

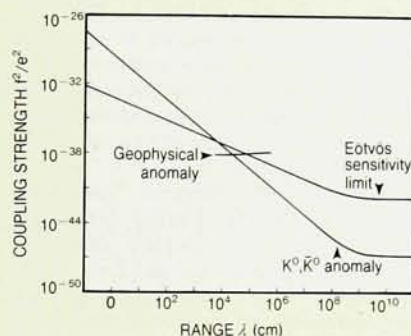
Reanalysis of old Eötvös data suggests 5th force . . . to some

Newton's gravitational constant has been with us for three centuries. Yet despite our long and intimate acquaintance, we know this fundamental constant of nature to little better than a part per thousand. Astronomical data are of scant use, because they always involve G multiplied by the mass of the Earth or some celestial body, and our knowledge of the mean density of such bodies is even more uncertain. Our best knowledge of G comes from modern variants of the classic Cavendish experiment, measuring the horizontal force between test bodies at distances up to a few meters in the laboratory.

At planetary distances, the inverse-square law—as distinguished from the numerical value of G —is very well tested, but there is a conspicuous gap between the one-meter laboratory scale and the hundred-kilometer scale of satellite flights, over which the distance dependence of the gravitational force has been subjected to very inadequate scrutiny.

In recent years Frank Stacey and his colleagues at the University of Queensland in Australia have been attempting to remedy this state of affairs by reviving a geophysical technique pioneered in the middle of the last century by George Biddle Airy. To calculate G from the acceleration g of a falling body at the Earth's surface, one would have to have a good independent measure of the Earth's overall density. But, Airy pointed out, if one measures the variation of g as one descends into a deep mine shaft, it suffices to know the local density of the Earth's crust from the surface down to the bottom of the mine.

The fascinating problem is that such recent geophysical measurements of G don't agree very well with the best Cavendish-type laboratory determinations. As Stacey's group has acquired more and more data from mines and deep boreholes throughout the world, with ever improving knowledge of local subterranean density, their value of G has stubbornly remained about one percent *higher* than the laboratory value. The uncertainty of the geophysical determination (six times the Ca-



Range and coupling constant of the speculative fifth force, as suggested by the anomalous geophysical and neutral-kaon data, would lie near the intersection of the two curves summarizing the data, yielding a range λ of about 200 m and a coupling constant f^2 about 10^{-38} weaker than e^2 , the electromagnetic coupling. Before reanalyzing the old Eötvös data, Ephraim Fischbach and colleagues plotted the sensitivity-limit curve of this historic experiment on the λ - f^2 plane and found that it passes surprisingly close to this intersection.

vendish uncertainty) is admittedly almost half the the magnitude of the discrepancy. But the persistence of the sign and magnitude of this discrepancy has tantalizingly suggested to the geophysics community that there may well be a previously unknown *repulsive* force with a strength on the order of 1% of gravity and a range of a few hundred meters. Well inside a deep mine shaft, such a force would go to essentially zero by spherical symmetry.

"The evidence for a defect in Newtonian gravity at kilometer range has improved with each new data set," the Australian group's latest publication tells¹ us. "But it still remains less than conclusive. . . . The remaining uncertainty arises from the possibility of a regional or extensive local bias in gradient by deep-seated mass irregularities that have not been recognized."

All of this might have remained for the time being within the parochial confines of the geophysics community, but for the work of particle theorist Ephraim Fischbach (Purdue) and his col-

leagues, which catapulted speculation about a "fifth force" onto the pages of *The New York Times*. Fischbach came to this subject from an entirely different direction. He had been working with Sam Aronson (Brookhaven), Gregory Bock (University of Chicago), and his Purdue colleague Hai-Yang Cheng on the interpretation of some very puzzling experimental results Aronson and Bock had culled from their earlier study of the high-energy interactions of neutral K mesons at Fermilab.

In what appeared to be an assault on all common sense, the fundamental parameters of the neutral-kaon system—the mass and lifetime differences between the short- and long-lived K^0 and η_{+-} , the complex parameter that describes the CP-violating decay $K^0_{\text{long}} \rightarrow \pi^+\pi^-$ —all seemed to vary with energy in these high-energy experiments. Of course the laboratory lifetime of a decaying particle varies trivially with the energy at which one observes it, but one is normally quite confident that a Lorentz transformation into the rest frame of the particle yields the fixed, proper mean lifetime. Aronson's data appeared to violate the sacrosanct Lorentz invariance.

