Laboratory Tests of Gravity Workshop
Eöt-Wash Laboratory
Jan 5. 2007

Schedule:
1:00  Welcome and introductions
1:10  Overview of lab tests of gravity  (Eric Adelberger)
1:25  Tests of the gravitational inverse-square law  (Eric Adelberger)
1:45  Tests of Einstein’s Equivalence Principle  (Stephan Schlamminger)
2:05  Measurements of Newton’s constant G  (Jens Gundlach)
2:25  First laboratory tour
2:55  Coffee, cookies and discussion
3:20  Lunar Laser Ranging  (James Battat)
3:40  LISA gravitational wave detector  (Scott Pollack)
4:00  Preferred frame (Lorentz invariance) tests  (Claire Cramer)
4:20  Second lab tour
5:00  Bus arrives to pick up participants
Problems in unifying gravity with the other forces in physics have convinced many of us that we must be missing something BIG.

Important to test cherished concepts for possible clues about what that could be

- $1/r^2$ law
- Equivalence Principle
- Preferred frames?
WMAP view of the Anisotropy of the Cosmic Microwave Background
There really is a preferred frame set by the universe as a whole!

AAPT Workshop, Seattle January 2007
The Eöt-Wash® group in experimental gravitation

Faculty
- EGA
- Jens Gundlach
- Blayne Heckel

Staff
- Erik Swanson

Postdocs
- Seth Hoedl
- CD Hoyle
- Stephan Schlamminger

Current Grad students
- Claire Cramer
- Ted Cook
- Charlie Hagedorn
- William Terrano
- Todd Wagner

Primary support from NSF Grant PHY0355012 with supplements from the DOE Office of Science and to a lesser extent NASA

AAPT Workshop, Seattle January 2007
3 FAMOUS PROBLEMS WITH GRAVITY

• WHY IS GRAVITY SO WEAK?

Comparison of electrical & gravitational attractions of e and p at a given separation r.

\[ F_e = \frac{1}{4\pi \varepsilon_0} \frac{q_1 q_2}{r^2} \]

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

\[ \frac{F_e}{F_g} = 2 \times 10^{39} \]

• WHY IS THE COSMOLOGICAL CONSTANT SO SMALL?

• Einstein’s biggest blunder?
• Discovery of cosmic acceleration (Type 1A supernovae)
• Particle-physics predictions for \( \Lambda \) (vacuum energy)
  \( \sim 10^{120} \) larger than observed value!

\( \sim 10^{50} \) if supersymmetry is just around the corner

• WHAT IS THE DARK MATTER?

we know that most of the “gravitational” effects in the universe are not produced by normal matter
Parameterising breakdowns of $1/r^2$ law

- **Old-fashioned way**
  \[ F(r) = G \frac{m_1 m_2}{r^{2+\epsilon}} \]
  \[ \uparrow \]
  no theoretical basis

- **Modern way**
  \[ F(r) = G \frac{m_1 m_2}{r^2} \left[ 1 + \alpha \left( 1 + \frac{r}{\lambda} \right) e^{-r/\lambda} \right] \]
  \[ \uparrow \]
  
  - exchange of boson with $m > 0$
  - extra dimensions scenario when $r \sim R^*$
Any given test of the \( \frac{1}{r^2} \) law is sensitive to a restricted range of length scales.

\[ \frac{T_A^2}{r_A^3} = \frac{T_B^2}{r_B^3} \quad ? \]

-- need many different approaches to cover a wide range of length scales.
95% confidence limits as of 2000

- Laboratory
- Geophysical
- Earth-LAGEOS
- LAGEOS-Lunar
- LLR
- Planetary
- Excluded region

\( |a| \) vs. \( \lambda [\text{m}] \)
Does dark energy define a new fundamental length scale in physics?

$$\rho_d \approx 3.8 \text{ keV/cm}^3$$

$$\lambda_d = \frac{4}{\sqrt{\hbar c / \rho_d}} \approx 85 \, \mu\text{m}$$

a second “Planck length”?
95% confidence limits as of 2000
the Irvine experiment

Hoskins et al. PRD 32, 3084 (1985)
The hierarchy problem

- mass scale of gravity
  \[ V_N(r) = G \frac{M_m m}{r} = \frac{kc}{\hbar^2} \frac{m}{r} \]
  \[ M^0 = \sqrt{kc/G} \sim 10^{16} \text{ TeV} \]

- mass scale of particle physics
  \[ M_{SM} \sim 1 \text{ TeV} \]

