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The “dark side” of gravitational experiments

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Abstract Theoretical speculations about the quantum nature of the gravitational interaction have motivated many recent experiments. But perhaps the most profound and puzzling questions that these investigations address surround the observed cosmic acceleration, or Dark Energy. This mysterious substance comprises roughly two-thirds of the energy density of the universe. Current gravitational experiments may soon have the sensitivity to detect subtle clues that will reveal the mechanism behind the cosmic acceleration. On the laboratory scale, short-range tests of the Newtonian inverse-square law (ISL) provide the most sensitive measurements of gravity at the Dark Energy length scale, $\lambda_{\rm d} = (\hbar c/\rho_{\rm d})^{1/4} \approx 85\,\mu$m, where $\rho_{\rm d} \approx 3.8\,$keV/cm^3 is the observed Dark Energy density. This length scale may also have fundamental significance that could be related to the “size” of the graviton. At the University of Washington, we are conducting the world’s most sensitive, short-range test of the Newtonian ISL.

Gravity and the fundamental nature of Dark Energy

Since ancient times, the skies have offered patient observers clues to use in answering the fundamental questions regarding the nature of our universe. The recent discovery of the cosmic acceleration [1–3], interpreted as the existence of “Dark Energy,” is a modern-day example of one of these groundbreaking

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realizations. For many, the fact that we have no concrete interpretation of this phenomenon, which observations [1–3] have determined comprises roughly 70% of the mass-energy density of the universe ($\rho_d \approx 3.8\,\mathrm{keV/cm^3}$), is the most fundamental problem confronting physicists and astronomers today. Indeed, quantum mechanics predicts such repulsive effects from the vacuum energy density; however, the observed ρ_d is at least 10^{60} times smaller than the value computed by standard methods (the "cosmological constant problem"). Thus, we are forced to accept that the accelerated universe must result from either quantum mechanical effects beyond the scope of the Standard Model or a new property of the gravitational interaction itself.

In order to answer the question "what is Dark Energy?" we must have theoretical inspiration and experimental innovation, because the manifestation of the effects of Dark Energy will be very subtle if investigated in the laboratory, or require the most sophisticated astronomical equipment. Investigations into the nature of gravity may also lead to insights regarding the properties of Dark Energy. It is not surprising that tests of gravity and research concerning Dark Energy are intimately related, as indeed Einstein had surmised with his introduction of the "Cosmological Constant," because both phenomena affect the dynamics of our universe over large (and possibly small) distance scales.

Experimental tests of gravity are traditionally motivated by the desire to observe its quantum mechanical properties, including effects predicted by string theory or hypothesized new forces mediated by exotic particles. However, several interpretations of the accelerated universe make specific predictions that could be observable in current high-precision experiments devoted to probing gravity at laboratory distance scales. The elegance of such experiments lies in the fact that they are able to test many facets of General Relativity and the Standard Model (and extensions of the two) as well as Dark Energy scenarios.

If it is indeed possible that Dark Energy will reveal its properties in gravitational tests, naturally we should turn our attention to the most precise experiments. Amazingly, the most sensitive short-range tests of gravity are still performed with modern, high-precision versions of an age-old instrument: the torsion pendulum! And at astronomical distances, the most precisely characterized gravitationally bound system we may investigate is that of the Earth and Moon. Although these are two vastly different experimental systems, the search for clues to understanding the nature of Dark Energy is underway through current research at the University of Washington utilizing both types of experiment: the Apache Point Lunar Laser-Ranging Operation (APOLLO) and the Eöt-Wash short-range tests of the Newtonian inverse-square law (ISL). In the interest of brevity, we will concentrate on the latter, although both systems are currently performing groundbreaking measurements of gravity.

"Fat" gravitons, the cosmic acceleration, and Newton's inverse-square law

Raman Sundrum proposed a model [4] that explains the acceleration of the universe as being a result of the fact that the graviton is a "fat" object and

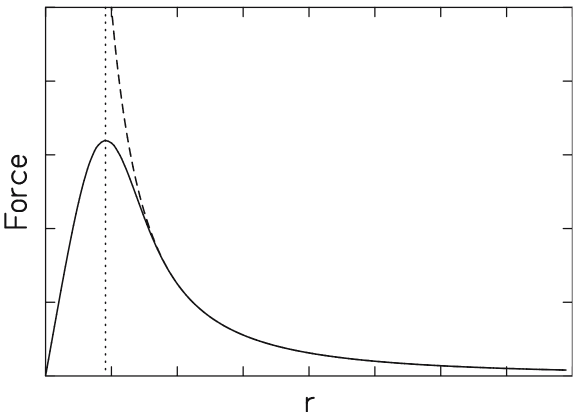

Fig. 1 Gravitational force between two point masses as a function of separation. The *dashed line* shows the usual Newtonian $1/r^2$ behavior. The *vertical dashed line* represents the Dark Energy length scale, λ_d, and the *solid curve* shows how the force would be reduced for small separations in Sundrum’s “Fat Graviton” model

