GRAVITY PROBE B: *I. THE SCIENTIFIC IMPLICATIONS*

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ABSTRACT

This paper describes the two primary and four secondary experimental tests of general relativity expected to be performed by the Gravity Probe B relativity gyroscope mission and reviews recent discussions about the significance of the experiment.

1. New Light on Gravity Probe B

This paper and the two following ones by D. Bardas and Y. M. Xiao and their coauthors form the sixth in a series of accounts of the Stanford-NASA Gravity Probe B Relativity Gyroscope program that have been given at successive Marcel Grossmann meetings, since 1976. Progress in these fifteen years has been enormous, culminating last year in the successful operation of FIST (First Integrated Systems Test) a full-scale prototype of the science instrument. Looking ahead to MG7 in 1994, we may expect by then to see the final instrument in test and STU (Shuttle Test Unit) a flight test system manifested on STS 73 (February 15, 1995) ready to go. By MG8 in 1997 the GP-B spacecraft should be in preparation for launch, allowing us to anticipate a final presentation of the experimental results at MG9 in the year 2000.

From MG1 to MG9 is 24 years. By the time GP-B flies, nearly four decades will have passed since George Pugh in 1959 and Leonard Schiff in 1960 independently proposed testing general relativity by means of observations on orbiting gyroscopes. Such are the exigencies of space research encountered not just by Gravity Probe B but by other larger NASA programs like HST (Hubble Space Telescope), the first Phase A study of which was completed in 1967, 23 years before that mission was launched. Can any physics experiment, even one as fundamental as Gravity Probe B still remain fundamental after so long a period? Early in the present year this question was forcefully and appropriately raised by an *ad hoc* NASA review panel chaired by Eugene Parker of the University of Chicago, and so strongly was the issue felt that it was deemed appropriate to elicit the views of no fewer than fifteen distinguished relativists internationally. The answers were impressive. Great as the experimental progress since 1960 has been and thoroughly demolished as many once plausible alternatives to Einstein's theory are, new insights gained over the past decade make Gravity Probe B all the more important. With the removal of so much intellectual rubble the challenges confronting general relativity stand out more sharply than ever.

The purpose of this paper is to summarize as simply as possible the main points brought out in and around the debate occasioned by the Parker report[1].

2. The Two Primary and Four Secondary Relativity Experiments Performed by GP-B, and the Geodesy Coexperiment

The primary goal of Gravity Probe B is to perform two very precise tests of Einstein's general relativity theory by means of observations on gyroscopes in a "drag-free" satellite in polar orbit around the Earth. The first is a measurement for the first time and with high precision (~0.3%) of one of the deepest predictions of Einstein's theory, the *dragging of the inertial frame* by rotating matter. The second is a measurement to about 1 part in 10^5 of the *geodetic* precession of a gyroscope due to its motion through the curved space-time around the Earth. The latter furnishes by far the most precise test to date of any of the positive predictions of general relativity. In a polar orbit the two effects are at right angles (Figure 1) and amount at 650-km altitude respectively to 0.042 and 6.6 arc-second/year. The measurements are made by referring the gyroscopes to a remote guide star via a telescope, with the absolute proper motion of the star being determined in a separate experiment.

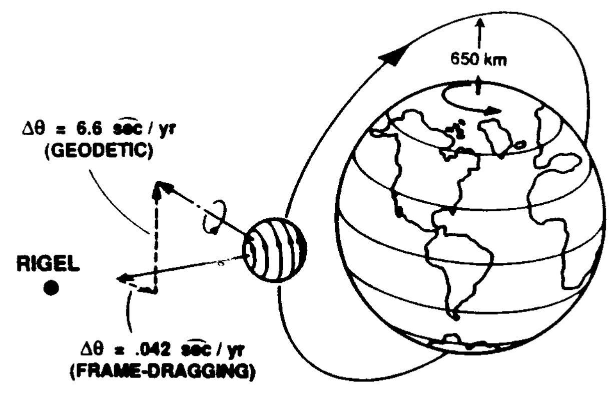

Figure 1. The two gyro effects predicted by Schiff.

