Physics for the 21st Century

Unit 3: Gravity

Eric Adelberger and Nergis Mavalvala

What is gravity?
Isaac Newton's gravity describes why an apple falls from the tree to the ground, and why the Moon orbits the Earth. But the rules of Newtonian gravity fall apart at the very smallest quantum scales and at enormous cosmological scales.

Eric Adelberger, of the University of Washington, is conducting experiments to see if gravity changes strength between our macroscopic world and the world of the subatomic.

> ERIC ADELBERGER*: And the test of this is very simply to study the gravitational force between two point masses, as you bring them closer and closer and closer together.*

Einstein's theory of general relativity describes gravity as the bending of space-time from matter and radiation. When the curvature of space-time becomes distorted by massive objects in motion, such as binary neutron star systems and black holes, a type of radiation known as gravitational waves is emitted and travels through space. But gravitational waves have not been directly confirmed.

> NERGIS MAVALVALA*: Einstein predicted them. He also worried that they were so tiny that they would never be observable. And direct observation has eluded us for the last century.*

Nergis Mavalvala, of the Massachusetts Institute of Technology, is working with the Laser Interferometer Gravitational Wave Observatory, or "LIGO," to directly detect, for the first time ever, a gravitational wave.

Mavalvala's work looks at gravity on the largest scales, while Adelberger peers into the smallest.

Both scientists may change the way the world understands gravity.

Part I: Gravity at the Shortest Scales

Eric Adelberger

At the University of Washington, Eric Adelberger is part of a team of researchers known as the Eot-Wash Group, who are making precise measurements of gravitational attraction at extremely short distances. Their measurements may provide insight to the role of gravity at the quantum level.

> ERIC ADELBERGER*: This is the laboratory of our Eot-Wash Group where we do all of our gravitational experiments. There are one, two, three, four, five, six, seven different gravitational experiments. In this big room is where a large number of the most precise laboratory experiments on gravity in the entire world have been done.*

Gravity is one of the basic forces we encounter in our lives and one of the first forces physicists tried to describe with equations. Yet 300 years after Newton first described gravity, it remains the least understood of the four forces of nature.

The Eot-Wash Group is attacking a puzzle that has long plagued gravitational physicists: why is gravity so weak compared to the other three fundamental forces of nature?

> BLAYNE HECKEL*: The other forces of nature, the strong nuclear force, the weak nuclear force and the electromagnetic force, are all similar in magnitude. They vary by maybe a factor of ten to the sixth, a million. Gravity is ten to the fortieth times weaker than those. That's one followed by 40 zeroes times smaller and that difference in scale is just a complete mystery.*

> ERIC ADELBERBER*: Why is gravity so weak compared to everything else? If you want everything to be unified you have a great problem explaining why one thing is 39 powers of ten weaker than another. How could they come from the same thing if they are so different?*

One possible scenario offered by theorists to explain the apparent weakness of gravity is that the universe is made up of more than three spatial dimensions. And that some of gravity's strength might be "leaking" into these extra dimensions.

> EA*: It's actually not weaker than anything else. It just looks weaker because lines of gravitational force so to speak can escape into*

these extra dimensions and the test of this is very simply to study the interaction between gravitational force, between two point masses, as you bring them closer and closer and closer together. If you get them sufficiently close, you would find that the inverse square law would break down for distances less than about a quarter of a millimeter and you would find gravity suddenly got much stronger than you would have expected if Newton were right.

To look for clues to explain quantum gravity, the Eot-Wash Group is currently testing Newton's 300-year-old inverse square law. They are testing gravity at the transition point where the influence of extra dimensions might appear between the macroscopic world and the quantum world.

EA: *People have speculated about possible experimental ways to see that something is wrong in the conventional picture of gravity and so our picture was we will take the things we believe in our hearts ever since we learned physics -- the inverse square law -- that are very very important and we will just test them to the best of our ability.*

Newton's inverse square law states that every object that has mass in the universe is attracted to every other object by a force that is inversely proportional to the square of the distance between them. This means that gravitational attraction between two objects becomes four times stronger each time the distance is decreased by half.

The law had only been tested to the scale of one millimeter. By testing at scales below one millimeter, the Eot-Wash team is looking for a departure from the inverse-square law in the strength of gravity. If they find a change in the strength of gravity, they may have found a clue to explain why gravity is so weak compared to the other three forces at the quantum scale, and could help solve the mystery of quantum gravity.

To try to accomplish this task, the Eot-Wash Group turned to a device from classical physics known as a torsion balance.

