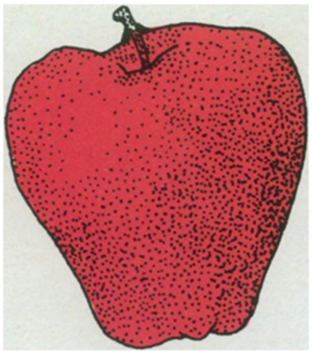


A New Gravity?

Challenging Einstein's general theory of relativity

By IVARS PETERSON

The apparatus features a spindly, suspended dumbbell — a light, rigid rod with a lead ball at each end. The dumbbell dangles horizontally from a long, twistable wire fastened to its midpoint.

A pair of hefty lead spheres, properly positioned near the ends of the dumbbell, causes the dumbbell to rotate, slightly twisting the wire. This modest deflection serves as a measure of the attractive force between the stationary lead spheres and the balls affixed to the rotating rod.

When Henry Cavendish performed this experiment in 1798, he did more than demonstrate the pull of gravity and provide experimental confirmation of Newton's law of gravitation for relatively small portions of ordinary matter. Data from his experiment enabled him to determine Earth's density and mass.

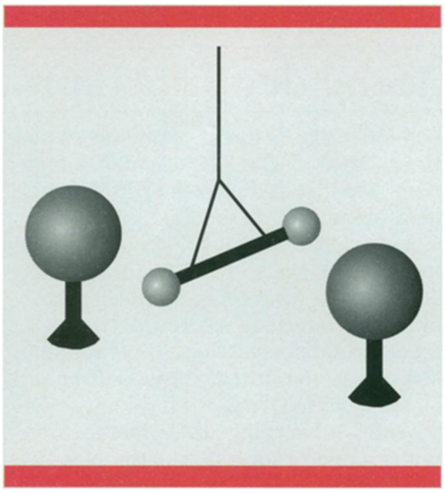
Since then, researchers have used the Cavendish experiment in various guises to confirm that the force of gravity decreases in proportion to the square of the distance between attracting bodies. They have also ascertained that the force depends only on the mass and not on the composition of the bodies.

And they have shown with great precision that inertial mass — a measure of a body's resistance to acceleration — is equivalent to gravitational mass — a measure of the same body's gravitational attraction. Hence, all bodies in the same location fall at the same rate.

When Albert Einstein developed his general theory of relativity as a new theory of gravity, he built it on the equivalence of inertial and gravitational mass. He reasoned that it isn't possible for an observer to tell the difference between an object falling off a table and the same object in a rocket accelerating upward. In both cases, the object would appear to move "downward."

Einstein rejected the Newtonian view that masses somehow produce a force that permeates the surrounding space and influences the motion of any bodies within range. He interpreted gravity as the curvature of space and time itself, with bodies traveling along the "straightest" possible paths through the dimpled spacetime continuum associated with the presence of masses and energy. Heavier bodies would simply create larger dimples and greater curvatures.

Now, the Cavendish experiment has a new role in elucidating a possible shortcoming of general relativity as formulated by Einstein.



In the Cavendish experiment, two large, stationary spheres attract two balls attached to a rod suspended so that it can swing horizontally.

Einstein's theory fails the Cavendish experiment, insists Hüseyin Yilmaz of the Electro-Optics Technology Center at Tufts University in Medford, Mass., and Hamamatsu Photonics in Hamamatsu City, Japan. In other words, the equations of general relativity have no solutions in which two bodies of finite size actually attract each other.

"Thus, strictly speaking, according to general relativity, an apple detached from its branch would not fall to the ground," Yilmaz declares.

It's a startling and highly controversial assertion.

"Many people realize that there's something wrong — that general relativity doesn't have the physics in it that one thinks," says physicist Carroll O. Alley of the University of Maryland at College Park, who has been working with Yilmaz. "I think we've been able to put our finger on where the trouble actually lies."

Others reject this stance. "[Yilmaz and Alley] are completely wrong," says Clifford M. Will of Washington University in St. Louis. Critics like Will charge that Yilmaz and Alley have failed to grasp what general relativity means and what it predicts.

Such criticism and skepticism have not deterred Yilmaz from developing an alternative theory, which preserves the notion of curved spacetime but changes how the theory handles energy and momentum. He and Alley have been using the new theory to make predictions about the behavior of matter under various circumstances.