Frame-dragging is a gravitational effect of moving matter with no counterpart in Newtonian theory, originating in off-diagonal terms in the metric whose source is the angular momentum of the central body. It has, as discussed below, a close relationship to questions of Mach's principle and the origin of inertia. An intriguing analogy, first drawn by R. L. Forward in 1961[2], exists between it and the effects of a moving electric charge in generating a magnetic field, as a result of which the phenomenon measured is often called gravitomagnetism. As with every analogy, the limits of validity need to be understood, and this has several; nevertheless, its pedagogical value is substantial.

In addition to the primary measurements, GP-B will yield four other tests of relativistic phenomena and an important geodesy coexperiment. The four auxiliary tests are (1) a remeasurement of the *gravitational deflection of light*, (2) a *redshift clock comparison* experiment, (3) a measurement of *relativistic perigee precession*, (4) a null experiment that may be interpreted as a second, indirect test of an effect of gravitomagnetism.

Starlight deflection is measured by in effect turning the experiment around and using the gyroscopes as references for the telescope. During the course of a year, the line of sight to Rigel, the chosen guide star, will vary in distance from the Sun, reaching a point of closest approach on June 10, on which day the angle from the Sun line is 30.14 deg and the expected relativistic deflection of light is 14.4 marc-s. Figure 2 illustrates the path of the displaced star image throughout the year, as calculated by T. Duhamel[3]. Since its time signature is very different from the linearly increasing geodetic and frame-dragging precessions, the effect can be readily separated from them in data reduction. The accuracy depends on gyro readout performance. Reasonable assumptions yield an uncertainty of around 0.5%, comparable to the current radioastrometric data from Very Long Baseline Interferometry (VLBI).

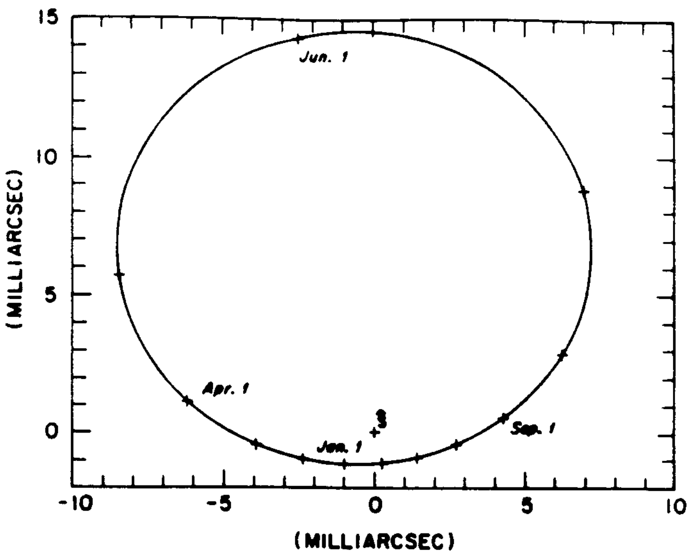

Figure 2. Deviation of Starlight.

The effect of light deflection as a disturbance in Gravity Probe B, but not the method of determining it, was first pointed out by R. F. O'Connell and G. L. Surmelian in 1970[4].

