General Relativity at 75: How Right Was Einstein?

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The status of experimental tests of general relativity is reviewed on the occasion of its 75th anniversary. Einstein's equivalence principle is well supported by experiments such as the Eötvös experiment, tests of special relativity, and the gravitational redshift experiment. Tests of general relativity have reached high precision, including the light deflection and the perihelion advance of Mercury, proposed by Einstein 75 years ago, and new tests such as the Shapiro time delay and the Nordtvedt effect in lunar motion. Gravitational wave damping has been detected to an accuracy of 1 percent on the basis of measurements of the binary pulsar. The status of the "fifth force" is discussed, along with the frontiers of experimental relativity, including proposals for testing relativistic gravity with advanced technology and spacecraft.

NOVEMBER 1990 MARKS THE 75TH ANNIVERSARY OF GENeral relativity (GR). During one remarkable month in 1915, Albert Einstein published a series of four papers in the proceedings of the Prussian Academy of Sciences that laid out the field equations of gravitation and calculated the perihelion advance of Mercury and the deflection of light (*1–5*). The repercussions of this scientific event are still being felt today.

GR is an active ingredient in the fields of astrophysics and cosmology, where black holes, neutron stars, gravitational lenses, sources of gravity waves, cosmic strings, inflationary universes, and wormholes are current hot topics. The search for a quantum theory of gravity and for a unification of GR with the other interactions is a major area of theoretical research at present.

At the time of the birth of GR, experimental confirmation was almost a side issue. To be sure, Einstein did calculate observable effects of GR, such as the deflection of light, which were tested, but, compared to the inner consistency and elegance of the theory, he regarded such empirical questions as almost peripheral (*6*). But today experimental gravitation is a major component of the field, characterized by continuing efforts to test the theory's predictions, to search for short-range components of gravity, and to detect gravitational waves. In this article, I shall review the 75-year history of experimental gravitation, summarize the current status, and attempt to chart the future of the subject.

Experimental Gravitation: A Modern History

The modern history of experimental relativity can be divided roughly into four periods: genesis, hibernation, a golden era, and an era of opportunism. The genesis (1887 to 1919) comprised the period of the two great experiments that were the foundation of relativistic physics—the Michelson-Morley experiment and the Eötvös experiment—and the two immediate confirmations of general relativity—the deflection of light and the perihelion advance of Mercury. This was followed by a period of hibernation (1920 to 1960), during which relatively few experiments were performed to test GR, and at the same time the field itself became sterile and stagnant, relegated to the backwaters of physics and astronomy.

But, beginning around 1960, astronomical discoveries (quasars, pulsars, cosmic background radiation), new experimental tools (atomic clocks, spacecraft tracking, radio interferometry) and theoretical developments pushed GR to the forefront. Experimental gravitation experienced a golden era (1960 to 1980), during which a systematic, worldwide effort was made to understand the observable predictions of GR, to compare and contrast them with the predictions of alternative theories of gravity, and to perform new experiments to test them. The period began with an experiment to confirm the gravitational frequency shift of light (1960) and ended with a report of the decrease in the orbital period of the binary pulsar at a rate consistent with the GR prediction of gravity-wave energy loss (1979). All these results supported GR, and most alternative theories of gravity fell by the wayside (*7*).

Since 1980, the field has entered what might be termed an era of opportunism. Many of the remaining interesting predictions of the theory are extremely small and difficult to check, in some cases requiring further technological development to bring them into detectable range. The sense of a systematic assault on the predictions of GR has been supplanted to some extent by an opportunistic approach in which novel and unexpected (and sometimes inexpensive) tests of gravity have arisen from new theoretical ideas or experimental techniques, often from unlikely sources. Examples include the use of laser-cooled atom and ion traps to perform ultraprecise tests of special relativity (SR) and the startling proposal of a "fifth" force, which led to a host of new tests of gravity at short ranges. Several major ongoing efforts also continue, including the Stanford Gyroscope experiment and the program to develop sensitive detectors for gravitational radiation observatories.

Not surprisingly, most of the progress in experimental gravitation has taken place during the past 30 years, yet the four experiments that date from the genesis 75 years ago continue to be important themes of the subject. As a way to illustrate the history of experimental gravitation, to celebrate the 75th anniversary of GR, and to give a sense of future trends, I shall trace each theme in turn from the beginning to the present.

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The Michelson-Morley Experiment and Tests of SR

Apart from its intrinsic importance in physics, Einstein's special theory of relativity (SR) is a crucial part of the foundation of GR. Without SR, there can be no GR. This is embodied in what has come to be known as the Einstein Equivalence Principle (EEP): In any local, freely falling reference frame (in which gravity is absent locally), the nongravitational laws of physics (such as mechanics, electromagnetism, quantum mechanics) must be compatible with SR. A consequence of this principle is that gravity must be described by space-time curvature [(*8*), chapter 2].

