Lunar Core and Mantle. What Does LLR See?

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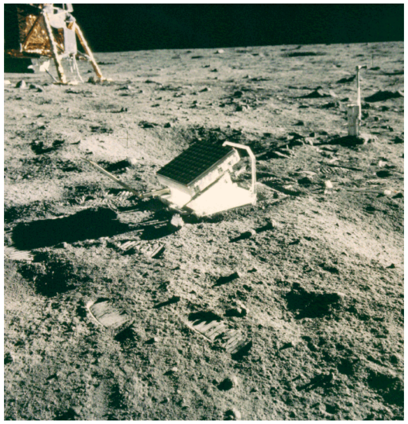
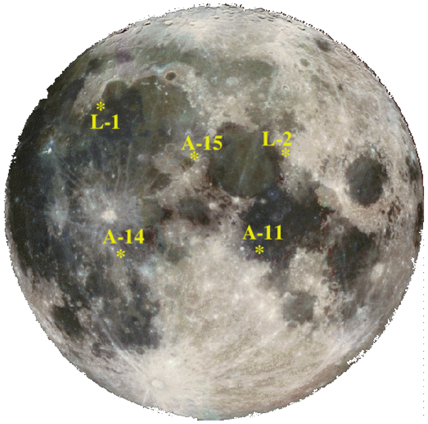
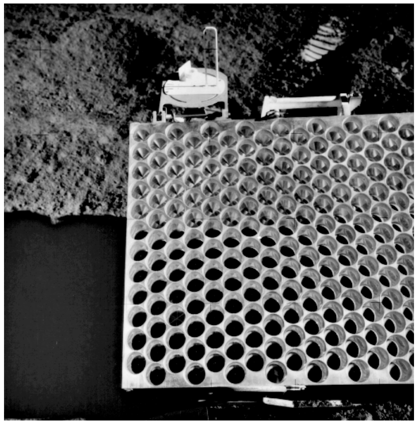
Introduction

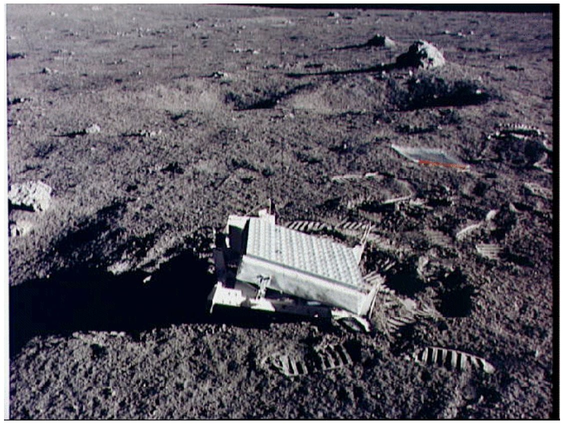
- Lunar Laser Ranging (LLR) from 1970-2008, from four ranging stations to four retroreflector arrays, determines lunar physical librations, tides and array locations.
- Lunar physical librations and tides give LLR sensitivity to mantle and core properties:
  - Determine Love numbers & tidal *Q*s.
  - Sense dissipation at and flattening of core/mantle boundary.
  - Determine core is fluid.

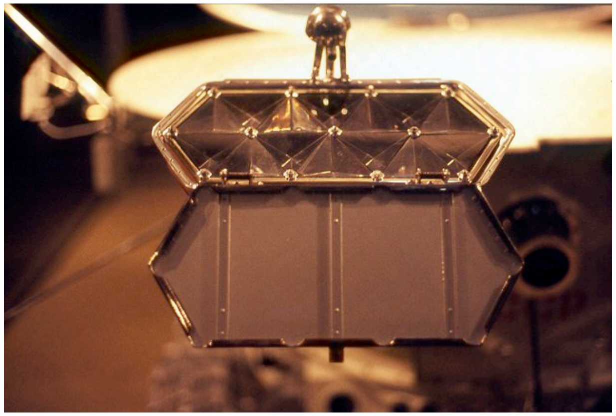
Retroreflector Arrays











What Other Techniques Give

- Mass and 1737 km mean radius from orbiting spacecraft give a mean density of 3.344 gm/cm^3, like rock.
- Apollo seismometry probed upper ~1100 km of mantle, but deeper rays were attenuated. High S-wave attenuation suggests lower mantle is a partial melt. Deep S-waves vanished leaving lower mantle and core a mystery. Unlike Earth, seismology has not determined all lunar structure.
- No global dipole magnetic field, so no active core dynamo.