can thus not participate in physics occurring over distance scales smaller than its “size,” where vacuum energy processes should be important. Furthermore, the graviton’s size may be related to the length scale associated with the Dark Energy density, $\lambda_d = (\hbar c/\rho_d)^{1/4} \approx 85\,\mu$m (a similar scenario with more general arguments was proposed by Beane [5]). Objects separated by less than this distance would feel a reduced gravitational attraction in this scenario, and the force vanishes for test masses with zero separation (see Fig. 1). Thus, Newton’s ISL will break down for test mass separations below about $100\,\mu$m if Sundrum’s picture is true. Astonishingly, distance scales comparable to λ_d were until recently experimentally unexplored by gravitational tests. This is due to the inherent weakness of gravity relative to electromagnetic, thermal, and other backgrounds in laboratory-scale experiments. In order to obtain gravitational sensitivity at the Dark Energy length scale, it is necessary to bring test masses within this distance and suppress electrostatic effects that are inherently 10^{40} times stronger. Remarkably, the torsion pendulum remains the most sensitive instrument for performing such measurements.

In the Eöt-Wash group at the University of Washington in Seattle, we are currently performing the most sensitive searches for deviations from the Newtonian ISL at the Dark Energy length scale. Our group has consistently performed the most sensitive experiments that probe gravity at short distances [6,7] since the renewed interest in such tests was brought about by speculations concerning the existence of large extra dimensions allowed by string theory [8]. Over the last few years, we have optimized our torsion pendulum design for short-distance measurements. The most recent version of the torsion pendulum, with the rotating attractor test masses, is shown in Fig. 2.

The “active” part of the pendulum, which hangs from an 80 cm-long tungsten fiber, is the molybdenum ring at its bottom containing 21 sets of holes spaced evenly spaced about the azimuth. Below the pendulum is a similar pair of rotating attractor disks. The “missing mass” of the holes in the pendulum ring interacts gravitationally with the missing mass of the attractor holes. Thus, as the attractor rotates, the gravitational potential energy varies with angle and

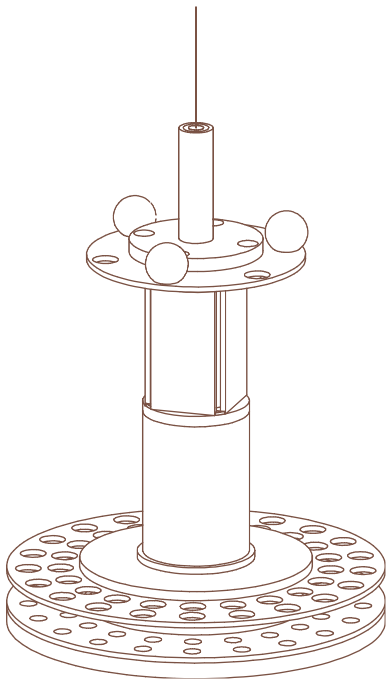

Fig. 2 Eöt-Wash torsion pendulum and rotating attractor used in short-range gravity tests. The three small spheres near the top of the pendulum are used for a continuous calibration of the torque scale. The four rectangular mirrors comprise part of the angle readout system. The rotating attractor disks can be seen below the pendulum. The 10 μm-thick conducting membrane that separates the pendulum and attractor is omitted for clarity

a torque is produced on the pendulum that is modulated 21 times per attractor rotation period. This torque causes the pendulum to twist by a small amount that is measured by the deflection of an optical beam. With the attractor rotating at frequency ω, a Fourier analysis of the pendulum twist reveals harmonic components of the applied torque at 21ω, 42ω, 63ω, etc. (the variation of the potential energy is not purely sinusoidal at 21ω). The lower attractor disk (made of tantalum instead of molybdenum) has holes that are placed precisely between those of the upper disk and produce a 21ω torque that is out-of-phase with that of the upper disk. This "cancellation" of the 21ω signal greatly reduces the Newtonian torque, while any short-range effect is not suppressed because it cannot "see" the holes in the bottom disk. By measuring the harmonic components of the torque on the pendulum as a function of its vertical distance above the attractor and comparing the measurements to a precisely calculated Newtonian prediction, we may search for a deviation from the ISL.

