THE FLUID-FIBER BASED TORSION PENDULUM: AN ALTERNATIVE TO SIMPLY GETTING A BIGGER HAMMER

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THE FLUID-FIBER BASED TORSION PENDULUM: AN ALTERNATIVE TO SIMPLY GETTING A BIGGER HAMMER

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In the preceding lectures I've given in this school, I've tried to suggest that sometimes one needs to look for a new or different approach to a problem rather than simply proceeding to do everything slightly better or to make the same type of apparatus somewhat bigger. Today I'm going to talk about an alternative to the traditional torsion fiber which we have developed in connection with an experiment to check the equivalence of gravitational and inertial mass. This experiment, which asks the question -- "Do all materials fall at the same rate in a gravitational field?" -- is also known as the Eötvös experiment.

Let me begin with the first slide (slide 1). This reminds you that during the Apollo 15 mission one of the astronauts performed an Eötvös experiment on the moon. He dropped a hammer and a feather, and television viewers throughout the world saw them fall at the same rate. Joe Allen, the scientist astronaut who came up with the idea for this experiment, told me that in planning it, NASA was very much worried that, when the astronaut released the two objects, electrostatic forces would keep the feather hanging onto his glove and only the hammer would fall. Given the planned world-wide and live television exposure, this would prove somewhat embarrassing. How were they going to solve it? One suggestion was that they could weave a golden thread into the feather and thereby ground out any possible electrostatic problems. That solution, however, didn't appeal to NASA because it would be slightly dishonest to say you were dropping a feather when in fact it was an electrostatically-modified feather. In the end they decided that practice would make perfect, and gave the astronaut several feathers so that before the television event he could practice dropping them so as to be certain that everything would work just right. As you may remember, when the big moment came, the television cameras turned on the astronaut, he explained what he was going to do, he released the hammer and the feather and they fell beautifully together and landed at the same time. (The fact that g is 6 times smaller on the moon made it even better since the smaller acquired velocities made it very easy to follow visually.) A few hours later, Joe Allen, who was at mission headquarters, talked by a radio link to the astronaut and said "Hey, that was great! Did you have any trouble dropping the feathers earlier when you were practicing?" And he was told, "Joe, you saw the first time I did it."

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This same experiment, one which Galileo is often credited with having done by dropping different balls from the top of the leaning tower of Pisa, is known today as the Eötvös experiment. It is so named after Baron von Eötvös who in about 1900 performed a torsion balance equivalent of Galileo's free-fall experiment (slide 2). The next slide (slide 3), which I took in the London Science Museum, shows an Eötvös "apparatus" -- an apparatus originally designed to look for mineral deposits by observing the local gravity gradients. The next slide (slide 4) is a picture of the man himself looking inside an awning-covered thermal enclosure which surrounded his apparatus in the field. Today we often talk about technological fallout or spin-off from basic scientific research; Eötvös did it just the other way around. He took a practical device used extensively in mineral exploration work, and with it performed this very fundamental experiment that asks whether different materials fall at the same rate in a gravitational field.

This next slide (slide 5) is the cover of the December 1961 Scientific American, which showed the Princeton Eötvös apparatus. Some of you might ask, "What do American graduate students do when they first go to graduate school?" In my case, I constructed the mirrored fused-silica triangle portion of this apparatus. And it took me a whole summer to do it!

The next slide (slide 6) shows some of the overall scheme of this experiment. The origin of the signal, given a breakdown in equivalence, can be understood from the upper left-hand portion of the drawing. For the geometry shown, should the gold mass fall slightly faster toward the sun than the aluminum mass, this would result in a clockwise twist on the torsion fiber; twelve hours later when the sun is on the opposite side, the twist will be counterclockwise. The experiment therefore looks for a (small) 24-hour-period signal in the orientation of the torsion bar which connects the masses. The next slide (slide 7) is a detailed schematic of the torsion fiber pendulum.

In this talk I'd like to tell you about our approach to the Eötvös experiment, emphasizing what we do differently. Clearly, what you'd like to do in designing an experiment is to optimize its sensitivity. And as you might guess, the larger you make the test masses, the greater the torque (given a breakdown of equivalence) and therefore the greater the sensitivity you can hope to achieve. There's only one problem. If you make these masses very much larger than the order of 100 grams each, then the fiber has to be quite a bit bigger in diameter than that which various workers have used in the past ($\sim 10^{-3}$ inches), otherwise it will simply break. That is obvious. What may not be immediately obvious is that as the fiber becomes bigger in diameter it becomes not only stiffer but stiffer as the fourth power of the diameter! So if you make the diameter twice as big (so that it will support four times the weight) it will unfortunately became sixteen times stiffer; and this places even more severe requirements on the position detector if you are to utilize the larger-mass generated increase in potential sensitivity.

What are we doing that is different? Let's go back. Suppose you say, "I want to do a particular experiment, but I want to do it better." You might look for and read every book that's been written since time immemorial on the subject and then see if you can't do just a little bit better here and just a little bit better there. That works so long as the work was not done by clever physicists in the first place. But if the work was carefully done, then the chances that you can do it much better really aren't very great. In our case, rather than trying for a bigger hammer -- so to speak -- we tried to invent a different hammer.

