Lunar Interior

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History of the Moon

• Giant impact, 4.5 Gya
• Moon almost entirely molten, 4 – 4.5 Gya
• Fractional Crystallization in Magma Ocean, > 4 Gya
  – Floating anorthosite crust
  – Partitioning of heat producing materials between crust and mantle
• Impact dominated (giant basin formation), 3.5 – 4 Gya
  – Interior melting from radioactive decay
  – Mantle partially melts, erupt as mare
• Geologically boring, < 3.5 Gya
  – Small craters
  – Last lava, 1 Gya
Accretion of the Moon

• Timescale of accretion determines whether the moon begins with a magma ocean

• Tidal evolution models disagree on whether the moon started with a magma ocean
Tidal Record
Tidal Evolution of the Moon

• Tidal Quality factor must change or the moon would be at the Earth’s surface, 2 Gya
  – Continent and Ocean arrangement play a big role

• Tidal record indicates a changing tidal dissipation rate
Inclination Problem

• Moon seems to start in inclined orbit
  – Hypothesis: Well-placed giant impact (second)
• Energy needed to change the moon’s orbit appropriately is very large
• “Thus, even an optimally aligned impact to the Moon capable of producing the lunar / could also cause significant disruption, and to the degree to which this occurred, reaccretion would tend to realign the Moon in the Laplacian plane.”
Disk Torque

- Resonant interactions between the disk and the moon
- Resonances interact with rings of disk material
- The last big resonance is a 3:1 vertical resonance
Crustal Thickness

• Calculated from gravity maps and topography
  – Assumptions about isostatic balance, Airy isostasy
Crustal Thickness

• Byproduct of differentiation
  – Depth of magma ocean, Efficiency of plagioclase
Dichotomy in Crustal Thickness

- Globally averaged depth, 40-45 km
- Apollo zone, 30-38 km
- Artifact from assuming crustal and mantle density homogeneity
  - Largest impact requires lower density crustal material to coat it
- Variations in composition both laterally (KREEP) and vertically (increasingly mafic with depth)
- Grail in 2011 combined with LRO topography will make things better
Mascons

- Large positive gravity anomalies
  - Center of large craters, but not all large craters
- Dense mare basaltic lava flow
- Structural uplift of dense mantle materials

Mare Serenitatis
Apollo Seismic Network

- Seismometers laid as part of the ALSEP on Apollo 12, 14, 15, 16
- Operated for 8 years
- 1800 meteroid impacts
- 28 energetic, shallow moonquakes
- 7000 weak, deep moonquakes
Velocity Profiles

- Waves take different amounts of time to travel through different material
- Crust and Mantle are distinctions in composition, so they show up
Velocity Profiles

• Uncertainty in arrival times can exceed 10 secs
  – Regolith disperses seismic wave fronts
• Two independent arrival-time datasets
• Network only lasted 8 of 18.6 year period
• Most recent work shows no velocity discontinuities in the mantle
Deep Moonquakes

• Very low stress drops, very weak
• Correlated with tides raised by the Earth
• Originate from 300 “nests”, repeatedly activated
• Nests appear to be located on Moon’s nearside
  – Hypothesis: Nearside more seismically active, correlates with mare basalts (huh?)
  – Hypothesis: Signal Attenuation (cont. next slide)
Deep Seismic Signal Attenuation

• Shear waves appear to be absent for those ray paths that probe the deepest portions of the mantle

• Consistent with laser ranging data suggesting a quality factor of 30 for the moon, good damper

• Scenario: Magma-filled fractures located in the deep mantle are relieving small stresses induced by Earth-raised tides
Core

- Core is smaller than other terrestrial/icy planets and satellites, 460 km
  - Density, radius, moment of inertia
  - Consistent with measurements of an induced magnetic field
- Rotational data indicates energy dissipation between a molten core and a solid mantle
Historical Magnetic Field

• Lunar samples have strong magnetizations
• Magnetization detected in orbit, but from what depth?
• Hypothesis: Moon had internal dipole
  – Difficult for such a small core
  – Age constraints indicate a field that turned on late, 3.9 Gya
• Hypothesis: Large impacts are responsible
Large impacts are responsible

• Generate a plasma that propagates strong transient magnetic fields

• High crustal fields appear to be correlated with basin ejecta

• Correlation between some strong crustal fields and the antipodes of some of the youngest and largest impact basins
  – Plasma cloud encircles moon and amplifies field diametrically opposite the impact
Both Hypotheses

• Early dynamo exits
• Iron poor regolith, does not retain signal
• Impact basins create by iron-rich impactors do retain field
• Antipodal fields are still created via plasma
• Still questions remain on how a field could be maintained with such a small core
Future Experiments Needed

• Seismic Network with lateral and temporal expanse
  – Characterize the core, measure waves that pass through it
  – Understand “nests”, tidal?
  – Crustal thickness, dichotomy?

• Samples
  – SPA, understand difference in morphology
  – How deep is magnetization?
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