WAS EINSTEIN RIGHT?

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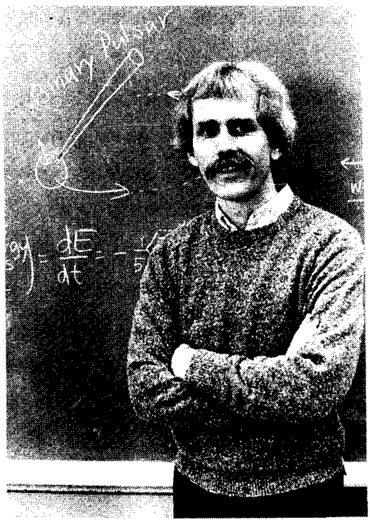

ABSTRACT

The experimental evidence for Einstein's general relativity is reviewed. Tests of the Einstein Equivalence Principle support the postulates of curved spacetime, while solar-system experiments strongly constrain the parameters of the post-Newtonian limit of gravitational theory to agree with the general relativistic values. Concepts for future tests are described. The binary pulsar provides an important test of gravitational radiation damping and of the strong-field nature of general relativity, while the "11 minute" binary system may yield interesting constraints on gravitational theory.

I. INTRODUCTION

Gravitation plays a fundamental role in our universe. On a local scale, up to 10^9 km, it determines our Earthbound environment, the nature of the Sun, the dynamics of the solar system. On scales ranging up to the largest observable distances, 10^{10} light years, it determines the structure and evolution of black holes, galaxies, clusters and superclusters of galaxies, and the universe itself. On scales ranging down to the smallest, the Planck scale, or 10^{-33} cm, gravitation forms the template for attempts to unify the interactions in a full quantum synthesis. It is remarkable that there exists one candidate theory of gravity, general relativity, that has the ability to treat gravitation over such a range -- 60 orders of magnitude -- of scales.

On the other hand, the viability of general relativity is determined by experiments that, with a few exceptions, are confined to the scale of the solar system. During the past 25 years, experiments have been spectacularly successful in verifying general relativity over this scale, and in ruling out many alternative theories of gravity.

But the need to extrapolate gravitational theory from solar system scales to such large and such small scales requires the most accurate verification possible at the experimentally accessible scales. Thus, despite its past successes, experimental gravitation continues to be an active and challenging field. New challenges, such as the possible existence of additional short-range forces, have recently been presented to theorists and experimentalists.

In this paper, we shall summarize the current state of our empirical knowledge of gravitational effects, and shall discuss some of the advanced concepts or projects currently under study for future experiments. Most of this experimental effort takes place in what might be loosely termed ''space-borne laboratories'' that use spacecraft or the solar-system environment as a testing ground. However, anothe important part of this effort uses astronomical laboratories, distant systems that are astrophysically sufficiently ''clean'', and exhibit sufficiently strong relativistic gravitational effects that they can provide important, precision tests of gravitational theory. The leading example, of course, is the binary pulsar. A promising prospect may be the ''11 minute'' binary, 4U1820--30.

In this review, we will not present full citations to the original literature on the subject, instead, wherever it is appropriate, we will refer the reader to review articles or monographs, specifically, reference 1, referred to as TEGP, reference 2, referred to as UPDATE, and reference 3, referred to as NEWTON.

II. EXPERIMENTAL GRAVITATION IN SPACE-BORNE LABORATORIES

There are three principal areas of activity in experimental gravitation involving Earth-based or solar-system laboratories: tests of gravitation theory in the post-Newtonian limit, the search for hypothetical feeble short-range forces, and the search for gravitational radiation. The second topic is the subject of many papers at this meeting; I will touch on it but briefly. The third topic is for other meetings.

Tests of Post-Newtonian Gravity

One of the fundamental postulates of gravitational theory is the Einstein Equivalence Principle (EEP), which states: (i) test bodies fall with the same acceleration (weak equivalence principle -- WEP); (ii) in a local freely falling frame, non-gravitational physics is independent of the frame's velocity (local Lorentz invariance); and (iii) in a local freely falling frame, non-gravitational physics is independent of the frame's location (local position invariance). If EEP is valid, then gravity must be described by a "metric theory", whose postulates are that there exists a symmetric metric $g_{\mu\nu}$, whose geodesics are the trajectories of structureless test bodies, and which reduces to the Minkowski metric in freely falling frames, where the laws of physics take their special relativistic forms. The EEP divides theories of gravity into two classes, metric theories, such as general relativity, the Brans-Dicke theory, and numerous others; and non-metric theories, such as Moffat's non-symmetric gravitation theory (NGT), and others.