They have also been trying to get the attention of their colleagues, with limited success so far. Yilmaz and Alley presented papers describing their ideas at a meeting on fundamental problems in quantum theory, organized by the New York Academy of Sciences and held last June at the University of Maryland, Baltimore County. Additional papers will appear in *Frontiers of Fundamental Physics* (Plenum, 1994).

A few people have been sympathetic. "General relativity has many mysteries," says Willis E. Lamb of the University of Arizona in Tucson. "Einstein certainly could have done things differently. What Yilmaz is trying to do seems quite plausible."

"These are not matters that can just be brushed away," Alley contends. "These are serious considerations."

When Einstein developed general relativity, he introduced a set of equations to describe how bodies would behave in a realm in which gravity, time, and three-dimensional space are fused into a single, universal entity.

Written in condensed form as $\mathbf{G} = k\mathbf{T}$, the 10 field equations of general relativity express the relationship between $\mathbf{G}$, the curvature of four-dimensional spacetime, and $\mathbf{T}$, a measure of the distribution and flow of energy and momentum, which is linked to the mass distribution. $\mathbf{T}$ is known as the stress-energy tensor, and k is a constant. These equations are

Laser beam from water tower (near center), as seen from the National Cathedral in Washington, D.C. The illuminated structure to the left on the horizon is a television broadcast antenna.

Alley

assumed to couple the sources of gravitation with the fields they generate.

The Einstein equations are notoriously difficult to solve, not only because there are 10 of them, in contrast to the single equation of Newtonian gravitation, but also because they are nonlinear. In other words, the gravitational effect, or potential, of a pair of masses isn't simply the sum of the individual gravitational potentials.

Moreover, these potentials depend on energy and momentum flow. This flow, in turn, is determined by the spacetime curvature, which is set by the potentials. "Spacetime grips mass, telling it how to move; and mass grips spacetime, telling it how to curve," says John A. Wheeler of Princeton University.

The circularity embedded in general relativity adds to the formidable challenge of solving the Einstein equations. Where they can't solve the equations directly, theorists often resort to special mathematical strategies to approximate the equations and obtain particular solutions.

Introduced in 1915 by Einstein, general relativity proved immensely appealing to physicists, despite its complexities and the horrendous difficulties of solving the equations for realistic situations involving more than one body. Swayed by the theory's elegance and its success in predicting the deflection of light in a gravitational field, the existence of gravitational waves, and several other effects, most researchers now accept the theory as the most appropriate way of describing gravity. The theory appears particularly successful at the relatively modest fields and slow speeds of planetary motion and orbiting pulsars, where it has apparently passed every observational test to date.

This doesn't mean that there are no concerns, dissidents, or alternative theories of gravity. Such proposals have a long history, and new problems continue to arise. For example, it's clear that general relativity, in its present form, is incompatible with quantum mechanics. In its relativistic garb, gravity stands apart from the other forces of nature.

Moreover, general relativity breaks down for immense concentrations of mass. The theory gives rise to singularities — extremely curved regions of spacetime where the mass density and energy become infinite (SN: 3/9/91, p.148).

It also suggests the existence of black holes. These objects are accumulations of mass so huge that they throw up an impenetrable spacetime curtain — an event horizon — that no observational probe can part. Yet there is no unambiguous evidence that such objects actually occur in the universe.

"Where we have been able to test general relativity is primarily in the weak-field, low-velocity limit of the theory," says Stuart L. Shapiro of Cornell University. "But general relativity is used by astrophysicists and others to explain highly nonlinear, strong-field phenomena. We have no tests of general relativity under these extreme conditions."

"If I stare at the naked evidence, I'm taking a lot on faith," he adds. "But I think the theory is probably in pretty good shape. It's so beautiful that it's hard for me to accept that it's subject to significant correction beyond what quantum mechanics will do."

Yilmaz and Alley maintain that general relativity has other, more fundamental shortcomings.

As a challenge to the relativity community, Yilmaz and Alley have proposed a setting in which they claim general relativity fails to show attraction between two bodies. The problem they consider is the gravitational interaction between two nearby slabs of matter — two parallel plates, each with an area much greater than its thickness — separated by a vacuum.

In this case, the geometry is simple enough to allow a solution in general relativity. Calculations by Yilmaz and Alley indicate that the slabs don't attract each other. They remain stationary, staying right where they started.

Charles W. Misner of the University of Maryland has confirmed their calculation, but he argues that other factors come into play in determining what happens.