SR has become such a successful and integral part of such areas of modern physics as quantum field theory, nuclear physics, and particle physics that physicists often take its validity for granted. But in many of these subdisciplines of physics, the experiments are designed to test the particular models rather than the underlying special relativistic framework. The Michelson-Morley experiment (*9*) and its modern-day descendants provide clean tests of SR in that they can constrain directly and quantitatively possible violations of SR.

There are a number of theoretical frameworks for analyzing violations of SR. In one developed and expounded by Haugan (*10, 11*), the compatibility between relativistic mechanics and electromagnetism is violated by permitting the limiting speed of material particles, c_m, to differ from the speed of electromagnetic waves, c_e, as measured in a preferred universal rest frame. The resulting observable violations of SR depend on the fact that Earth is moving through the universe (whose mean rest frame is represented by the cosmic microwave background) and are parametrized by $\delta = (c_m/c_e)^2 - 1$. By placing a limit on a difference in the speed of light in two perpendicular directions with the use of an interferometer, the 1887 Michelson-Morley experiment set a limit $|\delta| < 10^{-4}$ (see Fig. 1). Apart from a modest improvement on this result in the 1930s, little progress was made during the hibernation era, until a laser version of the experiment was carried out in 1979 (*12*). But in 1960, a substantial improvement in the limit on δ resulted from the Hughes-Drever experiments (*13*), in which magnetic resonance techniques were used to constrain a possible dependence of nuclear energy levels on the orientation of their quantization axis (as fixed by a laboratory magnetic field) relative to Earth's velocity vector through the putative universal rest frame. After 1980, opportunity knocked, when it was realized that the sensitivity of this type of experiment could be improved dramatically with the use of new techniques of atomic physics, such as laser-cooled ion and atom traps. A University of Washington experiment, for example, which studied the isotropy of energy levels of mercury isotopes, constrained δ to be smaller than 10^{-21}, a truly high-precision confirmation of SR (*14*). Other examples of recent opportunistic tests of SR include tests of the isotropy of the one-way speed of light based on resonant two-photon absorption of laser light by an atomic beam (*15*) and on propagation of light between two hydrogen maser clocks along a fiber-optic link at a National Aeronautics and Space Administration Deep Space Tracking Station (*16*).

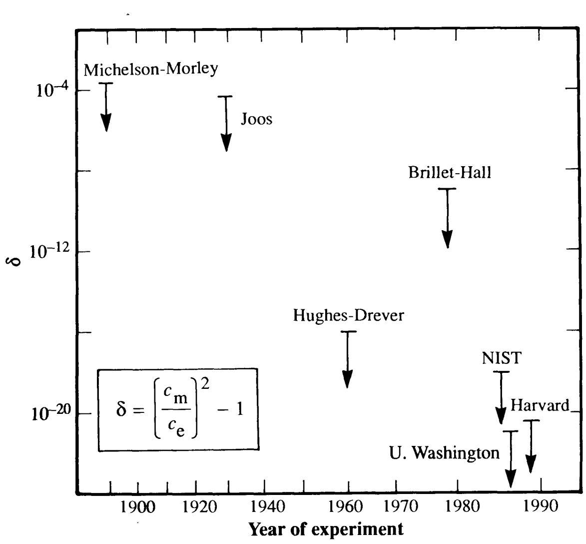

Fig. 1. Selected tests of SR showing the bounds on the parameter δ, which measures the degree of violation of Lorentz invariance in electromagnetism. The Michelson-Morley, Joos, and Brillet-Hall experiments test the isotropy of the round-trip speed of light, the Brillet-Hall experiment using laser technology. The remaining four experiments test the isotropy of nuclear energy levels. Limits assume an Earth speed of 300 km s^{-1} relative to the mean rest frame of the universe; NIST, National Institute of Standards and Technology. For discussion and references, see (*11*).

