Gravitational Theory and Observation

Fifty years after Einstein formulated general relativity, an expermentalist looks at the observational support for this theory. He finds that the evidence is at least as good for a scalar-tensor theory of gravitation.

by Robert H. Dicke

ON THE 50TH ANNIVERSARY of the publication of Albert Einstein's general relativity,[1] his theory of gravitation, it is appropriate to reconsider the observational support of this theory and its place in contemporary physics. Within the framework of most of today's specialized physical disciplines, gravitation appears superficially to be of little significance. Nonetheless, some of the most enigmatic and puzzling of physical problems intimately involve this phenomenon.

In this article I make no attempt to speak for the general relativists as a group or to present a survey of current theoretical developments. As an experimentalist I am more interested in the significance of the experiments and observations, for they provide the only dependable foundation for our beliefs. However, these observations cannot be discussed except in a theoretical framework, and from Einstein's time abstract ideas have provided the main support for this framework. Consequently it is necessary to present a balanced theoretical picture before discussing the observations. I shall indicate how the theoretical structure is based on broad physical principles and I shall present the observational support for our beliefs. But first I shall present a brief glimpse of gravitation in its relation to other parts of physics.

Gravitation is far too weak to be of interest as an interaction binding together the atom or nucleus, and we know too little about the structure of the elementary particle to judge its importance there. Although the gravitational fields produced outside the laboratory by astronomical bodies seem large, under Einstein's equivalence principle neglecting the effects of gravitational gradients, they are equivalent in a small region of space such as a laboratory to the more mundane uniform acceleration of the laboratory. It would appear that today's specialized physicist working in the laboratory on atomic or nuclear problems need not concern himself with gravitation. It is by looking at the big picture, astronomical bodies and the largest dynamical system of all, the whole universe, that one sees fascinating gravitational phenomena.

Consider the universe; we know observationally that it is uniformly expanding at a rate which, extrapolated back linearly, would show it completely collapsed 10^{10} years ago. As seen from the distributions of galaxies and radio sources it seems to be quite uniform and isotropic in its structure. It also seems to be filled with matter rather than a mixture of matter and antimatter. How did these symmetries come about? Why matter rather than antimatter? Why either? There is nothing in the structure of general relativity that requires the uniformity and isotropy of the universe or its matter content. We have no idea why it has this structure.

Fireball and element formation

I find it exciting that observations, now at five different wavelengths, continue to support the belief that the universe is filled with blackbody radiation at a temperature of 3° K, the adiabatically expanded and cooled residuum from the fiery birth of the universe. But I hesitate to speak of the "birth" of the universe for it was the belief that the universe was not "born" but rather evolved from an earlier collapsing phase that led us (James Peebles, Peter Roll, David Wilkinson and myself) to suggest that this residual radiation might still be present.[2]

The electromagnetic and neutrino radiation energy in a collapsing universe would be expected to increase dramatically as the radiation is adiabatically compressed until finally a thermal equilibrium state is established at a temperature in excess of 10^{10} °K. If in some presently unknown way this state of collapse could be reversed, the universe would expand out of this very hot state. In this picture the high temperature is needed to reprocess the dirty matter from the previous cycle of the universe into the clean hydrogen

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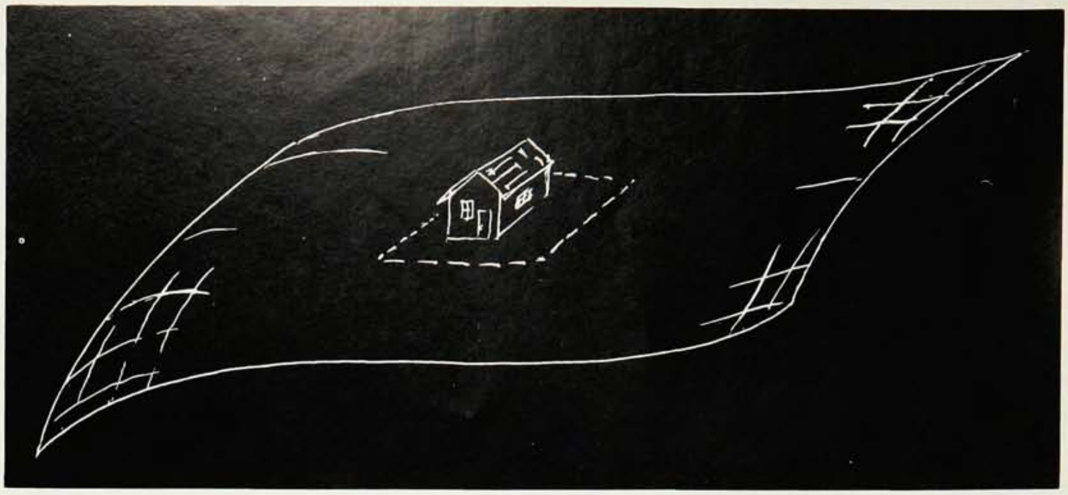


THE LABORATORY is too small for laboratory physics to be influenced by the large scale curvature of space.

found in our young galaxy.

Subsequent to this suggestion, the blackbody radiation was discovered by Arno Penzias and Robert W. Wilson[3] and confirmed by Roll and Wilkinson.[4] This discovery appeared to lend support to the idea of a collapse preceding the expansion of the universe. However, it was shown by S. W. Hawking,[5] who based his approach on earlier work of Roger Penrose,[6] that within the framework of general relativity and under extremely general conditions a singularity develops during the collapse. The full significance of this is not yet apparent. It may represent a basic inadequacy in either the theory or the physical model. It may also be resolved only by including quantum effects.[7]

Much earlier George Gamow[8] postulated an initially hot universe in an attempt to produce the heavier elements by nuclear reactions. He and his collaborators developed these ideas,[9] but ultimately the scheme collapsed because it failed to yield elements much heavier than helium. The scheme was later revived by R. J. Taylor and Fred Hoyle[10] as a means of producing helium. Peebles[11] appears to have been the first to make a modern careful and detailed calculation of this helium-formation process. He has also noted an important connection between the fractional helium production in the "fireball" and the present mass density and blackbody-radiation temperature of the universe. This connection involves the expansion rate of the universe, hence gravitational theory, in an intimate way.

Two recent observational results have an important bearing on Peebles's theory. First, there is the unpublished result of our colleagues R. B. Partridge and Wilkinson; fireball radiation is extremely isotropic in its distribution. This is of great importance because this radiation became decoupled from matter very early, assuming no large amount of ionized intergalactic gas, and hence mirrors the isotropy of the very young universe. Second, there is a recent observation[12] on extremely old horizontal-branch stars that shows that their helium content is over an order of magnitude lower than Peebles's theory predicts. It is too early to know where the difficulty lies. The spectroscopic interpretation could be at fault. In Peebles's theory the assumption of isotropy appears to be justified. The mass density of the universe appears to be well enough known. There could be a basic difficulty with the gravitational theory. It is interesting in this connection that an explanation of the very small helium content has been given within the scalar-tensor theory of gravitation to be described.

These are but a few examples of the fascinating questions encountered these days in the field of cosmic physics where gravitation is dominant. There are many others. Are there gravitational waves in space? What are quasars? Can a burned-out star collapse gravitationally to form a neutron star? Even more fascinating is the continuously imploding star that soon becomes cut off from the view of an external observer in all ways except through its gravitational field. Penrose[6] has shown that this solution to Einstein's equations cannot be continued indefinitely but that it develops a singularity in a finite time. Once again, what are these singularities trying to tell us? (See reference 7 for an interesting development of various aspects of the theory of gravitational collapse.)