The observational evidence in support of EEP is very strong. For example, Eötvös-type experiments have verified WEP to better than a part in 10^{11}, and improved space-borne experiments are planned. Local Lorentz invariance has been verified to high precision by several extraordinarily precise "mass-anisotropy" null experiments[4)]. Finally, gravitational redshift experiments test local position invariance: the 1976 rocket experiment using hydrogen maser clocks verified this effect to two parts in 10^4. (For a review of the theoretical and observational implications of EEP, see TEGP, chapter 2, or UPDATE, sec. 2; for a discussion of non-symmetric gravitation theories and WEP, see Ref. 5.)

When we restrict attention to metric theories of gravity and consider the weak-field slow-motion limit appropriate to the solar system, the so-called post-Newtonian limit, then it turns out that most such theories can be described by the parametrized post-Newtonian (PPN) formalism (for a detailed review, see TEGP, chapter 4, or UPDATE, sec. 3.3). This formalism characterizes the metric of the post-Newtonian limit in terms of a set of ten dimensionless parameters, γ, β, ξ, α_1, α_2, α_3, ζ_1, ζ_2, ζ_3, ζ_4 , whose values vary from theory to theory. Table 1 shows the approximate significance of these parameters, and gives their values in general relativity, and in theories of gravity that possess conservation laws for momentum (semi-conservative theories, all Lagrangian-based theories), and that possess conservation laws for momentum as well as angular momentum and center-of-mass motion. Several compendia of alternative theories and their PPN parameter values have been published (see for example TEGP, chapter 5, or UPDATE, sec. 3.4). In addition to its use as a tool for studying and classifying theories of gravity, the PPN formalism facilitates discussion of experiment, because the predicted size of various post-Newtonian effects depends on the values of the PPN parameters; therefore the measurement of an effect is tantamount to a measurement of the corresponding PPN parameter or parameter combination.

Table 1
The PPN Parameters and Their Significance*

Parameter	What it measures relative to general relativity	Value in general relativity	Value in semi-conservative theories	Value in fully-conservative theories
γ	How much space-curvature is produced by unit rest mass?	1	γ	γ
β	How much "nonlinearity" is there in the superposition law for gravity?	1	β	β
ξ	Are there preferred location effects?	0	ξ	ξ
α_1	Are there preferred-frame effects?	0	α_1	0
α_2		0	α_2	0
α_3		0	0	0
ζ_1	Is there violation of conservation of total momentum?	0	0	0
ζ_2		0	0	0
ζ_3		0	0	0
ζ_4		0	0	0

*For a compendium of PPN parameter values in alternative theories together with derivations, see TEGP, Chapter 5.

Two important experimental tests of general relativity are the deflection of light and the Shapiro time delay of light, both measuring the same thing, the coefficient $\frac{1}{2}(1+\gamma)$. A light ray which passes the Sun at a distance d (measured in solar radii) is deflected by an angle

$$\Delta\theta = \frac{1}{2}(1+\gamma)1''.75/d \quad , \tag{1}$$

and a light ray which passes the Sun on a round trip, say, from Earth to Mars at superior conjunction suffers a delay given, for d > 1, by

$$\Delta t = \frac{1}{2}(1 + \gamma)250(1 - 0.16 \ln d)\ \mu s \tag{2}$$

Measurements of the deflection of light have improved steadily during the past 70 years, from the early observations of stellar positions surrounding total solar eclipses (10 - 30 percent), to measurements of the deflection of radio waves from quasars during the period 1969-1975 (1.5 percent), to VLBI observations of radio source positions over the entire celestial sphere in the 1980s (approaching 1 percent) (UPDATE, sec. 4.1; Ref. 6).

