Probing gravity at extreme scales

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Reporting on work done with:
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Gravity is:
• the most evident
• the weakest
• the least well known interaction in Nature

<table>
<thead>
<tr>
<th>Fundamental interactions</th>
<th>Normalized Strength</th>
<th>Effective Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Nuclear Force</td>
<td>$10^{38}$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Electromagnetic Force</td>
<td>$10^{36}$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Weak Nuclear Force</td>
<td>$10^{25}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>Gravity</td>
<td>1</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

Most of the empirical features of gravity and differences in phenomenology from the other interactions can be understood in terms of the parameters above.
The first laboratory experiment on gravity

Apparatus by Rev. John Mitchell, used by Henry Cavendish to “Determine the Density of the Earth”.

Cavendish’s measurement, transformed to a measurement of $G$, gives

$$G = (6.74 \pm 0.04) \cdot 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2} \quad \sim 0.6\%, \quad 1798$$

The best modern number

[adapted from J. Beringer et al. (PDG), Phys. Rev. D86, 010001 (2012)]

$$G = (6.6738 \pm 0.0008) \cdot 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2} \quad \sim 0.012\%, \quad 2010$$

At the same time we know

- the QED coupling constant, $\alpha$, to 0.3ppb
- $G_F$ to 0.5ppm
But one wouldn’t expect to find new physics in the absolute value of $G$

More interesting is to test if there are deviations from the $1/R^2$ law for gravity?

Such deviations can be though of as due to new forces originating from the mass or “similar properties”.

A convenient (but not necessarily correct!) parameterization assumes a Yukawa potential:

$$V(R) = G \frac{M_1 M_2}{R} \left( 1 + \alpha e^{-R/\lambda} \right)$$

$\alpha$: magnitude of the effect

$\lambda$: scale of the effect
What do we know
What do we know
We want to extend the knowledge at the extremes of this scale because this is where we know the least and where we expect to find new physics.

\( \lambda (\text{m}) \)

\( |\alpha| \)

\( \lambda (\text{AU}) \)
Warning: this talk is far from complete!

I hope that in the future we’ll have a review talk on this very important topic that, I think, deserves more attention.

1) I have no time to review the theory motivations or other experiments.

2) I will shamelessly concentrate on our recent work:


D. C. Moore, A. D. Rider, G. Gratta, Phys. Rev. Lett. 113 (2014) 251801 “Search for millicharged particles using optically levitated microspheres” (Demonstration of a new technique being developed to measure $1/R^2$ at very short distance)

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The long distance regime

There is really nothing like “going there”.

So the plots showing limits on an extra Yukawa terms only tell part of the story.

True modifications of gravity like DGP or MOND are very different and not well described by an extra Yukawa term. And these are models motivated by the Dark Matter and Dark Energy puzzles (even if they may not work well yet)

So “going there” possibly allows to test for the most relevant physics!
The long distance regime

Important challenges and requirements:

1) Getting there!
   Requires a light payload, heavy launcher, gravitational assists

2) Drag-free system to minimize interactions with the outside
   (except for the gravity from solar system’s bodies).
   ➔ Spacecraft flies around a “Proof Mass” that is truly ballistic

3) Further identify/fit away interactions of Proof Mass with spacecraft
   by rotating the spacecraft perpendicularly to the Sun’s direction.

4) Good quality telemetry (R(t) and v(t)). Because of distance and
   spacecraft rotation, require a relay craft, trailing the science
   instrument by ~10km.

