THE CONFRONTATION BETWEEN GENERAL RELATIVITY AND EXPERIMENT*

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INTRODUCTION

The principal cornerstone of all scientific theory is observation and experiment. One of the strengths of this Texas symposium is that it brings together astrophysical theorists and observers and forces them to confront theories with observations (and vice versa). However, the symposium title also contains the word "relativistic," so at this point it is appropriate to focus on the confrontation between relativity—specifically general relativity—and experiment. This is especially timely in view of the near-coincident occurrence of two momentous events in this field: the beginning of the year of the centenary of Einstein's birth, and the announcement of the probable first discovery of the existence of gravitational radiation.

The confrontation between gravitation theory and experiment can be discussed on three levels. At a very fundamental level, a variety of experiments test the foundations of the gravitational interaction. These experiments verify, for example, that classical gravity is a geometric, curved-space phenomenon, but do not test general relativity itself. The first tests of general relativity occur at the "post-Newtonian" level, where experiments in the solar system play an important role. Finally, new arenas for testing general relativity are becoming crucial, in particular, the binary pulsar, where recent measurements by J. H. Taylor and his colleagues may provide make-or-break tests of gravitational theory.

TESTS OF THE FOUNDATIONS OF GRAVITATION THEORY

There is a class of experiments that probe the nature of gravity at a very fundamental level, such as the Eötvös experiment, the gravitational redshift experiment, and the Hughes–Drever experiment. These experiments test what has come to be called the "Einstein Equivalence Principle" (EEP), which states that "test" bodies follow geodesics of a space-time metric, and that in local freely falling frames of that metric, the nongravitational laws of physics take on universal forms, independent of the location and velocity of the frame. If EEP is valid, it is then possible to show that the correct classical theory of gravity must be a "metric" theory, one in which all the physical effects of gravitation are produced by space-time geometry.

A simple way to discuss and classify experiments that test EEP has arisen from the

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work of Dicke, Nordtvedt, and Haugan. One separates EEP into three subprinciples: the “Weak Equivalence Principle” (WEP), which states that “test” bodies fall with the same acceleration; the “absence of preferred-location effects” in local experiments involving nongravitational forces; and the “absence of preferred-frame effects” in such experiments. Although these subprinciples may involve very different kinds of experiments, theoretically they are intimately connected, in the sense that if one of them is violated, then one of the others must be violated. This bears out a 1960s conjecture by Schiff that the validity of WEP alone is sufficient for the validity of EEP.

FIGURE 1 summarizes these principles and their experimental tests. Any of the nongravitational interactions, strong (S), electromagnetic (E), or weak (W), could violate EEP by means of a “nonmetric” coupling to gravitation of strength \( \alpha_A g_A \) (A = S, E, or W), where \( g_A \) is the nominal coupling constant of the interaction. Experiments that check EEP thereby set upper limits on possible anomalous values of the \( \alpha \)'s, shown in Figure 1. These include the Eötvös experiment (Moscow version 1971, equality of acceleration for Al and Pt to parts in \( 10^{12} \)), the gravitational redshift experiment (Vessot–Levine hydrogen-maser rocket experiment 1976, accuracy one part in \( 10^6 \)), and the Hughes–Drever experiment (isotropy of inertial mass, verified to one part in \( 10^{23} \)). Another possible preferred-location effect that would violate EEP is a cosmological time dependence of the nongravitational constants. Major improve-

**FIGURE 1.** The Einstein equivalence principle. (For theoretical discussion, see reference 1; for summary of the experiments, see reference 2.) The horizontal arrows represent the intimate connection between the three subprinciples discussed by Dicke, Nordtvedt, and Haugan.
TABLE 1
THE PPN PARAMETERS AND THEIR SIGNIFICANCE

| PPN Parameter | Significance                                      | Value in General Relativity |
|---------------|---------------------------------------------------|-----------------------------|
| γ             | How much spatial curvature does mass produce?     | 1                           |
| β             | How "nonlinear" is gravity?                       | 1                           |
| ξ             | Are there gravitational preferred-location effects? | 0                           |
| α₁            | Are there gravitational preferred-frame effects?  | 0                           |
| α₂            |                                                   | 0                           |

Statements in the upper limits on such variations have been made by Shlyakhter, using analyses of fission yields from the Oklo Natural Reactor, a natural, sustained fission reactor believed to have occurred in West Africa around $2 \times 10^9$ years ago. The results shown in FIGURE 1, represent upper limits on the amount of variation of the constants over one Hubble time ($2 \times 10^{10}$ yr).