Observations of the Shapiro time delay began in the middle 1960s using radar echos from Mercury and Venus, and later made use of interplanetary spacecraft equipped with radar transponders, such as Mariners 6, 7, and 9, and the Viking landers and orbiters. Data from Viking produced the best measurement of $\frac{1}{2}(1 + \gamma)$ to date, namely 1.000 ± 0.001, in complete agreement with general relativity (UPDATE, sec. 4.2). For the Brans-Dicke theory of gravity, these results force a lower limit of 500 on the coupling constant ω (as $\omega \to \infty$, Brans-Dicke theory becomes indistiguishable from general relativity). The time delay in a one-way signal has been recently measured using timing data from the millisecond pulsar PSR 1937+21, with results in agreement with general relativity at the three percent level[7)].

The perihelion shift of Mercury is another key test of general relativity. Including the possible effect of a solar quadrupole moment J_2, the predicted rate of advance is given, in arcseconds per century, by

$$d\omega/dt = 42''.98\ \lambda \tag{3}$$

$$\lambda \equiv \frac{1}{3}(2+2\gamma-\beta) + 0.0003\ (J_2/10^{-7}) \tag{4}$$

The first term in the coefficient λ is the "classical" relativistic perihelion shift contribution, which depends on the PPN parameters γ and β. In general relativity, this term is unity (see Table 1). The second term depends on the Sun's oblateness; for a Sun that rotates uniformly with its observed surface angular velocity, so that the oblateness is produced by centrifugal flattening, J_2 is estimated to be 10^{-7}, so that in such a case, its contribution to λ would be very small.

Now, the measured shift is known accurately: after the perturbing effects of the other planets have been accounted for, the excess perihelion shift is known to about 0.5 percent from radar observations of Mercury since 1966, with the result that $\lambda = 1.003 \pm 0.005$. If J_2 were indeed as small as 10^{-7} this would be in complete agreement with general relativity. However, over the past 25 years, a range of values has been reported for J_2, from 2.5×10^{-5}, inferred from 1966 visual solar-oblateness measurements, to $(1.7 \pm 0.4) \times 10^{-7}$ inferred from solar oscillation data (for a review, see UPDATE, sec. 4.3 and 4.4, NEWTON, sec. 5.4.1), although conventional wisdom points toward the smaller value of J_2. An unambiguous measurement of J_2 through direct study of the Sun's gravitational field over a large range of distances could be provided by a space mission that has been under study by NASA since 1978. Known as Starprobe, it is a spacecraft that would approach the Sun to within four solar radii. Feasibility studies indicate that J_2 could be measured to an accuracy of ten percent of its conventional value of 10^{-7}. Unfortunately, it is not clear whether gravitational physics is part of NASA's current plan for this mission.

Another class of experiments tests what is called the Strong Equivalence Principle (SEP). This is a stronger principle than EEP, stating that *all* bodies, including those with self-gravitational binding energy (stars, planets), should fall with the same acceleration, and that in suitable "local" freely falling frames, the laws of *gravitation* should be independent of the velocity and location of the frame. General relativity satisfies SEP, but most other metric theories of gravity do not. Lunar laser ranging measurements since 1969 have shown that the Earth and the Moon fall toward the Sun with the same acceleration to 3 parts in 10^{12}, yielding the limit

$$|4\beta - \gamma - 3 - \frac{10}{3}\xi - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2| < 0.007 \tag{5}$$

If the laws of gravitation in a local system (for example, the locally measured Newtonian gravitational constant) depend on the motion of the system relative to the universe, then, according to the PPN formalism there should occur such effects as anomalous Earth tides and variations in the Earth's rotation rate, anomalous contributions to the perihelion shifts for Mercury and Earth, self-accelerations of pulsars, anomalous torques on the Sun that would cause its spin axis to be randomly oriented relative to the ecliptic, among other anomalies, known generically as "preferred frame" effects. Negative searches for these effects have produced strong constraints on the PPN parameters α_1, α_2, α_3, and ξ. A possible cosmological variation in Newton's gravitational constant, $\dot{G}/G$, has been constrained by analysis of Viking ranging data to be less than $10^{-11}\mathrm{yr}^{-1}$ (for a review of tests of SEP, see UPDATE, sec. 5, and Ref. 8). Apart from indirect limits such as that shown in equation (5), the only strong limit on the conservation-law parameters ζ_i is $|\zeta_3| < 10^{-8}$, from a test of Newton's third law using the Moon[9].