Other Techniques – Continued

- Magnetic induction found a small conducting core. For a high conductivity like iron, radius is 250-430 km. Lower conductivities would have larger cores.
- Formation 4.5×10^9 yr ago and radioactive decay heated the early Moon. The Moon's small size allowed cooling with the lithosphere growing thicker. Surface volcanism magma came from upper mantle partial melts, but sampled basalts are old (≥1/2 Moon age).
- A small, dense, conducting core is possible. Has cooling made a core solid after 4.5×10^9 yr?

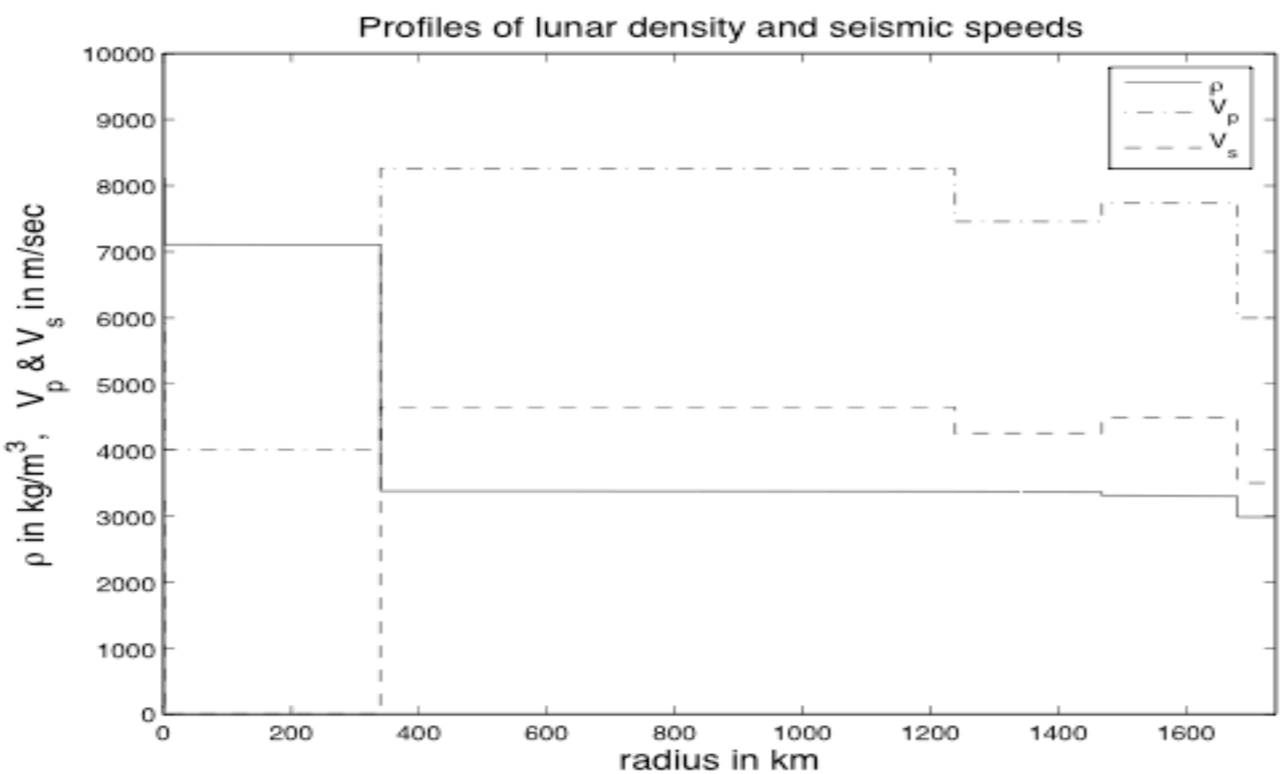
LLR Physical Librations + Spacecraft Gravity