SOLAR-SYSTEM TESTS OF POST-NEWTONIAN GRAVITY

The Parametrized Post-Newtonian Formalism

The experimental evidence shown in FIGURE 1 that supports EEP gives confidence that the correct theory of gravity must be a metric theory. In the weak-field, slow-motion, or "post-Newtonian" limit appropriate to the study of experiments in the solar system, most metric theories of gravity can be analysed in terms of a "theory of theories of gravity" that classifies them in terms of a set of arbitrary dimensionless parameters whose values vary from theory to theory. This theory of theories is known as the Parametrized Post-Newtonian (PPN) formalism. One version of the PPN formalism restricts attention to theories of gravity that possess momentum and energy conservation laws, called "semiconservative" theories. In this version there are five PPN parameters, $\gamma$, $\beta$, $\xi$, $\alpha_1$, and $\alpha_2$, whose significance and values in general relativity are shown in TABLE 1. TABLE 2 lists a number of recent semiconservative metric theories of gravitation and shows their PPN parameter values.

One can now regard solar-system tests of post-Newtonian effects as measurements of the "correct" values of these parameters. It is convenient to separate solar-system experiments into two classes: the "classical tests," and tests of the "strong equivalence principle".

The Classical Tests

Three solar-system experiments, light deflection, time delay, and perihelion shift, can be called the three "classical tests." This terminology differs from popular usage in which the term "classical tests" refers to gravitational redshift, light deflection, and perihelion shift. But the gravitational redshift is a test of EEP, not of general relativity.
## Table 2
### Metric Theories of Gravity*

| Theory (Gravitational Fields Present) | PPN Parameters | Obey SEP? | Post-Newtonian | Strong Field, Grav. Waves |
|--------------------------------------|----------------|-----------|----------------|--------------------------|
| (a) Purely Dynamical Theories         |                |           |                |                          |
| (i) General relativity (g)           | γ = 1, β = 1, ξ = 0, α₁ = 0, α₂ = 0 | Yes       | Yes            | Yes                      |
| (ii) Scalar-tensor (g, φ)             |                |           |                |                          |
| BWN-Bekenstein                       | 1 + ω/2, 1 + Λ | No        | Yes (ω → ∞)    | Yes (ω → ∞)              |
| Brans-Dicke                          | 1 + φ, 0       | No        | Yes (ω → ∞)    | Yes (ω → ∞)              |
| (iii) Vector-tensor (g, K)            |                |           |                |                          |
| 2 + ω                               | 1 + 1 + α₂/2 K₀/(1 + ½ K₀) | No        | Yes (K₀ → 0)   | Yes (K₀ → 0)             |
| (b) Theories with prior geometry     |                |           |                |                          |
| (iv) Bimetric theories               |                |           |                |                          |
| Rosen (g, η)                         | γ = 1, β = 1, ξ = 0, α₁ = C₀/C₁ - 1 | No        | Yes            | No                       |
| Lightman–Lee (g, η, h)               | γ' = 1, β' = 0, α₁' = α₂' | No        | Yes            | No                       |
| Rastall (g, η, K)                    | γ = 1, β = 1, ξ = 0, α₁ = α₂ | No        | Yes            | No                       |
| (v) Stratified theories               |                |           |                |                          |
| Ni (g, η, τ, φ, K)                   | a = 0, b = 0, ξ = -4 (a + 1 + ½c) - (d + 1) | No        | Yes            | No                       |

*For detailed discussion and references, see reference 2.
itself, and so should not be included in this class. Furthermore, the "time-delay" test, discovered by Shapiro in 1964, is, in its theoretical interpretation, on an equal footing with the light-deflection test. Actually, this latter test has yielded the most precise results of the three.

