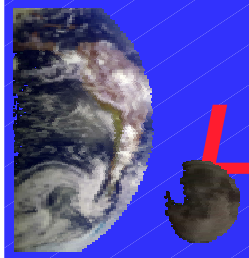

Lunar Geophysics, Geodesy, and Dynamics

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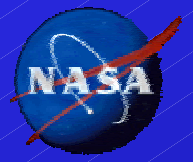
* **Acknowledgment: Dale H. Boggs, XX Newhall, J. Todd Ratcliff, E. Myles Standish & others especially the Staffs of CERGA, Haleakaula, and the University of Texas McDonald Observatory**



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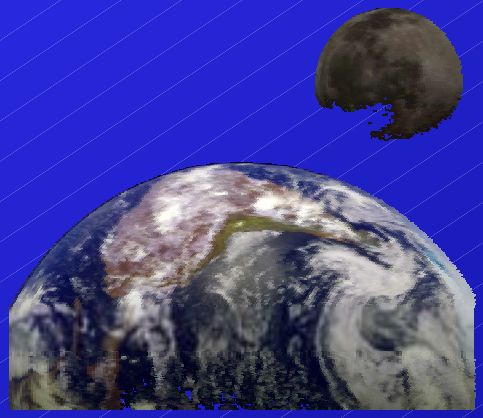
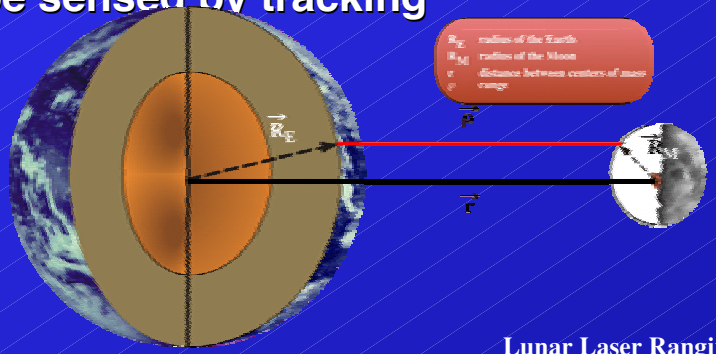
Majors Points

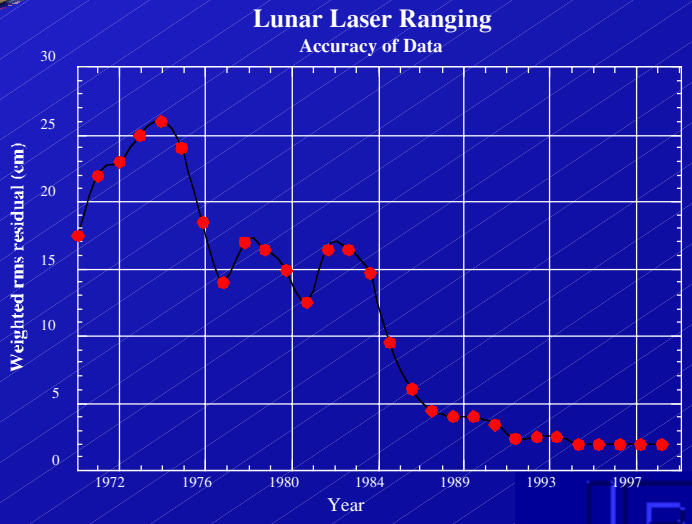


- Introduction
- Recent developments
- Comparison of the Earth and Moon
- Lunar Geodesy
- Lunar Interior studies
- Science Potential - from Centimeter toward millimeter Ranging Accuracy
- Concluding Remarks

Introduction

- Lunar tides and rotation are influenced by the interior properties of the Moon.
- Three-axis rotation and tides can be sensed by tracking lunar landers
  - 4 corner-cube retroreflector arrays
  - Three decades of accurate ranges
- Areas of Impact
  - Lunar Science
  - Gravitational Physics
  - Earth Science
  - Ephemerides and Constants