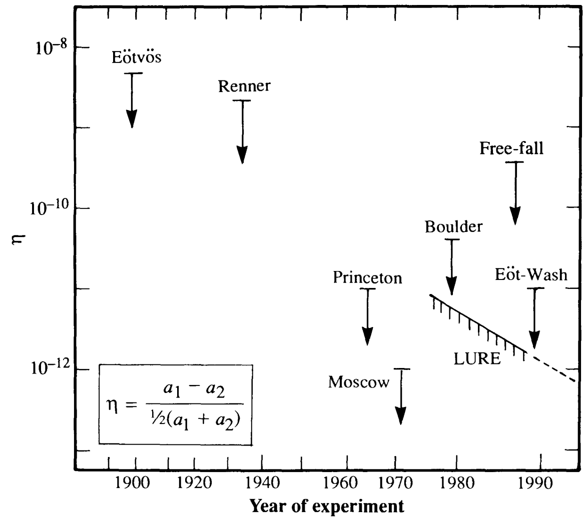

Fig. 2. Selected tests of the Weak Equivalence Principle, showing the bounds on η, which measures the fractional difference in acceleration *a* of different materials or bodies. The free-fall and Eöt-Wash experiments were originally performed to search for the fifth force. Hatched and dashed lines show current and projected bounds, respectively, on η for gravitating bodies (test of the Strong Equivalence Principle) from lunar laser ranging (LURE). For discussion and references, see (*8*).

The Eötvös Experiment, the Weak Equivalence Principle, and the Fifth Force

Another experiment that helped lay the foundation for GR was the Eötvös experiment (1889, 1908), which verified what is commonly called the Weak Equivalence Principle (WEP), the equality of gravitational acceleration of objects of different composition. The precision achieved was a few parts in 10^9 (*17*). In formulating EEP, Einstein assumed the validity of WEP, using it to establish the existence of the universal, freely falling frames in which SR was to be valid. Despite the fundamental importance of this experiment, only one attempt at improvement was made during the hibernation years. During the golden era, however, two new experiments, by Dicke at Princeton (*18*) and by Braginsky at Moscow State (*19*), improved the accuracy by two to three orders of magnitude. The resulting constraints on a parameter η, defined to be the difference in acceleration between objects of different composition divided by their average acceleration, are shown in Fig. 2. These results gave strong support to WEP and thereby to EEP.

Another consequence of EEP is the gravitational redshift of light, as Einstein found some 8 years before he completed the full theory (it can also be understood on simple grounds of energy conservation). Yet it was not confirmed experimentally until the Pound-Rebka experiment of 1960, in which gamma rays were observed rising and falling in a tower (*20*); the most accurate confirmation was a 1976 rocket experiment with hydrogen maser clocks, resulting in a 0.02% test (*21*). Recently, opportunistic use of the Voyager spacecraft provided a 1% test of the gravitational redshift of an ultrastable crystal oscillator as the craft sped through the gravitational field of Saturn (*22*).

In 1986, opportunism led to renewed interest in the Eötvös experiment. As a result of a detailed reanalysis of Eötvös's original data, Fischbach *et al.* suggested the existence of a "fifth force" of nature, with a strength of ~1% of gravity, but with a range (as defined by the range λ of a Yukawa potential, $e^{-r/\lambda}/r$) of a few hundred meters (*23*). This proposal dovetailed with earlier hints of a deviation from the inverse-square law of Newtonian gravitation derived from measurements of the gravity profile down deep mines in Australia (*24*). During the next 4 years, over a dozen new experiments looked for evidence of the fifth force by searching for composition-dependent differences in acceleration, with variants of the Eötvös experiment or with free-fall Galileo-type experiments. Although two early experiments reported positive evidence, the others yielded null results. Over the range between 1 and 10^4 m, the null experiments produced upper limits on the strength of a postulated fifth force of between 10^{-3} and 10^{-6} the strength of gravity. Interpreted as tests of WEP (corresponding to the limit of infinite range forces), the results of a free-fall experiment and of a University of Washington experiment (dubbed Eöt-Wash) are shown in Fig. 2 (*25*). At the same time, researchers carried out tests of the inverse-square law of gravity by comparing variations in gravity measurements up tall towers or down mines or boreholes with gravity variations predicted using the inverse-square law together with Earth models and surface gravity data mathematically "continued" up the tower or down the hole. Despite early reports of anomalies, three independent tower measurements now show no evidence of a deviation (*26*). The consensus at present is that there is no credible experimental evidence for a fifth force of nature (*27*).

The validity of WEP is a necessary condition for the validity of GR, but it is not a sufficient condition. Any theory of gravity that is based on a symmetric curved space-time (called a "metric theory") automatically satisfies WEP as well as EEP (*8*). Thus the tests of SR and of WEP described so far cannot distinguish GR from any other metric theory, of which numerous examples, such as the Brans-Dicke scalar-tensor theory, have been developed over the years.