The light-deflection and time-delay tests are related in the sense that they measure effects on the propagation of photons in the curved space-time around the Sun; in fact, they depend on the PPN parameter $\gamma$ in the same way. A ray of light that passes the Sun at a distance $d$ (in units of solar radii) is deflected by an angle

$$\delta \theta = \frac{1}{2} (1 + \gamma) \, 1'' \cdot 75 / d,$$

and a ray of light that similarly passes the Sun on a round trip, say from the Earth to Mars, suffers a delay that leads to an excess round trip travel time

$$\delta t = \frac{1}{2} (1 + \gamma) \, 250 [1 - 0.16 \ln d] \, \mu s.$$

The most precise light-deflection experiments are those that employ radio interferometry to measure the deflection of radio waves from quasars; since 1969 a series of such measurements has yielded values of the coefficient $\frac{1}{2} (1 + \gamma)$ in agreement with general relativity at levels of accuracy approaching 1.5 per cent (see FIGURE 2).^5

![FIGURE 2. Light-deflection measurements using radio interferometry. Bottom scale shows the value of the coupling constant $w$ of scalar-tensor theories that would give the corresponding value of $\frac{1}{2}(1+\gamma)$. (After reference 2.)](image-url)
Measurements of the time delay using radar ranging to planets and spacecraft have been carried out since 1967; recent data from ranging to the Viking orbiters and landers on Mars have yielded results in agreement with general relativity with published errors between 0.5 and 0.2 percent (FIGURE 3).6,7

The third of the classical tests is the perihelion shift, but here the situation is more complicated. In terms of the PPN formalism and Newtonian gravitation, the predicted advance of Mercury's perihelion due to the Sun is, in arcseconds per century,

$$\omega = 42.98 \left[ \frac{1}{3} (2 + 2\gamma - \beta) \right] + 0.013 \left( \frac{J_2}{1 \times 10^{-7}} \right), \quad (3)$$

where $J_2$ is the quadrupole moment of the Sun. From radar ranging to the inner planets, the measured perihelion shift agrees with $42''.98$ per century within about half of one percent. However, measurements of the visual solar oblateness by Dicke and Goldenberg in 1967 were interpreted as corresponding to a value $J_2 = (2.5 \pm 0.2) \times 10^{-5}$, which would contribute an anomalous $3''$ per century to the shift. Later measurements by Hill and colleagues yielded an upper limit $J_2 < 0.5 \times 10^{-3}$. Thus there remains some uncertainty in the interpretation of perihelion shift measurements as tests of relativistic gravity.2 A direct, unambiguous measurement of $J_2$ would be provided by a mission under study by NASA, known as the Solar Probe, 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 per cent of its nominal value $1 \times 10^{-7}$, that of a centrifugally flattened, uniformly rotating Sun.

\[\text{FIGURE 3. Radar time-delay measurements. (After reference 2.)}\]
Tests of the Strong Equivalence Principle

A number of tests of post-Newtonian gravity can be viewed as tests of the "Strong Equivalence Principle" (SEP). This principle has many of the essential features of EEP, except that it also incorporates the effects of local gravitational interactions. For example, for SEP to be valid, "test" bodies, bodies that are small compared to inhomogeneities in external gravitational fields, yet that themselves contain significant self-gravitational binding energy, must fall with the same acceleration (WEP). In addition, local gravitational experiments (such as Cavendish experiments), should show no preferred-location or preferred-frame effects (see Figure 4 and compare Figure 1). Although it is impossible to go beyond this to formulate a precise statement of SEP in parallel with that of EEP, it can be argued, at least heuristically, that SEP implies the presence of only one gravitational field, namely the physical metric. Some authors have gone further to argue, using primarily the techniques of field theory, that this implies general relativity uniquely.  

The "gravitational WEP" has been verified to one part in $10^{-5}$ by the lunar laser ranging experiment (the possibility of a violation of WEP here is called the "Nordtvedt effect"), setting a limit on a combination of PPN parameters shown in Figure 4. Geophysical measurements have set limits on preferred-frame and preferred-location effects in the local gravitational constant, and a variety of measurements have limited cosmic variations in the gravitational constant to a factor around unity in one Hubble time.
These experiments serve to limit the "theory space" available to alternative theories of gravity. To illustrate this, we take three of the five PPN parameters, \( \gamma^{-1} \), \( \beta^{-1} \), and \( \alpha_2 \), and define a three-dimensional part of "theory space"; Figure 5 then demonstrates the available region in this space as limited by the results of time-delay, perihelion-shift, laser-ranging, and geophysical experiments. One conclusion that is apparent from Figure 5 is that the Brans–Dicke theory must be constrained to have its coupling constant \( \omega \geq 200 \). In the limit \( \omega \to \infty \), this theory becomes indistinguishable from general relativity in all its predictions. On the other hand, the Rosen bimetric
theory can have $\alpha_2 \sim 0$, thereby satisfying the experimental constraints, yet remain a completely distinct theory from general relativity (as we shall see below). Many other theories have this property (see Table 2).

