Lunar Laser Ranging

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Outline

- History of LLR
- Measurements & Detectors
- Science enabled by LLR
- Summary
History

• First retroreflector array positioned on lunar surface by crew of Apollo 11, July 1969

• 4 more positioned by Apollo 14, 15, and French built arrays on Soviet Luna missions
History

- Early ranging measurements at Lick, McDonald (right), CERGA (France)
- Now, APOLLO (Apache Point Observatory Lunar Laser-ranging Operation)
History

• First measurements good to ~20cm

• Ground station changes get this down to ~2cm in the 1980’s (even with a smaller scope!)

• Early data still vital for studying effects with long characteristic timescales
Measurements

\[ \vec{\rho} = |\vec{r}| + \vec{R}_M \cdot \hat{r} - \vec{R}_E \cdot \hat{r} \]
Measurements

- Light leaves laser on the ground...
- Best atmospheric seeing from the ground is \( \sim 1 \) arcsecond
- Beam diverges to 1.8 km diameter on lunar surface
- Apollo 3.8 cm diameter corner cube retroreflector only catches \( \sim 4 \times 10^{-10} \) of the incoming light
Measurements

- Spread of Apollo retroreflector $\sim 10$ arcseconds
- Beam diverges to 20 km diameter area on Earth’s surface
- A 1m telescope on Earth receives only $2 \times 10^{-9}$ of returning photons
- Total losses: $\sim 10^{-20}$! (not including additional problems like detector QE, mirror reflectance, etc. on ground)
The APOLLO Laser

\[ \lambda = 532 \text{ nm} \]
\[ E_{\text{pulse}} = 115 \text{ mJ} \]
\[ \nu_{\text{pulse}} = 20 \text{ Hz} \]
\[ \sigma < 100 \text{ ps} \]

\[ \Rightarrow \quad 6 \times 10^{18} \text{photons/sec} \]

- Need many pulses for multiple detections!
Detectors

Apollo 3.8cm retroreflector (right), and a 10cm retroreflector just qualified for lunar environment (left)

Apollo 15 retroreflector (300 3.8cm corner cube retroreflectors)
Detectors

- Physical size of Apollo arrays is now the limiting factor
- Changing orientation due to lunar libration causes spread in return times
Future Detectors

- Retroreflectors > 10cm could provide returns as good as the Apollo arrays
- However, they are more susceptible to thermal expansion, which becomes significant systematic error around ~1 mm
Science

• LLR can be used to test gravitational theory, in addition to serving as a probe of the Moon’s interior

• First, must correct for:
  • Precession, nutation, tidal acceleration, and the relative orientations of Earth’s equator, the lunar orbit, and the ecliptic
Testing GR with LLR

1. Is the Equivalence Principle exact?

- Equality of gravitational and inertial masses
  \[ M_{\text{inertial}} \times a = M_{\text{gravitational}} \times g \]

- Nearly all alternate theories of gravity predict EP violations
Testing GR with LLR

- **Weak Equivalence Principle:**
  - Laws of *motion* are the same for freely falling bodies and bodies in inertial reference frames

- **Strong Equivalence Principle:**
  - Laws of *nature* are the same in uniform static gravitational fields and non-inertial reference frames
Testing GR with LLR

How does gravity pull on itself?
Testing GR with LLR

2. Does the strength of gravity vary with time?

\[ F = G \frac{m_1 m_2}{r^2} \]

Current LLR constraint:

\[ \frac{\dot{G}}{G} < (4 \pm 9) \times 10^{-13} \text{ / yr} \]
Testing GR with LLR

3. Do extra dimensions/new physics alter the inverse square law?

- Modifying gravity to explain dark energy has repercussions for lunar orbit
- Accuracy needed to falsify/confirm such theories is within a factor of 10 of current LLR
Testing GR with LLR

4. What is the nature of space-time?

- GR predicts that a gyroscope moving through curved space-time will precess
- “Geodetic precession” of 19.2 ms/yr
- Earth-Moon system = gyroscope (essentially)
- LLR Constraint:

\[ K_{gp} = (-1.9 \pm 6.4) \times 10^{-3} \]
Testing GR with LLR

- **Parameterized Post-Newtonian Formalism**
  \[ \gamma = \text{space-time curvature produced/unit mass} \]
  \[ \beta = \text{measure of gravity’s non-linearity} \]

- In GR, \( \gamma = \beta = 1 \)

- **Current Constraints:**
  \[ (\gamma - 1) = (2.1 \pm 2.3) \times 10^{-5} \]
  \[ (\beta - 1) = (1.2 \pm 1.1) \times 10^{-4} \]
  (Shapiro Delay) (LLR)
Testing GR with LLR

Current and future science deliverables from LLR. LLR is the best test for all but WEP.

<table>
<thead>
<tr>
<th>Science</th>
<th>Timescale</th>
<th>Current (cm)</th>
<th>1 mm</th>
<th>0.1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Equivalence Principle</td>
<td>Few years</td>
<td>$</td>
<td>\Delta a/a</td>
<td>&lt; 1.3 \times 10^{-13}$</td>
</tr>
<tr>
<td>Strong Equivalence Principle</td>
<td>Few years</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 4.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>Time variation of $G$</td>
<td>~10 years</td>
<td>$9 \times 10^{-13}$ yr$^{-1}$</td>
<td>$5 \times 10^{-14}$</td>
<td>$5 \times 10^{-15}$</td>
</tr>
<tr>
<td>Inverse Square Law</td>
<td>~10 years</td>
<td>$</td>
<td>\alpha</td>
<td>&lt; 3 \times 10^{-11}$</td>
</tr>
<tr>
<td>PPN $\beta$</td>
<td>Few years</td>
<td>$</td>
<td>\beta-1</td>
<td>&lt; 1.1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Lunar Science with LLR

- Range measurements change due to lunar libration and tides
- Moments of inertia, lunar Love number $k_2$, and variations in libration are related to the Moon’s composition, mass distribution, and internal dynamics
Lunar Science with LLR

1. Core Mantle Boundary (CMB) Dissipation
   • Fluid core first proven by LLR through energy dissipation by flow of fluid along CMB
   • Depends on fluid core size, viscosity, CMB roughness

2. Free Physical Librations
   • Could be stimulated by eddies at CMB, LLR would see as irregularities in polar wobble
3. Fluid Core Moment of Inertia

- Depends on core density and radius
- Requires accurate long time span data

\[
\frac{C_f}{C} = (12 \pm 4) \times 10^{-4} \sim 390 \pm 30 \text{ km}
\]

(uniform iron core)

4. Whole Moon Moment of Inertia
Lunar Science with LLR

\[ \delta \rho = \text{Lower Mantle Density Contrast} \]

Constraints on core radius from moment of inertia and lower mantle density contrast
Summary

• LLR provides best constraints for GR (other than WEP) to date

• Also can provide valuable information of lunar interior

• However, now limited by size of Apollo arrays

• A wider distribution of larger retroreflectors would enhance sensitivity and maintain returns
Questions?
Sources