Schiff in 1959, even before he investigated the two primary gyro effects, recognized that a spinning body might serve as a clock[5]. His hope was that gyroscope technology might pave the way to making a clock good to a part in 10^{18} for use in measuring the well known Einstein gravitational redshift to second order. Though that seems unlikely, T. Walter and J. P. Turneaure find that a gyro clock stable and measurable to 3 parts in 10^{14} may be achievable, which if true will allow another experiment of considerable interest, a null redshift comparison between the GP-B gyro clocks and ground-based hydrogen masers. The idea resembles that of the Turneaure-Vessot experiment[6] (1977) in which the rates of hydrogen maser and superconducting cavity stabilized oscillator (SCSO) clocks were compared with each other during the period around vernal equinox when the Earth's distance from the Sun, and with it the gravitational potential seen by the clocks, is changing by 2.8×10^{-12} parts per day. The question, first explicitly discussed by Schiff, is whether all clocks undergo an identical gravitational rate change as expected from Einstein's redshift formula. Such a measurement may, as Nordtvedt showed in 1975[7], be viewed as a check on the assumption of Local Position Invariance contained in the Einstein equivalence principle, testing in some form (the exact form depends on the type of clock) whether the fine structure constant α is independent of the potential. Since the total variation in gravitational potential from the eccentricity of the Earth's orbit is 3 parts in 10^{10}, the proposed experiment will check Local Position Invariance to a part in 10^4 — a precision two orders of magnitude higher than Turneaure and Vessot's and obtained with a different type of clock.

Auxiliary tests (3) and (4) — perigee precession and the null gravitomagnetic effect — are both byproducts of the *geodesy coexperiment* which is designed to supply new, greatly improved information on the geoid: the Earth's gravitational shape. All three depend on applying precise laser ranging and GPS (Global Positioning System) tracking to the very nearly ideal gravitational orbit provided by GP-B's drag-free control system. The null gravitomagnetic test, due to K. Nordtvedt[8], is a variant of the hypothetical 28-day non-Newtonian "Nordtvedt effect" oscillation in the Earth-Moon distance as the system rotates in the Sun's gravitational field. In most metric theories of gravitation there appears, as one of the series of terms that might contribute to that motion, a gravitomagnetic signal inversely proportional to the radius of the satellite orbit. For the Moon this term is small but for GP-B's 650-km altitude (7,000-km radius) orbit it is substantial. M. Tapley[9] has shown that when geodesy, gravitomagnetic and perigee precession data are simultaneously derived in a grand solution for the satellite's path, the relativistic perigee precession should be determinable to 0.3% and the null test of the gravitomagnetic potential to 0.06%.

The geodesy coexperiment is discussed elsewhere[10]. It will add to our knowledge of the phenomenon of glacial rebound and will strengthen NASA's Earth Resources program by enhancing almost by a factor of 10 the precision with which the TOPEX (TOPographical EXplorer) oceanography satellite can map long-term ocean currents and tidal effects.

3. Progress in Experimental Gravitation 1960-1980: The PPN Formalism and the Demolition of Alternative Theories

Amongst the many neat aphorisms that Einstein uttered, one of the best known is the remark that general relativity is such a coherent, self-consistent theory that if any single element in it were to fail, the whole structure would collapse.

At one level that assertion is demonstrably untrue. Numerous alternative metric theories of gravitation have been devised that shed some elements of general relativity while retaining others, and although most of those theories are now falsified their very existence disproves the claim. And yet at another level, and in another way, the claim stands. The forms the alternative theories have taken, and the process by which they have been demolished, together strongly suggest that when the true successor to Einstein's theory does emerge it will not be through some minor tinkering with known ideas but rather through a major change in the underlying intellectual paradigm. The change is likely to be as radical as the one Einstein himself introduced when he replaced Newton's picture of gravity as a force acting instantaneously at a distance with the picture of it as a field resembling the Maxwellian electromagnetic field but operating at a deeper level, modifying the structure of space and time.

It is just the need for such a transition of thought that has been brought back into focus by the recent discussions of Gravity Probe B.