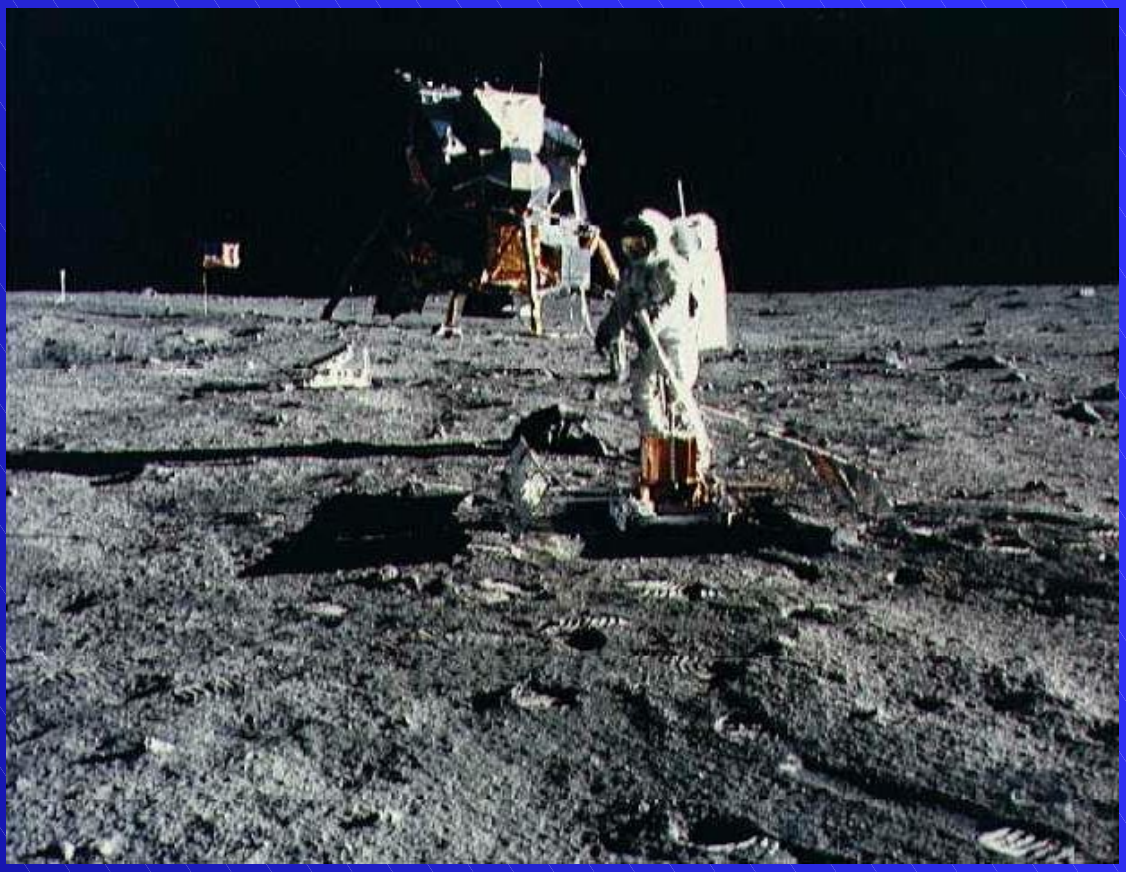


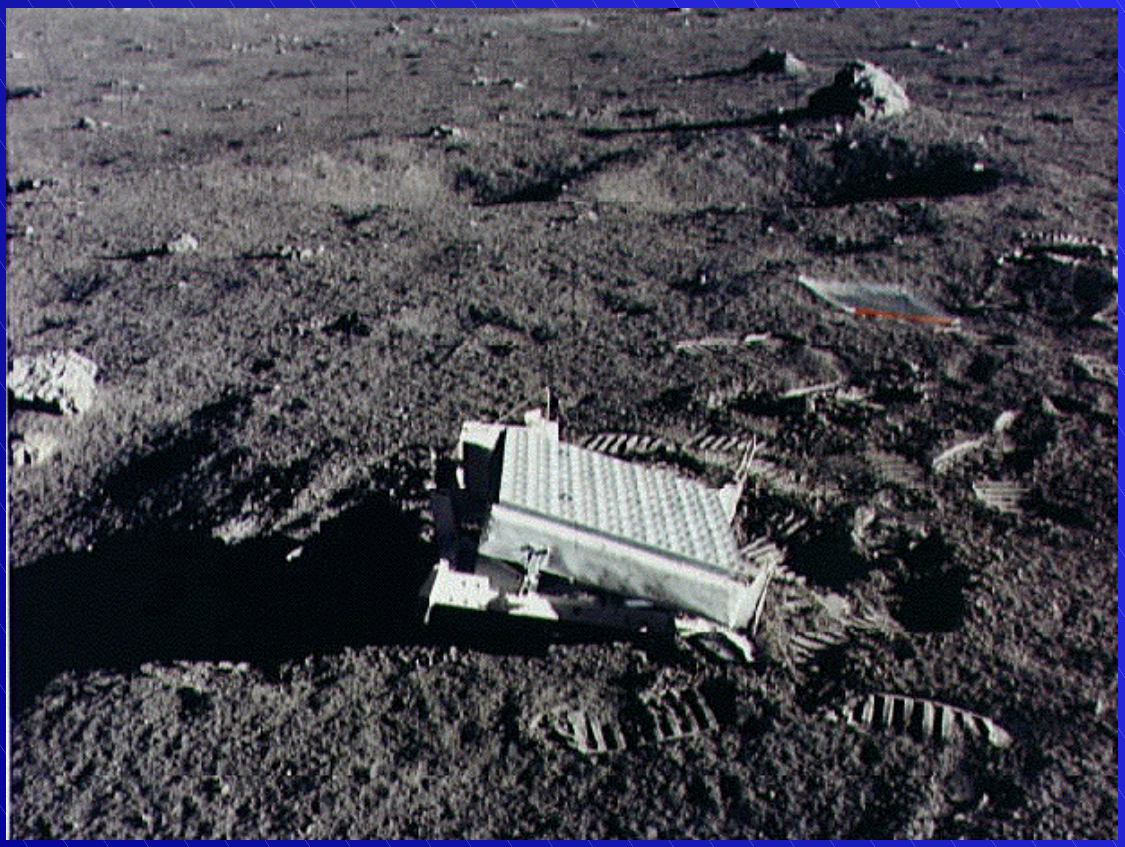


An Apollo -Era Experiment Still Going Strong!

- Laser Ranges between observatories on the Earth and retroreflectors on the Moon started in 1969 and continue to the present
- 4 retroreflectors are ranged: Apollo 11, 14, & 15 sites and Lunakhod 2 rover

- **Earth-basedObservatories:**
  - McDonald (Texas)
  - OCA (Grasse)
  - Haleakala (Hawaii - historic data)
  - Expected soon! : Matera & Apache Point





Comparison of the Earth and Moon I

Earth

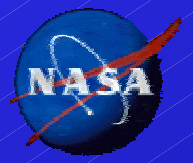
- Atmosphere, ocean & life!
- Rotation rapid
  - short period variation linked to atmosphere
- Tidal loading is important
- Non-grav effects are a challenge with short-arc solutions
- Plate motion
- Earthquakes

Moon

- No atmosphere, ocean & known life!
- Rotation is synchronous and slow (27.3 days)& not near rotational equilibrium
- Tidal loading is lacking
- Orbit is “quiet” with the largest non-grav effect of 4 mm ingle arc solution for 32 years with an rms of 17 mm
- No plate motion
- Moonquake (small in magnitude)

Comparison of the Earth and Moon II

	Earth	Moon
Radius	6371 km	1737 km
Mean Density	5.51 gm/cm^3	3.35 gm/cm^3
C/MR^2	0.3307	0.3932
Spin Period	1 d	27.3 d
Precession	26,000 yr	18.6 yr
Tilt to Ecliptic	23.44°	1.54°



Comparison of the Earth and Moon III

Earth

- Studies of the Earth's interior are advanced
- Solar perturbation are smaller
- Moment of Inertia ~ 0.33 smaller than the value expected from a solid body
- Center of Mass and J_2 variations are geophysical interesting & are under current study!
- Tides on the Earth- Large and complex
- Tidal dissipation - Earth's contribution dominates!

Moon

- Moon's interior is less well known -LLR analysis indicates a liquid core
- Solar perturbation are sizable!
- Moment of Inertia = 0.3932 ± 0.0002 (Konopliv et al., *Science*, 1998)close to the value expected from a solid body
- No analogy - Center of Mass variation
- J_2 time series would be rather ~ constant
- Tidal dissipation - Moon's contribution is small
- Tides on the Moon
  - Largest ~ 10 cm; Synchronous rotation keeps angular variation modest; solar tides ~4 mm