However, there is a generalization of EEP, known as the Strong Equivalence Principle (SEP), that does distinguish between alternative metric theories of gravity [(*8*), chapter 3]. Part of the SEP states, for example, that all bodies should fall with the same acceleration in an external gravitational field; this includes bodies with significant internal gravitational binding energy, such as planets, stars, and so forth. In WEP, one considers only laboratory-sized bodies, whose internal structures are dominated by nongravitational energies. Different theories of gravity can treat the effect of gravity on gravitational energy differently and so could predict violations of SEP by massive, self-gravitating bodies. GR is one of the few theories that actually obeys SEP. Brans-Dicke theory does not. Since 1969, SEP has been tested with lunar laser ranging (LURE) to look for the orbital effects of a possible difference in acceleration between Earth and the moon toward the sun [called the Nordtvedt effect (*28*)]. No orbital perturbation of this type has been found to date down to the 6-cm level, placing a limit on η of 3 parts in 10^{12} (*29*). The accuracy of LURE could reach the level of several millimeters, at which point the accuracy of this experiment as a test of the effect of gravity on gravitational energy (test of SEP) will be limited by the accuracy of tests of WEP, because the composition of Earth (iron-rich) and the moon (iron-poor) differ. Current and projected bounds on η from LURE are shown on Fig. 2.

The Deflection of Light

One of the first calculations that Einstein performed in November 1915, when he had the final (vacuum) field equation of GR, was the deflection of light (*3*). Earlier, in 1911, he had determined the deflection in a preliminary theory based essentially purely on EEP (*30*) and got the same answer as in a Newtonian gravity theory in which light was treated as a corpuscle [a calculation that had been carried out as early as 1784 by Cavendish and 1801 by von Soldner (*31*)]. The result of his 1915 calculation was to double the prediction. For a light ray that grazes the sun, for example, the deflection would be 1.75″ instead of 0.875″. The difference can be understood as follows: half the deflection indeed comes directly from EEP, or equivalently from a Newtonian ballistic calculation; the remaining part derives from the curvature of space near the sun relative to space far away. The first contribution is the same in any theory of gravity that is compatible with EEP. The second, space curvature contribution varies from theory to theory and is conventionally parametrized by γ, whose GR value is unity (*32*). In this parametrized language, the deflection of a light ray by the sun is given by

$$\Delta\theta = \tfrac{1}{2}(1 + \gamma)\ 1.75''/d \qquad (1)$$

where d is the distance of closest approach of the ray to the sun, in units of a solar radius.

The measurement of this effect by British astronomers during a total solar eclipse in 1919 catapulted Einstein and GR to worldwide fame. However, as indicated by Fig. 3, the accuracy was 20% at best (*33*). A few measurements during the hibernation years failed to

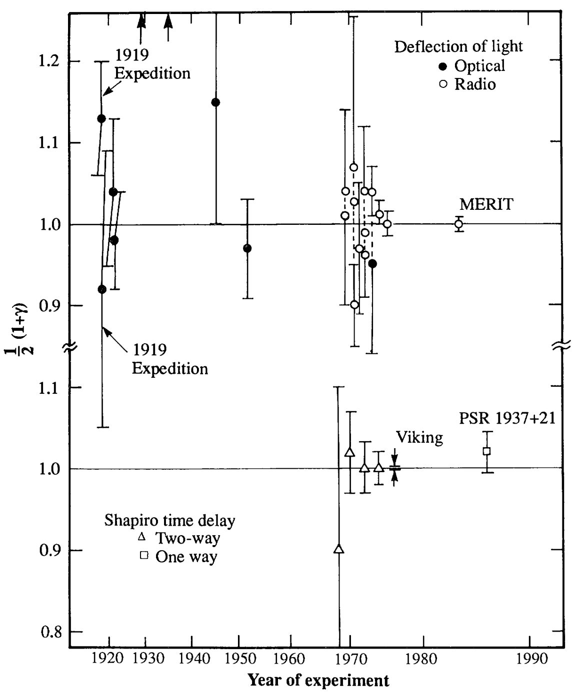

Fig. 3. Measurements of the coefficient $(1 + \gamma)/2$ from light deflection and time delay measurements. The GR value is unity. Arrows at the top margin denote anomalously large values from the 1929 and 1936 expeditions. Shapiro time delay measurements using the Viking spacecraft yielded $(1 + \gamma)/2 = 1.000 \pm 0.001$. For discussion and references see (*32, 43, 45*).

yield substantial improvements. The development of radio interferometry during the 1960s coupled with the discovery of quasars led to dramatically better accuracy. The technique involved monitoring the relative angle between a pair or group of quasars as they passed near the sun as seen from Earth. Between 1969 and 1975 a dozen measurements of this sort were carried out systematically (Fig. 3), culminating in confirmations of GR at about the 1.5% level (*34*). After 1975, further direct measurements of the deflection of light to test relativity essentially ceased. However, in 1984 an opportunistic test at about the 1% level was reported as a by-product of an effort (called MERIT) to monitor Earth's rotation state by means of very long baseline interferometric measurements of radio galaxies and quasars (*35*). The accuracy of these measurements reached the milliarc second level, making it necessary to take the relativistic deflection of light into account over the entire celestial sphere, not just near the sun, in order to achieve the required accuracy in determination of Earth's orientation (for a ray that approaches Earth from a direction 90° away from the sun, the deflection is 4 milliarc sec).