The next slide (slide 8) shows our torsion pendulum. So where is the fiber? It's something like the emperor's new clothes; there really isn't any; and yet the system acts as if there were. The electrodes and the fluid act as a surrogate fiber. For what does a fiber do? First it holds an object up, then it centers it, and finally when the object is rotated it produces a restoring torque. That's all a fiber is. It doesn't have to look like a wire. Where is the fiber now? First, the water provides the support function (holds it up). If I put a voltage (and therefore a charge) on the center ball of the lid, it is going to induce an image charge on the central ball of the float which is going to cause it to center. That's the centering part of the fiber. The only thing still lacking is the fiber's restoring force and zero. If I put voltages on the two outer balls on the lid then the image charges on the outer float balls are going to provide a restoring force until they are aligned directly under the outer lid balls. Further, by simply changing this outer-ball voltage you can change the torsion constant (diameter) of this fiber. In our initial fluid-fiber Eötvös experiment which used tungsten and copper as the test masses, they were arranged in semicircular fashion as shown on the left side of this slide.

We also ran the experiment with the temperature of the water at 3.98°C where it has a maximum density. (The other possible fluid one could use is deuterium oxide which has its maximum density at 11.2°C.) (slide 9). That means that if you change the temperature of the system slightly at some place, the water there won't get any lighter (because its density does not change) and therefore it won't rise and thereby cause convection.

The next slide (slide 10) shows the results of a simple experiment that illustrates this maximum density effect. Take a metal can and put room temperature water in it with a thermometer stuck in the middle. Now insert this into a beaker filled with ice and having some sort of insulating cover as is shown. Now record the central water temperature measured by the thermometer as a function of time. What you discover is that the water cools off, cools off, cools off, then it does something slightly funny, and then it cools off further. If you take the metal can out of the ice again, set it on the table and let it warm up, the central water temperature warms up, warms up, does something funny again, and then continues warming up. What is occurring when, as shown in the slide, "something funny happens?" A clue is that when this happens the temperature of the water is approximately 4°C. Initially, the reason it cools rapidly is because the process is aided by convection but at 3.98°C convection stops and the cooling rate is dictated solely by conduction and that's a much slower process. So even this simple system is seen to go from convective cooling to conductive cooling and then once below 4°C, back again to convective cooling.

With our 10 inch diameter float-- the next slide (slide 11) shows the overall view of the apparatus -- we obtained a test of equivalence which was good to a few parts in 10^{11} -- not quite as good as either the Princeton (or more recent Russian) measurement; but given that we were using a new method, it seemed very promising to us. Now I should mention that whenever you invent a new device, nature is going to invent a new set of problems. That's a theorem of life. The next slide (slide 12) lists various sources of noise. Let me in particular tell you about seismic noise. The main problem associated with a classical torsion fiber system is its sensitivity to vibration and ground motion. Why is that? If you have something hanging on a fiber and the world moves up and down, the fiber is going to stretch every time the support moves. And when it stretches, it wants to twist for it will always have some built-in preferential twist direction. Now what about a fluid fiber? In this case, the string is replaced by buoyancy, and when the ground moves up and down one can think of this as little g changing periodically. And with this driving term, nothing happens since an increase in buoyancy just cancels any increase in weight -- the "string" never stretches. What we observe in practice is that a fluid-based torsion fiber is extremely insensitive to vibration.

I could tell you that we anticipated this delightful insensitivity to vibrations, etc., etc. The fact is, however, we were amazed to discover how vibration insensitive our fluid fiber was; and it took us some time to understand it. In any event, it offers a tremendous advantage. You can almost jump around the apparatus without being noticed. In fact a large earthquake (magnitude 7+ on the Richter scale) occurred during one of our data runs and though we carefully looked, we could not find it in the float position read-out data. Had we had a torsion fiber pendulum hanging at that time, it would have gone crazy.

The obvious question to ask about a new approach is can you further improve on it? And in order to answer this you need to understand both what the limitations are and how things scale. The next slide (slide 13) begins this discussion. Consider a float of height h, radius R, with a separation from the outer walls d. The striped portion represents the water. The supported mass simply looks like the volume times the density of water. The signal torque of such a system depends on the mass, the free-fall acceleration toward the sun, the radius of the system, and the parameter η which measures the unequivalence of the gravitational and inertial mass. That's the signal torque. What is the noise torque? It depends on how well the apparatus is designed and how it responds to various sources of noise. However, no matter how clever you are, the one noise torque that you cannot eliminate is the Brownian motion torque. The equation for this torque (even if you've never seen it before) should appear reasonable for it looks very much like the equation for Johnson (kT) noise in a resistor. Here the dissipative part, the viscous damping constant b of the float, appears rather than the (lossy) ohmic resistance inside the square root.