Fischbach suggested a somewhat less heretical alternative. Reaching back to a 1964 speculation by T. D. Lee and others, he suggested that the neutral kaons traveling at high energy through the laboratory may interact with the surrounding material by way of a long-range force that couples to hypercharge. Hypercharge—the sum of baryon number B and strangeness S —is, in an ordinary atom, simply the number of neutrons plus protons, roughly proportional to the mass. But for the strange K mesons it is $+1$ for the K^0 and -1 for the $\bar{K}^0$. The opposite couplings of the two neutral K states to this long-range force exerted by all the surrounding nucleons might explain the anomalous energy dependence of the kaon parameters, Fischbach hypothesized.

Just as the anomalous gravitational results of the Australian geophysicists remain in some doubt, so also is the

neutral-kaon anomaly by no means an experimental certainty. Bruce Weinstein (University of Chicago), one of Aronson's principal collaborators on the experiment that originally produced these data between 1977 and 1979, argues that the data offer no credible evidence for such an anomaly. A more recent, lower-statistics experiment carried out at Fermilab by Weinstein, James Cronin and their University of Chicago colleagues fails to confirm the neutral-kaon anomaly. "We don't see it, but the results of the two groups differ thus far by only three standard deviations," says Cronin, who shared the 1980 Nobel physics prize for his discovery of CP violation in neutral-kaon decay. Fischbach speculates that the crucial difference between the two experiments might be the fact that the newer Chicago beam pipe was above ground, whereas Aronson's had been 10 ft underground.

Eötvös revisited. If there is such a force coupled to hypercharge—or, more generally, to some linear combination of baryon number and strangeness—it might well manifest itself to first order as an intermediate-range correction to gravity similar to what the Australians think they see, because baryon number and mass are closely proportional in ordinary, nonstrange matter. But they are not *exactly* proportional. Near the center of the periodic table, where nuclear bonding is tightest, the number of baryons per unit mass is a maximum, falling off toward hydrogen and uranium. Thus one would expect different materials to exhibit slightly different departures from canonical gravity due to this hypothetical intermediate-range force.

That's what set Fischbach to thinking about the classic test of the equivalence principle carried out early in this century by Baron Roland von Eötvös and his Budapest colleagues. A suspended mass on Earth hangs in a direction given by the resultant of the Earth's gravitational force and the centrifugal force due to the Earth's rotation. The equivalence principle insists that gravitational and inertial masses are rigorously proportional, completely independent of composition.

If, at middle latitudes, one hangs two balancing masses of different composition from opposite ends of a torsion balance oriented east–west, any difference in the ratio of inertial to gravitational mass between the two test masses would result in a torque on the fiber from which this dumbbell arrangement hangs. That is the essence of the Eötvös experiment, as a result of which, all the introductory textbooks tell us, the equivalence principle is validated to a part in 10^9 .

Quite apart from the equivalence of gravitational and inertial mass, Fisch-

bach considered that an Eötvös-type apparatus ought also to detect a torque due to an intermediate-range force coupled to baryon number, if the baryon number per unit mass density is sufficiently different for the two test masses. Two questions arise: Have such experiments been carried out with greater sensitivity since the days of Eötvös and his protégés? And if not, was the original Eötvös experiment sensitive enough to have detected a force of the magnitude and range suggested by the geophysical and neutral-kaon anomalies?

There have in fact been modern repetitions of the Eötvös experiment, by Robert Dicke and others. But they have all been configured to compare the gravitational accelerations of test masses to the Sun rather than the Earth. The Sun is of course much too far away to test a force with a range of a few kilometers, at most.