There is another important test of the propagation of light through curved space-time, which was not around in 1915 yet which is closely related to the deflection of light. It was first predicted as a consequence of GR by Shapiro in 1964 (*36*) and is now commonly called the Shapiro time delay. It is an excess propagation delay of light passing through a region of curved space near a body compared to the analogous propagation time if the ray passes far from the body. A light ray that passes the sun on a round trip, say, from Earth to Mars at superior conjunction, suffers a delay (in microseconds) given by [(*8*), chapter 7]

$$\Delta t \approx \tfrac{1}{2}(1 + \gamma)\, 250\, (1 - 0.16 \ln d) \qquad (2)$$

The close relationship between this effect and the deflection of light is reflected in the $(1 + \gamma)/2$ factor and is to be expected, because any phenomenon that bends light (refraction, curved space) is expected to alter its propagation time as well. Observations of the Shapiro time delay began in the middle 1960s with the use of radar echos from Mercury and Venus. Later, use was made of interplanetary spacecraft equipped with radar transponders, such as Mariners 6, 7, and 9, and the Viking landers and orbiters (Fig. 3). Data from Viking yielded a 0.1% test (*37*). This precise determination of the parameter γ was one of the crowning achievements of the golden era of experimental gravitation. In 1987, another product of opportunism was reported: a 3% measurement of the one-way Shapiro time delay of radio pulses from the millisecond pulsar (*38*). The deflection of light has now taken on an important astrophysical and cosmological role as the key ingredient in attempts to understand the structure of galaxies and galactic clusters that are acting as gravitational lenses (*39*), producing multiple images of distant quasars, and to determine the distance of the lensed quasars.

Mercury's Perihelion Shift: From Triumph to Trouble and Back?

The first effect that Einstein calculated in November 1915, using his new field equations, was the advance of the perihelion of Mercury (*3*). The discrepancy between the observed advance and the amount that could be accounted for from the Newtonian gravitational perturbations of Mercury by the other planets was a problem that had bedeviled celestial mechanicians for the latter half of the 19th century (*40*). GR predicted an amount that neatly accounted for the discrepancy. Einstein wrote later that he had palpitations of the heart upon finding this result (*5*). For another half century, this stood as one of the triumphs of GR. Yet, since 1965, this test has been mired in a controversy that has only recently approached resolution. The predicted rate of advance of the perihelion of Mercury (excluding the part from planetary perturbations) can be written in the following form, in arc seconds per century:

$$d\omega/dt = 42.98'' \lambda_p \qquad (3)$$

$$\lambda_p \equiv \tfrac{1}{3}(2 + 2\gamma - \beta) + 0.0003\, (J_2/10^{-7}) \qquad (4)$$

The first term in Eq. 4 is the relativistic contribution to the advance, in a form that encompasses a wide class of alternative metric theories of gravity. (In a wider class of theories, there are additional relativistic terms, but empirical constraints make them unimportant for the present discussion.) The parameter γ is the same parameter that appeared in the deflection of light and the Shapiro time delay, and the parameter β is a rough measure of how "nonlinear" gravity is in a given theory (*32*). Both parameters are unity in GR. The second term comes from the Newtonian effect of a possible oblateness of the sun, which will alter its external gravitational field from the pure inverse-square form of a spherical body. The oblateness is measured by the quantity J_2; for a sun that rotates uniformly with its observed surface angular velocity, so that the oblateness is caused by centrifugal flattening, J_2 is estimated to be of order 10^{-7}.

Now, the measured perihelion shift of Mercury is known accurately: after the perturbing effects of the other planets have been accounted for, the excess shift is known to about 0.5% from radar observations of Mercury since 1966 (*41*), with the result that $\lambda_p = 1.003 \pm 0.005$. If J_2 were indeed as small as 10^{-7}, this would be in complete agreement with GR. However, in 1966, a value for J_2 of 2.5×10^{-5} was inferred from 1966 visual solar-oblateness measurements (*42*), a result that, if confirmed, would have disagreed strongly with GR. Between 1966 and 1980, J_2 values ranging over two orders of magnitude were reported (*43*). Beginning around 1980, however, the observation and classification of modes of oscillation of the sun made it possible to obtain information about its internal rotation rate, thereby constraining the possible centrifugal flattening; current results favor a value $J_2 \approx 1.7 \times 10^{-7}$ (*44*). If further studies of solar oscillations continue to support this interpretation, the perihelion shift of Mercury will once again be a triumph for GR.