Let's look at the next slide (slide 14) and see how these things scale and see what size the apparatus ought to be. The side torque (due to the damping of the water on the side) is the force on the side walls of the cylinder times the radius, which is proportional to the difference in velocity between the outer wall and the float divided by d multiplied by the viscosity times the surface area times the float radius, R. To derive the torque from the bottom you have to integrate but you obtain a similar term. The resulting total damping coefficient on the float (the damping due to the sides and due to the bottom) is then as shown. We can write down the noise torque by simply putting this result in the noise torque equation which appeared on the preceding slide.

If we take the ratio of the torque signal (also from the previous slide) to this noise torque, the important thing to notice is that it scales (for the case when the kT noise is the limiting factor) as $R^{5/2}$. That means that (in this case) bigger is better. If you make the apparatus five times bigger, that means (since $5^{5/2}$ is roughly 50), that you've gained a factor of 50 in the accuracy you can obtain in some fixed integrating time. That's the good news. The bad news is that one of the other noise terms gets worse as the apparatus gets bigger, namely the quadrupole term. (See slide 15.) The problem is that the world has moving masses like you and me, and if we stand next to the apparatus we're going to produce a gravity gradient to which the float will respond, since inevitably it will have a small dumbbell mass distribution character about it. And these external moving masses are going to produce torques which to some extent will look like an Eötvös (24 hour period) torque. True, they will not have quite the same periodicity, but unfortunately they will contribute some noise power at the right periodicity. Note that the signal to noise in this case scales as 1/R — the bigger the apparatus, the worse the signal to noise. So, what can you do?

The slide reminds you of a simple theorem. (If things are simple enough I call them theorems because I understand them.) "If you have a sphere of matter of density ρ and radius R, the gravity gradient at its surface does not depend on R but only depends on ρ." Why is this an interesting observation? Because of the following -- in the laboratory I can out-gravity-gradient anything that nature does. What do I mean by that? Consider one typical noise term found in nature (slide 16). If a high-pressure region comes over, the atmospheric density will be higher and that will create a gravity gradient and hence a torque on any quadrupole moment of the apparatus. But you can surely model a high-pressure region as just a sphere of air of increased density adjacent to the apparatus. The good news is then that since the density of air is only one gram per liter, the additional torque is at least four orders of magnitude smaller than I can make if I roll a lead ball up next to the apparatus. In practice that means I can produce a much larger controlled gradient than nature does and therefore I can use this signal to tune out (by adding appropriately placed small masses) the float's response to all gravity gradients. This involves some effort, but it provides a solution to the external gravity gradient problem.

Now let me show you our recently constructed larger float (slide 17). The float diameter is 50 inches while the diameter of the smaller float (which we used earlier) was 10 inches. The diameter of the outer container is 56 inches. The test masses consist of 480 kilograms of copper and 480 kilograms of lead. Slide 18 may give you a somewhat better idea of the size of the float.

How well do we hope to do? The next slide (slide 19) summarizes recent experiments and (hopefully) our future result. For our new apparatus -- if we successfully reach the kT limit -- η is given by 10^{-13} over the square root of n, where n is the number of days the experiment is run.

I would remind you that what we are now trying to do is to scale up by a factor of 5 our new type of fiber and use it to carry out an improved version of the Eötvös experiment -- an experiment so princely that we only use "Kaisers" (Mac Keiser and Paul Keyser) to work on it. (I could not resist the pun.) Big, however, is never cheap and rarely easy. Once something exceeds the capacity of your instrument shop's lathes and/or milling machines, it becomes much more difficult to fabricate. As an example, when the float arrived (from a machine shop on the East coast where it was made) the top wasn't round. Did we send it back to the manufacturer? No, we used a hydraulic jack, and by distorting the top past its elastic limit we successfully re-shaped the top, to within a few thousandths of an inch of round. Also, due to the vastly increased size of the apparatus, price as well as ease of fabrication became much more critical factors in choosing the test mass materials (e.g., not only were gold and silver out of the question, but also tungsten was too expensive). We are using, as you see, lead and copper. Initially we had planned to use lead and zinc, however, the zinc castings proved to be not nearly as nonmagnetic as a sample had led us to expect, and they were therefore (permanently) returned to the manufacturer. The paramagnetism problem associated with CuO in our (replacement) Cu masses is avoided by using OFHC copper, and then gold-plating the masses to prevent any oxidation with time.