Because of this, one must look for new arenas for testing relativistic gravity, arenas that may involve astrophysical systems far outside the solar system. At this point, it becomes useful to adopt a slightly different attitude toward the significance of observational data from such systems. In the solar system, the physics that underlies most experiments is extremely well understood, so the observational data can be used to perform "clean" tests of gravitational effects, whose results can be viewed as squeezing available theory space, as in Figure 5. However, when complex astrophysical systems such as the binary pulsar are used as gravitational testing grounds, one can no longer be so certain about the underlying physics. In such cases, a better approach to the confrontation between theory and observation may be to assume that an individual theory is correct, then use the observations to make statements about the possible compatible physics underlying the system. The viability of a gravitation theory would be called into question if the resulting "available physics space" were squeezed into untenable, unreasonable, or *ad hoc* positions. Such a method will be most powerful for theories, primarily those with "prior geometry" (see Table 2), that make qualitatively different predictions in such systems. We shall see this procedure in operation when general relativity and the bimetric theory are confronted with the new data from the binary pulsar.

### New Arenas for Testing General Relativity

**Gravitational Radiation**

One new arena for testing relativistic gravity that involves gravitational effects in sources outside the solar system is gravitational radiation. Once gravitational waves (GW) have been detected and studied by laboratory GW telescopes, one can imagine a number of possible tests of gravitation theory. General relativity predicts that an arbitrary GW possesses only two states of polarization, while essentially all other metric theories predict more than two (up to six). Measurements of the number of polarization states in observed radiation could test some theories. A further test could be provided by comparisons of the arrival times of GW and electromagnetic pulses from an event such as a supernova. The two waves propagate with the same speed, according to general relativity, and so should arrive simultaneously. In many other theories, the speeds are different. Another aspect of gravitational radiation, the multipolarity of the waves and the amount of radiation damping, will be discussed when we deal with the binary pulsar.

**Cosmology**

Cosmological observations may provide tests of some gravitation theories, but because of uncertainties in our quantitative knowledge of the detailed physics of the early universe and its subsequent evolution, we must adopt the philosophy of "squeezing physics space" in order to make progress. For instance, some cosmological
models in the Rosen bimetric theory predict a low-density “bounce” of the universe in the past, and so must invent new mechanisms to explain the cosmic helium abundance and the existence and isotropy of the 3-K microwave background radiation.10

The Binary Pulsar

The most exciting new extra-solar-system gravitational testing ground is the binary pulsar. Discovered in the summer of 1974 by Hulse and Taylor,11 it is a pulsar of nominal pulse period 59 ms in a close binary system with an as yet unseen companion. From detailed analyses of the arrival times of pulses (see the paper by Taylor, Fowler, and McCulloch in this volume), extremely accurate orbital parameters have been obtained (see TABLE 3). Because the orbit is so close (~1 R⊙) and because there is no evidence of an eclipse of the pulsar signal or of mass transfer from the companion, it is generally believed that the companion is compact: a white dwarf, a neutron star, or a black hole. Thus the orbital motion is thought to be relatively “clean.” Furthermore, the data acquisition is also “clean” in the sense that the observers can keep track of the pulsar phase with an accuracy of 50 µs, despite gaps of up to six months between observing sessions. The pulsar has shown no evidence of “glitches” in its pulse period.

Three factors make this system a promising testing ground for relativity: the relatively large size of relativistic effects (v_{orb}/c ~ 10^{-3}); the short orbital period (8 hours), allowing secular effects to build up rapidly; and the cleanliness of the system (see reference 2 for review and references). However, there are still some uncertainties in the underlying physics, primarily involving the nature of the companion, that force us to adopt the philosophy of “squeezing physics space.” We shall assume in turn that particular gravitation theories are correct, then shall ask whether the available physical configurations consistent with the data are physically reasonable or natural, or whether ad hoc assumptions or models must be made. In this sense, the relativistic theory of gravity is being used as a tool for measuring astrophysical parameters, a new role for general relativity (or its competitors).

There are four basic pieces of data on the binary pulsar that we shall use for this purpose: the mass function f_o, the periastron shift ω, the redshift-Doppler parameter γ_{RD}, and the rate of change of the orbit period P_o. Given a relativistic theory of gravity, these can be expressed in terms of physical parameters of the system, such as the masses of the pulsar m_1 and companion m_2, and the inclination angle i of the orbit relative to the plane of the sky.