Apparently the physicist who leaves his laboratory and considers physics-in-the-large is rewarded by a host of fascinating gravitational problems. In the vista provided by general relativity the tiny coördinate patch occupied by the laboratory physicist is too small to show significant curvature effects. Special relativity works pretty well. Still this coördinate patch is only an insignificant part of the whole, and laboratory physics cannot really be completely divorced from the physics of the world outside.

If not for Einstein

If by some accident Einstein had not developed his general relativity and the problem of gravitation had lain fallow for the past half century waiting for one of today's bright young field theorists, it is easy to guess how he would have solved it. He would not have brought to the task Einstein's philosophical arguments and a new set of relativistic principles. Rather, he would have approached gravitation within the framework of special relativity as an elementary problem in classical field theory, and he would have succeeded.

His first attempt would have been to frame Isaac Newton's old gravitational theory as a Lorentz-invariant zero-mass scalar-field theory, the scalar field being coupled universally to particle mass. He would have been very pleased with some of the results. It would have been discovered that this theory gave a correct account of the very precise null of the Eötvös experiment,[13] all bodies falling with the same acceleration.[14] However, the theory would have been scrapped for failing to account for the gravitational deflection of light and for giving the wrong relativistic rotation of Mercury's perihelion.

(Historical note: This scalar theory was first published in 1912 by G. Nordström,[15] and there are reasons to believe that Einstein[16] may have earlier formulated more or less the same theory.)

The next step is equally predictable. After noting that neither a spinor nor a vector theory of gravitation is capable of giving an account of the observed constancy of the gravitational acceleration, independent of the composition of the body, he would have next considered a nonquantized massless tensor-field theory.

This theory would have been satisfactory, yielding a gravitational acceleration independent of the composition of the body, a gravitational deflection of light and a perihelion rotation for Mercury's orbit in agreement with observations.

Two features of this development would have been found exciting by the philosophically minded. First, the theory apparently contains two different approaches to the same inertial effect. Second, the tensor field so distorts meter sticks and clocks relative to the Minkowski metric that they fail to measure this metric, the one assumed for the geometry. The equation of motion is obtained from a variational equation containing the free-particle Lagrangian and the interaction of the particle with the tensor field h_{ij}. This interaction term is quadratic in the appropriately defined four velocity u^i of the particle (in order to be invariant under Lorentz transformations).

$$0 = \delta \int [\tfrac{1}{2} m u_i u^i + h_{ij} u^i u^j] d\tau,$$

$$u^i = dx^i/d\tau$$

The resulting Euler equations of motion of the particle contain two types of tensor forces, one quadratic in the four velocity and the other proportional to the acceleration of the particle. The first might be called the gravitational force and the second an inertial force acting on the particle. Thus in this theory there seem to be two inertial effects. One is an acceleration-dependent force originating in an interaction with the tensor field of force. The other is geometrical and represents the acceleration "caused" by the tensor force as well as by the other forces acting on the particle. The equation of motion without other force is

$$m \frac{d}{d\tau} u_i = \left[\frac{\partial h_{jk}}{\partial x^i} u^j u^k - 2 \frac{\partial h_{ij}}{\partial x^k} u^j u^k \right] - 2 h_{ij} \frac{d}{d\tau} u^j$$

mass $\times$ acceleration = gravitational force + inertial force

The duality in inertial effects suggests that one of these may be superfluous.

This situation raises two questions: (a) Could the left side of this equation be set equal to zero and Newton's second law be modified to read "a particle moves in such a way as to cause the total force acting on it to be zero?" (b) Alternatively, could the tensor force field be dropped and the Minkowski metric tensor generalized and given field status as the metric tensor of a Riemannian geometry? We shall return to these questions.

Deflection and distortion

As mentioned above, the second remarkable effect of the interaction of the tensor field with light rays and matter is the resulting deflections of light rays and the apparent distortions induced in matter. These "distortions" are referred to the basic Minkowski metric of the theory. Owing to the universal character of the distortions, they are locally invisible; they do not appear when the matter is compared with local standards of mass, length and time based on the atom. Also the distorted meter sticks and clocks constructed from the matter do not measure the Minkowski metric, which in fact is consequently unobservable.

Clearly the best thing to do with an unobservable distortion of matter is to deny its existence. Then it is found that the geometry measured by light rays, rods and clocks is Riemannian. The metric tensor of this geometry is a linear combination of the Minkowski tensor and the gravitational field tensor. The old unobservable Minkowski metric tensor becomes amalgamated with the field tensor, and it loses its identity as a separate element in the theory.

A somewhat similar situation would have been found with the more elementary scalar field theory of gravitation discussed above. As will be shown, the mass of a particle interacting with a scalar becomes a function of that scalar. Consequently the lengths of rods and the periods of clocks constructed from such particles are functions of the scalar. Because of this distortion, the geometry measured with these rods and clocks is again Riemannian. (The metric tensor defined by these measurements is conformally flat with the factor of correction from the metric of flat space a function of the scalar.)

Although this distortion of matter is similar to that with a tensor field there is one important difference. The scalar field is measurable and the distortions of the meter sticks and clocks are observable in principle. The Minkowski metric would be measured by the operationally defined gravitational units. These units of mass, length and time are $[\hbar c/G]^{1/2}$, $[\hbar G/c^3]^{1/2}$, and $[\hbar G/c^5]^{1/2}$ respectively, and the distortions of matter are "seen" by making a comparison with these units. The scalar theory exhibits more clearly than the tensor theory the fact that the metric properties of a physical space are not intrinsic properties of the space alone, that they generally depend also upon the definition of units and the means of measure employed to survey the space.[17]

It appears that one of our younger field theorists working within his conventional Lorentz-invariant field theory would have been drawn inexorably toward general relativity. He might not have noticed that his Minkowski metric tensor had only a formal significance until after he had arrived at his goal. (Historical note: Lorentz-covariant theories of gravitation have been investigated in recent years by Nathan Rosen,[18] Suraj Gupta,[19] Richard Feynman[20] and W. E. Thirring.[21])

How Einstein did it

So much for general relativity as it might have been invented. How did it really happen? Here one must turn to Einsten's writings, his paper of 1916,[1] his book on *The Meaning of Relativity*,[22] and his Autobiographical Notes.[16]

Initially Einstein appears to have

followed the path as we described it above, about 1908 investigating in a preliminary way the elements of a Lorentz-covariant scalar field theory of gravitation.[16] He apparently did not think enough of this theory to publish it. However, in 1914 he published with A. D. Fokker a variation of the Nordström theory expressed in a form based on a Riemannian geometry.[23] Strangely enough, in his Autobiographical Notes he does not mention the conflict with the observed perihelion rotation as a reason for rejecting the scalar theory. (The gravitational deflection of light was unknown in 1916.) He gives the compositional independence of the gravitational acceleration, that is, the great precision of the Eötvös experiment and its implications, as a justification for excluding it. However, as was mentioned above, the conditions of the Eötvös experiment are as well met by the Lorentz-covariant scalar theory as by general relativity.[14]

The scalar field distorts matter in such a way as to permit formulation of the equations of motion in a Riemannian geometry. These equations of motion of matter in a given scalar field, hence Riemannian geometry, have the same form as in general relativity. Consequently the null result for the Eötvös experiment is as well understood as in general relativity.

Equally important was Einstein's concern[16] for Mach's principle.[24] He believed that the inertial properties of a test particle should be determined by the total matter distribution in the universe and should not appear as an intrinsic property of an absolute space as in special relativity. This difficulty with respect to Mach's principle suggested the generalization of Minkowski space to a Riemann space, with the metric tensor now coördinate dependent and affected by the matter distribution. The equations of motion of the generalized metric and the remainder of the dynamical system were to be generally covariant.

In this theory, gravitation does not appear as a force but as an aspect of the geometry of curved space. A structureless and spinless particle moves freely under the influence of pure gravitation along geodesic paths of geometry. A particle is accelerated relative to a locally inertial coördinate system only if some force (other than gravitation) acts on it.