The current best limits on PPN parameters are summarized in Table 2. General relativity is consistent with all of them.

Table 2
Current Limits on PPN Parameters

PPN Parameter	Experiment	Value or Limit	Remarks
γ	time delay	1.000 ± 0.002	Viking ranging
β	perihelion shift	0.99 ± 0.02	$J_2 \approx 10^{-7}$
$\lvert\xi\rvert$	Earth tides	$<10^{-3}$	gravimeter data
$\lvert\alpha_1\rvert$	orbital preferred-frame effects	$<4 \times 10^{-4}$	combined solar system data
$\lvert\alpha_2\rvert$	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
$\lvert\alpha_3\rvert$	perihelion shift	$<2 \times 10^{-7}$	
	acceleration of pulsars	$<2 \times 10^{-10}$	statistics of dP/dt for pulsars
$\lvert 4\beta-\gamma-3 - \frac{10}{3}\xi - \alpha_1 + \frac{2}{3}\alpha_2 - \frac{2}{3}\zeta_1 - \frac{1}{3}\zeta_2\rvert$	Nordtvedt effect	< 0.007	lunar laser ranging
$\lvert\zeta_3\rvert$	Newton's third law for the Moon	$<10^{-8}$	lunar acceleration

The Search for Feeble Short-Range Forces

The inverse square law of gravity has recently come under intense theoretical and experimental scrutiny, as the papers in this and recent Moriond Meetings will attest. One reason for this interest is the possibility that examination of the inverse square law could reveal information about unified theories of the strong, weak, electromagnetic and gravitational interactions. In some models, the existence of particles of small but non-zero mass (axions in QCD, dilatons in superstring theory, hyperphotons, etc.) can lead to a Yukawa-type contribution to the interaction potential between bodies that could be of sufficiently long range to be observable. In some models these interactions depend on the composition of the materials, while in others they do not. For ranges in excess of about 10 km, the strength of such forces relative to Newtonian gravity is constrained by observations of planetary and spacecraft orbits to be small: from less than 10^{-4} at 10 km to less than 10^{-9} at 10^8 km. At laboratory scales (1 cm to 1 m), the strength is constrained by Cavendish-type experiments to be less than 10^{-4} to 10^{-3}. However, in the intermediate range, say 10 m to 10 km, the constraints are weaker, and indeed, some evidence has been touted as indicating the presence of short-range forces, although there have been conflicting claims. Observations of the gravity profile down deep mines and boreholes and up tall towers, a reanalysis of the Eötvös experiment, and observations of the relative acceleration of different materials toward steep cliffs have given positive results, while a free-fall Galileo-type experiment, reanalyses of the reanalysis of the Eötvös experiment, and independent relative acceleration experiments near slopes have given negative results (for reviews to mid 1986, see Refs. 10, 11). Considerable progress on the experimental front has been made during the past year, and reports of many of the active groups are contained in these proceedings. Space experiments may play a role in this controversy by contributing new constraints in the 10 to 100 km range using low orbiting spacecraft.

Planned or Proposed Projects

Despite the past successes of experimental probes of the gravitational interaction, 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 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. What follows is a sample of those concepts that are primarily directed toward space experiments; many other ideas for laboratory experiments and advances have been proposed, including the ongoing efforts to search for short-range forces.