During the golden era, many other experiments and observations were carried out to test relativistic gravity in the solar system. These tests could be summarized with the use of parameters such as γ and β that characterize the weak-field, or post-Newtonian, limit of a class of metric theories of gravity [this is known as the Parametrized post-Newtonian (PPN) framework]. The current best limits on some of the ten PPN parameters are listed in Table 1 (*45*).

The Binary Pulsar: An Astronomical Relativity Laboratory

In 1915, Einstein could not have conceived of the binary pulsar. The concept of a neutron star was still 20 years in the future, radio astronomy 16 years, the discovery of pulsars 52 years. Yet some of the themes present at the genesis of GR still play a role in this remarkable system: the binary-star analog of the perihelion shift, the gravitational redshift, and SR.

Until 1974, the solar system provided the principal testing ground for GR, because it is a "clean" system (few uncertain or messy physical processes to complicate the gravitational effects) and it is accessible to high-precision tools. However, the discovery of the binary pulsar PSR 1913 + 16 in 1974 (*46*) showed that certain kinds of distant astronomical systems may also provide precision laboratories for testing GR. The system consists of a pulsar with a period of 59 ms in an 8-hour orbit with a companion that has not seen directly but that is generally believed to be another neutron star. The unexpected stability of the pulsar "clock" and the cleanliness of the orbit allowed radio astronomers to determine the orbital and other parameters of the system to extraordinary accuracy. Furthermore, the system is highly relativistic ($v_{\text{orbit}}/c \approx 10^{-3}$, where v_{orbit} is the orbital velocity of the binary pulsar and c is the speed of light). Observation of the relativistic periastron advance ($4.22660° \pm 0.00003°$ year^{-1}) and of the effects on pulse arrival times of the gravitational redshift caused by the companion's gravitational field and of the special relativistic time dilation caused by the pulsar's orbital motion (0.15% accuracy) have been used, assuming that GR is correct, to constrain the nature of the system. In GR, these two effects depend in a known way on measured orbital parameters and on the unknown masses m_p and m_c of the pulsar and companion (assuming that the companion is sufficiently compact that tidal and rotational distortion effects can be ignored), and consequently the two masses may be calculated with these two pieces of data, with the result $m_p = 1.439 \pm 0.001$ and $m_c = 1.389 \pm 0.001$ solar masses. The measurement of the rate of change of orbital period in 1979 gave the first evidence for the effects of gravitational radiation damping (*47*). GR provides a formula, which is a generalization of one first derived by Einstein in 1916 (*48*), known as the quadrupole formula, which determines the loss of energy and the consequent orbital damping due to gravitational-wave emission from binary systems such as this (*49*). The result is a decrease in the orbital period. Using the measured orbital elements and the two masses, one can obtain the predicted rate $dP/dt = -2.403 \times 10^{-12}$. The accuracy of the observations is now better than 1%, with $dP/dt_{\text{observed}} = -(2.42 \pm 0.02) \times 10^{-12}$, agreeing completely with the prediction (*50, 51*).

Some have argued that, in addition to verifying the existence of gravitational radiation, this provides a "strong-field" test of GR, in contrast to the solar system "weak-field" tests, in the following sense. Because the companion, like the pulsar, is probably a neutron star, both bodies contain strongly relativistic internal gravitational fields. Nevertheless, the observations show that their motion and generation of gravitational waves agree with calculations in GR based only on their weak interbody gravitational fields and low orbital velocities and do not reflect their internal relativistic structure. This irrelevance of the internal structure is part of SEP, which GR satisfies.

By contrast, in most alternative theories of gravity, the motion of compact objects is affected by their internal structure (violation of SEP); in addition, most theories predict "dipole" gravitational radiation in addition to the quadrupole part, whose source is the difference in internal gravitational binding energies of the two stars [(*8*), chapter 10]. Because of these two phenomena, violations of SEP and dipole gravitational radiation, many alternative theories of gravity, which otherwise might agree with solar system observations, could be strongly tested by systems such as the binary pulsar (*52*).

Experimental Gravitation: Is There a Future?

Although the golden era of experimental gravitation may be over, there remains considerable opportunity both for refining our knowledge of gravity and for exploring new regimes of gravitational phenomena. Nowhere is the intellectual vigor and continuing

Table 1. Significance and current limits on the PPN parameters. For a compendium of PPN parameter values in alternative theories of gravitation, see (*8*), chapter 5, or (*43*). For discussion of experiments and primary references, see (*8*), chapters 7 through 9, and (*43, 45*). Inequalities correspond to upper limits on the absolute values of the parameter.