Largest Lunar Radial Variations

Interaction Type	Amplitudes
• Ellipticity	20905 km
• Solar perturbations	3699 & 2956 km
• Jupiter perturbation	1.06 km
• Venus perturbations	0.73, 0.68 & 0.60 km
• Earth J_2	0.46 & 0.45 km
• Moon J_2 & C_{22}	0.2 m
• Earth C_{22}	0.5 mm
• Lorentz contraction	0.95 m
• Solar potential	6 cm
• Time transformation	5 & 5 cm
• Solar radiation pressure	4 mm
• Note ratio smallest to the largest = 2 x 10**-10	

Lunar Science Questions

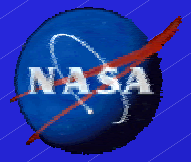
- What are the properties and structure of the deep interior?
- What are the core properties?
  - Iron or Silicate?
  - Solid or fluid?
  - Does an inner core exist?
- What causes strong tidal dissipation?
- What were the roles of tidal and core dissipation in the thermal and dynamical evolution?
- What stimulates free librations?

CAUSES OF ROTATIONAL VARIATIONS

- Departure from uniform rotation and precession is caused by
  - Static figure, moments of inertia, and gravity field
  - Tidal k_2 and oblateness of fluid-core/solid-mantle boundary
  - Tidal dissipation and dissipation at fluid-core/solid-mantle boundary

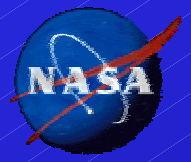
Elastic Tides

- Love numbers
  - Depend on the elastic properties of interior
  - Elastic tidal displacement: h_2 & l_2
  - Tidal distortion of 2nd degree gravity potential: k_2
- Values of k_2
  - LLR determines k_2 more accurately from lunar rotation
    - > $k_2 = 0.0266 \pm 0.0027$
  - Spacecraft determined values agree
    - > $k_2 = 0.026 \pm 0.003$ (Konopliv et al., Icarus, 2000)
  - Simple structural models produce lower values of k_2
    - > Something like partial melt in the deep mantle could bring model results into better agreement with measurements



EVIDENCE FOR A CORE

- Moment of inertia
- Rotation effects
- Magnetic induction
- Ancient magnetized basalts



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Tidal Dissipation

- Tidal dissipation Q
  - A bulk physical property of the Moon
  - Depends on radial distribution of material Q's
- LLR detects 4 dissipation terms
  - Infers a weak dependence of tidal Q on frequency
  - Surprisingly low Q's ($Q_{Moon} \approx 37$ vs $Q_{Solid\ Earth} \approx 200\text{-}600$)
  - Location of the low Q material not determined by LLR
- At seismic frequencies
  - Low Q material was found in the deep mantle
  - Suspected to be partial melt

Fluid Core/Solid Mantle Dissipation

- Fluid core
  - Doesn't share axis of rotation of the solid mantle
  - Weakly coupled to precessing mantle
  - Torque due to core-mantle velocity difference dissipates energy
- LLR analysis
  - Several dissipation terms considered in order to separate tidal from core dissipation
  - Yoder's (1995) turbulent boundary-layer theory gives
    - > Fe: $R_{core} \leq 352$ km
    - > Fe-FeS eutectic: $R_{core} \leq 374$ km

Future - Previews of Coming Attractions

- LLR data from Matera
- New ranging system with improved accuracy and sensitivity (see Tom Murphy presentation)
  - Currently under construction at Apache Point Observatory (UW)
  - 3.5 meter telescope with 1-arcsec typical performance
  - 10 mm single-photon system uncertainty --> mm accuracy quickly achievable
  - Will allow ranging to single corner-cube reflectors
- Advent of a new era in LLR analysis enabling new breakthroughs in many areas

Expected Scientific Advances I

- Einstein's Theory is not a quantum theory & is expected to break down at some small level - may be observed by LLR.
- Improved in relativity parameters
  - Both longer data span and higher accuracy
  - Improved in PPN parameters
  - dG/dt improves as the times squared
- Improved J_2 of Sun expected

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Expected Scientific Advances II

- Lunar Interior: Targets from possible detection
  - Fluid-core/solid-mantle boundary oblateness
  - Additional tidal dissipation terms
  - Core moment term
  - Solid inner core effect ?
  - free core nutation ?
  - Free libration stimulating events?