Now, in theories of gravity that violate SEP (e.g., the Rosen bimetric theory), the strong self-gravitational fields of the neutron star (that presumably is the pulsar) and possibly of the companion, if it is a neutron star or a black hole, cause the masses that determine the dynamics of the system to be renormalized.12 For example, if m_1 and m_2 are the masses of the bodies as measured by Keplerian test-body orbits far from them, then the Newtonian limit of their mutual orbital equations of motion is given by

\[
\frac{dv}{dt} = -\frac{\mathcal{G}m_1m_2x}{r^3}.
\]  

(4)

‡ We use units in which the local gravitational constant far from gravitating matter and the speed of light are unity.
where $\mathcal{G}$ is a function of the self-gravitational binding energies per unit mass, denoted $s_1$ and $s_2$, of the bodies. In general relativity, $\mathcal{G} = 1$, while in the Rosen bimetric theory, $\mathcal{G} = 1 - \frac{1}{3} s_1 s_2$. Such an effect could be regarded as a renormalization of the effective gravitational constant by the presence of the highly relativistic bodies (violation of SEP). In such a case, the measured orbital period $P_b$ is related to the total mass $m = m_1 + m_2$ and the semimajor axis $a$ by $(P_b/2\pi) = (a^3/\mathcal{G} m)^{1/2}$. A consequence of this is that the mass function $f_i$ is related to $m_1$, $m_2$, and $\sin i$ by

$$f_i = \mathcal{G} (m_2 \sin i)^3/m^2.$$  

(5)

A similar effect occurs in the periastron shift. Even though a given theory may predict the same periastron shift as general relativity in the strict weak-field post-Newtonian limit, (as does the bimetric theory) the presence of strong fields in the pulsar can cause a renormalization of the predicted shift. The periastron shift per orbit, $\Delta \omega$, can be written most conveniently in the form $\Delta \omega = \mathcal{P} \mathcal{G}^{-1}(6\pi m/a(1-e^2))$, where $\mathcal{P}$ is also a function of $s_1$ and $s_2$. In general relativity $\mathcal{P} = 1$, while in the Rosen bimetric theory, $\mathcal{P}$ can be as small as 0.3, depending upon the mass and structure of the pulsar and its companion. When the known eccentricity and orbital period of the system are used, the rate of periastron advance becomes

$$\dot{\omega} = 2.10 \mathcal{P} \mathcal{G}^{-4/3} (m/m_o)^{2/3} \text{deg yr}^{-1}.$$  

(6)

Unfortunately, here, as in the case of Mercury’s perihelion shift, there may be complications. If the companion is a rapidly rotating white dwarf, centrifugal flattening could produce a quadrupole moment $(J_2)$ and make an additional contribution to the periastron shift. If the companion is a neutron star or a black hole, no such effects occur.

The parameter $\gamma_{RD}$, which measures the effect on the pulse arrival times of the gravitational redshift due to the companion’s gravitational potential and of the second-order doppler shift due to the pulsar’s orbital motion, is also affected by renormalizations, namely

$$\gamma_{RD} = 2.93 (m_2/m_o)^{2/3} (m_2/\mathcal{G} m)^{1/3} (1 + \mathcal{G} m_2/m) \text{ms}.$$  

(7)

Finally, the possibility of a secular change in the orbit period $P_b$ has an immediate interpretation in terms of gravitational radiation damping. According to the “quadrupole” formula of general relativity, radiation damping should cause the orbit energy, and thereby the period of the orbit, to decrease according to

$$\dot{P}_b/P_b = -1.9 \times 10^{-9} (m_1 m_2/m_o^2) (m/m_o)^{-1/3}.$$  

(8)

However, in most (if not all) alternative theories, dipole gravitational radiation can also exist, generated by the varying dipole moment of the gravitational binding energy of the two bodies. The result, in the bimetric theory, is an orbit period increase, given by

$$\left(\dot{P}_b/P_b\right)_{\text{dipole}} = 2.1 \times 10^{-4} (m_1 m_2/m m_o) (s_1 - s_2)^2 \text{yr}^{-1}.$$  

(9)

