signing of drugs but it does not tell all.

There seem to be many disorders which arise from excesses of this or that hormone. The possibility of controling some of these in the manner indicated seems enticing. Especially is this so when it begins to become clear that several drugs which have been discovered and used empirically for the control of certain disorders are in fact antimetabolites of some hormone or other essential metabolite.

The practical applications of the antimetabolites to attempts at chemotherapy could have been illustrated equally well with a variety of other drugs which have been introduced recently. None of these is completely satisfactory from a practical standpoint, and there are still those who maintain that it is unlikely that this record can be improved. The examples chosen were selected because they are well known to me and because they indictate the status of the field as it exists today.

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CURRENT PROBLEMS IN RESEARCH

New Research on Old Gravitation

Are the observed physical constants independent of the position, epoch, and velocity of the laboratory?

R. H. Dicke

While fully aware of the hazards, both natural and occult, incident to the discussion of experiments not yet completed, I welcome the opportunity to say something about our research on gravitation, particularly about its motivation, for there appears to be considerable misunderstanding of the state of knowledge of this important force field.

With the exception of a few isolated experiments, there has been essentially no basic experimental research on gravitation in the past 30 years. There are several reasons for this. First, because of the weakness of the gravitational field, such experiments are invariably difficult, and many of the most important are impossible. Second, because of the successes as well as the basic simplicity and elegance of Einstein's relativistic theory of gravitation, the feeling has been widespread that this theory must be correct. Third, it has been generally believed by physicists that the gravitational interaction is too weak to be important for modern physics.

Needless to say, my coworkers and I do not agree with this diagnosis. First, new experimental techniques now make possible experiments formerly impossible. Second, while Einstein's theory is admittedly elegant, we are not sure that nature has quite the predilection for an elegant theory that man apparently possesses. Third, although gravitation is weak, it may play a crucial role in the structure of a particle. If, as is believed by many physicists, an elementary particle is a complex structure of very small size consisting of a core particle surrounded by a swarm of attendant virtual particles, the gravitational interaction may be one of the dominant forces acting on very-high-momentum particles found at the core. It has been suggested that it is the failure to take into account such interactions which is the root of the difficulty leading to divergences in quantum-field theories.

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Observational Evidence for Theory of General Relativity

The experimental and observational support for Einstein's theory of general relativity consists primarily of facts available before the construction of the theory. These consist of the large body of data on planetary motion, including the anomalous rotation of the perihelion of Mercury's orbit. There is also the accurate experiment of Eötvös (*1*) and others on the equivalence of inertial and gravitational mass. The only observational facts found subsequently are the gravitational deflection of light by the sun and the gravitational red shift. Because of the smallness of these effects, both of these checks of the theory of general relativity are inaccurate. The astronomical observations of planetary orbits are very accurate; however, a comparison between the observed orbits and calculated orbits always shows small systematic discrepancies (*2*). The discrepancies are believed to be due primarily to computational errors and systematic errors in observation. While this may be true, there is always the possibility that some of the systematic error may be of a more fundamental character. It should also be remembered that the velocities of the planets are so low that gravitational retardation effects are essentially unobservable.

Conceptual Difficulties

In addition to dissatisfaction with the scanty observational evidence supporting Einstein's theory of gravitation, there are certain conceptual difficulties which are a source of doubt concerning the complete correctness of the theory in its present form. These difficulties are associated with the problem of inertial coordinate systems and the existence of inertial forces.

In the mechanics formulated by Newton in the 17th century it was assumed that there existed an absolute physical space which could be characterized by a Euclidean geometry. An acceleration of a particle with respect to this space required a force. Equivalently, in the accelerated coordinate frame for which this particle was at rest, there appeared an inertial force acting upon the particle.

This situation long appeared enigmatic, and some of the difficulties were discussed as early as 1710 by Bishop Berkeley (*3*). Among the difficulties are the following. There is a basic difference between the conceptual space of the mathematician and the physical space of the physicist. A mathematician merely needs to assume the existence of a set of points having certain properties to define a space. A physicist must consider the physical significance of such mathematical concepts as points, lines, and geodesics. If the physical space in question is a vacuum, assumed to be a void—that is, structureless—it is not clear what is the physical significance of points in such a space or the meaning of either velocity or acceleration with respect to such a space. It is also not clear how such a space is to be parameterized—the first step in the construction of a geometry.

Mach's Principle

In 1872, E. Mach (*4*) made a notable suggestion: he surmised that the inertial force did not arise from motion relative to space but had its origin in the acceleration of a particle relative to distant matter. Equivalently, in the coordinate system with the particle at rest, it was the acceleration of distant matter which was to be regarded as the source of the inertial force acting on the particle.