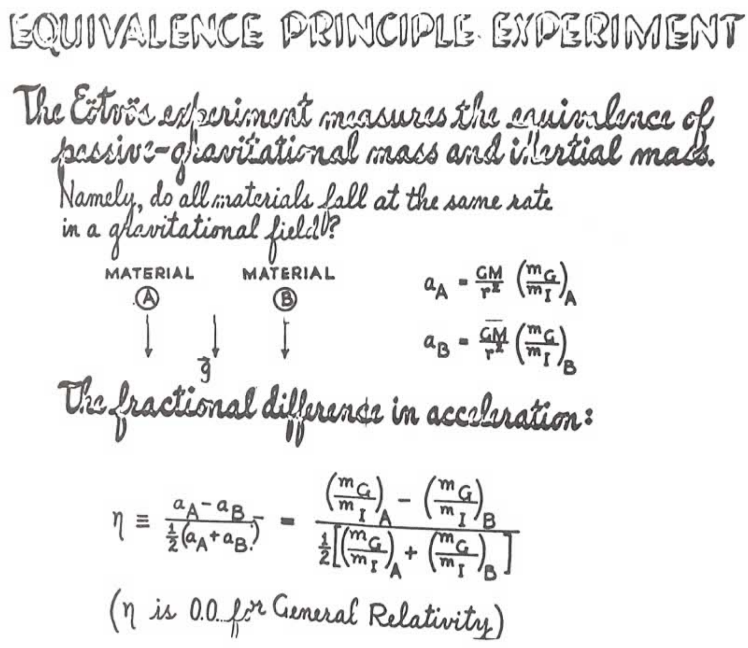
A new sensing system (slide 20) which we have devised for this experiment promises to have a very high mechanical stability: the sensing optics are a part of the same container lid on which the zero-determining electrode array is located. In brief, this new sensing system consists of an infrared light-emitting diode -- IR LED (whose output light is focused into a line image by a cylindrical glass "lens" attached to the top of the float) and a split photodiode detector. As the float turns, the cylindrical lens moves with respect to the LED-photodiode pair, causing the line image to move its position on the split photodiode. This results in a change in the output of the two halves of this device, giving rise, when amplified, to a rotation-dependent voltage as shown on the right half of the slide. With two such detection systems -- one on each side -- and proper summing of their outputs, the detector becomes insensitive to sideways motion of the float without sacrificing any of its sensitivity to rotation.

This new large apparatus is now in the final stages of assembly, and we are beginning a prolonged (possibly a year-long) shake-down trial of the full apparatus. We plan to make the initial tests without cooling; and, by careful temperature control we hope to achieve sufficient temperature stability to greatly inhibit convection. Cooling, while straightforward and serving to reduce the linear expansion coefficient of water -- and therefore its tendency to convect -- by more than an order of magnitude, extracts a very high price in experimental convenience. This is particularly true in a system of this size, and therefore we will proceed as far as we can without paying this price.

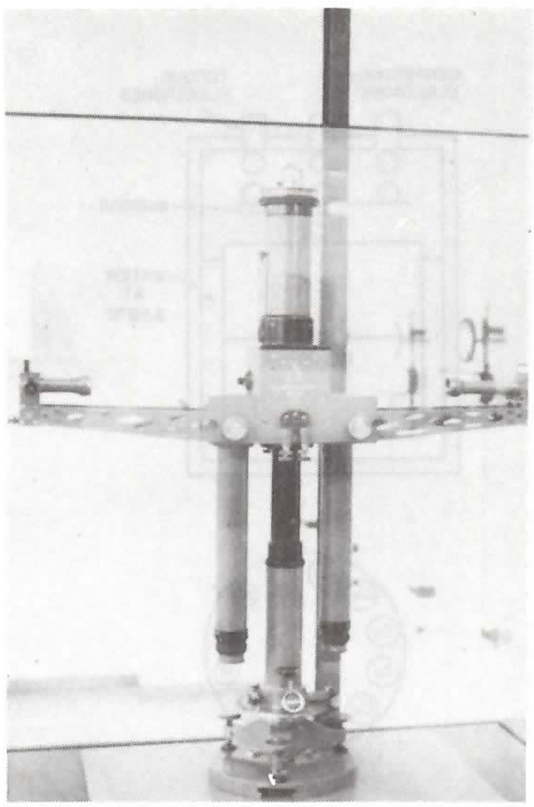
In conclusion, in this lecture I've told you about an alternative to the traditional torsion fiber. Torsion fibers have been used since Cavendish used one to measure big G. Whether our surrogate fluid fiber will prove to be better, not as good, or about the same in quality as a traditional fiber, is yet to be seen. However, given that its learning curve is characterized by years rather than centuries, I think we have a good chance of making some advances in physics by using it. Thank you for your kind attention.


DID YOU KNOW THAT A FEATHER AND A HAMMER DROPPED FROM THE SAME HEIGHT IN A VACUUM WILL STRIKE THE GROUND AT THE SAME TIME?
PROVE IT.
OK, BUT IT'S GONNA COST YOU ABOUT 4 BILLION CLAMS.

