Recent re-analyses of the Apollo lunar seismic data: Insight into the Moon’s deep interior

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Moon’s moment of inertia roughly approximated by homogeneous sphere 
\( I_{\text{solid}}/MR^2 = 0.3930\pm0.0003 \), so if a core is present, it must be small.
Seismic measurements found...

- No seismic energy originating from far side penetrated the core, so it is likely attenuating
- Deepest moonquake source regions ~1200-1400km depth; so core likely 300-500km radius
Indirect measurements found...

Lunar Laser Ranging (LLR):

- LLR began precise monitoring of the Moon’s geodetic parameters in 1969
- Dissipation provided the first LLR evidence for a fluid core
- Fluid core radius = 352km if iron, or 374km for a Fe-FeS eutectic composition
Magnetic Induction

- In April of 1998, the Lunar Prospector orbit plane was nearly parallel to the Sun-Moon line, optimally oriented for using the magnetometer to detect an induced moment in the Earth's geomagnetic tail.
- Assuming that the induced field is caused entirely by electrical currents near the surface of a highly electrically conducting metallic core, the preferred core radius = 340+90 km.
- For an iron-rich composition such a core would represent 1 to 3% of the lunar mass.

Crustal remnant magnetization also suggests the Moon’s core once supported a dynamo.
Compositional constraints:

- Over the past 30 years, estimates of siderophile ("metal-seeking") elements in the lunar mantle have been used to argue for the presence of a small metallic core (0.1–5.5 lunar wt%).

<table>
<thead>
<tr>
<th>Study</th>
<th>Core Mass Fraction (%)</th>
<th>Core Radius (km)†</th>
<th>Silicate Mantle Degree of Melting (%)</th>
<th>Core Ni Abund. (wt%)</th>
<th>Bulk Moon Comp.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newsom (1984)</td>
<td>2.0 – 5.5</td>
<td>369 – 517</td>
<td>2 – 9</td>
<td>12 – 25</td>
<td>CI</td>
</tr>
<tr>
<td>O’Neill (1991)</td>
<td>~1</td>
<td>~ 293</td>
<td>0</td>
<td>35 – 55</td>
<td>PUM, CI, H</td>
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<tr>
<td>Ringwood &amp; Seifert (1986)</td>
<td>0.4</td>
<td>216</td>
<td>0</td>
<td>40</td>
<td>PUM</td>
</tr>
<tr>
<td>Righter &amp; Drake (1996)</td>
<td>1</td>
<td>293</td>
<td>100</td>
<td>43</td>
<td>PUM/CI/H</td>
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<tr>
<td>Righter &amp; Drake (1996)</td>
<td>5</td>
<td>500</td>
<td>100</td>
<td>8.3</td>
<td>PUM/CI/H</td>
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<tr>
<td>Righter (2002)</td>
<td>0.7 – 1.0</td>
<td>260 – 293</td>
<td>100</td>
<td>20.0 – 25.7</td>
<td>Proto-Earth/Impactor</td>
</tr>
</tbody>
</table>

*CI (CI chondrite); PUM (Primitive upper mantle); H (H chondrite).

†Assuming a core density of 7 g cm⁻³
Uncertainties are also evident in seismic velocity models

seismic only:
Nakamura 1983
Khan 2000, 2002
Lognonne 2003
Gagnepain-Beynix 2006

joint seismic & gravity:
Khan 2007

free oscillations:
Khan 2001
Uncertainties are also evident in seismic velocity models

sources of velocity uncertainty include:

• P and S pick error
  o Long-duration codas caused by the scattering and reverberations of seismic energy in the highly fractured lunar regolith, which leads to emergent, rather than impulsive arrivals.
  o Limited bandwidth of the Apollo instruments meant that many events occurred at or near the detection threshold of the instruments

• Small number and limited geographical extent of seismic stations
• Depth and location uncertainty of moonquakes
• Assumed velocities in overlying layers

Error level:

➢ Anywhere from 100 to several hundred m/s uncertainty in seismic velocities, the lower bound of which is on the threshold for mineralogical interpretations
Some attempts at seismic tomography

- P- and S-wave arrivals from a variety of seismic signals are fit on a 3-D grid via velocity perturbations in the mantle and crust (Zhao et al., 2008 & 2012)
seismic models of the core based on recent re-analyses

