Fundamental Gravitation Physics
with a Torsion Pendulum

Jason H. Steffen
Brinson Postdoctoral Fellow, Fermilab
Princeton Physics Seminar
March 27, 2007
Fundamental Gravitation Physics
with a Torsion Pendulum

University of Washington
Paul Boynton, PI
Michael Moore
Ricco Bonicalzi
Keven McKenney

University of California
Riley Newman, PI
Eric Berg
William Cross

Fermilab
I
What Does “non-Newtonian” Look Like?

\[ V = -\frac{Gm}{r} \left(1 + \alpha e^{-r/\lambda}\right) \]
What Does “non-Newtonian” Look Like?

\[ V = -\frac{Gm}{r} \left(1 + \alpha e^{-r/\lambda}\right) \]

- regular gravity
- interaction length
- strength relative to gravity
What Does “non-Newtonian” Look Like?

\[ V = -\frac{Gm}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]
Detecting non-Newtonian Interactions
Detecting non-Newtonian Interactions

Newtonian gravity should cancel leaving residual non-Newtonian interaction
Identifying the Leading Systematic Effect

\[ U = \int \rho V d^3r \]
\[ = \int \rho \left( 1 + x \frac{d}{dx} + y \frac{d}{dy} + z \frac{d}{dz} + x^2 \frac{d^2}{dx^2} + \ldots \right) V \, dx \, dy \, dz \]

\[ \vdots \]

algebra

\[ \vdots \]

\[ = \sum_{nlm} M_{nlm} V_{nlm} \]
Identifying the Leading Systematic Effect

\[ U = \int \rho V d^3r \]
\[ = \int \rho \left( 1 + x \frac{d}{dx} + y \frac{d}{dy} + z \frac{d}{dz} + x^2 \frac{d^2}{dx^2} + \ldots \right) V dx dy dz \]

algebra

\[ = \sum_{nlm} M_{nlm} V_{nlm} \]

symmetries of electron orbitals
field moments
mass moments
Newtonian gravity satisfies Laplace's Equation. Thus, only terms for which $n = l$ contribute to the interaction. Call these “Newtonian Moments”.

Non-Newtonian forces do not satisfy Laplace's Equation and can contribute to the interaction for any combination of $n$ and $l$. When $n \neq l$, call these “non-Newtonian”.
Identifying the Leading Systematic Effect

large $n = l = m = 2$ mass moment (M222)

fabrication error
Identifying the Leading Systematic Effect

unwanted V222 gravitational field

pendulum response
What would be nice...
What would be nice...

No Newtonian mass moments.
What would be nice...

No Newtonian mass moments.

Large non-Newtonian mass moments.
What will do...
What will do...

No low-order Newtonian mass moments

One large, low-order non-Newtonian mass moment
Newtonian mass moments:

\[ V_{22m} = 0 \]
\[ V_{33m} = 0 \quad \text{(for all m)} \]
\[ V_{44m} = 0 \]
\[ V_{551} = 0 \]
\[ V_{661} = 0 \]
\[ V_{771} = 0 \]
\[ V_{881} = 0 \]

non-Newtonian moment:

\[ V_{311} = \text{Large} \]
How to design what will do...

Start with 5 rings.
How to design what will do...

Start with 5 rings.

5 radii
How to design what will do...

Start with 5 rings.

5 radii

5 heights
How to design what will do...

Start with 5 rings.

5 radii

5 heights

5 masses

15 parameters

Only \( m = 0 \) moments.

Use parameters to null Newtonian moments and to maximize 310 moment.
How to design what will do...

Now rotate by 90 degrees.

Nulled Newtonian moments remain zero.

Large 310 moment rotates into a large 311 moment.
How to design what will do...
Now for the Source Mass

Newtonian Potentials:
\[ V_{22m} = 0 \text{ (for all } m) \]
\[ V_{331} = 0 \]
\[ V_{441} = 0 \]
\[ V_{551} = 0 \]
\[ V_{661} = 0 \]
\[ V_{771} = 0 \]

non-Newtonian Potential:
\[ V_{311} = \text{Large} \]
Leading Systematic Effect

fabrication errors
Leading Systematic Effect

small unwanted gravitational field

very small pendulum response

small unwanted mass moment
Minimizing the Leading Systematic Effect

Exaggerated Source Mass Configurations

221
331
441
Minimizing the Leading Systematic Effect

Exaggerated Pendulum

221 pendulum

\[ V_{441} = \frac{d}{dz} V_{331} = \frac{d^2}{dz^2} V_{221} \]
Parts List: ISLV Pendulum

gold coated, fused silica, 240 grams
Parts List: ISLV Source Mass

stainless steel, 1500 kg
Part List: Exaggerated 221 Pendulum

aluminum, 240 grams
Parts List: Instrumentation

Room Temperature Apparatus
Parts List: Instrumentation

Cryogenic Apparatus
Parts List: Batelle Facility

Nike Missile Bunker
State of the System

- Both cryogenic and ambient temperature instruments are operating at BGPL
- Optimization and calibration will require another 3 to 4 months
- ISLV measurement tasks will begin in the summer of 2007
- Completion expected by spring of 2009
Conclusions

• Second-order sensitive to fabrication errors
• Source mass produces no low-order Newtonian fields by design
• Pendulum is not sensitive to low-order Newtonian fields by design
• Both pendulum and source are maximally sensitive to a gradient of the Laplacian of the non-Newtonian potential
• Cryogenic apparatus to reduce thermal noise and improve magnetic shielding
• Quiet both geologically and anthropogenically