It is a measure of Einstein's insight that he was able to proceed directly to this geometrical picture of gravitation without first being led to it through the construction of a massless spin-2 Lorentz-covariant field theory.

Is geometry required?

We return now to the two questions posed earlier. Can gravitation be eliminated as a force and a theory constructed for which gravitational effects are incorporated into the space-time geometry? The answer is clearly in the affirmative for this is precisely the type of theory Einstein constructed.

Consider the second question: Is it possible to remove the requirement (as an a priori condition) that gravitation be a geometrical phenomenon, to interpret it instead as the effect of a force field, not as the Lorentz-covariant theory previously described but in a geometry without a metric? With such a theory the only geometrical conditions imposed a priori are those of an unconnected differentiable manifold (that is, with neither a metric nor affine connection). The tensor g_{ij} is to be interpreted as an ordinary force field on a par with electromagnetism and other fields. The field equations are to be derived from a generally covariant variational principle. Again the answer is "yes."[25]

This is not to preclude the possibility of the tensor g_{ij} serving a secondary role as the metric tensor of a Riemannian geometry. If g_{ij} is found to serve this function, it is to be thus interpreted as a secondary property of the tensor, as a characteristic derived from the theory, not as an a priori condition on the theory. Quite generally the various force fields acting on the rods and clocks are expected to affect their structure and hence to affect the character of the geometry that would be measured by such units of length and time.

With Einstein's general relativity, it clearly should not matter in a fundamental way which of these two verbal descriptions is given of the variational equation and the resulting field equations of the theory. However, the geometrical description is certainly to be preferred as it is more easily visualized. A significant difference between the two descriptions first appears only when possible extensions or modifications of the theory are considered.

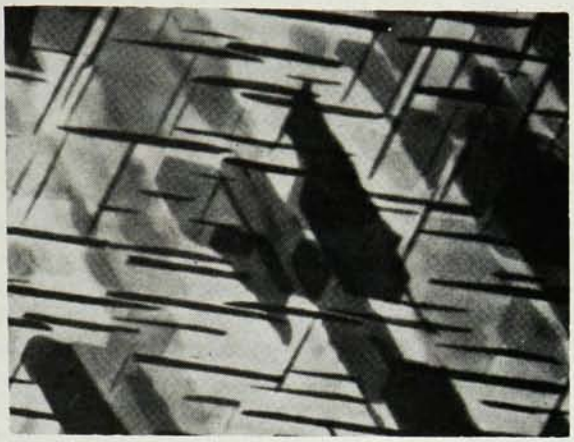
It is strange but undeniable that the type of physical picture evoked by a theoretical formalism, and the language used to describe the formalism can profoundly influence the process of invention. One has only to recall Faraday's picture of lines of force and its influence on the development of electricity and magnetism. Historically the various ill-fated attempts at modifying general relativity to generate a satisfactory "unified field theory" were geometrical in concept. These were direct extrapolations based on Einstein's geometrical description of his formalism. These unified field theories are not to be confused with the program of John A. Wheeler and his collaborators who, without modifying general relativity, have been attempting to understand elementary particles along geometrical lines.[26]

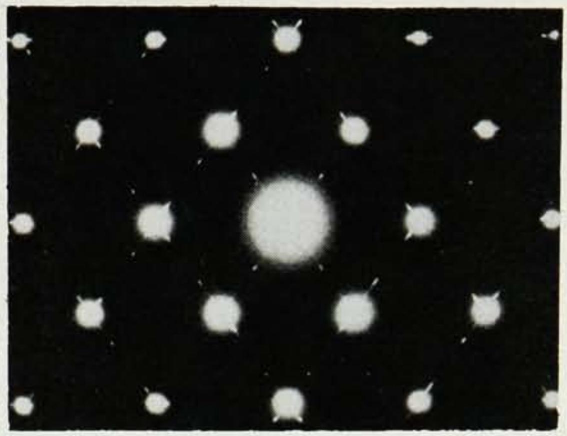
The great elegance of Einstein's formulation of general relativity stems directly from the geometrical description of the theory. Through its geometrical foundations and very little more the theory is given a definite and inviolable form. This is no slippery story to be modified every time there is a new measure. It stands or falls by the observations.

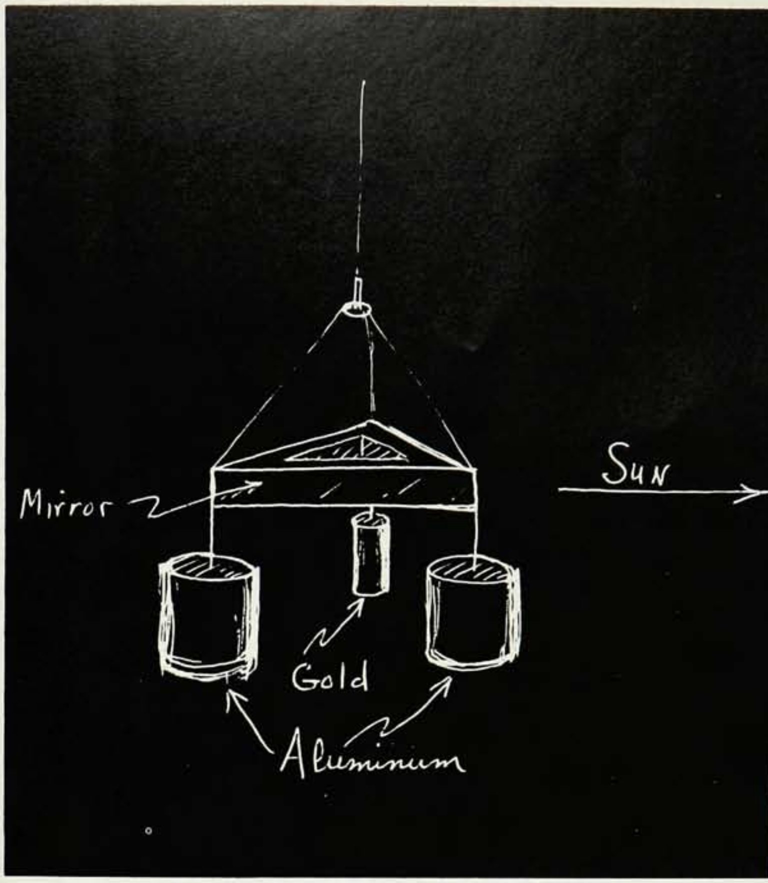
Based on a geometry without a metric, the field-theoretic description of gravitation is the very opposite of this. With gravitation interpreted as an effect of one or more force fields acting on matter, only a very general framework is defined, not a unique theory. A host of generally covariant variational equations can be constructed, theories attempting to ascribe gravitation to various combinations of scalar, vector and tensor fields. Out of such a plethora of possibilities only observation weeds out such absurdities as a theory of gravitation based on a vector and a scalar field or on two tensor fields. By contrast in the framework of Einstein's geometrical description such theories appear as absurd from the start. They are eliminated by the philosophical arguments which underlie his picture.

A tensor-scalar theory

The experimentalist might question the belief that nature always follows







EÖTVÖS EXPERIMENT (Princeton version). Aluminum and gold fall toward the sun with same acceleration (within 1 part in 10^{-11}).

the beautiful path, and he might like to ask how far the observations go in eliminating the pathological field theories. I have made an attempt at such an investigation.[27] Although I cannot claim to have investigated all the conceivable generally covariant field theories, my indications are that only two types of theories pass all the observational tests to their present accuracies. One is Einstein's general relativity. The other is some form of combined tensor-scalar theory of gravitation.