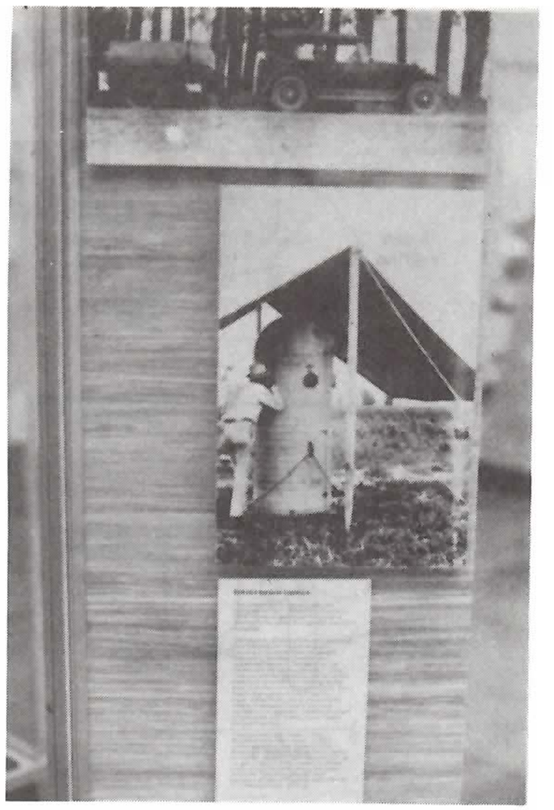
(1)


EQUIVALENCE PRINCIPLE EXPERIMENT
The Eötvös experiment measures the equivalence of passive-gravitational mass and inertial mass.
Namely, do all materials fall at the same rate in a gravitational field?
MATERIAL A
MATERIAL B
g
$a_A = \frac{GM}{r^2}\left(\frac{m_G}{m_I}\right)_A$
$a_B = \frac{GM}{r^2}\left(\frac{m_G}{m_I}\right)_B$
The fractional difference in acceleration:
$\eta \equiv \frac{a_A - a_B}{\frac{1}{2}(a_A + a_B)} = \frac{\left(\frac{m_G}{m_I}\right)_A - \left(\frac{m_G}{m_I}\right)_B}{\frac{1}{2}\left[\left(\frac{m_G}{m_I}\right)_A + \left(\frac{m_G}{m_I}\right)_B\right]}$
(η is 0.0 for General Relativity)

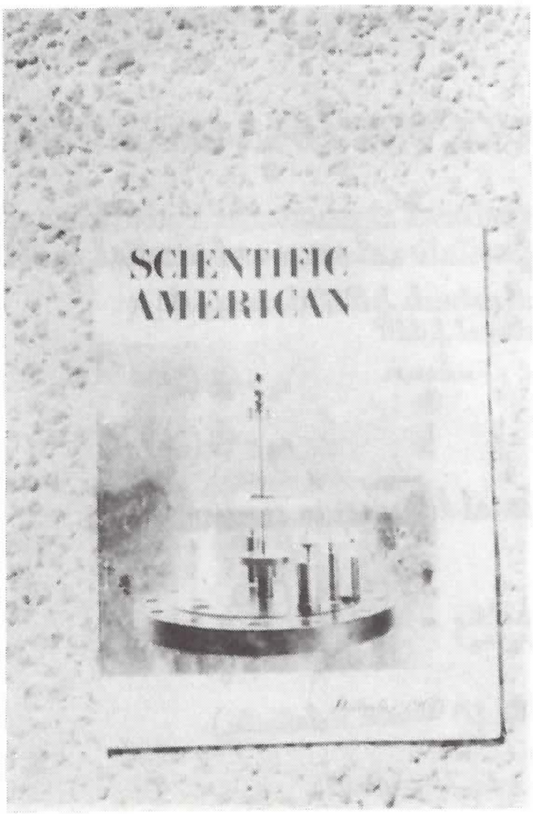
(2)



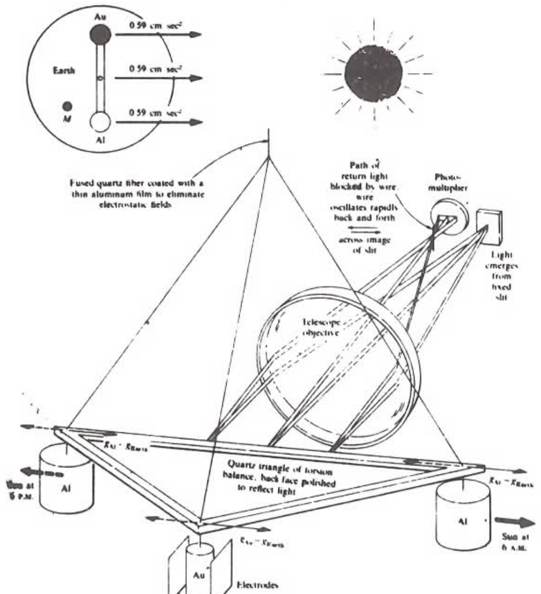
(3)



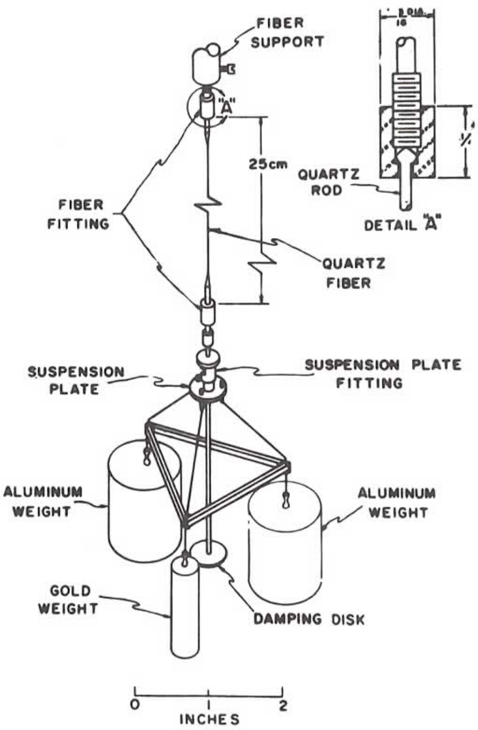
(4)