Search for gravitomagnetism. According to general relativity, moving or rotating matter should produce a contribution to the gravitational field that is the analogue of the magnetic field of a moving charge or a magnetic dipole. The Relativity Gyroscope Experiment at Stanford University is in the advanced stage of developing a space mission to detect this phenomenon. A set of four superconducting-niobium-coated, spherical quartz gyroscopes will 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 milliarcseconds per year, and the accuracy goal of the experiment is about 0.5 milliarcseconds per year. Currently, a full-size flight prototype of the intrument package is being built and will be tested as an integrated unit. Plans call for a test of the final flight hardware on board the Space Shuttle around 1992, and a Shuttle-launched experiment around 1994[12)]. Another proposal to look for the effect of gravitomagnetism is to measure the relative precession of the line of nodes of a pair of LAGEOS satellites with supplementary inclination angles[13)]; the inclinations must be supplementary in order to cancel the dominant nodal precession caused by the Earth's Newtonian gravitational multipole moments. A third proposal envisages orbiting an array of three mutually orthogonal, superconducting gravity gradiometers around the Earth, to measure directly the contribution of the gravitomagnetic field to the tidal gravitational force[14)].

Improved PPN parameter values. A number of advanced missions have been proposed in which spacecraft anchoring and improved tracking capabilities would lead to significant improvements in values of the PPN parameters, of J_2 of the Sun, and of $\dot{G}/G$. For example, a Mercury orbiter, in a two-year experiment, with 3 cm range capability, could yield improvements in the perihelion shift to a part in 10^4, in γ to 4×10^{-5}, in $\dot{G}/G$ to $10^{-13}\mathrm{yr}^{-1}$, and in J_2 to a few parts in 10^8. An Icarus lander could yield similar accuracies for the perihelion shift, γ and J_2. A Phobos lander, with 1.5 years of data at 15 m range uncertainty, could improve $\dot{G}/G$ to $3\times10^{-12}\mathrm{yr}^{-1}$, and could lead to refined asteroid masses (for discussion of these and other missions, see Ref. 15).

Probing post-post-Newtonian physics. It may be possible to begin to explore the next level of corrections to general relativity beyond the post-Newtonian limit, into the post-post-Newtonian regime. One proposal is POINTS, a precision optical interferometer in space with microarcsecond accuracy. Such a device would improve the value of γ to the 10^{-6} level, and could possibly detect the second-order term, which is of order 10 microarcseconds at the limb. Such a measurement would be sensitive to a new ''PPPN'' parameter, which has not been measured heretofore[15)]. Here, the experimental effort to enter the PPPN arena will have to be accompanied by theoretical work to devise a simple yet meaningful PPPN extension of the PPN framework[16)].

Tests of the Einstein Equivalence Principle. The idea of performing an Eötvös experiment in space has been studied[17)], raising the possibility of testing WEP to 10^{-18} . The gravitational redshift could be improved to a few parts in 10^6 in an advanced redshift experiment using a hydrogen maser clock in an Earth-orbiting satellite in an orbit of 0.5 eccentricity[18)]. A hydrogen maser on Starprobe would further improve the first-order redshift, and would be sensitive to second-order corrections (these corrections are still part of the post-Newtonian limit, and depend on γ and β). Other elativistic benefits of Starprobe would be an improvement in J_2 to 2×10^{-8}, in α_1 to 0.007; ir addition, J_4 and time variations in J_2 might also be detectable[15,19)].

III. EXPERIMENTAL GRAVITATION IN ASTRONOMICAL LABORATORIES

Until 1974, the solar system provided the principal testing ground for gravitational theories, 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 in 1974 showed that certain kinds of distant astronomical systems may also provide precision laboratories for testing general relativity. 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 ($v_{orbit}/c \simeq 10^{-3}$). Observation of the relativistic periastron advance (0.001 percent accuracy), of the effects on pulse arrival times of the gravitational redshift and second-order Doppler shift (0.5 percent accuracy), and of periodic post-Newtonian orbital effects (7 percent), have been used, assuming that general relativity is correct, to constrain the nature of the system. The measurement of the rate of change of orbital period (1 percent) gives the first evidence for the effects of gravitational radiation damping. In general relativity, these four 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). In the gravitational radiation case, the relevant formula is the "quadrupole formula", whose foundation is the basic fact that, in general relativity, the lowest multipole moment involved in the emission of gravitational waves (in situations where a multipole decomposition is relevant) is quadrupole. The system is thus highly overdetermined (four constraints on two parameters m_p and m_c), yet all four constraints share a common overlap region within the errors, yielding $m_p = 1.442 \pm 0.003$ and $m_c = 1.386 \pm 0.003$ solar masses: a completely consistent solution in general relativity (for a review, see UPDATE, sec. 8; for recent data, see Ref. 20). The observed rate of change of orbital period, $\dot{P} = -(2.43 \pm 0.03) \times 10^{-12}$, agrees completely with the predicted value, using the measured orbital elements and the two masses, $\dot{P} = -2.403 \times 10^{-12}$.