Parameter	What it measures relative to GR	Value in GR	Experiment	Value or limit	Remarks
γ	How much space-curvature is produced by unit rest mass?	1	Time delay	1.000 ± 0.002	Viking ranging
β	How much "nonlinearity" is there in the superposition law for gravity?	1	Perihelion shift	0.99 ± 0.02	$J_2 = 10^{-7}$ assumed
			Nordtvedt effect	1.00 ± 0.002	$\eta = 4\beta - \gamma - 3$ assumed
ξ	Are there preferred-location effects?	0	Earth tides	$<10^{-3}$	Gravimeter data
α_1	Are there preferred-frame effects?	0	Orbital preferred-frame effects	$<4 \times 10^{-4}$	Combined solar system data
				$<3 \times 10^{-7}$	Binary pulsar
α_2		0	Earth tides	$<4 \times 10^{-4}$	Gravimeter data
			Solar spin precession	$<4 \times 10^{-7}$	Assumes alignment of solar equator and ecliptic are not coincidental
α_3		0	Perihelion shift	$<2 \times 10^{-7}$	
			Acceleration of pulsars	$<2 \times 10^{-10}$	Statistics of dP/dt for pulsars
η*	Is WEP violated for self-gravitating bodies?	0	Nordtvedt effect	<0.007	Lunar laser ranging
ζ_1	Is there violation of conservation of total momentum?	0	Newton's third law	$<10^{-8}$	Lunar acceleration
ζ_2		0			
ζ_3		0			
ζ_4		0			

*Here η is a combination of other PPN parameters given by $\eta \equiv 4\beta - \gamma - 3 - \frac{10}{3}\xi - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2$. In many theories of gravity, $\xi = \alpha_i = \zeta_i = 0$.

excitement of this field more apparent than in the ideas that have been developed for experiments and observations to push us to the frontiers of knowledge.

Search for gravitomagnetism. According to GR, moving or rotating matter should produce a contribution to the gravitational field that is the analog of the magnetic field of a moving charge or a magnetic dipole. Although gravitomagnetism plays a role in a variety of measured relativistic effects, it has not been seen to date, isolated from other post-Newtonian effects.

The Relativity Gyroscope Experiment at Stanford University is in the advanced stage of developing a space mission to detect this phenomenon directly (*53*). A set of four superconducting niobium-coated, spherical quartz gyroscopes are to be flown in a low polar Earth orbit, and the precession of the gyroscopes relative to the distant stars will be measured. The predicted effect of gravitomagnetism is about 42 milliarc sec per year, and the accuracy goal of the experiment is about 0.5 milliarc sec per year. Recently, a full-size flight prototype of the instrument package was tested as an integrated unit. Plans call for a test of the final flight hardware on the Space Shuttle followed by a Shuttle-launched experiment around 1996.

Another proposal designed to look for an effect of gravitomagnetism is to measure the relative precession of the line of nodes of a pair of laser-ranged geodynamics satellites (LAGEOS), with supplementary inclination angles; the inclinations must be supplementary in order to cancel the dominant nodal precession caused by Earth's Newtonian gravitational multipole moments (*54*).

A third proposal envisages orbiting an array of three mutually orthogonal, superconducting gravity gradiometers around Earth. These would measure directly the contribution of the gravitomagnetic field to the tidal gravitational force (*55*).

Improved PPN parameter values. A number of advanced space missions have been proposed in which spacecraft orbiters or landers and improved tracking capabilities could lead to significant improvements in values of the PPN parameters (see Table 1), of J_2 of the sun, and of a possible rate of change of the Newtonian gravitational constant, $\dot{G}/G$. For example, a Mercury orbiter, in a 2-year experiment, with 3-cm range capability, could yield improvements in the perihelion shift to 1 part in 10^4, in γ to 4×10^{-5}, in $\dot{G}/G$ to 10^{-13} year^{-1}, and in J_2 to a few parts in 10^8 (*56*).

Probing post–post-Newtonian physics. It may be possible to begin to explore the next level of corrections to Newtonian theory beyond the post-Newtonian limit, into the post–post-Newtonian regime. One proposal is to place a precision optical interferometer with microarc second accuracy into orbit. Such a device would improve the deflection of light to the 10^{-6} level and could possibly detect the second-order term, which is of order 10 microarc sec at the limb (*57*). Such a measurement would be sensitive to a new "PPPN" parameters, which has not been measured heretofore.