So Fischbach, Aronson and their Purdue colleagues Daniel Sudarsky, Aaron Szafer and Carrick Talmadge were forced to take a closer look at the original Eötvös experiment. If one parametrizes the supposed new force by a Yukawa-type potential energy

$$U(r) = +f^2 Y_1 Y_2 e^{-r/\lambda} / r$$

where r is the distance between two point objects with hypercharges Y_1 and Y_2 , neither the geophysical nor the neutral-kaon data alone are sufficient to specify the coupling strength f^2 or the range λ of the force with any precision. But they can be represented by two somewhat fuzzy curves in the f^2 – λ plane, crossing one another somewhere near a λ value of a few hundred meters and an f^2 about 10^{38} times smaller than e^2 , the electromagnetic coupling strength. An f^2 of $+10^{-38} e^2$ translates into a repulsive force between particles of ordinary matter, about a hundred times weaker than the gravitational attraction at separations much shorter than λ .

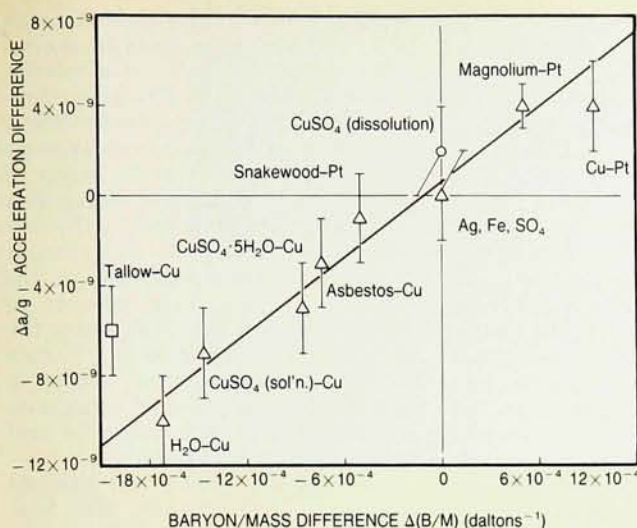
On this same f^2 – λ plane, Fischbach and his colleagues calculated a curve representing the limits of sensitivity of the original Eötvös experiment, simply assuming that the apparatus could detect departures from the Newtonian acceleration as small as one part in 10^9 . "The astonishing result," Fischbach told us, "was that this Eötvös curve came very close to crossing the intersection of the geophysical and neutral-kaon curves." If there were a hint of the new fifth force, unnoticed but retrievable, in the published Eötvös data, it would have to lie close to this curve. If f^2 and λ lay much above the curve, the apparent departure from the equivalence principle would have been too blatant to miss in the first place; and if they lay much below the curve, the Eötvös data would be totally insen-

sitive to the new force. The coming together of these three curves, from three completely unrelated sources, at more or less the same spot in the f^2 – λ plane, suggested that anything new coming out of the old Eötvös data might well be reconcilable with the geophysical and neutral-kaon anomalies.

This was the impetus that led Fischbach and his colleagues to undertake a laborious and detailed reanalysis of the Eötvös experiment from the data extensively tabulated in the original publication, which appeared in *Annalen der Physik* in 1922, three years after Eötvös's death, and a somewhat puzzling 14 years after the last data had been taken. Whereas the Eötvös paper had simply tabulated Δa , the apparent difference of the gravitational acceleration of a pair of materials as measured by the twistings of the fiber for various materials compared on the torsion balance, Fischbach and company added a new wrinkle. They plotted the Eötvös Δa data points against $\Delta(B/M)$, the difference of baryon number per unit mass between the two materials being compared. If the hypercharge-force conjecture is right, the data points thus plotted should lie on a straight line passing through the origin.

As Fischbach tells the story, his confidence grew as each new data point culled from the Eötvös tables fell nicely on the emerging line. But then there was a momentary setback. Talmadge, his graduate student, came in to report that the point comparing crystalline copper sulfate against copper was way off. "How did you calculate B/M for copper sulfate, I asked him." "From the chemical formula CuSO_4 ," was Talmadge's reply. At that point Fischbach's background as a chemistry major came to the rescue. He pointed out that crystalline copper sulfate always has five waters of hydration, whereupon Talmadge went back and recalculated the baryon number per unit mass for $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, and all was well. The remaining data points all fell nicely on the straight line, within the errors quoted in the original Eötvös paper.