Misner notes that in Newtonian theory, one can postulate the existence of a slab of infinite extent, finite thickness, and uniform density and get a simple answer for the gravitational field in the slab's vicinity. One never has to worry about how the slab manages to keep its shape.

In contrast, the pressures and stresses within such a slab as it resists collapse do play a significant role in the Einstein equations. And these effects may have large gravitational consequences, Misner says.

He suggests that high pressures and tensions in nearby parallel slabs may produce antigravity — a repulsive gravitational force originating in unexpected fields produced within this highly stressed matter, which appears quite unlike any known matter. The fact that two such slabs fail to accelerate toward each other is simply a consequence of the "peculiar" matter from which they must be constructed in order to exist, Misner concludes.

Yilmaz and Alley reject this interpretation. They see no rationale for invoking peculiar matter to explain the lack of movement of the two slabs.

William G. Unruh of the University of British Columbia in Vancouver has also responded to the challenge. "There *are* a number of solutions to the two-slab problem showing attraction," he contends.

However, finding such solutions proved trickier than Unruh expected. "I thought that I could build a solution much more easily than it turned out I could," he says. Indeed, Unruh's first attempt, which he presented to Yilmaz and Alley, was faulty.

Since then, Unruh has worked out new solutions for the two-slab problem. "It was a good exercise," he remarks. "It raised some interesting issues about general relativity."

Yilmaz and Alley have now examined the second set of results, and they contend that these solutions also present difficulties and are equally unsatisfactory.

Yilmaz first became involved with general relativity in the early 1950s, when he was a graduate student at the Massachusetts Institute of Technology. It was a time when the field of general relativity was a stagnant backwater of physics and astronomy, and few researchers pursued it seriously.

In his attempt to understand the theory, Yilmaz discovered what he saw as a contradiction in the answer to a particular problem involving accelerated motion and gravitational fields. The general relativistic solutions didn't seem to make physical sense.

Yilmaz ended up finding a more acceptable solution by altering some aspects of the Einstein equations. But discouraged by the largely negative response to his idea at the time, he turned to electrical engineering and worked in industry. Nonetheless, he continued to refine and rework his concept and during the last decade has put a great deal of effort into clarifying crucial aspects of his proposed theory.

Alley first encountered the Yilmaz theory when he was a graduate student with Robert H. Dicke at Princeton. But he didn't start collaborating with Yilmaz until the early 1980s. Alley was then in the midst of extremely sensitive tests of relativistic effects in a terrestrial setting.

The Yilmaz theory, as it now stands, preserves the curved spacetime of Einstein's theory. The crucial change occurs on the energy-momentum side of the equation. Yilmaz replaces the single Einstein variable **T** with the sum of a pair of tensors, **T** + **t**. In other words, there are really two parts to the energy-momentum side of the equation.

"The physical idea is that all energy has a mass equivalence and the field energy of gravitation is no exception," Alley says. Thus, **T** represents the energy and momentum associated with any masses present, and **t** represents the energy and momentum of the resulting gravitational field itself.

"This is a neat way of putting the fact that gravity gravitates," Alley says. "All stress-energies ought to contribute to the curvature."

Using the resulting equations, Yilmaz and Alley have been able to calculate solutions showing that two parallel plates do indeed attract each other. They have also been able to compute the motions of planets around the sun accurately enough to account for non-Newtonian perturbations, particularly in the motion of Mercury.

The new theory "resolves essentially all the difficulties and paradoxes met in general relativity," Yilmaz and Alley insist.

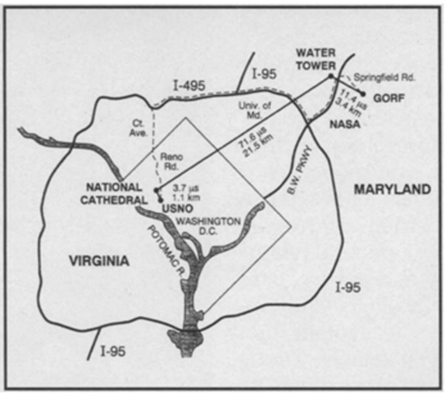
For example, although it allows great concentrations of mass, it predicts no black holes, no event horizons, no singularities. Light can escape from these mass concentrations, though quantum effects become important when matter collapses to a sufficiently small size.