- LLR gets $(C–A)/B$ and $(B–A)/C$, where principal moments of inertia are $A<B<C$.
- Spacecraft get $J_2 = (C–A/2–B/2)/MR^2$ and $C_{22} = (B–A)/4MR^2$
- Combine to get polar C/MR^2=0.3935±0.0002 and mean moment I/MR^2 = 0.3934±0.0002, only 1.65% less than 0.4 of a uniform body.
- Mean lunar density and moment both imply that any dense core must be relatively small.

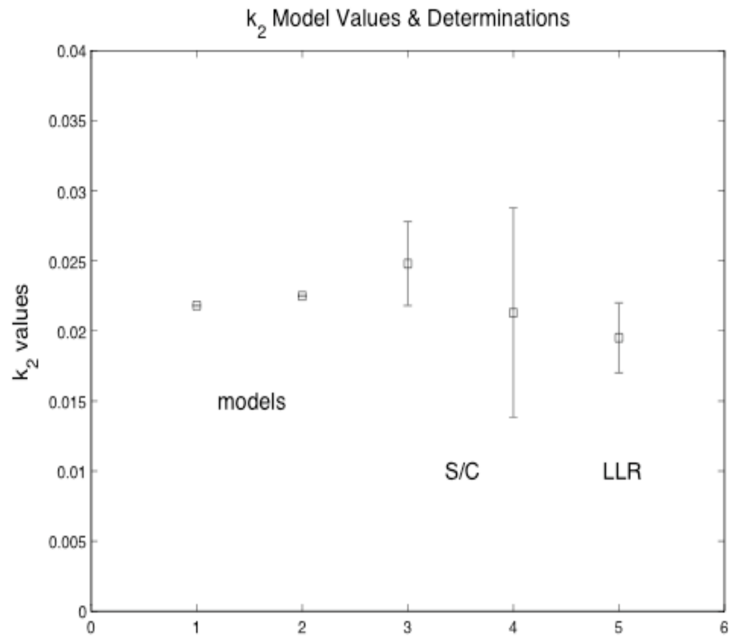
Tides on Moon

- Largest lunar tidal periodicities are ~9 cm.
- LLR detects both changes in moments of inertia through physical librations and retroreflector tidal displacements. Those give 2nd-degree Love numbers k_2 = 0.020±0.003, h_2 = 0.043±0.008 with l_2 fixed at a model value of 0.0105.
- Both core size and lower mantle elasticity are unknown and affect Love number values. Cannot separate, but can make models.

Nakamura Seismic Model + Deep Mantle Extension + 340 km Liquid Iron Core



Lunar k_2 Model Values and Current Determinations



- Lunar Prospector k_2 values are higher than LLR.
- Spacecraft will get an accurate future value.

Lunar Tidal *Q*s

- LLR detects tidal dissipation at four physical libration periods. Specific dissipation $Q \approx 30$ at 1 month tidal period and $Q \approx 35$ at 1 yr.
- A slight dependence of tidal *Q* on frequency is expected, but with opposite slope.
- Tidal *Q* must be mostly from mantle. Low *Q* value may be from lower mantle partial melt that seismic data suggested.

Dynamical Evolution

- Tidal dissipation on the Earth causes a positive lunar orbit eccentricity rate, but tidal Q of the Moon gives a negative rate. Total rate is positive. The current lunar orbit a, e, & i result from 4.5×10^9 yr of evolution.
- LLR can also determine tidal dissipation on Earth and some orbit changes.