Some have argued that this provides a "strong-field" test of general relativity, in contrast to the solar-system "weak-field" tests, in the following sense. It seems likely that the companion, like the pulsar, is a neutron star, therefore both bodies contain strongly relativistic internal gravitational fields. Nevertheless, their motion and generation of gravitational waves are characteristic of their weak interbody gravitational fields and low orbital velocities, and are independent of their internal relativistic structure. This irrelevance of the internal structure is part of the Strong Equivalence Principle (for a detailed review of equations of motion in general relativity see Ref. 21).

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 whose source is the internal gravitational binding energy of the two stars. In a system like the binary pulsar, dipole radiation can lead to significantly larger damping than quadrupole radiation because it depends on fewer powers of the small parameter v_{orbit}/c. Because of these two phenomena, violations of SEP, and dipole gravitational radiation, the likelihood of a consistent solution for m_p and m_c in a given alternative theory of gravity is small. For example, the Rosen bimetric theory, which otherwise agreed with solar-system observations, was a casualty of this test (see TEGP, sec. 10.3 and 11.3, and UPDATE, sec. 7.3 for discussion). On the other hand, because the Brans-Dicke theory is "close" to general relativity in all its predictions, it is not strongly constrained by the binary pulsar, because of the near equality of the masses, and the consequent suppression of dipole radiation by the symmetry of the system. The data quoted above place only the weak bound $\omega > 40$ [22].

Other tests of quadrupole and dipole gravitational radiation damping may now be possible using such systems as the "11 minute binary", 4U1820--30, in which radiation damping and mass transfer are intimately coupled. Admittedly, this system is complicated by the mass transfer process; nevertheless, one can obtain interesting, if model dependent, bounds on alternative theories of gravity, such as the Moffat nonsymmetric theory[23] and the Brans-Dicke theory[22]. Table 3 shows the bounds on the Brans-Dicke ω that result for different assumptions about the masses of the two stars in 4U1820--30 (a neutron star and a low-mass helium dwarf), and for soft and stiff neutron-star equations of state, given the current upper limit on the rate of change of orbital period[22].

TABLE 3

Bounds on ω_{BD} from 4U1820-30 with $\dot{P}/P < 2.7\times10^{-7}\ yr^{-1}$

$m_1(M_\odot)$	$m_2(M_\odot)$	EQUATION OF STATE	BOUND ON ω_{BD}
1.4	0.067	SOFT[1]	610
		STIFF[2]	140
1.3	0.055	SOFT	320
		STIFF	90
1.1	0.043	SOFT	100
		STIFF	30

IV. CONCLUSIONS

During the past 25 years, experiments have tested whether Einstein was right to unprecedented levels of precision. Yet the story does not necessarily end here. In one sense, the field of space-based and astronomy-based experimental gravitation has a bright future.

The field is rich with ideas and proposals to continue to probe the gravitational interaction to new levels of refinement and to new regimes of validity. In another sense, however, the future is less assured. Implementation of these exciting ideas and proposals requires financial support, access to space and advanced levels of technology, for which there is intense competition with the military, the manned space program, commercial users of space, and other branches of space physics and astronomy. Even within experimental gravitation, there is competition among different factions and proposals. Nevertheless, to this lowly theorist, the past 25 years of experimental gravitation have been an extremely exciting time, and, despite the uncertainties, I look forward to continued excitement in the years ahead.

This work was supported in part by the National Science Foundation [PHY 85-13953] and the National Aeronautics and Space Administration [NAGW-122]. Parts of this article are based on a lecture given at the XXVII Plenary Meeting of the Committee on Space Research (COSPAR), July, 1988, to appear in *Advances in Space Research* (1989), and on an invited talk at the 14th Texas Symposium on Relativistic Astrophysics, December 1988, to appear in *Annals of the New York Academy of Sciences* (1989).

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