

Testing Newton's $1/r^2$ law of gravity at sub-millimeter distances.

University of Washington Research Experience for Undergraduates

with

The Eöt-Wash Group

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Gravity was the first of the fundamental forces to be discovered, yet today it remains one of the least understood and most enigmatic areas of physics. From the days of Newton a basic understanding of gravity has existed, including quite accurate descriptions of its behavior over long distances. Yet today the highly successful Standard model fails to explain gravity's presence even while encompassing nearly all of the rest of what is known about physics. What leads to this inability to account for gravity along with numerous other gravitational mysteries? The answer may lie not in the vastness of solar systems and galaxies or in the unfathomable smallness of the Planck length, but instead at millimeter sized distances that we see around us each day.

There are numerous questions related to the problems of gravity, and with them comes plentiful motivation for further investigation into gravity. Topics such as the cosmological constant, evidence of additional spatial dimensions, the hierarchy problem, tests of the equivalence principle, planet formation, and numerous others are all likely candidates to be found in any discussion of the importance of a greater understanding of gravity.

These motivations are certainly related to the $1/r^2$ law tests being done by the Eöt-Wash group. However, the problems that may eventually be solved are only loosely connected to the work that was actually done in this project. As such the focus of this paper will remain on the significance of the new design and the work that was done, rather than the motivations

behind such work.

However, a brief discussion of the $1/r^2$ law itself along with one major application related to it will be appropriate, and may allow for some more concrete understanding of what is to be gained by these tests.

In the three plus one (three spatial plus one time dimension) world that is observed around us gravity spreads in the three spatial dimensions, effectively in a sphere. As gravity spreads, its force is “diluted” in conjunction with the increase in the surface area of the sphere. The surface area of a sphere is proportional to the square of the radius of the sphere. Thus, in the readily observable universe gravity appears to fall off at a rate proportional to this dilution. This results in the familiar Newtonian equation for gravity.

$$F = G m_1 m_2 / r^2$$

This description of gravity has proven to be very accurate on large scales since its inception. However, only recently have measurements of this phenomenon on small distance scales (less than one centimeter) begun to take place. Thus, it is possible that this equation may no longer hold at distances smaller than this. On its own this may seem to be of little consequence. There may seem to be no real motivation to think that gravity would behave differently on these scales, or even on any scale.

However, many of the problems in gravity tie to this in some way. For example, String theory predicts that there are additional spatial

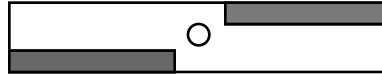
dimensions. Some theorists believe that some of these dimensions may be macroscopic instead of on the order of the Planck length. Because the strength of gravity as we know it is based on a three spatial dimension universe it is easy to see that a situation with additional spatial dimensions would result in a different law of gravity (i.e. not $1/r^2$, but for n spatial dimensions you would expect $1/r^{(n-1)}$). Thus, testing the $1/r^2$ law on shorter distances can rule out scales for these extra dimensions. In other words, if gravity obeys the inverse square law at distances of one millimeter, then any extra dimensions must be no larger than one millimeter.

In the past the $1/r^2$ tests being done by the Eöt-Wash group have involved a multi-fold rotationally symmetric torsion pendulum. This design has met with considerable success and has been used to significantly improve the level at which gravity has been tested.

This project involves a completely new design involving a vertical plate “step” pendulum. This design takes advantage of the fact that the gravitational field above a uniform infinite plane is constant. A mass placed at any point near the plane will always experience the same gravitational attraction. It is important to note that this is only true in three dimensions, that is, when the $1/r^2$ law is correct.

With this in mind, a large flat attractor mass can be used to provide a uniform gravitational attraction for the step pendulum (see Figure 1).

Top view of step pendulum.



“Infinite” attractor plate.

Figure 1: Shown from above a step pendulum made of two materials hangs near a larger attractor plate. For small separations this approximates and infinite plane.

For small separations between the pendulum and the attractor plate, the plate will simulate an infinite plane. The step pendulum is made of two materials. The bulk of the pendulum is a light material (such as aluminum or titanium) while the small inserts are a much more dense material (such as tantalum). Because the gravitational attraction of the plate is the same at all points it does not matter that the steps are different distances from the plate. Thus if the one inverse square law is not violated the pendulum will experience no torque. However, if gravity were to depend instead on a $1/r^4$ law then the attractor plate could only “see” the closer insert. The more distant insert would be too far away and the pendulum would then experience a torque.

The work that has been done this summer has been the actual construction of such a system including work on optics for detection of

pendulum movement, a vacuum chamber, a “non-mechanical” (i.e. not geared and very smooth motion) apparatus for moving the attractor plate, translation stages for pendulum placement, construction of hydraulics for the control of the attractor mass apparatus, and electronics for capacitive feedback control of the attractor mass.

Some design work was also done on the step pendulum, however, further revision will be required before a reasonable design can be reached. This work will include determining optimum materials for both the pendulum body and the inserts as well as determining a method for creating a mirror finish on the pendulum. Both the body and insert surfaces must have a mirror finish to allow for the optical detection of pendulum motion.

The significant portion of this work has been very practical applications in machining, vacuum systems, electronics, hydraulics, optics, computer aided design, and other areas. A significant amount of time was also spent reading relevant literature. This included literature about previous work in the Eöt-Wash group as well as material about the motivations behind gravitational testing including both experimental and theoretical work.

In time this pendulum will provide important information one way or another. If the design is successful it is reasonable to expect an improvement in the limits on the size of extra dimensions by a factor on the order of one hundred. However, there is one problem in particular that

may pose a challenge to the success of this design. This problem is that of “patch effects”. This refers to the uneven distribution of dipole moments on the surfaces of the pendulum and the attractor mass. Such distributions could cause attractive or repulsive forces between the plate and the pendulum that would far outweigh the desired gravitational effects.

Even if these patch effects do not allow this design to provide its full potential benefits, the knowledge gained about patch effects will be important none the less. In particular the upcoming NASA project LISA (Laser Interferometer Space Antenna) is interested in these effects. This is a possible source of funding for the $1/r^2$ project, even though the LISA group’s interest is not based on the $1/r^2$ results, but instead on the information about how close the pendulum and attractor mass can be without being affected by patch effects.

This is an interesting example of the ability of a project to function in more than one way and benefit more than one group. Certainly, the results from this pendulum may shed important light on extra dimensions, the LISA project, as well as many other gravity related questions both more and less directly.

The immediate future of this project is fairly clear. A suitable pendulum must be designed. Although some work can be done with something as simple as a glass mirror pendulum, most of the substantive work will require a step pendulum. In the meantime there is more work to

be done with electronics and the actual assembly of the existing parts. Although much work has been done, there is much more to do. However, in the foreseeable future the first real runs with this pendulum will be possible.