Arkani-Hamed et al. solution to the problem


**assume that:**

- gravity propagates in all of the 7 extra dimensions of string theory
- SM particles are confined to a 4-dim "brane"
- some of the 7 extra dimensions are "large" while the remainder are "curled up" at the Planck scale \[ R_p = \sqrt{\frac{G \hbar}{c^3}} = 1.6 \times 10^{-33} \text{ cm} \]
Only gravity propagates in all the space dimensions

graviton is a closed string

standard model particles are open strings stuck to the 'brane'
  - quarks
  - leptons
  - gauge bosons

3+1 dimensional 'brane'
embedded in 10+1 dimensional space
Gauss’s Law and extra dimensions

Illustration from Savas Dimopoulis

AAPT Workshop, Seattle January 2007
Why might gravity get weak at separations less than 0.1 mm?

- The repulsive "gravity" deduced from cosmological data indicates that empty space has an energy of \( \rho = 4 \text{ keV/cm}^3 \).
- This corresponds to a length scale:
  \[ \lambda = \sqrt{\frac{\hbar c}{\rho}} \approx 0.1 \text{ mm} \]
- Sundrum's suggestion: the graviton string has a size of 0.1 mm. This prevents it from "seeing" the short-distance physics that produces most of the predicted vacuum energy.
- Prediction: gravity gets very weak at separations less than 0.1 mm.
PREDICTIONS FOR $\frac{1}{r^2}$ LAW BREAKDOWNS

![Graph showing predictions for different forces with arbitrary units vs. distance in millimeters. The graph compares Newton, ADD extra dimensions, and Sundrum models. There is an arrow indicating an unexplored region.]
The original Eöt-Wash instrument for testing the ISL at short length scales

**Advantages:**

- Planar geometry
- Can place rigid conductor between detector & attractor
- Signal $\omega \neq$ disturbance $\omega$
- Approximate null for Newtonian gravity with no cancellation of new short-range physics
- Twist readout insensitive to pendulum & wobble modes
the 10-hole pendulum

PhD project of CD Hoyle

AAPT Workshop, Seattle January 2007
the Stanford ISL Experiment using low-temperature micro-cantilevers

50 x 50 x 30 nm^3 Gold Test Mass

Cantilever

f_0

Au/Si Drive Mass

Fiber for interferometer

Cantilever

Cover wafer

Shield wafer

25 µm

Metallization

Drive mass

Piezo Actuator (+/- 130 µm at f_0/3)

Figure Not to Scale

All Figures courtesy of S.J. Smullin

J. Chiaverini et al, PRL 90, 15101 (2003); S.J. Smullin et al., PRD 72, 122001 (2005)
95% confidence-level constraints as of 2004
the 42-hole pendulum

- tungsten fiber, 20μm diameter, 80cm length
- leveling mechanism
- 3 aluminum calibration spheres
- 4 mirrors for tracking angle of deflection
- detector: 1mm thick molybdenum ring with 42 holes arranged in 21-fold rotational symmetry
- not pictured, 10μm thick Au-coated BeCu membrane, electrostatic shield

attractor: rotating pair of discs with 21-fold rotational symmetry, holes in lower attractor out of phase with holes in upper attractor to cancel Newtonian gravity

7cm
Dan Kapner assembling the 42-hole instrument

It doesn’t show, but he had a beard also

AAPT Workshop, Seattle January 2007
These data were taken with a calibration turntable stationary.

The raw signal is shown in the chart, with a 2-pt digital filter used in our 10-hole work and a 5-pt digital filter.
combined analysis of all 3 experiments
some “gee-whiz” numbers

- typical error corresponds to light spot on detector moving by 0.6 nm
- typical torque in our 42-hole experiments is \( \sim 1 \text{fN-m} \) with statistical uncertainty of \( \sim 0.006 \text{fN-m} \)
- corresponds to a force \( \sim (40 \pm 0.24) \text{ fN} \)
- suppose you could cut a postage stamp into \( 10^{12} \) equal pieces
- typical force is 60 times the weight of 1 of those pieces
- typical statistical error is \( \sim 1/3 \) the weight of 1 piece
the Fourier-Bessel pendulum

will be the PhD project of Ted Cook

AAPT Workshop, Seattle January 2007
The time has come to greet exhilaration and accomplishment at the bottom of this mountain. Decades of experience have lead you to the edge. Each moment must be precise and confident. At this point there is one direction: forward.
Velocity = Mass \times Acceleration

The time has come to greet exhilaration and accomplishment at the bottom of this mountain. Decades of experience have led you to the edge. Each moment must be precise and confident. At this point there is one direction: forward.