The process by which so many alternative theories have been demolished has been one of the most interesting achievements of modern physics. Notice first that nearly all of the known alternatives are *metric theories* — theories that follow in one way or another Einstein's basic idea of relating gravity to space-time curvature. Only two nonmetric theories can be named that have been sufficiently well formulated to merit serious attention: the general Lagrangian theory of Belinfante and Swihart (1958), and Moffat's more recent nonsymmetric theory of gravitation (NGT). And yet to quote from Kip Thorne and Clifford Will (letter to E. Parker, 2 May 1991):

> There is a great richness of possibilities in the realm of nonmetric theories, a richness that has been only little explored — except for studies (e.g., via the TH$\epsilon\mu$ formalism) of the constraints placed on nonmetric behavior by Eötvös and redshift experiments. If, in fact, general relativity is incorrect, then we (Cliff and Kip) would think it most likely to fail in a nonmetric-theory direction: Physicists' attitudes about gravity have been heavily conditioned by general relativity; metric theories are designed to be as much as possible like general relativity, while introducing some modest departures due to the presence of additional gravitational fields that help to determine what the metric is, and they thus are easy to analyze and have been much analyzed. However, we see no reason why Nature should conform to the present convenience of physicists; if she has chosen to go a different route from general relativity in some subtle but important way, we see no reason why she should do so in a metric-theory manner. If she does take a nonmetric route, this will shake the foundations of physics much more seriously than would a metric-theory-type violation of general relativity. A GP-B result pointing to some nonmetric feature of gravity would thus be of enormous importance. Unfortunately, nonmetric theories have been so little studied that we don't begin to understand what the possibilities are.

I return later to nonmetric theories. Meanwhile between 1920 and 1970 some 80 alternative metric theories of gravitation were constructed, beginning with the one given in 1921 by the philosopher-mathematician A. N. Whitehead. Some, like Whitehead's theory, have had a preferred reference frame; others have involved specific additional fields like the scalar field added to general relativity by Jordan, and later adopted by Brans and Dicke in the hope of making general relativity consistent with Mach's principle. For many years this efflorescence of theorizing brought sheer confusion until Nordtvedt, Will and others in the late 1960s invented the parametrized post-Newtonian (PPN) framework for comparing the various metric theories of gravitation formulated up to that time. PPN was basically an extension of an idea of Eddington's who in 1922 had investigated the significance of Einstein's tests of general relativity by writing the metric of an ideal nonrotating gravitating body in a more general form than the standard Schwarzschild solution, with two principal free parameters, one γ representing the curvature of three-dimensional space, the other β representing the nonlinearity of the time component of the metric. PPN has been through several modifications; in its current most general form it contains ten free parameters to be fixed by observation. It must be emphasized that PPN is *not all-inclusive even of metric theories*. Discussed below are some counterexamples of metric theories that do not fit PPN.

A remarkable outcome of PPN was Kenneth Nordtvedt's discovery (1968) that previously unrecognized *negative experiments* rule out many of the alternative theories. Best known is the hypothetical "Nordtvedt effect" oscillation in the Earth-Moon distance mentioned earlier, to be expected in some theories but not general relativity. Laser ranging to retroreflectors on the Moon has brought the search for this to a precision of about 20 cm and placed stringent limits on certain theories. Note that the non-Newtonian oscillation, if any, has to be deduced in the presence of a *Newtonian* tidal effect of the same frequency and phase and amplitude 150 km — 10^6 times larger than the current measurement limit. The observed nonexistence of any Nordtvedt effect can be interpreted in three interlocking ways:

(1) as a test of the equivalence of gravitational and inertial mass for the different materials of the Earth (silica-iron) and the Moon (silica)
(2) as a test that the gravitational self-energy of the Earth (about 10^{-9} of its mass) contributes equally to both gravitational and inertial mass
(3) as a test that the combination ($4\beta - \gamma - 3$) of PPN parameters (plus other parameters in the full PPN structure) sums to zero.

Interestingly, as Damour has pointed out[11], Newton in his *Principia*, correctly saw that the motions of the Earth-Moon system provide a test of equivalence in the first sense, one that Laplace subsequently carried through analytically to a part in 10^7. Lunar ranging has allowed Laplace's result to be refined to the level of 1.5 parts in 10^{11}, comparable with the best existing ground-based experiments. The same data confirm the equivalence of gravitational self-energy to about 1% and gives a limit on ($4\beta - \gamma - 3$) at the level 1 part in 300.

This strange conjunction of the space-curvature coefficient γ in null combination with the nonlinear time coefficient β deserves more thought than it has yet received.