A theory of the tensor-scalar type was first introduced by Pascual Jordan.[28] It grew out of geometrical considerations, a generalization of the five-dimensional geometrical theory of O. Klein and T. H. Kaluza. In this formalism, the five-dimensional metric tensor with its 15 independent components provides the elements needed to represent the metric tensor of four-dimensional projective space, the electromagnetic four potential and a scalar potential in this space. Jordan introduced this formalism to provide a theoretical foundation for Dirac's cosmology.[29]

Carl Brans and I[30] constructed a theory subsequently found to be closely related to a special case of Jordan's theory. It is a four-dimensional scalar-tensor theory of gravitation which can be expressed in many formally different but physically equivalent forms.[17] The one most easily described is the form for which two gravitational fields, tensor and scalar, separately exert forces on matter.

Our interest in a scalar-tensor theory of gravitation was aroused by a difficulty we had in understanding Mach's principle within Einstein's general relativity. Although a philosophical principle, such as Mach's, is too verbal in its conception to imply an unambiguous mathematical theory, Einstein was apparently led straight to general relativity through his considerations of this principle. Few general relativists now consider the principle to be significant, preferring to view curved space as an absolute dynamical structure having a physical meaning even in the absence of all matter. But some of us believe that we still have much to learn from Mach.

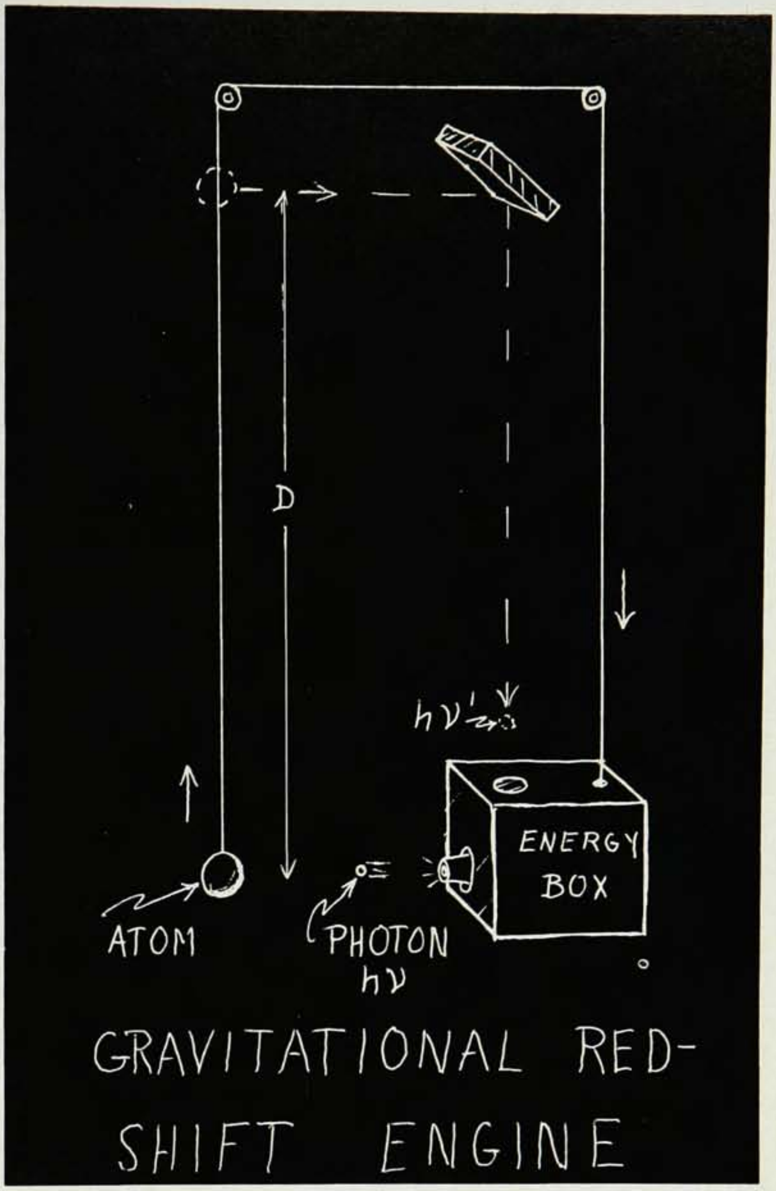
From a field-theoretic viewpoint the tensor field is essential to Mach's principle. It is the source of the inertial force that acts on a test body. If the tensor field were to be determined uniquely by the total mass distribution it might be expected that Mach's principle would be satisfied. However, a scalar field interacting with matter also influences inertial effects because it modifies the inertial mass of the particle on which it acts. The question then concerns the scalar field. Is it needed in addition to the tensor for a formulation of Mach's principle?

The difficulty we experienced in understanding Mach's principle within the framework of general relativity is easily seen by considering the space inside a spherical cavity within a mass distribution isotropic about the center. In Einstein's theory the space in this spherical enclosure is flat and the inertial properties of a test particle in space are independent of the outer mass, its radial distribution and its radial motion. While the directions of inertial coördinate axes are fixed relative to the external distant matter distribution, the magnitude of inertial effect induced by this distribution is independent of the details of the radial distribution. Not so when a scalar field is present. The scalar is affected by the external matter distribution and this externally generated field in turn affects the inertial masses of bodies upon which it acts.

Gyroscope in a shell

To speak in a quantitative way about the magnitude of the induced inertial effect, an operational definition is required. This can be provided by the old Lense-Thirring effect.[31] A small rotating mass shell of a sufficiently small mass is placed at the center of the large spherical enclosure. Inside the inner hollow mass shell is a spinning gyroscope. According to both general relativity and the tensor-scalar

REDSHIFT ENGINE. The operator fires the photon, which excites the atom. Atom is lifted through a distance D by a winch inside the energy box, photon is emitted and atom is then lowered to its final position. Null result of Eötvös experiment suggests that the excited atom is heavier by an amount $gh\nu/c^2$. Excess work required to raise the excited atom is approximately $g(h\nu/c^2)D$. From energy conservation $h\nu' - h\nu = gD(h\nu/c^2)$.



theory the spin axis of this gyroscope precesses in response to a modification of the tensor field induced by the rotating shell.

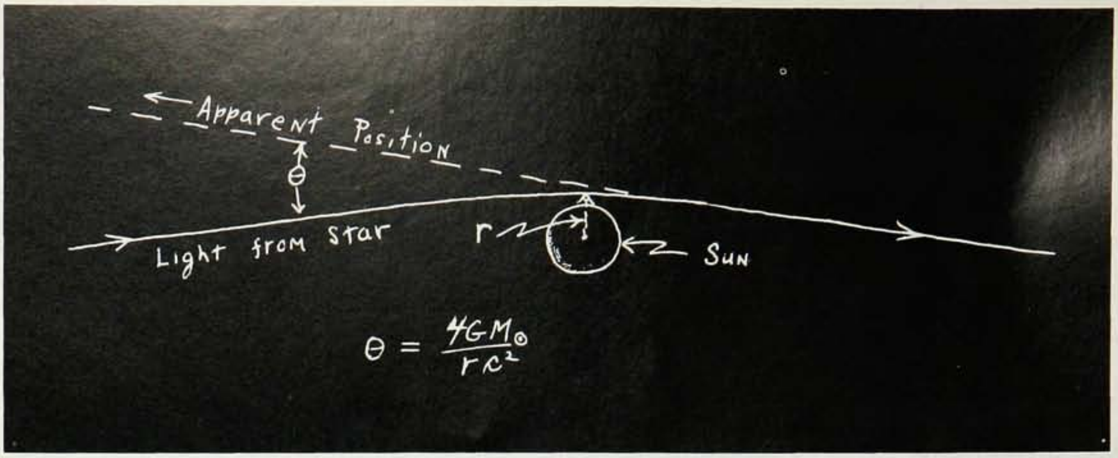
From the viewpoint of Mach's principle the precession of the gyroscope mirrors the result of a competition between the mass shell and the rest of the universe in determining the inertial coördinate system in the interior of the shell. The shell might be expected to gain or lose the battle, the gyroscope precession to increase or decrease, if the matter outside the shell were at either greater or smaller distances.