SCIENTIFIC
AMERICAN

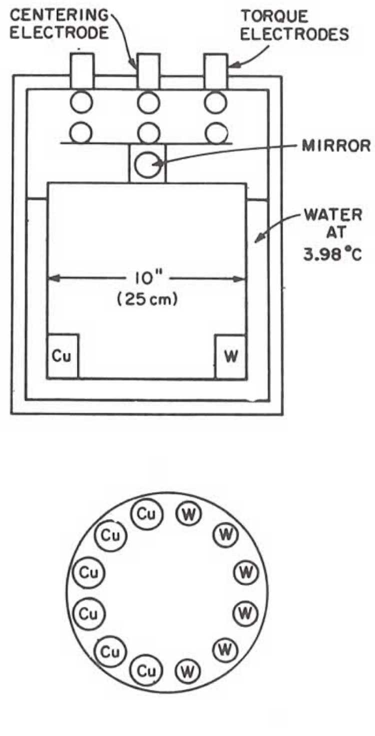
(5)


Au
0.59 cm sec⁻²
Earth
0.59 cm sec⁻²
M
0.59 cm sec⁻²
Al
Fused quartz fiber coated with a thin aluminum film to eliminate electrostatic fields
Path of return light blocked by wire. wire oscillates rapidly back and forth across image of slit
Photomultiplier
Light emerges from fixed slit
Telescope objective
Quartz triangle of torsion balance, back face polished to reflect light
Sun at 6 P.M.
Al
Al
Sun at 6 A.M.
Au
Electrodes

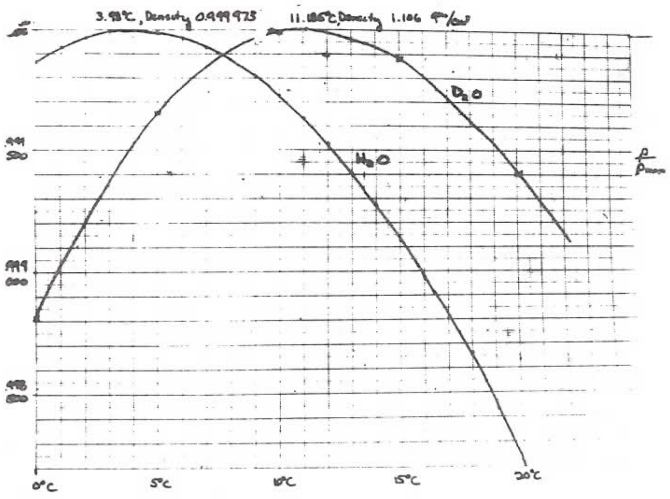
(6)


FIBER SUPPORT
"A"
25cm
QUARTZ ROD
DETAIL "A"
FIBER FITTING
QUARTZ FIBER
SUSPENSION PLATE
SUSPENSION PLATE FITTING
ALUMINUM WEIGHT
ALUMINUM WEIGHT
GOLD WEIGHT
DAMPING DISK
0
1
2
INCHES

(7)


CENTERING ELECTRODE
TORQUE ELECTRODES
MIRROR
WATER AT 3.98°C
10"
(25 cm)
Cu
W
Cu
W
Cu
W
Cu
W
Cu
W
Cu
W
Cu
W

(8)