Philosophically the existence of such negative experiments is of great interest. Many others occur, for example, the Will effect[12], a possible but nonexistent solid Earth tide directed towards the center of the galaxy, which rules out Whitehead's theory, and certain negative strong field tests in binary pulsar systems conceived by T. Damour[13]. In Clifford Will's words, Einstein's theory emerges as a *minimalist theory*: elegant in assumption and with few experimental deviations from Newtonian theory by comparison with other theories. A deeper investigation of the intellectual basis of this minimalism is called for, as well as a deeper understanding of the role of negative experiments in physics.

The broad effect of PPN has been to demolish most of the alternative theories hitherto proposed while leaving general relativity intact. That happy result does not make general relativity secure. Only few distinct true positive tests of Einstein's theory exist, plus one half-test, and all are in the weak field domain ($GM/c^2R \ll 1$).

The half-test is the gravitational redshift, now checked to 1.4 parts in 10^4 by Gravity Probe A, Einstein's equivalence principle rather than general relativity itself. The four true tests with variants are set forth in Table 1, two being Einstein's own, the gravitational deflection of light and the anomalous perihelion motion of Mercury. Starlight deflection is checked to 0.5% through VLBI (Very Long Baseline Interferometry) measurements between quasars lying in the ecliptic plane, while the closely related radar time-delay test is established to 0.1% through ranging measurements to the Mars Viking lander (1976). Another new test, based principally on lunar ranging is the measurement to 2% of the geodetic precession of the Earth-Moon system as it moves through the curved space-time around the Sun — a result related to the ultraprecise geodetic measurement to be performed in GP-B. *Within PPN*, the geodetic effect is allied to starlight deflection and radar ranging;

they depend on the space-curvature parameter γ as $(1 + \gamma)$ while it is proportional to $(1 + 2\gamma)$. *Outside PPN the two results become decoupled* as explained below.

TABLE 1. THE FOUR TRUE POSITIVE TESTS OF GENERAL RELATIVITY.

type	effect	how measured	precision
electromagnetic	(1) starlight deflection	VLBI	0.5%
	radar time-delay	radar ranging to Mars	0.1%
massive body	(2) geodetic effect	VLBI + lunar ranging	2%
	(3) perihelion/periastron precession	Mercury	0.3%
		pulsar timing	0.8%
		eclipsing binaries	strong disagreement with G.R.
gravitational radiation	(4) radiative damping of pulsar orbit	pulsar timing	~ 0.8%

Most exciting among the new observations is the apparent decay of the binary pulsar's orbit at a rate agreeing to within 0.8% with the expected loss in energy from gravitational radiation. Seen also in the same object are a time-delay effect and a periastron precession analogous to Mercury's perihelion precession. And yet the case for perihelion/periastron precession has arguably been weakened. Although earlier doubts about Mercury's precession seem to be settled, quite good observations on eclipsing binary stars disagree sharply with general relativity without a satisfactory Newtonian explanation.

What are the implications for Gravity Probe B? Within PPN the geodetic measurement provides a determination of the space curvature coefficient γ with a precision approaching a part in 10^5, a factor of 100 better than the best radar ranging result. The frame-dragging measurement, performed to about 0.3%, determines the combination of parameters $(\gamma + \alpha_1)$ where α_1 is a coefficient, zero in general relativity, characterizing preferred frame theories. Since α_1 has already been shown through various negative experiments to be less than 10^{-3}, a superficial judgment would say that the geodetic measurement because of its high precision is the more important of the two, and that frame-dragging yields nothing new. Even within PPN that view has problems. The coefficient γ enters frame-dragging in a different way from the geodetic effect, involving other components in the metric transposed to yield the γ. One has here a first hint of the limitations of PPN, important as the formalism is. More fundamentally the conclusion is so contrary to the instincts of most relativists that one is forced to dig deeper.

The next two sections confront the limitations of PPN and the need for deeper considerations.