Choosing a coördinate system in which the gyroscope does not precess, the dimensionless ratio of the angular velocity of the mass shell to the angular velocity of distant matter could be taken as a measure, at the center of the mass shell, of the magnitude of the inertial effect induced by the outer mass distribution to that of the mass shell. The small mass shell with its internal gyroscope is to be interpreted as a measuring instrument. The dimensionless ratio of angular velocities provides a measure of the inertial effect induced locally by the distant matter, a measure in units provided by the mass shell. In general relativity this ratio is independent of the amount and distribution of distant matter. With the tensor-scalar theory the inertial inductive effect of distant matter increases if the distance to remote matter is decreased or the amount of remote matter is increased.[30]

What are the locally observed consequences with the tensor-scalar theory of an increase in the magnitude of the inertial induction of distant matter? There are no discernible effects on nongravitational laboratory physics, for the inertial masses of all elementary particles would scale together relative to the fundamental gravitational mass $[\hbar c/G]^{1/2}$. But the accelerations of bodies interacting gravitationally would decrease.[30] This can be interpreted as a result of an increase in the ratio of the inertial to the gravitational mass of all local bodies.

The problem of understanding Mach's principle within general relativity has been noted from the earliest days of relativity.[22,32] The popular recourse now appears to be to deny that Mach's principle has a significance for gravitation. If the principle is accepted within general relativity, however, the obviously unsuitable mass distributions must be eliminated as non-Machian. A completely empty space must clearly be excluded if, in line with Mach's principle, inertial effects are due to distant matter. But mass distributions with only a tiny content of external matter must also be excluded because we are concerned with a situation where this matter is a source of a dynamical effect, not where it serves only to provide signposts in an otherwise empty space. Newton would have been happy with tiny lanterns in outer space to show where the "real" physical space lay. Not so for Mach! He wanted the matter to be the actual source of the inertial interaction.

Einstein[22] suggested that with general relativity, a closed-space, stat-



GRAVITATIONAL deflection of light.

ic, uniform and isotropic distribution of matter was suitable umder Mach's principle. More recently Wheeler[33] and H. Hönl[34] have concluded that arbitrary closed-space solutions of Einstein's field equations are permissible. In addition Wheeler[33] has remarked in his detailed discussion of Mach's principle that under his interpretation the constant Lense-Thirring precession, independent of the radial distribution of the external matter in closed space, would be expected.

Apparently there is room for disagreement. Mach's principle may be without significance for gravitation, but if it is significant various interpretations of the principle are possible. Perhaps an observation will eventually provide the key to our understanding of this important question of philosophy.

It has been noted that the mass of a particle interacting with a scalar field is a function of the scalar. This is such an interesting result that it is worth demonstrating in an elementary way in the case of Nordström's theory. The Lorentz covariant equation of motion of a particle interacting with a scalar field is

$$dP_i/d\tau = -m\partial\phi/\partial x^i \qquad i = 1, 2, 3, 4 \tag{1}$$

where φ is the scalar field variable and τ is proper time. For a particle falling in a static field $\partial\varphi/\partial x^4 = 0$, and $P_4 = \text{const}$. Thus the particle energy $P_4 = m/(1 - v^2)^{1/2}$ is constant even though the velocity is changing. This clearly implies that m is variable. Quite generally if equation 1 is multiplied by the components of the four velocity u^i, it follows that $m = m_0 \exp -\varphi$.

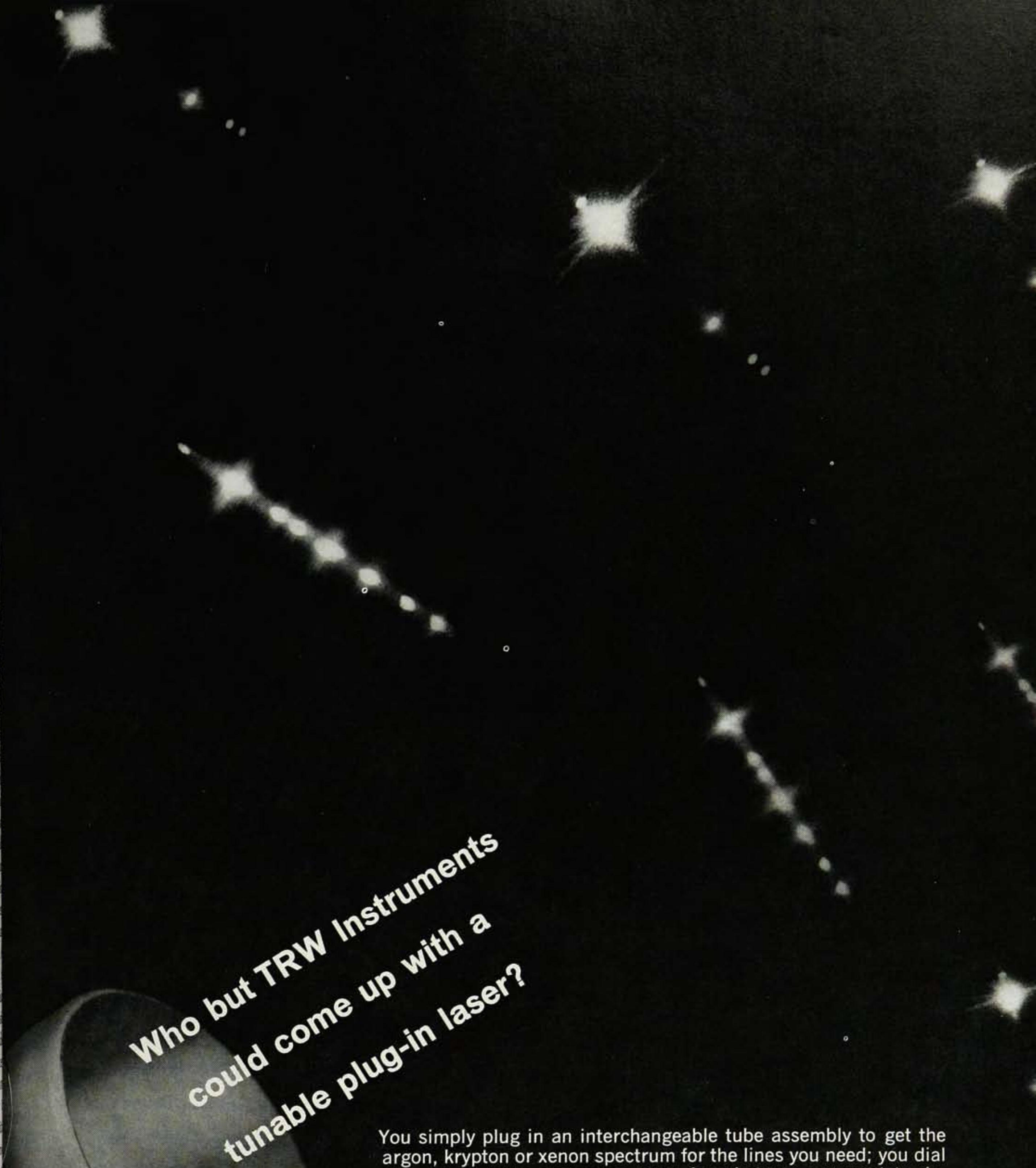
In this theory the masses of all bodies would change by the same factor $\exp -\varphi$, making the change unobserved in comparing the masses of two bodies with each other. The mass change is observable in gravitational physics, however, and it can be seen by comparing particle masses with the fundamental gravitational mass $(\hbar c/G)^{1/2}$. Thus the dimensionless gravitational coupling constant of an elementary particle, $GM^2/\hbar c$, is a function of the scalar, varying as $\exp -2\varphi$.