Tests of EEP. The concept of an Eötvös experiment in space has been developed, with the potential to test WEP to 10^{-17} (*58*). The gravitational redshift could be improved to the 10^{-9} level and second-order effects could be discerned if a hydrogen maser clock were placed on board Solar Probe, a proposed spacecraft that would travel to within four solar radii of the sun (*59*).

Further fifth-force searches. Because they are relatively inexpensive and because they have the potential to constrain certain classes of models of particle physics, fifth-force experiments are likely to continue at some level for a time (*27*).

Gravitational-wave astronomy. A significant part of the efforts in the field of experimental gravitation is devoted to building and designing sensitive devices to detect gravitational radiation and to use gravity waves as a new astronomical tool. This important topic has been reviewed thoroughly elsewhere (*60*).

Conclusions

On the 75th anniversary of the genesis of GR, we find that the theory has held up under extensive experimental scrutiny. The question then arises, why bother to continue to test it? One reason is that gravity is a fundamental interaction of nature and as such requires the most solid empirical underpinning we can provide. Another is that all attempts to quantize gravity and to unify it with the other forces suggest that gravity stands apart from the other interactions in many ways. Thus the more deeply we understand gravity and its observational implications, the better we may be able to confront it with the other forces.

Finally, and most importantly, the predictions of GR are fixed; the theory contains no adjustable constants, so nothing can be changed. Thus every test of the theory is potentially a deadly test. A verified discrepancy between observation and prediction would kill the theory, and another would have to be substituted in its place. Although it is remarkable that this theory, born 75 years ago out of almost pure thought, has managed to survive every test, the possibility of suddenly finding a discrepancy will continue to drive experiments for years to come.

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Research Articles

The Energetic Basis of Specificity in the Eco RI Endonuclease–DNA Interaction

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High sequence selectivity in DNA-protein interactions was analyzed by measuring discrimination by Eco RI endonuclease between the recognition site GAATTC and systematically altered DNA sites. Base analogue substitutions that preserve the sequence-dependent conformational motif of the GAATTC site permit deletion of single sites of protein-base contact at a cost of +1 to +2 kcal/mol. However, the introduction of any one incorrect natural base pair costs +6 to +13 kcal/mol in transition state interaction energy, the resultant of the following interdependent factors: deletion of one or two hydrogen bonds between the protein and a purine base; unfavorable steric apposition between a group on the protein and an incorrectly placed functional group on a base; disruption of a pyrimidine contact with the protein; loss of some crucial interactions between protein and DNA phosphates; and an increased energetic cost of attaining the required DNA conformation in the transition state complex. Eco RI endonuclease thus achieves stringent discrimination by both "direct readout" (protein-base contacts) and "indirect readout" (protein-phosphate contacts and DNA conformation) of the DNA sequence.

PROTEINS THAT INTERACT WITH PARTICULAR TARGET SEquences in DNA may show sequence selectivities ranging from stringent to fairly permissive, depending on the requirements imposed by their functions. Extreme selectivity is exemplified by restriction endonucleases, which must efficiently cleave small (4 to 6 base pairs) recognition sites on foreign DNA, but must avoid potentially lethal cleavage of the cellular genome at sites that differ by as little as one base pair. By contrast, gene-regulatory proteins bind at larger sites (12 to 30 bp) and some bind a series of related sites in a graduated fashion (*1, 2*).

Sequence specificity is determined in part by protein contacts to the DNA bases (direct readout). Structural studies of the Eco RI endonuclease–DNA complex show that both strands of the GAATTC site are recognized by hydrogen bonds with each purine base (*3, 4*) and contacts to the pyrimidines (*4*). However, the tightly complementary surfaces in DNA-protein complexes (*3–6*) also include extensive contacts to the DNA backbone.

It has been suggested that the sequence-dependence of DNA conformation (*7*) might provide an indirect readout (*6, 7*) by affecting the attainment of optimal complementarity both for protein-base hydrogen bonding (*8*) and for the precisely positioned (*3, 5, 6*) interactions between protein and DNA phosphates. However, there has been no evidence to indicate which phosphate interactions are indispensable to recognition, which make only nonspecific contributions to binding free energy, and which (if any) are altered when a protein interacts with a closely related but incorrect site. For Eco RI endonuclease, it has been suggested (*9*) that indirect readout may also contribute to specificity because the energy required to attain the "kinked" DNA conformation in the complex (*3*) is least unfavorable for the GAATTC site.

To determine the roles of direct protein-DNA contacts and of sequence-dependent DNA conformation, we analyzed the energetics of stringent discrimination, using a rigorous measure of the Eco RI–DNA interaction in transition state complexes. We manipulated

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