4. The Limitations of PPN and the Question of Nonmetric Theories

The assumption that PPN offers the most general framework within which metric theories of gravitation can fit is now exploded.

The PPN expansion is restricted to simple positive power of the classical potentials U, ϕ_1, V^α etc. That restriction was appropriate in the 1960s and 1970s for the metric theories then under consideration. In 1984, however, I. Ciufolini[14] pointed out that other theories involving fractional or inverse powers of the classical potentials might be constructed. Recently (letter to E. Parker, 5 May 1991; *Phys. Rev. Letters*, in review) Ciufolini has further investigated fractional potentials, while R. Matzner (letter to E. Parker, 29 April 1991) has studied a model theory containing an inverse power of the classical potentials which has the remarkable feature of giving a geodetic effect identical with that of general relativity but *a frame-dragging effect quantitatively different from the general relativity result.*

The primary interest of the Ciufolini-Matzner models so far is as *counterexamples*. Even though M. Reisenberger[15] has shown that they can be cast into Lagrangian form, they are still far from being fullly articulated theories; they do not yet and may never have an intelligible physical basis; and it has yet to be shown that they are not ruled out on other grounds, for example through existing negative experiments. Nevertheless, with all acknowledged limitations they do serve an important function in establishing boundaries to PPN and revealing the danger of taking it as more than it is.

Another related investigation is by T. Damour (letter to E. Parker, 4 June 1991) who has formulated a model theory containing besides the Einstein potential an additional *finite range tensorial field* with relatively long range, 10^3 km say. The possible existence of *scalar* fields of finite range first came to prominence some years ago through an alleged short-range violation of Newton's inverse square law, now discredited. Nevertheless, as Y. Fujii discusses elsewhere in these *Proceedings*, good theoretical motivations exist for expecting interactions of this kind to occur. Damour's theory has the merit of being rigorously formulated and agreeing with all known tests of general relativity, including tests of the equivalence principle and Newton's inverse square law, while at the same time proving that "in a GP-B type experiment, both the Lense-Thirring (T_{0i}-generated) and the DeSitter (space-curvature-linked) effects could be arbitrarily different from the G.R. predictions (k [coupling constant] and μ [range] being yet essentially unconstrained)."

I return now to *nonmetric theories*. Only two really count, the Belinfante-Swihart[16] and the Moffat theories. The former is usually considered to be excluded by the results of the Braginsky-Panov experiment (1972) which has been claimed as proving the weak equivalence principle to a part in 10^{12}. Some experimentalists, including myself, wish to see that result reverified, but be that as it may. Moffat's theory (NGT), as already indicated, resembles general relativity in basic framework but allows both the metric and the connection to be nonsymmetric. The field sources are the stress tensor as well as a new conserved charge ℓ^2. Unfortunately, the interpretation of ℓ^2 in terms of matter has not been fixed yet. If a model for ℓ^2 is adopted, NGT can be made, with some difficulty, to fit all the known tests while offering a natural way of accounting for the otherwise very puzzling periastron data from eclipsing binaries[17]. For gyroscopic motions, the theory gives identical frame-dragging but a geodetic effect differing from Einstein's by up to 3.4 milliarc-seconds/year, testable in GP-B to within 3%.

Recently K. Nordtvedt[18] has developed a new framework embracing a wide (but still incomplete*) range of metric and nonmetric theories, within which the geodetic effect in nonmetric theories becomes decoupled from starlight deflection and radar ranging through the addition of a new parameter c_7 to be fixed by experiment. For frame-dragging the nonmetric effects are even more surprising. In addition to the secular differences allowed through the parameter c_7, there exist in theories with a preferred reference frame possible large cyclic precessions with period one year, readily measurable by GP-B.

5. General Relativity, Gravitomagnetism, Mach's Principle and Unification

If, as now seems clear, the four positive tests just described, with the Nordtvedt-Will negative experiments, together demolish most of the known PPN theories, that by no means ends the story. As R. Jantzen has said (letter to E. Parker, 9 May 1991) PPN is "basically a way of describing a family of mostly bad alternatives to general relativity ... if general relativity is wrong, it is entirely possible that PPN is wrong as well, requiring some new and better theory which goes beyond either one."