As I have said many formally different but physically equivalent versions of the tensor-scalar theory of gravitation can be generated. One is the theory described above for which the scalar is coupled to matter; particle masses becoming a function of the scalar.[17] Another version is the theory for which the scalar does not interact with matter, hence does not affect nongravitational laboratory physics; but does couple to an invariant defined by the tensor field.[30] In this version the particle masses are fixed but the gravitational constant varies. The two theories differ only in their definitions of the units of mass, length, and time.

Philosophical arguments

The intrinsic weakness of a theory based so heavily on epistemological considerations, philosophical principles as vague as those of Mach, and such criteria as simplicity and beauty is obvious to all. Yet Einstein was amazingly successful with these techniques and they cannot be ridiculed. Moreover, when so few observations are available, philosophical considerations are essential to limit the range of possible theories to a reasonable number.

Thus observations can be considered meaningful only in relation to a set of basic assumptions that limit the bounds of interpretation. I shall state mine[25] explicitly with the recognition that other choices are possible. First, as was noted above, and contrary to the current majority view, I am impressed by Mach's principle. I also believe that Einstein was right in requiring general covariance of the field equations of physics. This belief is related to Mach's principle; for by permitting arbitrary labeling of spacetime points one avoids imposing a priori conditions on empty space (reference 25, page 49). I do not believe, however, that it is essential to adopt Einstein's strong equivalence principle as a basic assumption of the theory. This "strong principle" goes well beyond the "weak principle," the simple statement that all bodies fall with substantially the same acceleration. The strong principle is the statement that locally in a freely falling and nonrotating laboratory the laws of physics take on a standard form and a standard numerical content. In combination with general covariance this is a very rigid constraint on the theory and leads directly to general relativity. As we have seen, this theory appears to be in conflict with our interpretation of Mach's principle. It might be desirable to permit more flexibility, to depend more upon observations in determining the validity of this assumption. In similar fashion my preference is to eliminate the requirement that gravitation be a purely geometrical phenomenon. This assumption is not to preclude the possibility of such an explanation but only to put more burden on the observations to help define the theory. I believe that, within the framework of these and a few other fundamental assumptions and the available observations to be discussed, only two possibilities remain for future consideration. One of these is Einstein's general relativity and the other



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is a scalar-tensor theory of gravitation.

Between the two theories there are three principal points of departure that should be remembered in considering the observations. With our version of the scalar-tensor theory[17,30] the gravitational deflection of light is less than that in Einstein's theory by the factor $1 - s$ where s is a fixed parameter, the fraction of a body's weight due to the scalar interaction. In similar fashion the expected perihelion rotation differs from Einstein's value by the factor $1 - 4s/3$. The third departure appears in the cosmologies based on the tensor-scalar theory. Here the rate of change with time of the scalar, an effect of the expansion of the universe, results in a time dependence of the gravitational coupling constants and a steady weakening of gravitation in relation to the other interactions.

With the Dirac-Jordan cosmology the gravitational coupling constants decrease at a rate somewhat greater than 1 part in 10^{10} per year. With the Brans-Dicke cosmology the rate of decrease would be roughly a factor of 10 slower.

The gravitational red shift is the same for both general relativity and the scalar-tensor theory.

The strong coupling between gravitational physics measured in the laboratory and the structure of the universe (through the scalar field) is the feature of the scalar-tensor theory that might be considered repulsive by many physicists. From the very beginning the physicist has kept his sanity and made the most progress with his science by isolating his problem, eliminating unwanted disturbances, and ignoring the complexities of the rest of the universe. It would indeed be disquieting if now it were to be found that the laboratory could not be isolated, even in principle.

Table 1. Gravitational Deflection of Light*

Eclipse	*Result (seconds of arc at sun's limb)*	*Different analysis (seconds of arc at sun's limb)*
1919	1.98 ± 0.12	2.0 to 2.2
		2.16 ± 0.14
		2.06
		1.95 ± 0.09
	1.61 ± 0.30	
1922	1.72 ± 0.12	2.2
		2.14 ± 0.18
		2.12
		2.00
		1.83 ± 0.20
	1.82 ± 0.15	2.1
		2.07
	1.18 to 2.35	
	1.42 to 2.16	
1929	2.24 ± 0.10	1.98 ± 0.20
		1.75 ± 0.13
		2.06
		1.96 ± 0.11
1936	2.71 ± 0.26	2.70 ± 0.40
	1.28 to 2.13	
1947	2.01 ± 0.27	2.01 ± 0.27
		2.20 ± 0.35
1952	1.70 ± 0.10	1.43 ± 0.16

* Theoretical result from general relativity is 1.75 seconds of arc. Table from Klüber (1960).[43]

Nulls and red shifts

How do the observations stand? They range from a null measurement with a precision of 10^{-22} to a host of observations little better than qualitative.

The two most important null experiments are the test for local spatial anisotropy performed by Vernon Hughes and his collaborators[35] and independently by R. W. P. Drever,[36] and our version of the Eötvös experiment.[13] Neither experiment is useful in choosing between general relativity and the scalar-tensor theory of gravitation, but they provide very strong support for the relativistic principles and arguments against such pathologies as a gravitational theory based on two separate tensor fields,[37,27] or a theory with a small contribution from a vector field.[38]

The Hughes-Drever experiment tests for spatial anisotropy by looking for an orientation dependence in the weak-field Zeeman splitting of nuclear magnetic substrates. Because of the motion of the earth around the sun and of the sun relative to the rest of the universe, it can also be interpreted as a very stringent test for local Lorentz invariance.

The improved Eötvös experiment[13] showed that the acceleration toward the sun of aluminum and gold were equal with a probable error of 10^{-11}. This experiment is compatible with Einstein's strong equivalence principle. It is fallacious, however, to interpret this null experiment as a sufficient test of strong equivalence. This principle contains aspects[25] that lie completely beyond the range of this experiment.

The numerous experiments on elementary particles at high energy and the precision spectroscopic experiments, both of which demonstrate the range of validity of special relativity, are in a certain limited sense also gravitational experiments; for they provide detailed justification for our picture of space as seen in a small coördinate patch. Unfortunately these observations are also of no help in deciding between these two classes of gravitational theory.

Another important test of gravitational theory in general, a test that does not distinguish between the two types of theory, is the gravitational red shift. After much hard work by R. V. Pound, R. L. Snider and other collaborators, the approach using the Mössbauer technique has been improved until the accuracy is 1%.[39] The best observation of the red shift of a solar spectroscopic line has an accuracy of about 5%.[40]

Future experiments

We are looking forward to the

outcome of an experiment suggested by Leonard Schiff,[41] and in preparation by William Fairbank and his collaborators at Stanford, involving the measurement of the precession of a top orbiting the earth in an artificial satellite. This should be capable of showing the Lense-Thirring precession due to the nearby rotating earth. It should also show the larger geodesic precession resulting from the motion of the top around the earth. This experiment is of particular interest to me because it is capable of distinguishing between general relativity and the tensor-scalar theory.

An experiment in preparation by my former colleague, Henry Hill, shows good promise of being able to measure accurately the gravitational deflection of starlight by the sun without the benefit of a solar eclipse. This experiment is particularly exciting as it is an old classic observation that is capable of distinguishing between the two theories.

Irwin Shapiro[42] has suggested using radar observations of planetary orbits to obtain a result of similar significance.