Mach apparently had in mind a type of instantaneous action at a distance as the means by which very distant matter would produce this force. It would be more in keeping with modern notions of the nature of forces if the inertial force could be some day traced to a purely local interaction with the particles of a quantized field. This field would be assumed to have its source in all the matter of the universe. As was emphasized by Sciama (*5*), there is every reason for assuming that this inertial field is not some new type of field but merely the gravitational field of distant matter. A particle at rest at the origin of a coordinate system in which distant galaxies are streaming uniformly and isotropically away from the origin would feel no force, by reason of symmetry. However, an acceleration destroys this symmetry, and it would be expected that this distant accelerated matter would be a source of a gravitational field. Kaempffer (*6*) has also discussed this question. Earlier Einstein (*7*) and Davidson (*8*) discussed Mach's principle from the point of view of the theory of general relativity.

Einstein made substantial progress in devising a system of mechanics in accord with Mach's principle. First, in connection with his contributions to the special theory of relativity, he early emphasized that it is only the motion of matter relative to other matter which is physically significant. However, this theory considered only uniformly moving—that is, inertial—coordinate systems and failed to come to grips with the central problem, the relation of inertial coordinates to the matter distribution of the universe.

Because of the way in which Einstein's general theory of relativity arose as a generalization of the special theory, it also failed to attack squarely the problem of the origin of inertial forces. This is evident, for example, in the fact that Einstein's field equations have solutions usually regarded as meaningful even in the absence of all matter. It has not yet been found possible to systematically eliminate such solutions. On the other hand, it was early recognized by Einstein (*7*) and Thirring (*9*) that at least some of Mach's program had been realized in the theory of general relativity. Thus, for example, it was shown by Thirring (*9*) that a hollow rotating massive sphere tended to drag the inertial coordinate system around with it.

It early appeared that only solutions of Einstein's equations for which there was some definite total amount of matter at great distances could be reasonably said to be in accord with Mach's principle. The root of the difficulty is easily illustrated by an example due to Sciama (*5*). Consider a universe empty except for a hollow-mass sphere containing near its center two particles attracting each other gravitationally. In a coordinate system with one of these particles at rest, the gravitational pull of the other particle is assumed to be balanced by the gravitational pull having its origin in the accelerated massive shell. It would be expected that the more massive this spherical shell, the greater the inertial force, and that only for a particular mass for this shell would the correct inertial force be obtained. The simple dimensional arguments given below are sufficient to obtain the required relation.

It would be expected from Newton's second law that the inertial force would be proportional to the mass and acceleration of the particle experiencing the force. It would also be reasonable to expect it to be proportional to the mass of the hollow sphere. The force should also depend upon the radius of the sphere, the gravitational constant, and the velocity of light. A not unreasonable expression for the inertial force is, therefore,

$$F = bmMaG^{\alpha}r^{\beta}c^{\gamma} \qquad (1)$$

with m the mass of the particle, M the mass of the spherical shell, a the acceleration of the sphere relative to the mass particle, and r the radius of the sphere; b is a dimensionless constant which would be expected to be of the order of unity, and α, β, and γ are other constants. The only possibility for the constants α, β, and γ which is compatible with dimensions on both sides of the equation is

$$\alpha = 1, \beta = -1, \gamma = -2$$

which, since Newton's second law

$$F = ma \qquad (2)$$

must be satisfied, implies that

$$GM/rc^2 \simeq 1 \qquad (3)$$

Considerable support for this interpretation of Mach's principle is obtained when it is noted that the actual mass density of the universe is such that Eq. 3 is approximately satisfied with M and r interpreted as the mass and radius of the visible part of the universe. It should be pointed out, however, that the actual mass density of the universe is but poorly known. Because of the expansion of the universe, if it is assumed that gravitation propagates with the velocity of light, it would be expected that the effect of distant masses would become vanishingly small at the radius of the visible universe and that masses lying outside this radius would be without effect.

What interpretation is to be made of Eq. 3? Einstein (*7*) and more recently Davidson (*8*) consider this to imply that only certain universes are possible. Thus, Davidson has pointed out that a condition of the type of Eq. 3 is satisfied for an expanding universe which is flat, and that the continuous-creation universe requires this type of cosmology. He, therefore, considers this to be an argument for a continuous-creation cosmology.