BLAYNE HECKEL*: So, a torsion balance is a very thin fiber, long thin fiber from which is suspended some sort of mass distribution. The simplest thing to imagine is a little dumbbell. If you move then a mass that will try to twist this dumbbell, suspended from the fiber by a small angle.*

By measuring the twisting of the pendulum, accurate measurements of the attractive force between the masses can be made. The Eot-Wash Group redesigned the classic torsion balance, dramatically increasing its

precision and pushing the boundaries of what could be measured.

They changed the dumbbell design to a more sophisticated one with horizontal discs. The top disc hangs from a thin fiber and is attracted to a similar disc below it. Then they drilled holes in the two disks.

> ERIC ADELBERGER*: To twist the torsion pendulum we came up with the idea of the holes. If there hadn't been any holes in this ring and there weren't any holes in this disc, gravity would simply pull straight down on this thing and there would be no way to twist it. Okay?*
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> *And so what we're doing is we're going to turn the disc underneath the pendulum very slowly very uniformly measure that twist by shining a light off of one of these 4 mirrors on the pendulum and we're going to measure the deflection, the twist of this pendulum, and that's going to be a measure of how strong gravity is.*

The gravitational force between the pendulum and the attractor depends on the position of the holes.

If the holes in the pendulum are perfectly aligned with the holes in the attractor, the gravitational pull is downward and the pendulum does not rotate. If the holes are misaligned, the attractor exerts a gravitational torque on the pendulum causing it to rotate.

To measure how strong gravity is between the two discs, laser light is bounced off the mirrors above the top pendulum disc. When the discs move back and forth, the deflected laser light is read by a sensor. These minute deflections are measured in nanoradians, only a billionth of one degree. These slight fluctuations are the data points for understanding if the inverse square law holds true.

> TED COOK: *So on the data here we're looking at the twist angle of the pendulum. We're also monitoring things like the pressure of the vacuum. And we also have lots of sensors just for looking at the temperature of the environment.*

The raw data the team collects includes extraneous effects in the lab. Seismic activity, traffic in the surrounding area, and even changing temperatures must be separated from the gravitational signal.

Once the extraneous effects are removed, the team graphs their clean gravity data. They then compare their data to the signal they would expect from Newtonian gravity.

The data from the first Eot-Wash pendulums showed that the inverse square law did, in fact, hold true down to a distance of 1/5 a millimeter or 200 microns…a distance that is only 1/10 the thickness of a penny. --- But that was only the beginning of their research. They went on to create a torsion balance that measured the attraction of gravity between two discs separated by less than 100 microns. This new 42-hole pendulum design tested the inverse-square law at distances that could indicate the existence of extra dimensions larger than 60 microns.

At this distance, the challenge for the Eot-Wash team was to design a torsion balance that could shield the overwhelmingly strong electromagnetic signal.

To minimize the electrostatic effects, the housing and the torsion balance were all coated in gold.

> ERIC ADELBERGER*: The number one problem in testing the inverse square law is getting rid of the effects of much, much stronger forces due to electromagnetism and almost anything else. And so the whole problem is getting rid of what we would call extraneous forces, non-gravitational forces.*
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> *So the basic strategy is to minimize electrostatic effects by having a pendulum that has no way except gravity to know what the attractor is doing underneath.*

The design reduced the electrostatic noise considerably and Adelberger and his team measured the inverse square law successfully at a distance of 1/10 of a millimeter. This astonishingly precise measurement further constrained the parameters in which extra dimensions could exist. Theorists who had previously predicted that gravity would change at these scales had to re-examine their ideas.

> EA: *Our latest published result says that the inverse square law holds down to a separation of 56 microns. So that's the important bottom line. We know the inverse square law now works down to that distance.*

The results from the EoT-Wash team again confirmed Newton's 300-year-old inverse square law. Their data refuted theories that predicted that extra dimensions would be revealed at this close distance. The fact the measurements didn't indicate a strengthening of gravity was a disappointment to extra dimension theorists --- and in some ways to the Eot-Wash Group as well.

> BLAYNE HECKEL*: Unfortunately Newton and Einstein have been*

right so far. I say it's unfortunate just because every experimentalist would like to make a discovery that is groundbreaking. But we're still looking for that effect that is actually out there that hasn't been detected before.

ERIC ADELBERGER*: And so the ultimate goal, of course, is to have one theory that explains everything including gravity, including strong interactions, including electromagnetic interactions, including weak interactions. So this goal is a very compelling one, certainly to me, because it's hard for me to believe that quantum mechanics doesn't operate in the gravitational realm as well as in everything else.*

"Why is gravity so weak?" still hasn't been answered. So, theorists will continue to refine their ideas and change their predictions for the size of extra dimensions. And the Eot-Wash Group is already keeping pace with a new generation of torsion balances. A pendulum with 120 wedge-shaped holes and a vertical plane pendulum have been designed to measure gravity at distances as small as 20 microns - a separation that is smaller than a single piece of dust. What they will find at these distances is completely unknown.