Snakewood. Several problematic data points were left out of the plot Fischbach and company published² in January. But when they were later plotted, they too fell on the same straight line. One provided an amusing anecdote, the other a temporary occasion for criticism. The Eötvös paper had recorded a comparison for snakewood (*Schlangenhölz*) against platinum. But no one seemed to know what snakewood was, except that it was an unusually dense tropical wood. If it was purely wood, no matter how dense, one could simply calculate B/M from the chemical formula for cellulose. But some very dense woods contain infusions of silica or other alien materials,



Differential-acceleration data from the original Eötvös paper, replotted by Fischbach and colleagues against $\Delta(B/M)$, the difference in baryon number per unit mass (in amu) between the two materials being compared at the ends of the torsion balance. A fifth force coupled to hypercharge, or simply baryon number, predicts that $\Delta a/g$, the fractional difference in acceleration between the two materials, plotted in this way, should lie on a straight line passing through the origin. The two points nearest the origin have the same nuclear populations on both sides of the balance, differing only in chemical state. The linear fit through the Eötvös data thus plotted yields a slope three times that tentatively suggested by the geophysical data and the surroundings of the historical experiment.

and that would make a difference. Eventually Fischbach was able to track down a Bulgarian emigré balalaika maker with a treasured cellar full of aged snakewood. The wood was chemically analyzed, the point was plotted, and once again fell nicely on the line.

A more serious issue was raised by the Eötvös data comparing platinum against radium bromide. Concerned that radioactive heating might have created disturbing convection, Fischbach and company originally discarded this point. Critics then pointed out that the Pt-RaBr₂ datum called the consistency of the entire Eötvös experiment into serious question. Noting that the tiny quantity of radium bromide (borrowed from Marie Curie) was held in a brass container, they argued that this datum was effectively just a comparison of platinum against copper. But there was already in the Eötvös tabulation a datum for Pt-Cu, and it was quite different from the Pt-RaBr₂ value: a serious contradiction. This time Talmadge came to the rescue by going back to the raw scale-deflection data, also tabulated in the Eötvös paper. Indeed he found that a sign error had been committed by the Eötvös group in converting the raw datum to Δa . The consistency of the original Eötvös data was upheld, yet another point fell on the hypercharge-force straight line, and this particular criticism was withdrawn.

This criticism had been but one of many that greeted the January *Physical Review Letter* in which Fischbach

and company presented their reanalysis of the Eötvös data. But criticism was by no means the only response. The paper generated extraordinarily wide interest, and a flurry of theoretical and experimental activity. One object of early criticism was the slope of the best-fit straight line drawn through the Eötvös data plotted against $\Delta(B/M)$. This slope is a measure of the strength and sign of the supposed hypercharge force, and it ought to be consistent with what one expects from the geophysical data. In fact, however, incorporating the geophysical parameters in Fischbach's formalism predicted a slope an order of magnitude smaller than that found by plotting the Eötvös data against hypercharge. Even worse, several critics pointed out, the sign of the slope implied an attractive rather than a repulsive correction to gravity. This discrepancy had at first gone unnoticed because of a compensating sign error in the formalism. Was this, critics asked, the vaunted consistency between the Eötvös and geophysical data?

The closer examination of these serious discrepancies soon made it clear that there was a fundamental flaw in the formalism by which Fischbach and company had treated the expected response of the Eötvös apparatus to a finite-range force. For convenience, they had analyzed the Eötvös experiment in terms of a perfectly spherical Earth. This turns out to be a suitable approximation when one is only considering, as Eötvös was, a force of infinite

range. But when one looks for an additional force of finite range, the rotational flattening of the Earth cannot be neglected. Donald Eckhardt (Air Force Geophysical Laboratory), among others, pointed out³ that a short-range force of the kind under consideration, unlike a simple violation of the equivalence principle, would produce absolutely no torque on a torsion balance, unless the local terrain departed from the idealized "geoid" surface of the Earth.

The idealized Earth surface—what one would have if the land were flooded—is a pseudo-equipotential of the gravitational and centrifugal forces, everywhere normal to a local plumb line or the torsion fiber of an Eötvös balance. The source of a short-range fifth force would be the local Earth surface. Such a coupling, Eckhardt pointed out, would change the magnitudes of the downward forces on the test masses, but it would not change their directions. The axial symmetry of the local (idealized) source prevents a short-range force from exerting any torque on an Eötvös fiber.