There are, however, certain difficulties in assuming that Mach's principle imposes a structural condition upon the universe. The gravitational force is very weak, and one could imagine universes whose structures are determined not by gravitation but by the enormously stronger electrical forces. To give a trivial example, a spherical shell in the form of a monomolecular layer of hydrogen would require roughly 10^{80} atoms if Eq. 3 were to be satisfied. If the same 10^{80} atoms were arranged in a double-layered shell, Eq. 3 would not be satisfied for the same values of G and c. Of course, the universe cannot be tinkered with in quite so drastic a fashion, but it should be possible to take some of the matter at great distance and bring it in closer to change the effective value of M/r. For example, a physicist might build a massive concrete shell around his laboratory. It might be expected that this would change the effective ratio of M to r in Eq. 3. With this interpretation, either Mach's principle is not satisfied or one or the other, or both, of the constants G and c in Eq. 3 are not constant. There is considerable evidence for at least the approximate constancy of c, and consequently it is G which would be expected to vary.

Gravitational Constant as a Field Variable

While the above argument is admittedly highly conjectural, it raises interesting questions. If this interpretation of the gravitational constant as a field variable is correct, there are three important ways in which observable changes in G may occur: (i) through the expansion of the universe; (ii) through the effect of nearby matter, and (iii) by motion relative to distant matter.

A time-varying gravitational constant resulting from the expansion of the universe would have far-reaching geophysical and astrophysical consequences. Some of these have been previously discussed (*10*). The possible effect on the gravitational constant of nearby matter is less startling. Thus, the effect of the sun's mass on the gravitational constant at the earth would result in a decrease of G of very roughly 1 part in 10^8.

Many years ago Dirac proposed that from the sizes of a number of important physical and astrophysical constants one might conclude that the gravitational constant is varying inversely as the age of the universe. It is therefore interesting to note that the condition of Eq. 3 results from Dirac's argument. With the Dirac cosmology, the radius of the visible universe expands more rapidly than matter at that radius. This sweeps more and more matter into the visible region, causing M/r to increase proportionally to the time. Eq. 3 continues to be satisfied as G varies inversely as the time.

If the gravitational constant is really a variable, what about other atomic constants? On the basis of the sizes of dimensionless representations of these constants it would appear that if such numbers as, for example, the fine-structure constant

$$\alpha = e^2/\hbar c$$

were to vary with time, its variation would very likely be slow. Landau has suggested, from considerations of renormalized field theories, that the fine-structure constant may be approximately the reciprocal of

$$\log_e (\hbar c/Gm^2)$$

with m the mass of the electron. If so, its variation would be only logarithmic in time, if it is assumed that G varies inversely with the time.

In addition to the gravitational constant, the only atomic constant which could be reasonably expected to vary strongly with time is the weak-coupling constant. The weak-coupling constant determines the rate of decay of the π- and μ-mesons as well as β decay of radioactive nuclei. As a result, with the assumption of a time variation of the β-decay rate, discrepancies between α- and β-decay ages for old rocks and meteorites could appear (*11*).

Principle of Equivalence

The problem of the constancy of the atomic constants is directly related to the fundamental postulates of the theory of general relativity. The principle of equivalence, as used by Einstein in formulating his theory, assumes that, except for the effects of inhomogeneities in the gravitational field, the laws of physics observed in a freely falling laboratory are independent of time and place. This interpretation of the equivalence principle has been called the "strong principle of equivalence." On the other hand, there is a weak form of the principle which assumes that the gravitational acceleration of a body is independent of its structure. The very accurate Eötvös experiment constitutes strong support for the validity