Information now available

So much for the beautiful experiments in preparation. What about the information in hand? Here the situation is rather discouraging. The first observation of the gravitational deflection of light was made in 1919 by photographing the star field in the vicinity of the sun during a solar eclipse. This observation has been repeated many times during the past half century with some improvements in technique and little improvement in the results. Because of the rapid decrease of the camera temperature, the changing atmospheric conditions during the eclipse, and the necessity for calibration pictures taken at night months later, it has been impossible to make the usual stringent control observations to test for systematic errors. Most of the results to date are given in table 1. It is evident from the large scatter and the possibility of a substantial systematic bias that the gravitational deflection is presently uncertain to at least 10%.

As will be seen from the discussion below, we are particularly interested in the possibility that approximately 4–8% of the weight of an object is due to the interaction with a scalar field. It is clear that the corresponding gravitational deflection as small as 1.6 seconds of arc cannot be presently excluded by the observations of light deflection.

Mercury's orbit, solar oblateness

There is presently only a single accurate measurement capable of distinguishing between the two theories. This is the observation of the rotation of the major axis (or perihelion) of the orbit of Mercury. The rotation is referred to the conventional coördinate system provided by the ecliptic and equinoxes. Owing to the precession of the spin axis of the earth the equinoxes of this coördinate system rotate relative to the local inertial coördinate frame. This large rotation and also the effect of planetary perturbations must be subtracted from the observed rotation. Any reasonable doubt about the perturbation induced by Venus was removed in 1963. Its mass was then determined from the orbit of Mariner II perturbed by this planet. After subtractions are made for planetary perturbations there remains an excess rotation of 43 sec/century, which agrees with Einstein's calculated value, 43.03 sec. The details of the various contributions to the perihelion rotation are given in table 2.

Before Einstein's invention of general relativity the large excess rotation had been frequently thought to be due to perturbations by an undiscovered planet close to the sun (Vulcan), dust and gas about the sun or a solar gravitational quadrupole moment. If it existed, a planet large enough to be significant should have been discovered long ago. Also we now know enough about the corona and zodiacal light to rule out this type of matter as a significant source of perturbation.

We do not know enough about the solar interior to exclude a significant contribution to the perihelion precession of Mercury caused by a solar quadrupole moment. We know from classical astronomical observations of the solar oblateness, and from planetary motions, that this effect could not be great enough to cause the entire excess perihelion rotation of 43 sec/century. But if the sun should have a moment large enough to induce an appreciable fraction of the observed excess precession, one could not argue that the observed 43 sec/century agrees with the 43 sec/century predicted by Einstein's theory. In that event one has no evident simple recourse but to turn to the mixed tensor-scalar theory. This can be expressed quantitatively.

A solar oblateness $\Delta r/r = 6 \times 10^{-5}$, $\Delta r = r_{eq} - r_{polar} = 0.06$ sec would imply a 10% reduction of the relativistic effect to 39 sec/century.[45] This oblateness is too small to be excluded by the old observations.

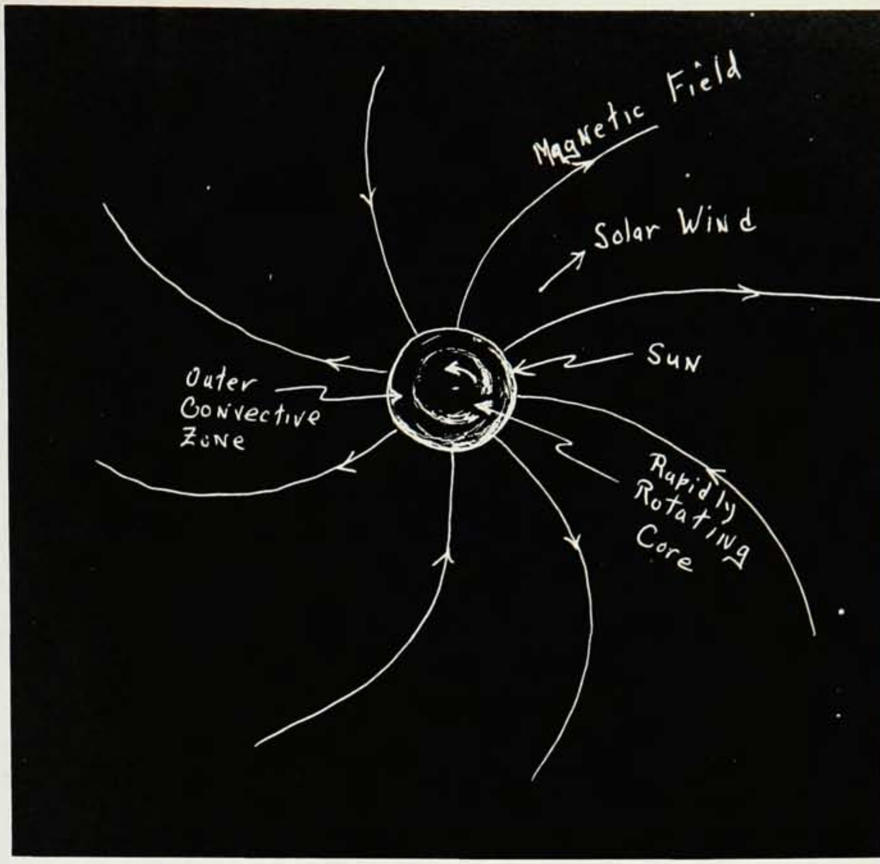
There are astronomical reasons for considering reasonable the hypothesis of a solar gravitational quadrupole having its origin in a rapid internal rotation of the sun.[45,46] Among these are the implications of the solar-wind observations obtained with several artificial satellites and planets. They have lent support to the belief that the

Table 2. Contributions to Mercury's Perihelion Rotation*

Contribution	*Rotation (sec/century)*
Observations	5599.74 ± 0.4
General precession plus planetary perturbations	5556.68 ± 0.2
Difference	43.1 ± 0.5
Perturbation induced by Venus	278
Perturbation induced by Jupiter	154
Perturbation induced by Earth	90
Perturbation induced by Saturn	7
General precession	5025

* Observed rotation of the perihelion of Mercury's orbit and the residual rotation after subtracting general precession and planetary perturbations.[44]

DOES THE SUN have a gravitational quadrupole moment arising in a rapidly spinning core? The rotation of the outer convective zone may be retarded by the magnetic brake that acts on the sun's surface.



corona has a magnetic structure that applies a substantial magnetic torque to the surface of the sun.[45] This torque has been calculated to be large enough to slow down the rotation of the outer convective layer of the sun with an *e*-folding time of only a few hundred million years.[45] The fact that this layer has not yet substantially stopped rotating shows that angular momentum is being absorbed from the interior. The uncertainty in the implied rotation of the interior stems from the uncertainty in the angular-momentum transport mechanism. If the transport is through viscosity in the strongly stratified radiative core of the sun, the indicated rotation period of the core is short,[45] of the order of one day. It could be an order of magnitude greater if magnetic coupling plays a significant role.

The solar quadrupole moment can be determined from the shape of the solar surface without direct observational contact with the deep interior.[45] In the absence of significant stress contributions from magnetic and velocity fields at the surface, the surfaces of constant P, ρ, T and Φ coincide. Here Φ is the gravitational potential supplemented by the centrifugal potential of surface rotation. Mark Goldenberg and I have just completed a long series of observations of the solar oblateness using an instrument designed for that purpose. The data are still being analyzed but we hope to be able to make a significant statement about the oblateness soon.