5) Reliable (10yr lifetime) drag-free system micro-thrusters.
## Instrument/flight parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag Free spacecraft mass</td>
<td>200 kg</td>
</tr>
<tr>
<td>Experiment duration</td>
<td>7 yr</td>
</tr>
<tr>
<td>Distance reached</td>
<td>100 AU</td>
</tr>
<tr>
<td>Proof mass</td>
<td>1 kg</td>
</tr>
<tr>
<td>Proof mass radius (Pt)</td>
<td>5 cm</td>
</tr>
<tr>
<td>Thruster bandwidth</td>
<td>$10^{-2}$ Hz</td>
</tr>
<tr>
<td>Proof mass sensing deadband</td>
<td>10 µm</td>
</tr>
<tr>
<td>Correction period</td>
<td>100 s</td>
</tr>
<tr>
<td>Ranging measurement period</td>
<td>20 day</td>
</tr>
<tr>
<td>Proof mass discharging period</td>
<td>2 day</td>
</tr>
<tr>
<td>Micro-thrusters fuel mass (FEEPs)</td>
<td>&lt;50g</td>
</tr>
<tr>
<td>Spacecraft angular velocity</td>
<td>0.1 Hz</td>
</tr>
<tr>
<td>Spacecraft radial initial velocity</td>
<td>14 AU/yr</td>
</tr>
<tr>
<td>Relay craft distance</td>
<td>~10 km</td>
</tr>
<tr>
<td>RTG power</td>
<td>&lt;1 kW</td>
</tr>
</tbody>
</table>

Assume that a mission to 100AU with a ~2yr maneuvering phase and a ~5yr coast is feasible  
Realistic navigation with realistic launch windows needs to be designed by experts  

~100 AU is as far as one can go  

Maneuvering propulsion stage jettisoned before coast (when relay craft undocks and proof mass is released).
Dominant systematics

- Non-solar gravity in the solar system
  - Mass and density distribution of Kuiper Belt very poorly known
  - Best trajectory is polar; this can be achieved with a last gravitational assist designed to deflect the craft to the ecliptic plane (unique viewpoint!)
  - As a by-product the mission would measure
    \[ \delta G M_{KB} \sim 5 \times 10^{-4} \, G M_{Earth} = 0.5\% \, @ \, G M_{KB}^{\text{MAX}} = 0.1G M_{Earth} \]
    and KB’s mass weighed radius and ecliptic plane offset

- Ranging accuracy
  - Assume 1 m accuracy (this is conservative; feasible now with NASA DSN and “off the shelf” transponders)
  - Also use an aggressive option with 10 cm accuracy (possible with laser ranging under development)
Effect of the Kuiper Belt with a 1 m ranging accuracy, polar trajectory
Projected accuracy for Yukawa parameters

... and for non-Yukawa modification of gravity going to 100 AU is key.
Short distance regime: the challenges

1. G is very small (gravity is very weak). Since gravity can’t be shielded this is not obvious in very large objects.

2. Since \( F = G \frac{M_1 M_1}{R^2} = G \frac{\rho_1 V_1 \rho_2 V_2}{R^2} \)
   for materials we have access to (no Neutron Stars here!)
   \( \rho_1 \sim \rho_2 < 20 \text{ g/cm}^3 \), there is no silver bullet.
   In addition \( V \sim R^3 \), so \( F \sim G \frac{\rho^2 R^6}{R^2} \) It is clear that measurements at short distance become exceedingly difficult.
   Often the measured quantity is the acceleration of the test mass: \( a \sim G \frac{\rho R^3}{R^2} \sim G \rho R \)

3. At distances <100µm even neutral matter results in residual E&M interaction that are a dangerous background for these measurements
Most inverse-square law measurements done with wonderfully sophisticated versions of Cavendish’s setup.

As distances become shorter this approach becomes clumsy and substantial efforts have to do with “artificial” issues (e.g. how to machine a 5 cm diameter disk flat to µm level...).

In addition all previous measurements use mechanical springs.

We will use a force sensor similar in size to the range of interest and use “optical springs” that are much more versatile than the mechanical ones.