Thus any effect on the Eötvös data from the fifth force would be due entirely to local inhomogeneities—buildings, basements, and terrain departing from the geoid. Having come to the same conclusion independently of their critics, the Fischbach group set out to recalculate the Eötvös slope expected from the geophysical data in the light of this new understanding. With a λ of about 200 meters, details of walls, cellars and nearby buildings become crucial. A cellar, for example, being a hole in the source field of this repulsive force, becomes an object of attraction. The sign of the slope can depend on whether a cellar was on the right or on the left. Armed with a somewhat sketchy knowledge of the local configuration at the time of the Eötvös experiment, the group has now calculated⁴ that the slope of the straight-line fit to the Eötvös data is only about a factor of three larger than what one expects from the geophysical data. And what's more, the sign of the slope now seems to be correct. The critique turned out to be a boon in disguise. Fischbach is planning a trip to Budapest to obtain more detailed information about the Eötvös laboratory and its surroundings. James Faller (Joint Institute for Laboratory Astrophysics, Boulder, Colorado) points out that the departure of the local terrain from the geoid, which the recent Fischbach analysis has not yet taken into account, may prove to be more important than manmade structures.

All this attention to the distant past is quite unusual for physics, and for the long run, quite inadequate. But in the absence of newer data, it was a bold

first step. The 11th International Conference on General Relativity and Gravitation, held in July in Stockholm, gave proof that experimenters are now addressing themselves in increasing numbers to the question of the fifth force. In several sessions devoted to this highly speculative issue, the conference heard reports of gravitational-gradiometer, free-fall, Eötvös-type and Cavendish-type experiments in the planning stages or already under way. The current fashion in Eötvös experiments, first advocated³ by Peter Thieberger (Brookhaven), is to set them up at cliff sides. Unfortunately there were not yet any substantive results from the new experiments at the time of the Stockholm conference.

What do the particle theorists make of all this? A repulsive force with a range on the order of 10^2 meters implies that its quantum—already labeled the hyperphoton, γ_Y —will be a vector boson with the extraordinarily small mass of 10^{-9} electron volts. “Alas, the theoretical motivation for very light intermediate vector bosons is also very light,” comments⁵ CERN theorist Alvaro De Rújula. But, he adds with tongue in cheek, “the fifth force proudly shares with every detail of the standard model... the property of *not* being a superstring prediction.”

De Rújula also points out that hypercharge is, in the modern language of quark flavors, a somewhat antiquated and arbitrary quantum number. He would replace it by a linear combination of proton and neutron numbers. Referring to a force coupling to hypercharge as a “theoretically hideous possibility,” De Rújula reminds us that a number of theorists have pointed out that a simple hypercharge coupling, with the parameters suggested by the geophysical data, is already ruled out by the experimental upper limits for the charged-kaon decay modes $K^\pm \rightarrow \pi^\pm + X$, where X is a single neutral particle of negligible mass. Such experiments, motivated by the search for the axion, another very light particle hypothesized by the theorists, rule out the decay $K^\pm \rightarrow \pi^\pm + \gamma_Y$ at the rate one would expect if the hyperphoton simply coupled to hypercharge in the most straightforward way.

But if one generalizes hypercharge to the linear combination $B\cos\theta + S\sin\theta$ of baryon number and strangeness, where θ is a Cabibbo-like mixing angle to be determined, Fischbach argues that one could probably bring the predicted rate for $K^\pm \rightarrow \pi^\pm + \gamma_Y$ down into agreement with the axion searches by making θ small. Of course if one makes θ too small the theory loses all connection with the neutral-kaon data that started it all. But Fischbach expects that there is a value of θ that will reconcile the axion-search

and neutral-kaon data.

A number of theorists who like the idea of a new long-range force would prefer that it have no coupling to an unconserved quantum number such as strangeness, or that it be attractive (between like “charges”) rather than repulsive, thus doing away with the need for a new vector boson. Itzhak Bars and Matt Visser (University of Southern California) would like to see the fifth force couple simply to baryon number, but they welcome a new vector boson of tiny mass. “We’ve found a scenario that would generate the outlandishly small coupling strength and boson mass of the new force,” Bars told us. Employing a 5-dimensional “toy model” simplification of the 10-dimensional superstring theories (*pace* De Rújula), they find⁶ that compactification to 4 dimensions generates a vector boson of minuscule mass that couples to ordinary quarks with an incredibly “feeble” coupling constant given by the ratio of the typical quark mass to the Planck mass (10^{19} GeV), just about what the geophysical data suggest.