Earth as an atomic clock

Of the observations discussed, only the perihelion rotation of Mercury's orbit has the requisite accuracy and unique interpretation to provide a strong test for general relativity (after the solar oblateness is known). One other characteristic feature of the scalar-tensor theory, however, distinguishes it from general relativity and this could conceivably provide an astrophysical or geophysical test of these theories. As was noted above, under the scalar-tensor theory the expansion of the universe leads to a time dependence of the scalar and a steady weakening of gravitation relative to the strong and electromagnetic interactions (that is, a decrease of the gravitational coupling constant). This coupling of local physics to the structure of the cosmos has a number of fascinating implications for both astrophysics and geophysics, but unfortunately the intrinsic complexity of these phenomena precludes a clearly unique and unchallengable interpretation of the results. But still this is an interesting approach to a fundamental physical problem.

We shall consider only effects that can be discussed quantitatively. One such possible test is provided by the mechanics of planetary motion in the solar system. With units of length and time provided by the atom, a slow decrease in the strength of gravitation relative to the strong and electromagnetic interactions leads to a lengthening of planetary orbital periods and an increase of their orbital radii. Parameters such as eccentricity and inclination are adiabatic invariants and are not affected appreciably. The telescopic observations over the past two centuries are of a sufficiently good quality to exhibit a change in the planetary period induced by a gravitational weakening as small as 10^{-11} parts/year, providing a suitable atomic clock were available for this period. Real atomic clocks have not been available nearly long enough to be useful and we are forced to use a somewhat poor version of an atomic clock, the earth spinning on its axis. This clock is "atomic" because the radius of the earth, and consequently its spin rate, are determined primarily by the dimensions of the atom.

Unfortunately the rotating earth is not a very good clock. It undergoes fluctuations, probably caused by random motions in the earth's fluid core coupled magnetically to the solid mantle. These irregularities are of roughly a decade duration and are sufficiently large to preclude a highly precise time measure over a period as short as a century.

Over a period of 2000–3000 years the random fluctuations tend to average out and the earth seems to provide a rather good clock. By combining the

Table 3. Acceleration of Earth's Rotation Based on Recent and Ancient Observations*

Eclipse	*Time B.P. (before 1960)*	*Acceleration*[48] *(10^{-11} parts/yr)*
Plutarch	−1889	-15.4 ± 0.1
Phlegon	−1931	-15.6 ± 0.2
Hipparchus	−2088	-16.1 ± 0.1
Archilochus (Paros)	−2607	-16.2 ± 0.4
(Thasos)		-17.9 ± 0.4
Babylon	−3022	-16.2 ± 0.2

* Average acceleration of the earth's rotation from the indicated time till the present. Results are derived from telescopic observations coupled with information from the indicated eclipse. Errors quoted are contributions from the eclipse only. In addition there is an error common to all of about ± 0.6 having its origin in the telescopic observations.[47]

information derived from a single ancient eclipse of the sun with the telescopic observations of the past two centuries the average acceleration of the earth's rotation for this time span can be determined on a time scale determined by the earth's orbital motion.[47] The only information needed about the total eclipse of the sun is the simple fact that the eclipse was total at a certain point. As neither time nor angle measures are required, a simple news item in an ancient copy of the *Babylonian Gazette* could be enough to permit the calculation of a precise value for the average acceleration of the earth's rotation. Unfortunately a clear description of the eclipse and its location is seldom found. The account may be hidden in a poem or a play and clothed in a statement vague enough to make the oracle of Delphi envious.

Table 3 gives the results obtained from the five most reliably determined and useful eclipses described by Fotheringham.[47,48] In the case of the Archilochus eclipse it is not known from which of two islands Archilochus saw the eclipse and the observation was reduced twice, once for each island. An examination of table 3 will show that there is now no evidence for a substantial fluctuation of the clock. It even suggests that on 6 April 648 B.C. Archilochus might have been found on the Greek islands of Paros.

The telescopically observed increase in the moon's period permits a calculation of the lunar tidal couple on the earth. This in turn implies a range of possible values for the nonatmospheric solar tidal couple.[49] The atmospheric solar couple is calculated from the barometric fluctuations.[49] The net result of all this is that the torque decelerating the earth's rotation is rather reliably known to lie in a limited range and the observed acceleration of the earth's rotation can be corrected for the effect of this torque. Also, it is necessary to correct for the change in the moment of inertia due to rising sea level. Although this correction is somewhat questionable because of uncertainty in the degree of afterflow of the earth's mantle, limits can be set. Table 4 summarizes these results.[47]

Table 4. Residual Acceleration of Earth's Rotation

Mechanism	*Acceleration (10^{-11} parts/year)*
Observed acceleration of Earth's rotation	-15.9 ± 0.7
Tidal acceleration (depending on mechanism)	-25.6 to -23.5
Effect of rising sea level (depending upon speed of isostatic recovery)	$+3.0$ to $+0.5$
Unexplained residual in Earth's acceleration	$+4.6$ to $+9.2$

If geophysical explanations of this residual acceleration could be conclusively excluded, a fractional weakening of gravitation at a rate from 2.1 to 4.2×10^{-11} parts/year would be indicated. Although an extensive and careful search failed to show another explanation,[47] it cannot be argued that this result constitutes a compelling test of gravitational theory. The earth is too complicated a physical system to permit such a fundamental conclusion to be drawn with confidence.

Ages of stars and galaxy

The last result to be discussed is the apparent discrepancy between the evolutionary ages of stars and other ways of dating the galaxy.[50,51] After a star is first formed it converts hydrogen to helium at its center. When the central hydrogen is exhausted, the star rather quickly reddens and brightens. The theory of stellar interiors[52] permits a calculation of the duration of this central hydrogen burning phase in terms of the mass and composition of the star. The oldest stars in the galaxy are believed to have been formed only a few hundred million years after the start of the expansion of the universe. Depending upon the original helium content assumed for these stars, and other factors, the ages obtained range from $12–25 \times 10^9$ years. If the recent spectroscopic evidence[12] for low helium stands, an apparent age toward the upper end would be indicated.

This is to be contrasted with the galactic age of about 7×10^9 years indicated by the decay of uranium[53] and the age of $5–13 \times 10^9$ years obtained from the galactic-red-shift data.

The uranium age[53] is based on a technique due to William Fowler and Hoyle.[54] It should be reasonably accurate if the assumptions made are valid.[51,53] However, other assumptions have given an age twice as great.[54] The Hubble expansion age has been modified drastically in the past two decades. The changes resulted from corrections in previous errors in interpretation. The new value of 10^{10} years has been obtained in several different ways and is believed by the experts to be fairly reliable.

If a cosmology based on the scalar-tensor theory were valid, the stronger gravitational interaction in the past would brighten the star and shorten its

life. It has been shown that with 7% of a body's weight due to the scalar field (gravity weakening 1–2 $\times$ 10^{-11} parts/year) a consistent age pattern can be obtained in this way, a star apparently 15–25 $\times$ 10^9 years old being in actuality only 6–8 $\times$ 10^9 years old.[51] The evolution of the sun would also be affected[55,56,57] by weakening gravitation.

But again it is the complexity of the situation that makes impossible a compelling conclusion. Observational deficiencies are known, and the interpretations could be faulty at some critical point.

Observations favor poor cousin

How do things stand? I have presented rather fully the observational basis for our understanding of gravitation. The observations are so few in number that I was disposed to include all that might be significant. I have tried to indicate where there was reasonable doubt in interpretation.

Some may disagree with me for limiting the allowed theories to only general relativity and the tensor-scalar theory. Some may object to my even considering the tensor-scalar theory a reasonable alternative to Einstein's theory. Nonetheless the observations, insecure as they are, seem to favor this poor cousin of general relativity.

The crucial tests are still coming. The results from the solar oblateness observations should be available soon. The results concerning the gravitational deflection of light and the geodesic precession of the spin axis of a top may be some years off.

It is unfortunate that the highly precise null experiments[13,35,36] do not provide a means for deciding between these two theories. Nonetheless their importance is great because they represent the principal observational support for our belief in the validity of the relativistic foundation of gravitational theory.

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