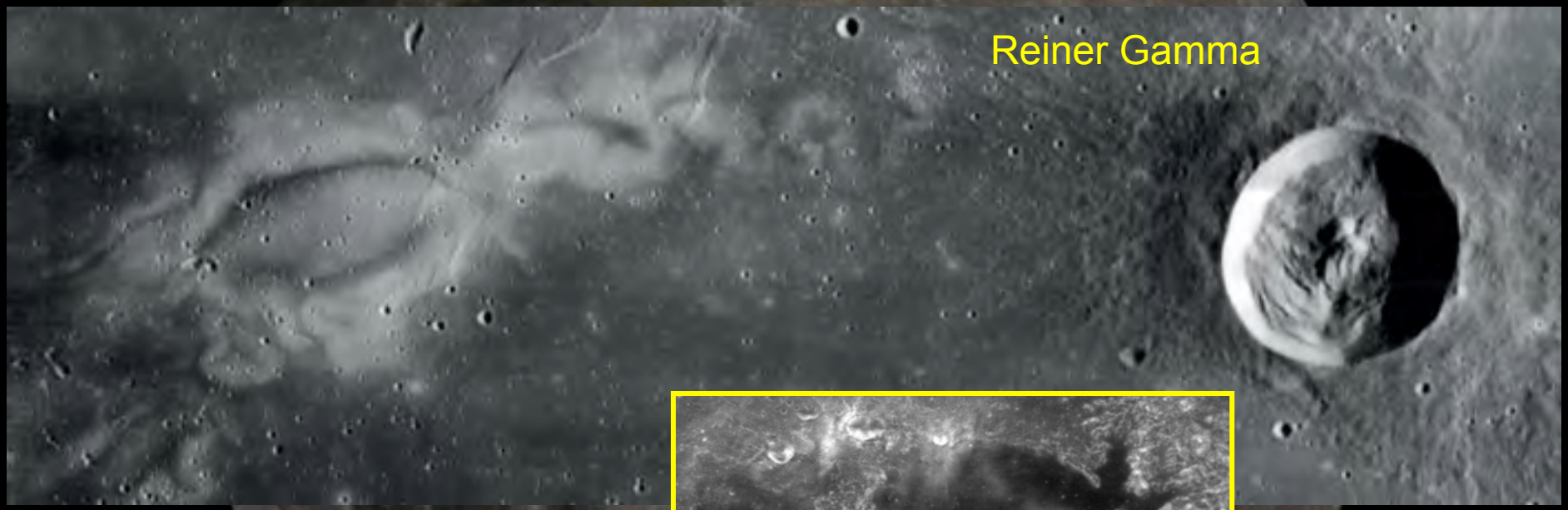


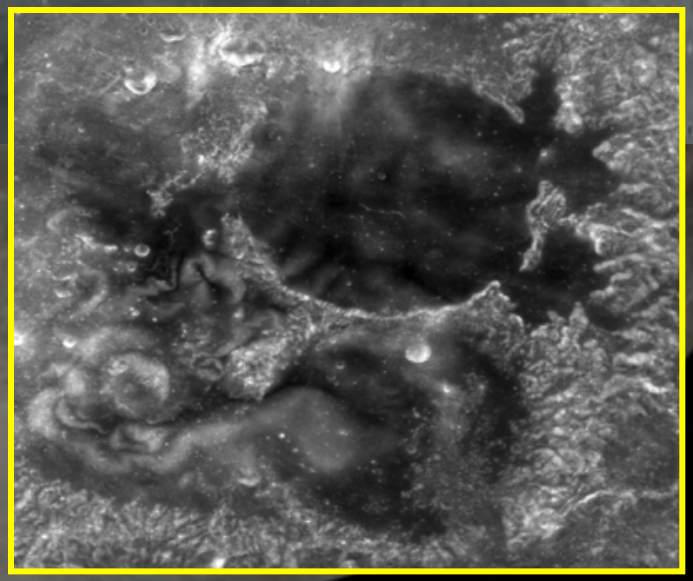


Lunar Network Science

Long-Lived Exosphere/Space Environment Network

Do lunar swirls afford some protection from space weather?





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What's Next for the Moon?

Lunar Exploration

ISRU Prospecting/Technology Demonstration

Lunar Science

SPA Sample Return.

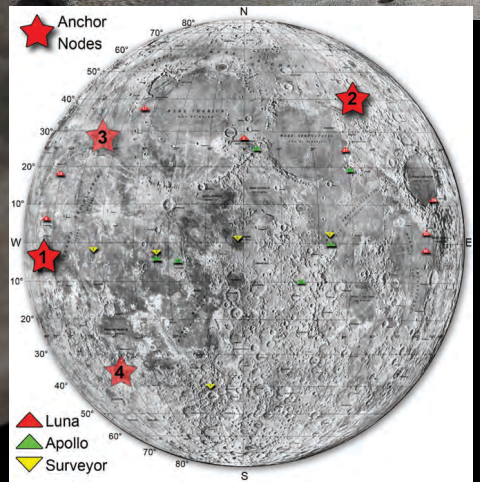
The nature of polar volatiles.

The significance of recent lunar activity.

Tectonic-magmatic evolution of the Moon.

Lunar Science & Exploration

Network science.




GIANT LeAP...


...SMALL STePS...
...NASA WANTS TO SPeND HOW MUCH? TO DO WHAT?!
JEFF PARKER ©1994 FLORIDA TODAY

Proposed Future Robotic Lunar Missions

COUNTRY	NAME	TYPE	YEAR
China	Chang'e 3	Lander	2013
USA	LADEE	Orbiter	2013
India	Chandrayaan-2	Lander	2014?
Russia	Lunar Glob	Lander	2014?
Private	GLXP	Landers	2014
China	Chang'e 4	Lander	2015
Russia	Lunar Grunt	Orbiter/Lander	2015
Japan	SELENE-2	Lander	2016
China	Chang'e 5	Lander	2017
Europe	MoonNext	Lander	2015-2018
Russia	Lunar Poligon	Lander	2020
South Korea	Moon Orbiter	Orbiter	2020
South Korea	Moon Lander	Lander	2025