[Note: The ideal probe for such a measurement would be a neutron, because its charge radius is ~1fm instead of ~1nm (for atoms). Unfortunately we do not know how to manipulate a neutron sufficiently well to use it here.]
Optical traps offer important advantages

- In high vacuum can cool the force sensor (µsphere) with everything else at room temperature.
- Thermal and vibrational noise from mechanical support minimized.
- Test mass position can be controlled and measured precisely with optics.
- Trap parameters can be changed instantaneously.
- Control of optical potential and motion in all 3 DOF allows powerful differential measurements.
- Dielectric spheres from ~10 nm to 10 µm commercially available.
- Extremely low dissipation is possible: \( Q \sim 10^{12} \) at \( 10^{-10} \) mbar

Geraci et al., PRL 105 (2010) 101101
Simplified optics setup

- 1064 nm trapping laser, up going using single mode fiber as spatial mode cleaner
- 650 nm imaging laser
- Position sensitive PD for high bandwidth feedback and CCD cameras for imaging
- FPGA forms feedback signals on the laser power (vertical) and beam steering (horizontal) DOFs
- μspheres are dropped in ~1 mbar N₂ from a vibrating quartz beam
- System pumped to ~10⁻⁶ mbar while starting the feedback cooling
Can readily cool µspheres to <100 mK, with everything else in the apparatus being at room temperature.

- Note that this is the “temperature” of the center-of-mass DOFs. We do not know the internal temperature of the µsphere.
- Can maintain µspheres in this state for days.
µspheres are often left in a charged state after being trapped.

- This can be measured by applying an RF potential to a set of plates
- µspheres are discharged by flashing a UV light.
How close to 0 is “0 charge”?

There are small residuals but the response is not consistent with an effective charge.

The largest residual can be conservatively used as a limit to particles with a “millicharge” bound into/onto the μspheres.

Kim et al., PRL 99 (2007) 161804

Recently re-built the system to attack gravity.

Stiffer optics & optics enclosure to mitigate air currents ➔ lower noise.

Can also be He filled (not tried yet)
Force sensitivity was limited by the residual charges on some of the components in the vacuum system, particularly the lenses forming the traps. ➔ New system has “funnels” shielding the lenses and makes extensive use of Au-plating.

6 “funnels” can be independently biased.
We expect the effect of the shielding to be dramatic.

Simulated field from 10 V on one of the lenses
We are in the process of doing a first measurement of Casimir’s forces at a range of distances to a Au-plated cantilever.

By now we can bring the µsphere <1µm from the cantilever
First attractor-set will alternate Au-Cu and will be Au-coated to reduce the EM contrast. Will be mounted on a fast flexure stage to swing it in front of the μsphere.
Expected backgrounds: Casimir forces

We will measure this next, using higher E&M contrast from an un-coated Au-Cu array.
Topography and surface potential for sputtered Au film:

Expected backgrounds:

Patch potentials

Calculation of force due to patch potentials:

- Current force sensitivity
- Pressure limited, $10^{-9}$ mbar
Projected sensitivity

Current force sensitivity
(noise at $5 \times 10^{-17} \text{ N Hz}^{1/2}$)
Pressure limited sensitivity
(at $10^{-9} \text{ mbar}$)

Existing limits are the envelope of:
- Decca et al, PRL 94 (2005) 240401 (microoscillator)
- Sushkov et al, PRL 107 (2011) 171101 (torsion pendulum)
- Geraci et al, PRD 78 (2008) 022002 (micromechanical torsion oscillator)
- Kapner et al, PRL 98 (2007) 021101 (torsion pendulum)
Conclusions

• Dark Matter and Dark Energy, along with theoretical difficulties in quantum gravity may suggest that gravity is the next frontier!
• The experimental study of gravity at extreme scales may reveal exciting physics beyond the SM.
• We have produced the 0th order design of a relatively modest (as these things go) deep space mission to improve our sensitivity to Yukawa corrections to the $1/R^2$ law of gravity by more than a factor of 100 at 100AU and, maybe more important, directly sample gravity there.
• We have developed a technique to measure very small forces at $<100\mu m$ distance using dielectric $\mu$spheres and, as a spring, the field of a focused laser in vacuum.
• The ability of manipulating $\mu$spheres and the force sensitivity well below $10^{-18}$ N promise to obtain a very sensitive method for detecting new forces at short distance.