Two historical parallels are worth reflecting on. By the 1880s no fewer than eight alternatives to Maxwell's electromagnetic theory existed, all but one of which were reduced to a common Lagrangian framework by J. J. Thomson in 1884. Twenty years later Maxwell's theory was found to be deficient: light is quantized. If one asks whether those theories or that framework contained any hint of quantization, the answer is, of course, no. Quite new considerations from quite unforeseen experiments marked the limits of Maxwell's theory. The second example, even closer, is the breakdown of Newtonian gravitation revealed by Leverrier's discovery of the anomalous precession of Mercury's perihelion. People sometimes imagine that new evidence only comes from going to extremes, as that general relativity must hold except in strong fields or at short distances near the Planck length (10^{-33} cm). Analogous reasoning would have made study of Mercury's perihelion an exercise in futility. Newtonian theory was already confirmed to higher order both at greater distances (the outer planets) and smaller ones (the Moon). So used are we to Einstein's triumph that we miss how unreasonable it was to expect anything new, and how kind it was of the Creator to place a body at just the right distance from the Sun for the anomaly to be discovered.

All this may lead us to share Irwin Shapiro's robust conviction (letter to E. Parker, 29 April 1991) that "We cannot rely on theories or theorists." Nevertheless recognizing that our

* Both Damour's theory and the Ciufolini-Matzner counterexamples fall outside the Nordtvedt framework.

worries may be the wrong worries, it is worthwhile summarizing four basic worries about Einstein's theory, beginning with Mach's principle.

5.1 Mach's Principle and Rotation

The most telling of Newton's arguments in favor of absolute space was the apparent absoluteness of rotation, as demonstrated in his ice pail experiment and the effect of centrifugal forces in generating the Earth's equatorial bulge. The argument seemed decisive until Berkeley in 1738 pointed out that centrifugal effects might originate in the action of all the other matter in the Universe rather than of space. The same idea was revived by Ernst Mach in 1885; Einstein called it Mach's principle.

This idea that rotation is a relative phenomenon strongly influenced Einstein but his theory only partly supports it. At first all seemed well. In 1918 W. Lense and H. Thirring studied rotation in general relativity. One of their conclusions was that a spherical shell of matter rotating around an ideal gyroscope or Foucault pendulum would drag the reference direction with it by an amount depending on the mass of the shell. A plausible extrapolation seemed to be that if all the matter in the Universe were set in uniform rotation, space-time would be dragged around by just enough to keep the gyro axis permanently aligned with the stars. Regrettably, the argument only works with very special assumptions about the amount and distribution of matter in the Universe; worse, as Kurt Gödel proved in 1948, valid solutions to Einstein's equations exist that explicitly contradict Mach's principle; worse yet, a case can be made (letter of B. Mashhoon to E. Parker, 2 May 1991) that the Lense-Thirring argument only accounts for Coriolis forces leaving centrifugal force unexplained.

Mashhoon's argument is controversial and may not be correct. It leads to the paradoxical conclusion that a measurement of frame-dragging by GP-B has the exact opposite implication from what one might expect. If on Mach's principle one takes the Earth to be at rest and the Universe to be rotating, then the Lense-Thirring argument accounts for the Foucault effect but cannot explain the additional rotation caused by the presence of the Earth. The distant masses themselves will not (within general relativity at least) produce any such effect; hence in Mashhoon's words *"A direct measurement of the gravitomagnetic field of the Earth by GP-B is observational proof of the absolute rotation of the Earth!"* Right or wrong this argument points to the profundity of the questions raised by general relativity and Mach's principle, and the significance of the frame-dragging measurement by GP-B.