Garcia et al., 2011

Average of scaled ScSH NRJ over all events

Core radius (km)

Radius inside the Moon (km)

Vp or Vs (in km/s) or density (in kg/cm^3)

core radius = 380 ± 40 km
seismic models of the core based on recent re-analyses

Weber et al., 2011

core radius = 330 ± 20 km
Williams et al., 2014 family of core models consistent with geodetic parameters

### Table 8. GRAIL Primary Mission (GPM) Models That Satisfy Mean Density, Mean Solid Moment, Love Number, and a Deep Mantle Low-Velocity Zone

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GPM1</th>
<th>GPM2</th>
<th>GPM3</th>
<th>GPM4</th>
<th>GPM5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_f$</td>
<td>372 km</td>
<td>350 km</td>
<td>325 km</td>
<td>300 km</td>
<td>278 km</td>
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<tr>
<td>$R_i$</td>
<td>0</td>
<td>183 km</td>
<td>230 km</td>
<td>259 km</td>
<td>277 km</td>
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<tr>
<td>$R_{iv}$</td>
<td>507 km</td>
<td>520 km</td>
<td>534 km</td>
<td>545 km</td>
<td>554 km</td>
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<tr>
<td>$M_f/M$</td>
<td>0.0150</td>
<td>0.0107</td>
<td>0.0064</td>
<td>0.0028</td>
<td>0.0001</td>
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<tr>
<td>$M_i/M$</td>
<td>0</td>
<td>0.0028</td>
<td>0.0055</td>
<td>0.0079</td>
<td>0.0097</td>
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<tr>
<td>$l_f/l_m$</td>
<td>$6.9 \times 10^{-4}$</td>
<td>$4.9 \times 10^{-4}$</td>
<td>$2.9 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>$2.9 \times 10^{-6}$</td>
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<tr>
<td>$I_{iv}/l_m$</td>
<td>0</td>
<td>$3.1 \times 10^{-5}$</td>
<td>$9.7 \times 10^{-5}$</td>
<td>$1.8 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
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<tr>
<td>$l_m/MR^2$</td>
<td>0.39338</td>
<td>0.39330</td>
<td>0.39322</td>
<td>0.39316</td>
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<tr>
<td>$k_2$</td>
<td>0.02422</td>
<td>0.02422</td>
<td>0.02422</td>
<td>0.02422</td>
<td>0.02422</td>
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<tr>
<td>$h_2$</td>
<td>0.04237</td>
<td>0.04237</td>
<td>0.04240</td>
<td>0.04240</td>
<td>0.04242</td>
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<tr>
<td>$l_2$</td>
<td>0.01076</td>
<td>0.01077</td>
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<td>0.01078</td>
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<tr>
<td>$k_3$</td>
<td>0.00951</td>
<td>0.00952</td>
<td>0.00952</td>
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<tr>
<td>$h_3$</td>
<td>0.02344</td>
<td>0.02345</td>
<td>0.02348</td>
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<tr>
<td>$l_3$</td>
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<td>0.00298</td>
<td>0.00298</td>
<td>0.00298</td>
<td>0.00297</td>
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<tr>
<td>$k_4$</td>
<td>0.00536</td>
<td>0.00537</td>
<td>0.00537</td>
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<tr>
<td>$k_{2f}$</td>
<td>1.441</td>
<td>1.441</td>
<td>1.440</td>
<td>1.439</td>
<td>1.439</td>
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<tr>
<td>$h_{2f}$</td>
<td>2.441</td>
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<td>2.439</td>
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<tr>
<td>$l_{2f}$</td>
<td>0.721</td>
<td>0.720</td>
<td>0.720</td>
<td>0.720</td>
<td>0.719</td>
</tr>
</tbody>
</table>

*The reference $R = 1737.15$ km.*
Is a partial melt layer required?

yes:

Khan et al., 2014

Inversion of lunar geophysical data (mean mass and moment of inertia, tidal Love number, and electromagnetic sounding data) in combination with phase-equilibrium computations

no:

Nimmo et al., 2012

viscoelastic dissipation model based on laboratory deformation of melt-free polycrystalline olivine
how to reduce uncertainty?

topic of presentation by R. Garcia