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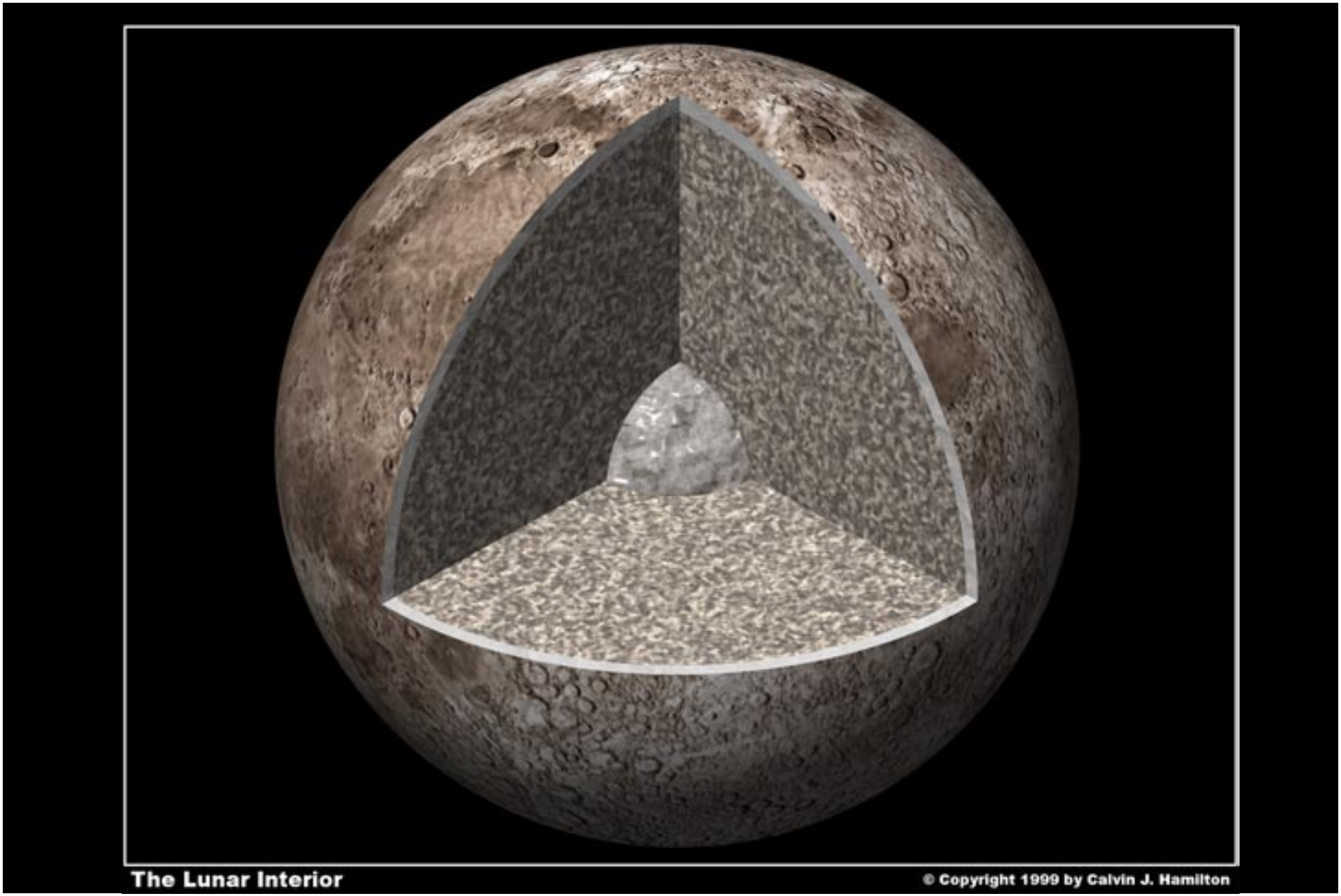
Summary

- LLR is an unique ground-based tool for lunar study... only working experiment from the Apollo Program
  - Complements orbiter and seismic experiments
- The best is yet to come!
  - Matera is coming on-line!
  - New Apollo Program at Apache Point (Murphy, UW)under development with 1 mm accuracy goal!!
- LLR data favors fluid core ~ 350 km
  - Longer time (more measurements) & greater coverage (more retroreflectors) will permit detection of smaller signals (oblateness, moment?)
- Heat available from tidal dissipation and turbulent dissipation at the CMB could power early core convection and dynamo
- Major advances expected in Gravitation and Relativity


The Lunar Interior
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