The measured values for these quantities as announced by Taylor at this Texas symposium are shown in TABLE 3. The constraints that these values place (via Equations 5–9) on the system are most conveniently displayed on a plot of $m_1$ versus $m_2$. In general relativity, the results are shown in FIGURE 6. One constraint is provided.
TABLE 3
PARAMETERS OF THE BINARY PULSAR*

| Parameter                                      | Value                                                                 |
|-----------------------------------------------|-----------------------------------------------------------------------|
| Pulse period                                  | $P = 0.059029995269 \pm 2$ s                                          |
| Derivative of period                          | $\dot{P} = (8.64 \pm 0.02) \times 10^{-12}$ s$^{-1}$                 |
| Projected semimajor axis                     | $a_1 \sin i = 2.3424 \pm 0.0007$ light s                              |
| Orbital eccentricity                         | $e = 0.617155 \pm 0.000007$                                          |
| Binary orbit period                          | $P_b = 27906.98172 \pm 0.00005$ s                                    |
| Mass function                                | $f_1 = 0.13227 \pm 0.00004 m_\odot$                                   |
| Periastron shift                              | $\omega = 4.226 \pm 0.002$ deg yr$^{-1}$                              |
| Redshift-Doppler                             | $\gamma_{RD} = 0.0047 \pm 0.0007$ s                                  |
| Derivative of orbit period                    | $P_{b'} = (-3.2 \pm 0.6) \times 10^{-12}$ s$^{-1}$                    |

*After reference 14.

**Figure 6.** The $m_1-m_2$ plane in general relativity. The shaded region fits all the formal observational constraints, however, the point marked “a” is the most likely configuration, with $m_1 = 1.39 \pm 0.15 m_\odot$, $m_2 = 1.44 \pm 0.15 m_\odot$. (After reference 14.)
by the mass function \( f \) and by the fact that \( \sin i < 1 \). The periastron shift constrains
the system to lie along the straight line BH–NS–WD, if the companion is a black hole,
neutron star, or nonrotating white dwarf. However, if the companion is a rapidly
(uniformly (U) or differentially (D)) rotating white dwarf, the system could lie in the
regions denoted U and D. The constraints set by \( \gamma_{RD} \) and by \( \dot{P}_b/P_b \) then leave the
shaded region available. The deviation (~1.2 \( \sigma \) of the \( \dot{P}_b \) data) between the shaded
region and the BH–NS–WD line cannot be called significant at present, and so a
natural interpretation of the system is that of a pulsar of mass \( m_1 = 1.39 \pm 0.15 \) m
and a companion of mass \( m_2 = 1.44 \pm 0.15 \) m (point "a" of FIGURE 6). There are two
possible (though unlikely) additional contributions to \( \dot{P}_b/P_b \). If the companion is a
rotating white dwarf, and if a strong source of viscosity such as magnetism or
turbulence is present in its atmosphere, then tidal dissipation of orbital energy could
account for some \( \dot{P}_b \). However, if the white dwarf rotates too rapidly, the effect can
cause \( \dot{P}_b \) to increase. Another possible source of \( \dot{P}_b \) is a distant third body that gives the
binary system an acceleration. Such an acceleration will lead to both \( \dot{P} \) and \( \ddot{P} \) for both
the orbital and pulsar periods. A measurement of an upper limit on the second time
derivative of the pulse period, \( \ddot{P}_b \), could rule out such a possibility by setting a lower
limit on the mass of the third body given by
\[
m_3 \geq 60 m (\delta/10^{-9} \text{ yr}^{-1})^2 (\eta/10^{-13} \text{ yr}^{-2})^{-1}.
\]
where \( \delta \) is the amount of \( \dot{P}_b/P_b \) that the third body is assumed to produce, and \( \eta \) is the
upper limit on \( \dot{P}_b/P_b \) for the pulsar.

Thus, barring these remote possibilities, general relativity leads to a natural
physical configuration for the system, and the results support the conclusion that the
measurement of \( \dot{P}_b \) represents the first observation of the effects of gravitational
radiation.

In the Rosen bimetric theory, on the other hand, the situation is very different. The
self-gravitational renormalizations of masses (factors of ~2–3) lead to qualitative
differences in the \( m_1–m_2 \) plane, FIGURE 7. For example, the companion cannot be a
nonrotating white dwarf, since such a configuration would violate the condition \( \sin i < 1 \).
If the companion is a neutron star, the system lies along the curve "NS", with total
mass ~7 m. Black holes do not exist in this theory. When the \( \gamma_{RD} \) constraint§ is folded
in, the theory is left with a major problem. Dipole gravitational radiation causes the
system to gain energy and the period to increase at rates shown in FIGURE 7. The
theory then must produce a mechanism (tidal dissipation or a third body) to account
for the observed period decrease. The contrived and ad hoc nature of such mechanisms
casts serious doubt upon the viability of this theory.