EA*: I would love it if we found something. Obviously, that would be profound. I mean I can't imagine the more exciting discovery than finding that the world really has more than three dimensions. I mean that's a fantastic thing.*

<u>Part II: Gravity</u>

Nergis Mavalvala

As Eric Adelberger continues to search for evidence that may help unify the four forces, Nergis Mavalvala is one scientist in a team of hundreds working on the Laser Interferometer Gravitational Observatory, known as LIGO.

Operated by California Institute of Technology and the Massachusetts Institute of Technology, LIGO's mission is to measure the wavelike effects of gravity at astronomical scales. Einstein predicted that massive energetic objects in the universe could warp space-time, and would leave a fingerprint of this space-time distortion known as gravitational waves.

NERGIS MALVALVALA: *So the idea there is as that wave radiates out it will deform the space around it and it arrives to us, as an observer, as a wave that's propagated out from a source, very* *similar to when you drop a rock in a pond and a ripple radiates out from where the rock was dropped.*

In Einstein's theory of general relativity, the structure of space is warped by the mass within it. When massive astronomical bodies, such as binary star systems and black holes move, they create space-time ripples that travel outward through the universe.

NM: *There is indirect evidence of these gravitational waves, but certainly we can't say we've directly gone out there and measured a gravitational wave interacting with a detector that was designed to measure them. Einstein predicted them. He also worried that they were so tiny that they would never be observable. And direct observation has eluded us for the last century.*

To try to directly measure the impossibly small signal of a gravitational wave is the life's work of Dr. Mavalvala and her LIGO colleagues. They have created a sophisticated "laser-based yardstick." This yardstick is among the most accurate in the world. It measures changes in distances that are almost inconceivably small, smaller than one-thousandth the diameter of a single proton.

This laser yardstick will be used to detect miniscule, fleeting changes in its overall measured length as gravitational waves sweep over it. The LIGO team is confident that their yardstick, made of two four-kilometer-long laser beam interferometers in Hanford, Washington and Livingston, Louisiana, will detect what has never been detected before.

GABRIELA GONZÁLEZ: *An interferometer measures the interference of light. The laser light goes 4 kilometers that way and you may be able to see at the very end. That's a building that houses the mirror that sends the light back again to us. Perpendicular to that we have the Y arm and it's the interference between these two beams what we use to measure the distortion in space-time produced by the gravitational wave. So what we are actually measuring is how different is that distance from that distance produced by this gravitational wave going through.*

This is the largest and most accurate interferometer ever built.

Inside the main building, a beam of laser light is split in two at a beam splitter and travels down the two perfectly sealed vacuum chambers that form the arms of the interferometer. After traveling four kilometers, the light bounces off mirrors at the end of the arms and returns to the beam splitter.

At the beam splitter, the returning laser beams are recombined. What

happens when the beams recombine depends on the distance they have traveled compared to each other. The LIGO team takes data by comparing the two beams relative phase -- how the peaks and valleys in the two waves of laser light line up. If the two waves are perfectly out of phase, if the peaks in one beam line up exactly with the valleys in the other, they cancel each other out, a phenomenon called destructive interference. In its normal undisturbed state, the LIGO mirrors are aligned for perfect destructive interference. The team takes advantage of this effect to detect gravitational waves.

> NERGIS MALVALVALA: *The gravitational wave, as it travels through space it's really warping the space-time. So, if there is a gravitational wave going in this direction here, as it moves through space-time it actually shrinks and stretches the space-time. So it's literally doing that.*

When a gravitational wave reaches the interferometer on Earth, it will shrink one arm and stretch the other arm. The distance between the mirror and beam splitter will change in each arm; therefore, the two laser beams will not be completely out of phase when they recombine. Instead, the peaks and valleys in the two waves will overlap, and as a result, when the beams recombine, some light will leak through the beam splitter and be recorded on the detector.

> RAINER WEISS*: And if a gravitational wave comes along which stretches the Y arm and shrinks the X arm, a little bit of light will then go to the anti-symmetric port and be detected. That little bit of light tells you that a gravitational wave has come by to disturb the balance of the two arms and that in fact is the signal that we detect.*

> NERGIS MALVALVALA: *You have these two sine waves that interfere at the beam splitter and, depending on what their relative phase was, the interference pattern translates into a light beam. It's essentially just a light beam whose brightness or dimness is proportional to the position of the mirrors.*

> *So, what we do is we take that light beam that's coming off of the beam splitter and we let it shine onto a photo detector. Now a photo detector is a device that takes light or photons and converts them into electrons, which is current. So what we are really doing in the end is we are actually measuring a current that's proportional to the light beam that hit the photo detector.*

> *We turn that current into a voltage and we turn it into a digital signal and store on our computers and then analyze that signal for gravitational wave sources.*

The first generation of the LIGO experiment has been observing for several years and has not detected any gravitational waves. One of the reasons they haven't is because of noise.