Shmuel Nussinov (Tel Aviv University) and his University of Maryland collaborators Darwin Chang and Rabi Mohapatra prefer an attractive force, mediated by the exchange of scalar Goldstone bosons. Last year they pointed out that the standard theory of electroweak and hadronic interactions suggests the existence of a long-range force not unlike Fischbach’s, except for the sign. A repulsive force, they argue, would be inconsistent with the standard model. While the geophysical data clearly prefer a repulsive force, the Eötvös slope, involving as it does the location of basements and the like, does not, for the moment, pin down the sign of the fifth force very securely.

After the appearance of the *Physical Review Letter* by Fischbach and company, Nussinov pointed out⁸ that, despite the outlandish weakness of the supposed fifth force and the lightness of its quantum, if one takes the canonical quotient m/f , where m is the hyperphoton mass, one gets something quite familiar and suggestive: about 100 GeV, close to the mass of the intermediate vector bosons that mediate the ordinary weak force, and also close to the mass of the supposed Higgs particle that gives them their mass. This suggests to Nussinov that the hyperphoton might get its mass by the same Higgs mechanism. If all this is not just a numerical coincidence, it suggests a deep connection between the fifth force and the standard model of the electroweak force.

Other theorists, looking in the opposite direction, point to the similarity between the strength of the fifth force and that of gravity; G times the square of the proton mass is about $100f^2$.

There is a class of gravitation theories in which such corrections to general relativity, on the order of a percent, arise quite naturally. The nonsymmetric gravitation theory of John Moffat (University of Toronto), is an example of such a theory with the virtue of making very distinctive predictions that can easily be tested in the new generation of Eötvös experiments. Moffat, a veteran advocate of the search for a fifth force, predicts an attractive tensor force, coupled to fermion number. Falling off as r^{-5} , such an infinite-range force, unlike a Yukawa form, would exert a torque on an Eötvös balance, even when the local terrain is a perfect geoid.

Looking at the numerical relations between the hypothetical fifth force and gravity on one side, and the electroweak force on the other, Fischbach harbors the fond hope that this new intermediate-range force, if it exists, may prove to be “the cement that binds them all together.”

He is quick to concede that there may be no such fifth force after all. “But it would be an extraordinary coincidence if there’s nothing behind the fact that three experimental anomalies, from three quite unrelated fields, converge on roughly the same force parameters.”

Sheldon Glashow (Harvard) summarizes the evidence somewhat differently: “Unconvincing and unconfirmed kaon data, a reanalysis of the Eötvös experiment depending on the state of the Baron’s wine cellar, and a two-standard-deviation geophysical anomaly! Fischbach and his friends offer a silk purse made out of three sows’ ears, and I’ll not buy it.”

—BERTRAM SCHWARZSCHILD

References

1. S. Holding, F. Stacey, G. Tuck, *Phys. Rev. D* **33**, 3487 (1986).
2. E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, S. Aronson, *Phys. Rev. Lett.* **56**, 3 (1986).
3. D. H. Eckhardt, to be published in *Phys. Rev. Lett.* (1986). A somewhat similar argument had already been made by P. Thieberger, *Phys. Rev. Lett.* **56**, 2347 (1986); this 2 June issue of *Phys. Rev. Lett.* contains a number of other comments on reference 2.
4. E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, S. Aronson, to be published in *Proc. 2nd Conf. on Interactions Between Particle and Nucl. Phys.*, Lake Louise, Canada, May 1986.
5. A. De Rújula, CERN preprint TH.4466/86 (1986).
6. I. Bars, M. Visser, *Phys. Rev. Lett.* **57**, 25 (1986).
7. D. Chang, R. Mohapatra, S. Nussinov, *Phys. Rev. Lett.* **55**, 2835 (1985).
8. S. Nussinov, *Phys. Rev. Lett.* **56**, 2350 (1986).
9. J. W. Moffat, D. Savaria, E. Woolgar, Univ. Toronto preprint (March 1986). □