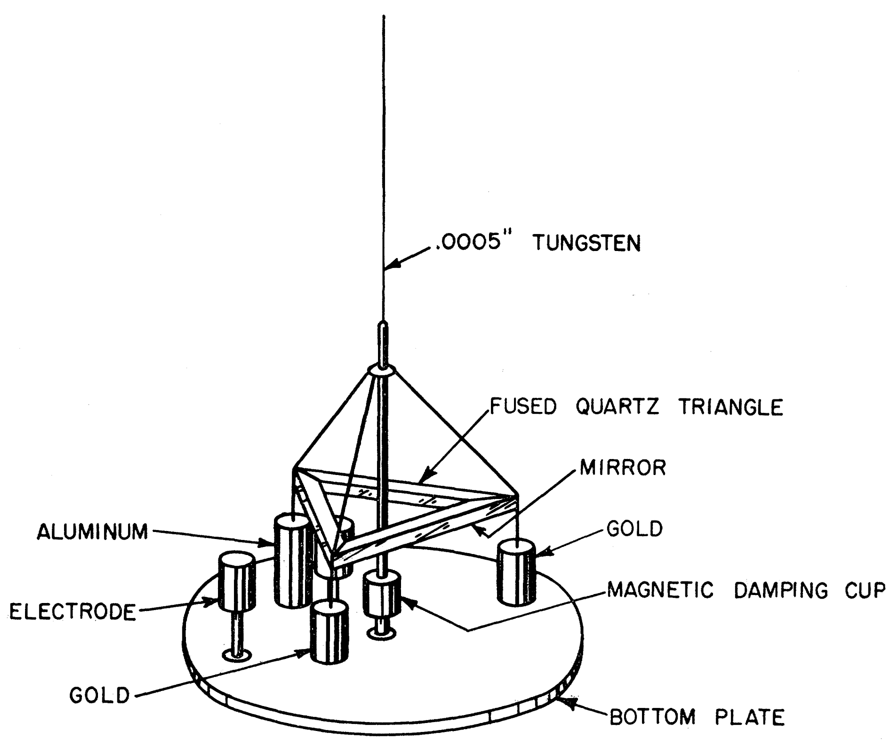

Fig. 1. Apparatus for investigating the equivalence of inertial and passive gravitational mass. With the sun on the horizon in a direction defined by a line through the two gold weights, the earth and laboratory are accelerated toward the sun. Inertial forces pull backward on all three weights; gravitational forces produced by the sun pull forward. If there should be an inequality in these forces for gold compared with aluminum, a torque would result, twisting the fine wire. The rotation is detected automatically by means of light reflected from the mirror to a photocell. The detection system is capable of seeing a rotation of 10^{-8} radians. Voltages proportional to the rotation are applied to the electrodes to decrease the response time of the instrument and to damp oscillations. To the present accuracy of the observations ($\sim 3 \times 10^{-10}$), no positive effect has been observed. The inertial and passive gravitational masses are equivalent.

of the weak form of the principle but not necessarily for the strong version. The strong principle implies the constancy of the atomic constants. Also, as was pointed out by Sciama (*5*), Mach's principle seems to require the validity of the weak form of the equivalence principle. Thus it appears that there is good direct experimental support for the weak form of the principle but not necessarily for the strong form.

The above extended discussion has served to illustrate the basis for our suspicion that the usual interpretation of Einstein's theory of gravitation may not be completely correct. It is only the weak form of the equivalence principle which has a sound experimental basis. For this reason we feel that it is important to use the greatly improved modern experimental techniques to investigate the fundamental facts about gravitation, in particular to test the strong principle of equivalence.

Improved Experimental Techniques

Because of the very important position of the weak version of the equivalence principle, it was decided, first, to attempt to improve the classic Eötvös experiment. Two experiments are being set up, and one has already yielded a preliminary measurement which seems to represent an order-of-magnitude improvement over Eötvös' (*1*) experiment. In this experiment (Fig. 1) a torsion balance employing a torsion pendulum in the form of a horizontal equilateral triangle is supported from a fine tungsten wire. Equal masses are supported from each of the three corners. Two are gold and one is aluminum. An acceleration of the earth and apparatus toward the sun causes inertial forces to act on the three masses. If these were not closely balanced by the gravitational forces, a torque would result which would twist the fine wire. This torque should then vary in the proper way with the sun's position. No such effect was observed. A variation of this experiment in which an oscillating pendulum is employed is being set up by one of our group, Sidney Liebes.

Two of the members of the group, William Hoffmann and James Faller, are designing gravimeters which, it is hoped, will be capable of long-term stability. By measuring the earth's gravitational acceleration we hope to be able to say something about possible annual variations in the gravitational constant due to a velocity-dependence of the gravitational interaction.

A member of the group, Carroll Alley, is constructing a very precise atomic clock employing rubidium vapor. This will be compared with a similar clock employing a beam of cesium atoms. As the atoms of the cesium clock are moving in a definite direction, motional effects on the fine-structure constant and/or other constants may show up as a daily variation in a discordance between the two clocks (*12*).

The group is also greatly interested in atomic clocks per se. A most important experiment is a comparison of an atomic measure of time with a good gravitational measure in order to look for a secular variation which could be attributed to a secular variation in the gravitational constant. Also an annual variation in the two time rates could support the suspicion that there may be a velocity-dependence of the locally observed gravitational constant. In this connection it has been suggested that a satellite be used to give an improved measure of gravitational time.

It is hoped that the application of improved experimental techniques can give increased information about the spectra of atoms on the sun and hence about the gravitational red shift and the value of the fine-structure constant on the sun as compared with the earth. An experiment of this type is presently being planned.

Some preliminary design work has also been done on an experiment to attempt to improve the accuracy of the information on the gravitational deflection of light (*13*).

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