Noise can come from many sources: seismic events, a truck driving by, or even a person walking in the observatory. If the noise signal is too high, then it will easily overwhelm a gravitational signal.

> GABRIELA GONZÁLEZ: *This graph is measuring the seismic noise that's coming from the oceans and storms on the oceans and we call this micro seismic noise and we are very sensitive to it.*
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> *This graph is showing us the ground moving very slowly usually due to earthquakes. And if an earthquake happens then we can see the ground moving a lot and that's what happened 12 hours ago. So we have to learn to handle all these different situations to make sure we are able to push the mirrors and keep them in place.*
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> BRIAN O'REILLY: *One of the clever ideas is when the ground moves you can compensate using this hydraulic actuation system and move the suspended optic in a different direction -- in the opposite direction. So that when the ground comes up, in a very loose sense, the optic moves down. And so we can use that to suppress a type of noise that we see quite loudly here from the ocean waves hitting the coast of the United States basically.*
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> *And using the combination of the hydraulic system and this sensitive seismometer we're actually able to reduce that motion by a factor of ten. And it makes a huge difference~~.~~*

All of the changes currently being made to reduce noise are known as Advanced LIGO. When Advanced LIGO is complete, it is expected to be ten times more sensitive due to the reduction of seismic and thermal noise. These noise reductions will drastically improve Advanced LIGO's chances to confirm the existence of gravitational waves by making the interferometer sensitive to regions of space that are ten times further away, increasing the possible detections by a factor of 1000.

Once the seismic and thermal noise have been dramatically decreased, Mavalvala and the LIGO team must face an issue inherent in the interferometer design: light itself moves the mirrors.

One of the techniques Mavalvala is testing is known as squeezing light.

> NERGIS MAVALVALA: *So what did we do in this experiment? In*

this experiment, we had a very miniaturized version of a LIGO interferometer. But this interferometer has one very special added feature, which is that the mirrors at the ends of the interferometer are very small. They are one gram. They are about the size of a dime basically. And they still hang from little glass fibers but we keep them so small compared to the LIGO mirrors which are ten kilograms or advanced LIGO mirrors which are 40 kilograms because we want to study an effect that's going to show up in advanced LIGO without building advanced LIGO. So what is this effect? This is the effect of radiation pressure.

Photons of light carry momentum, and what happens is when you shine a light beam on an object, that light beam imparts its momentum to the object, and so indeed what we are trying to do in this experiment here is to observe the motion of this little one gram mirror due to the fact that it's being driven by the radiation pressure.

So your laser beam is made up of photons. The quantum mechanics tells us that you can never know the number of photons in your laser beam with infinite precision so you have some fluctuation in the number of photons. Now if you take that fluctuating number of photons and you let them hit your mirror, the radiation pressure fluctuates and the mirror motion fluctuates because of that so essentially we're trying to measure the fluctuating motion of the mirror due to this photon pressure.

The mini LIGO is set up to eliminate some of the uncertainty due to the fluctuating number of photons hitting the mirrors. A photon bouncing off of a mirror creates, however extremely tiny, a displacement. The noise in this displacement, if not corrected for, limits the ultimate accuracy of the experiment.

NM: *That's what we want to do in the mini-mirror experiment. We want to first show that the mirror is being driven by these quantum fluctuations of the light and then to test ideas for how to reduce those fluctuations so that you can improve the sensitivity of advanced LIGO. That's really part of what we're trying to study the mini-mirror experiment.*

Mavalvala and the LIGO team are continuing the painstaking, precise improvements in the sensitivity of LIGO, and one day they may become the first direct observers of gravitational waves. If they do so, they will confirm a prediction of Einstein's theory of general relativity. And they will open a window into viewing and understanding our universe on a deeper level.

NM: *And the payoff will be enormous regardless because if we* *really start detecting gravitational waves routinely then we've opened a new window into the universe, and if we don't, we have set off a new direction of head-scratching as to what is it about nature we don't understand.*

While Nergis Mavalvala waits for data that may confirm the effects of gravity at large scales, Eric Adelberger continues to design experiments to look for changes in gravity at the smallest scales.

Both scientists' work may soon produce results that change the way the world defines and understands the 300 year-old concept of gravity.