5.2 Quantization, Geometrization and Rotation

The peculiar role of rotation in general relativity has been emphasized from a different angle by C. N. Yang (letter to the NASA Administrator, 5 December 1983). Yang connected the problem of quantizing general relativity with Einstein's long-stated wish to move the right-hand side of the field equation (the mass energy term) over to the left side in order to convert it into a geometrical concept, stating that "... Most of us believe that when the right side of his equation is moved to the left side and converted into the correct beautiful and symmetrical geometrical concept that it should be, then the quantizing problem would be also resolved." He then asked

> What is this new geometrical symmetry? We do not know. (The recent explosion of activities in supersymmetry and supergravity is precisely because they might give a hint of the sought-after new concept.) However, many of us believe that whatever this new geometrical symmetry will be, it is likely to entangle with spin and rotation, which are related to a deep geometrical concept called torsion. But, no one has figured out what precise new concept related to rotation is the relevant one. From the viewpoint of gauge theory, I had pointed out (*Phys. Rev. Letters* 33, 445 (1974)) that the natural amalgamation of Einstein's theory with gauge theory is to involve the derivatives of R_{ik} [the curvature tensor], hence to involve spin.

And went on to say: "That the amendment of Einstein's theory may not disturb the usual tests is quite easy to imagine, since the usual tests do not relate to spin. The proposed Stanford experiment is especially interesting since it focusses on the spin. I would not be surprised at all if it gives a result in disagreement with Einstein's theory."

5.3 New Problems and New Approaches in Unification

Physicists in 1991 who seek to unify gravitation with the other forces of Nature confront a situation markedly different from Einstein's — different even from the situation of the late 1960s when PPN was formulated and so many alternative theories were laid to rest. Thus while Einstein's preoccupation was unifying gravitation with classical electromagnetism, modern physics must embrace also the strong interaction binding the nucleus together and the weak interaction that governs β decay; and it does so in a context where the unification sought is no longer a static one. The interactions are seen as having evolved over time through some symmetry-breaking process in the early history of the Universe[19]. These shifts do not make Einstein's original concerns obsolete. Instead they add new ideas and opportunities while shaking the triumphalism about general relativity that characterized the period in the 1970s immediately after the demolition of the older alternative theories.

The way forward is far from clear. All one can do is offer pointers. Take *string theory*[20] which is one possible road to unification. Its natural gravitational theory has a scalar as well as a tensor potential like the Brans-Dicke theory that was supposedly ruled out by earlier tests. A factor of 100 improvement in the determination of the PPN parameter γ as obtained in GP-B's geodetic measurement is therefore suddenly more interesting. Another line of theorizing has been the study of interactions with a *finite but relatively long range*, as in Damour's model. Yet another is the investigation of nonmetric theories.

Summarizing this rather confused theoretical picture as it applies to the two primary GP-B measurements — frame-dragging and the geodetic effect — we have the following:

- Both Mach's principle and the problems of quantization and geometrization make the frame-dragging measurement in Yang's words "a key test of Einstein's theory in a new direction where Einstein's theory is weakest in structural beauty and experimental cogency."

- More specifically individual theories give these predictions. In Moffat's theory the frame-dragging is identical with Einstein's but the geodetic effect may differ from it by up to 3.4 milliarc-seconds/year. In Damour's finite range metric theory both geodetic and frame-dragging effects differ from Einstein's by large calculable amounts. In the Ciufolini-Matzner metric theories the geodetic effect is identical with Einstein's but the frame-dragging is different. In nonmetric theories that fit the Nordtvedt framework both the geodetic and frame-dragging effects are modified through the new parameter c_7 while in addition theories with a preferred reference frame may exhibit large cyclic frame-dragging effects with period one year, measurable by GP-B.

Gravity Probe B specifically discriminates between each of these new variant theories and general relativity, and in addition provides a test of the existence of a scalar field as expected from string theory a factor of 100 more precise than any previous test.

I thank the many correspondents named and unnamed in this letter, and P. Carini, M. Jarnot, D. Kalligas, M. Reisenberger, M. Tapley and T. Walter for comments and corrections.

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