Because gravity is inherently weak and thus the pendulum twist is very small, the characterization of the pendulum and attractor masses, as well as suppression of backgrounds and systematic effects, requires very special attention. The largest source of possible systematic uncertainties arises from electrostatic backgrounds, but this concern is effectively avoided because we stretch a 10μm-thick conducting membrane between the pendulum and attractor masses that essentially eliminates electrostatic communication between the two. Other systematic effects are carefully reduced to negligible levels so that the dominant source

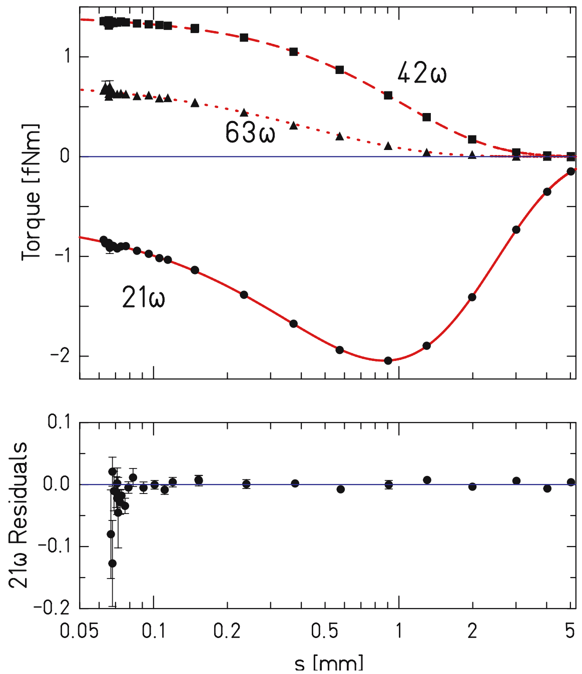

Fig. 3 *Top* Harmonic components of the torque on the pendulum as a function of distance above the attractor, *s*. *Bottom* Newtonian residuals of the 21ω torque. The agreement with the ISL is good for test mass separations above 80μm; however, we are currently investigating the small discrepancy at very short distances

of noise in the experiment is the thermal noise in the torsion fiber itself! Fig. 3 shows the measured harmonic components of the torque on the pendulum as a function of vertical distance from the attractor for the most recent completed data set, the residuals to the Newtonian fit are shown in the bottom panel. The experimental sensitivity is highly dependent on the minimum attainable separation, which for this data was $\sim 65\,\mu$m. The agreement with the inverse-square prediction is striking except for separations below about $80\,\mu$m, where the 21ω torque is smaller than the Newtonian prediction. While this happens to be consistent with Sundrum's model, it is also possibly due to a very subtle, unmodeled systematic effect such as finite temperature Casimir forces [9,10]. We are currently repeating the data set and investigating these possible spurious forces. If the deviation does not persist after careful analysis of all systematic effects, Newton may still be correct.

One may be easily convinced that the best way to search for deviations from the gravitational ISL is to reduce the size of the test masses to the length scale of interest, thereby reduced the Newtonian background and enhancing any short-range effects. We are currently planning a new pendulum and attractor configuration using modern precision fabrication techniques that will provide a dramatically increased experimental sensitivity. The active part of this "wedge" pendulum is shown in Fig. 4. The pendulum ring will be made from a rhenium foil, $50\,\mu$m-thick, with 120 wedge-shaped slots removed as shown. The foil will be attached to a flat substrate and the attractor disk will be identical. Due to the small characteristic length of the interacting test masses (wedges), the high

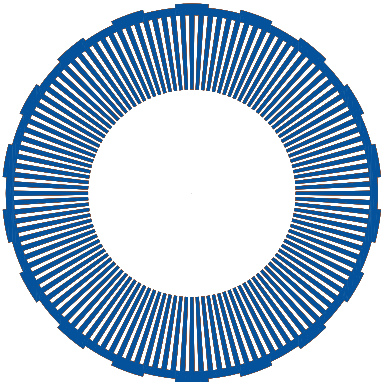

Fig. 4 Top view of the active mass of the new wedge pendulum design. The 120 pendulum wedges will interact with an identical, rotating attractor mass to produce a 120ω torque on the pendulum. The 18 wedges on the outer rim will provide an additional, long-range signal. The outer diameter of the ring is approximately 5cm

(21.04g/cm^3) density of rhenium, and a host of other apparatus improvements, we may expect a sensitivity increase of roughly a factor of 100 relative to our previous version. This new setup, expected to be operational this year, will have the sensitivity to probe any observed deviation from Newtonian physics to an unprecedented degree.

From the "Dark Ages" to a new enlightenment?

Just as experimentation in the field of electrodynamics experienced a "golden age" at the end of the nineteenth century, with current and forthcoming instruments designed for high-precision tests of General Relativity, it seems we are entering a similar "golden age" for gravitational physics. While probing a fascinating array of possible new evidence for string theory, quantum gravity, and extensions of the standard model, new experimental innovations and novel techniques could produce revelations about the true cause of our accelerating universe. One of the most sensitive techniques for performing such measurements is through short-range tests of gravity. In the near future we may be able to answer the puzzling questions posed by the existence of Dark Energy.

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