Yilmaz and Alley believe that the new theory of gravity is compatible with quantum mechanics, and at the June meeting, Yilmaz described a possible route toward quantizing the theory.

At the weak-field, slow-motion limit, the Yilmaz theory and general relativity make very similar predictions, and both agree with all experimental observations to date. Alley and Yilmaz contend that general relativity seems to work because researchers must use approximations to solve the Einstein equations, and they incorporate within these approximations extra information not contained in the theory itself.

"People are smarter than the theory," Yilmaz says. "They put in things by implicit assumption that are unwarranted by the theory."

Most relativists reject this point of view. "In the past 15 years, these approximation methods have been placed on a much stronger, more rigorous footing than ever before," says Washington University's Will. "None of the answers have changed, but the theoretical foundation has become much more solid."



Alley

This map shows the path followed by laser light pulses traveling between the NASA Goddard Optical Research Facility (GORF) and the U.S. Naval Observatory (USNO). The dashed line indicates the route along which researchers transport a high-precision atomic clock to synchronize clocks at both facilities for timing the pulses.

"There *are* serious alternative theories of gravity," he adds. "But I do not consider [the Yilmaz] theory to be a serious alternative."

The Yilmaz theory, however, does make a definite, potentially testable prediction that may distinguish it from general relativity. It predicts that the speed of light locally is the same in all directions, even when measured within an accelerated frame of reference.

Because Earth rotates, such an effect should be evident in the speed of light measured eastward and westward on the planet's surface. "We're trying to do, for the first time, an actual measurement of the difference in one-way propagation times to the east and west," Alley says.

The experiment involves a direct comparison of the difference between propagation times of a laser light pulse from a water tower outside Washington, D.C., to and from the National Cathedral tower within the city. It requires carefully transporting a high-precision atomic clock back and forth between the NASA Goddard Optical Research Facility and the U.S. Naval Observatory to calibrate clocks at each site.

"I hope that within a year we will have a sufficiently accurate experiment to decide this question," Alley says.

General relativity plays a key role in the operation of the Global Positioning System (GPS), the array of satellites operated by the U.S. Air Force for military and civilian navigation. The system relies on highly accurate timekeeping by atomic clocks, and relativity theory provides the corrections needed to compensate for the fact that the clocks aboard the satellites run differently than those on Earth's surface.

This system constitutes "a grand-scale laboratory for the application and study of relativistic effects on clocks," Alley says. "If the modeling of the known gravitational potential and motional effects is not applied correctly, systematic errors will result and system performance will be degraded."

Indeed, small, unexpected discrepancies continue to plague the operation of the GPS. "We are now engaged in an extensive study to identify these suspected problems," Alley says.

Yilmaz and Alley would like to get the attention of more people than the handful of researchers who have examined their work. "Irrespective of whether the new theory is eventually right or wrong, general relativity is clearly inadequate," Yilmaz says, "and it must be recognized as such to ensure healthy progress in the theory of gravity and its possible quantization."

But general relativity is an awesome, gigantic beast.

Although students now routinely encounter general relativity in college courses, many issues remain in the domain of specialists. Understanding the subtleties and intricacies of particular aspects of general relativity requires extensive study and attention to detail. Extracting physical meaning out of the tangled mathematics is also a tricky proposition.

Thus, it isn't easy for any one person to grasp the full theory in all its details. Relativists often specialize, developing a distinctive viewpoint and becoming the leading authority on a particular aspect of the theory. This necessitates a tremendous commitment of time and energy and leaves little time for pondering alternative theories, which in the past have usually proved flawed.

"It's like the blind man and the elephant," says David W. Hobill of the University of Calgary in Alberta. "It's such a big beast, and everybody is analyzing a very small part of the animal. Each person has a different point of view as to what he's actually seeing."

"We all do what we can to try to get a better feeling for what's going on in the theory itself," he adds. "But there are going to be a lot of controversial points where interests and results clash."

In the end, experimental tests will decide the fate of general relativity. In particular, the ongoing effort to detect gravitational waves may provide new insights (SN: 6/26/93, p.408).

"The predictions of [general relativity] are fixed; the theory contains no adjustable constants, so nothing can be changed," Will wrote in a Nov. 9, 1990 SCIENCE article marking the 75th anniversary of general relativity. "Thus every test of the theory is potentially a deadly test. A verified discrepancy between observations and prediction would kill the theory, and another would have to be substituted in its place." ☐