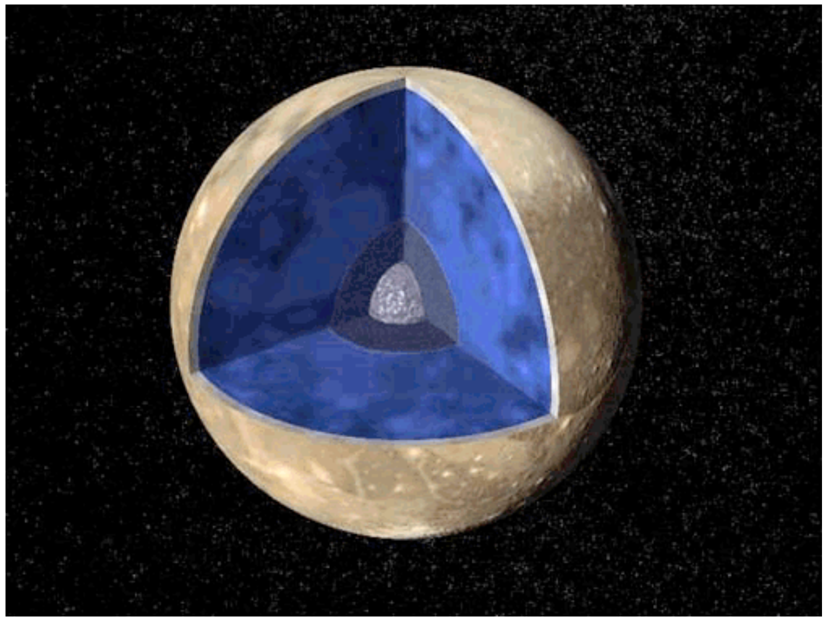
Fluid Core Evidence from Physical Librations

- Dissipation at fluid-core/solid-mantle boundary (CMB) is separate from tidal *Q*.
- New! Fluid core moment I_f/I_{total}=(9±5)x10^{-4}.
- CMB flattening *f* correlates –0.9 with I_f. Get fI_f/I_{total}=(3±1)x10^{-7}. Is *f*=(3.5±2.7)x10^{-4} larger than equilibrium value of 2x10^{-5}?
- The 74.6 yr free wobble is large, 28x69 m. It may be stimulated by fluid eddies at the CMB (Yoder, 1981).

Core Properties

- Conducting fluid.
- Composition is not directly measured. It could be Fe rich like the Earth, some Fe mixture such as Fe-FeS, or a dense silicate.
- Fe-FeS or Fe-C mixtures have much lower melting points than pure Fe.
- If core has density of liquid Fe (7.1 gm/cm^3), then radius is 310-400 km (18-23% of total R) and mass 1.2-2.6% of total. Get larger core radius with lower density.

Lunar Structure



- Crust, mantle, and fluid core are detected. A solid inner core may have frozen out of the cooling liquid, but is undetected.

Future Goals

- It is very important to improve the determination of interior properties, particularly core moment, by continuing to collect multiple array data. Need both long time span and good accuracy.
- The physical libration data analysis model needs to be improved. We are currently limited to 0.1 nsec fits. Want better fits, more accurate solution parameters, and more parameters.

Future Possibilities

- A solid inner core is plausible, but undetected. LLR might detect an inner core through the physical librations.
- It may be possible to observe free libration stimulating events.
- Orbiting spacecraft can improve the k_2 accuracy.

Future Possibilities – Continued

- Expanding the distribution of LLR sites on the Moon would help separate parameters.
- Finding Lunokhod 1 would expand distribution
- New retroreflector arrays or optical transponders may be placed on the Moon by future missions.

Summary

- Lunar Laser Ranging (LLR) determines physical librations, tides and retroreflector array locations.
- Lunar physical librations and tides give LLR sensitivity to mantle and core properties:
  - determine core is fluid and get its moment of inertia
  - determine Love numbers and find low tidal *Q*s
  - sense strong dissipation at and flattening of core/mantle boundary.

Summary – Continued

- Future goals:
  - continue to collect quality LLR data
  - improve fits and solution parameter results, and add new parameters.
- Future possibilities:
  - seek inner core
  - find Lunokhod 1
  - place new LLR sites on Moon.