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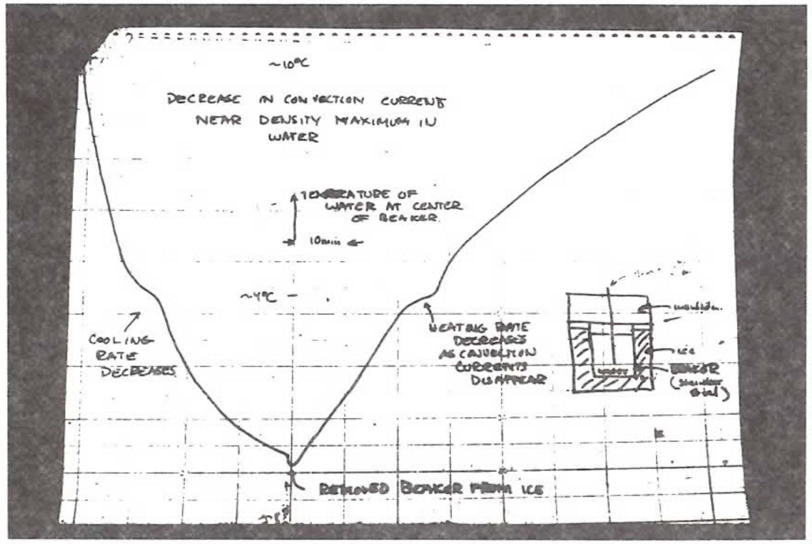
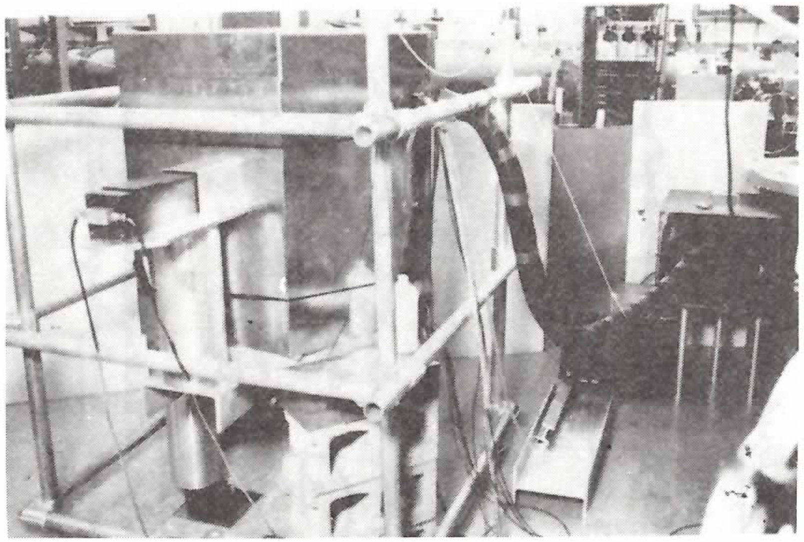


(10)



(11)

SOURCES OF NOISE

convection currents

magnetic fields
- permanent dipole
- induced dipole
  - eddy currents
  - different susceptibility of masses

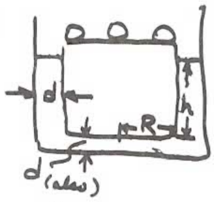
- gravitational fields
- instrumental effects
- seismic noise
- Brownian motion

(12)

①

Eötvös Experiment

How do things scale?



Mass

$M = \pi R^2 h \rho$, ρ = density of water

Signal Torque

$\tau_s = M a R \eta_E = \pi R^3 h \rho a \eta_E$

a = sun's acceleration (.62 cm/sec²)

η_E = Eötvös parameter $\eta = \dfrac{\left(\frac{M_G}{M_I}\right)_A - \left(\frac{M_G}{M_I}\right)_B}{\frac{1}{2}\left[\left(\frac{M_G}{M_I}\right)_A + \left(\frac{M_G}{M_I}\right)_B\right]}$

Noise Torque (Brownian Motion)

$\tau_{NB} = \sqrt{4 K_B T\, b\, \Delta f}$

b = damping constant : $I\ddot{\theta} + b\dot{\theta} + k\theta = \tau$

$\Delta f = \dfrac{1}{\text{period of observation}}$

Damping constant $b = \left(\text{damping sides}\right) + \left(\text{damping bottom}\right)$

(13)

②

Torque from side damping

$\tau = RF = R\eta A \dfrac{\Delta V}{d}$

$= R\eta\,(2\pi R h)\dfrac{R\omega}{d}$

$= \left(\dfrac{2\pi R^3 h \eta}{d}\right)\omega = b_s \omega$

Torque from bottom damping

$d\tau = R\eta\, 2\pi R\, dR\, \dfrac{R\omega}{d}$

$\tau = \left(\dfrac{\pi}{2}\dfrac{R^4}{d}\eta\right)\omega = b_b \omega$

Total damping coefficient

$b = \left(\dfrac{\pi R^3 \eta}{d}\right)\left(2h + \dfrac{R}{2}\right)$

So the Noise Torque due to Brownian motion

$\tau_{NB} = \left[4 K_B T \Delta f\, \dfrac{\pi R^3 \eta}{d}\left(2h + \dfrac{R}{2}\right)\right]^{1/2}$

Signal to Noise

$\dfrac{\tau_S}{\tau_N} = \dfrac{\pi R^3 h \rho a \eta_E}{\left[4 K_B T \Delta f\, \frac{\pi R^3 \eta}{d}\left(2h + \frac{R}{2}\right)\right]^{1/2}} \left(\dfrac{R^4}{R^{3/2}}\right) \rightarrow \propto R^{5/2}$

Provided relative dimensions are kept constant

(14)

③

Noise due to Quadrupole Moments

$\tau_{NQ} \propto f MR^2$

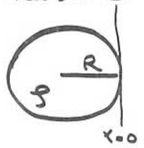
where f is the fraction of MR^2 → largest quadrupole moment

Signal to Noise (Quadrupole gradients)

$\dfrac{\tau_S}{\tau_{NQ}} \propto \dfrac{M \cdot R}{MR^2} \propto \dfrac{1}{R}$

What can one do — against this problem

Theorem



Gravity gradient @ x = 0 due to a just-contacting sphere of density ρ is not a f(R): Grad $\propto \dfrac{M}{R^3} \propto \dfrac{\rho R^3}{R^3}$

So Gradient ∝ ρ !