This result may, in fact, apply to many other theories, particularly those with
"prior geometry" (see TABLE 2). In such theories, SEP is violated, and the differences
between the theories and general relativity become larger the stronger the gravita-
tional fields. Thus one can expect qualitative mass renormalizations similar to those in
the bimetric theory. Furthermore, all such theories are expected to predict dipole
gravitational radiation of magnitude comparable to that in the bimetric theory. So it is

§There is an additional SEP-violating effect that modifies the dependence of \( \gamma_{RD} \) slightly. If
the local gravitational constant felt by the pulsar depends on the proximity of the companion,
the pulsar's structure, moment of inertia, and rotation rate may vary with the orbital motion. This
produces an effect of identical signature to the redshift-Doppler effects. In the Rosen bimetric
theory, the result is a 20% modification of the effective value of \( \gamma_{RD} \); this does not alter our
general conclusions.
very likely that the binary pulsar data will be able to rule out a broad class of alternative gravitation theories.

On the other hand, the class of "purely dynamical" theories has the property that the effects of the additional gravitational fields can be made as small as one chooses, both in weak field and in strong field or gravitational radiation situations, by choosing sufficiently weak coupling constants ($\omega^{-1} \rightarrow 0$ in Brans–Dicke, for instance). Thus, Brans–Dicke theory, with $\omega \gtrsim 200$, is consistent with the present binary pulsar data, even though it, too, predicts dipole gravitational radiation. Thus the binary pulsar can yield do-or-die tests of a wide range of gravitation theories, and can help put severe constraints on others.
CONCLUSIONS

Shortly after Eddington reported the successful measurement of the deflection of starlight by the Sun, Einstein was asked what would have happened if Eddington had gotten a different value for the deflection than that predicted by general relativity. Einstein is reputed to have replied, “Well, it would be too bad for God.” As we begin 1979, the year of the centenary of Einstein’s birth, it is clear that both God and Einstein are “hanging in.” But with new discoveries such as the binary pulsar, it is also clear that the confrontation between gravitation theory and experiment will continue to be an exciting challenge for some time.

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REFERENCES

1. HAUGAN, M. P. 1979. Energy conservation and the principle of equivalence. Ann. Phys. (N.Y.) 118: 156–186.
2. WILL, C. M. 1979. In General Relativity: An Einstein Centenary Survey. S. W. Hawking & W. Israel, Eds. Cambridge University Press. Cambridge.
3. SHLYAKHTER, A. I. 1976. Nature (London) 264: 340.
4. WILL, C. M. 1974. In Experimental Gravitation. B. Bertotti, Ed.: 1–110. Academic Press. New York.
5. FOMALONT, E. B. & R. A. SRAMEK. 1977. Comm. Astrophys. 7: 19–33.
6. SHAPIRO, I. I., R. D. REASENBERG, P. E. MACNEIL, R. B. GOLDBERG, J. P. BRENDLE, D. L. CAIN, T. KOMAREK, A. I. ZYGIELBAUM, W. F. CUDDY & W. H. MICHAEL, JR. 1977. J. Geophys. Res. 82: 4329–4334.
7. CAIN, D. L., J. D. ANDERSON, M. S. W. KEESEY, T. KOMAREK, P. A. LAING & E. L. LAU. 1978. Bull. Am. Astron. Soc. 10: 396.
8. WEINBERG, S. 1972. General Relativity and Cosmology: 171. Wiley. New York.
9. EARDLEY, D. M., D. L. LEE & A. P. LIGHTMAN. 1973. Phys. Rev. D 10: 3308–3321.
10. CAVES, C. M. 1977. In Proceedings of the 8th International Conference on General Relativity and Gravitation: 104. Preprint.
11. HULSE, R. A. & J. H. TAYLOR. 1975. Astrophys. J. Lett. 195: 51–53.
12. WILL, C. M. & D. M. EARDLEY. 1977. Astrophys. J. Lett. 212: 91–94.
13. WAGONER, R. V. 1975. Astrophys. J. Lett. 196: 63–65.
14. TAYLOR, J. H., L. A. FOWLER & P. M. McCulloch. 1979. Nature 227: 437–440.
15. EARDLEY, D. M. 1975. Astrophys. J. Lett. 196: 59–62.