So what?

This means that in the laboratory we can produce a much larger gravity gradient than nature does ...

(15)

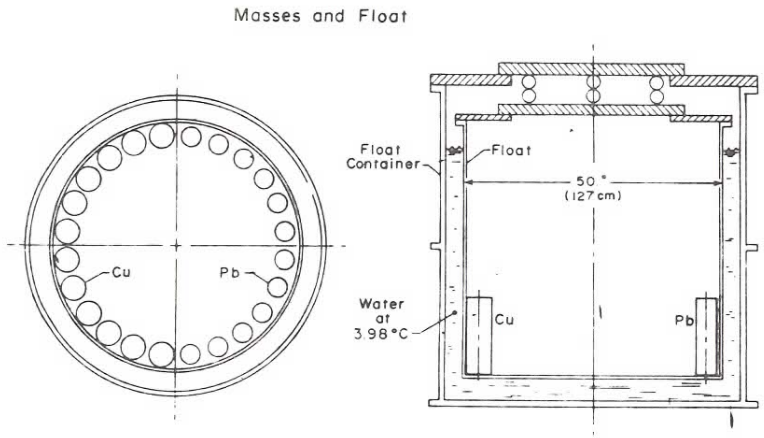
④

Consider the magnitude of an arriving high pressure region in the atmosphere. Model as spherical mass of density ρ = 1 gm/liter or 10^{-3} gm/cm³. This atmospheric density is 4 orders of magnitude smaller than ρ laboratory which we could use (eg Pb). ∴ can produce a far larger controlled signal and in turn use this to tune out floats quadrupole moments. Depends only on two observations

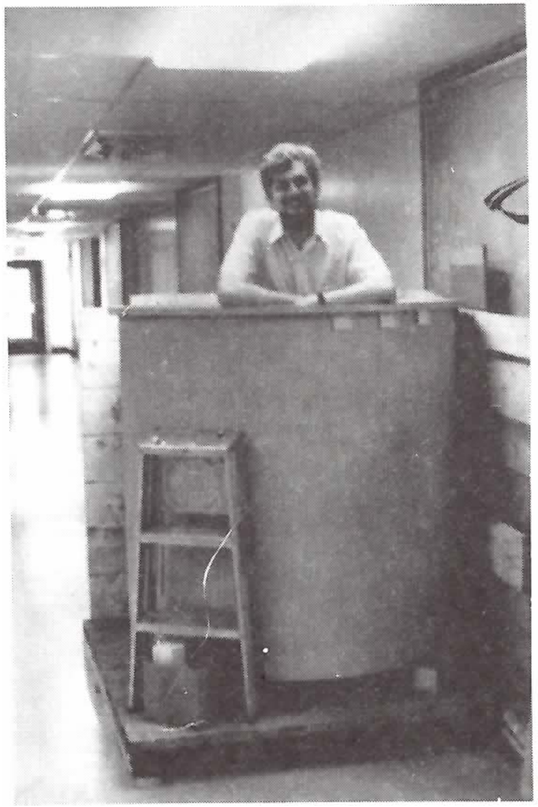
① Grav Gradient at Surface of Sphere = f(ρ) only and

② $\rho_{Pb} \gg \rho_{Air}$ ....

(16)



(17)



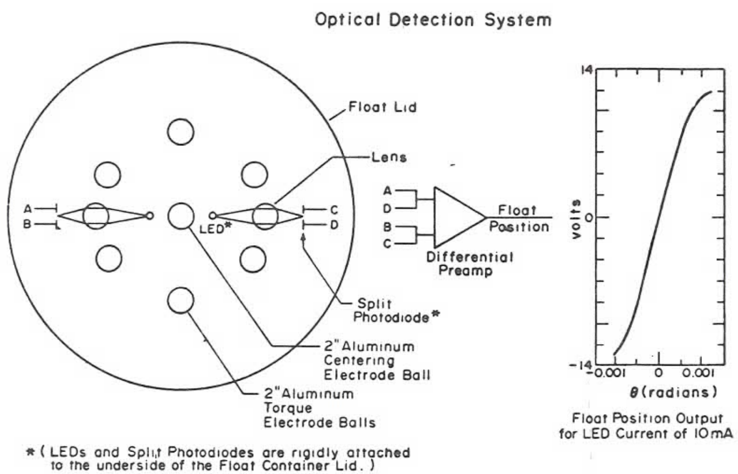
(18)

PAST RESULTS

YEAR	EXPERIMENTERS	METHOD	MATERIALS	η
1964	ROLL, KROTKOV, DICKE	TORSION	Al & Au	$3 \cdot 10^{-11}$
1971	BRAGINSKY, PANOV	TORSION	Al & Pt	$.9 \cdot 10^{-12}$
1978	KEISER, FALLER	FLUID	Cu & W	$4 \cdot 10^{-11}$
197	KEYSER, FALLER	FLUID	Cu & Pb	?

expected η is about 10^{-13} or 10^{-14}

(19)



(20)