Theory and experiment in gravitational physics

CLIFFORD M. WILL

Department of Physics, Washington University, St. Louis

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To Leslie

Preface

For over half a century, the general theory of relativity has stood as a monument to the genius of Albert Einstein. It has altered forever our view of the nature of space and time, and has forced us to grapple with the question of the birth and fate of the universe. Yet, despite its subsequently great influence on scientific thought, general relativity was supported initially by very meager observational evidence. It has only been in the last two decades that a technological revolution has brought about a confrontation between general relativity and experiment at unprecedented levels of accuracy. It is not unusual to attain precise measurements within a fraction of a percent (and better) of the minuscule effects predicted by general relativity for the solar system.

To keep pace with these technological advances, gravitation theorists have developed a variety of mathematical tools to analyze the new high-precision results, and to develop new suggestions for future experiments made possible by further technological advances. The same tools are used to compare and contrast general relativity with its many competing theories of gravitation, to classify gravitational theories, and to understand the physical and observable consequences of such theories.

The first such mathematical tool to be thoroughly developed was a "theory of metric theories of gravity" known as the Parametrized Post-Newtonian (PPN) formalism, which was suited ideally to analyzing solar system tests of gravitational theories. In a series of lectures delivered in 1972 at the International School of Physics "Enrico Fermi" (Will, 1974, referred to as TTEG), I gave a detailed exposition of the PPN formalism. However, since 1972, significant progress has been made, on both the experimental and theoretical sides. The PPN formalism has been refined, and new formalisms have been developed to deal with other aspects of gravity, such as nonmetric theories of gravity, gravitational radiation, and the motion of condensed objects. A recent review article (Will, 1979) summarizes the principal results of these new developments, but gives none of the physical or mathematical details. Since 1972, there has been a need for a complete treatment of techniques for analyzing gravitation theory and experiment.

To fill this need I have designed this study. It analyzes in detail gravitational theories, the theoretical formalisms developed to study them, and the contact between these theories and experiments. I have made no attempt to analyze *every* theory of gravity or calculate *every* possible effect; instead I have tried to present systematically the *methods* for performing such calculations together with relevant examples. I hope such a presentation will make this book useful as a working tool for researchers both in general relativity and in experimental gravitation. It is written at a level suitable for use as either a reference text in a standard graduate-level course on general relativity or, possibly, as a main text in a more specialized course. Not the least of my motivations for writing such a book is the fact that it was my "centennial project" for 1979 – the 100th anniversary of Einstein's birth.

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Introduction

On September 14, 1959, 12 days after passing through her point of closest approach to the Earth, the planet Venus was bombarded by pulses of radio waves sent from Earth. Anxious scientists at Lincoln Laboratories in Massachusetts waited to detect the echo of the reflected waves. To their initial disappointment, neither the data from this day, nor from any of the days during that month-long observation, showed any detectable echo near inferior conjunction of Venus. However, a later, improved reanalysis of the data showed a bona fide echo in the data from one day: September 14. Thus occurred the first recorded radar echo from a planet.

On March 9, 1960, the editorial office of *Physical Review Letters* received a paper by R. V. Pound and G. A. Rebka, Jr., entitled "Apparent Weight of Photons." The paper reported the first successful laboratory measurement of the gravitational red shift of light. The paper was accepted and published in the April 1 issue.

In June, 1960, there appeared in volume 10 of the *Annals of Physics* a paper on "A Spinor Approach to General Relativity" by Roger Penrose. It outlined a streamlined calculus for general relativity based upon "spinors" rather than upon tensors.

Later that summer, Carl H. Brans, a young Princeton graduate student working with Robert H. Dicke, began putting the finishing touches on his Ph.D. thesis, entitled "Mach's Principle and a Varying Gravitational Constant." Part of that thesis was devoted to the development of a "scalar–tensor" alternative to the general theory of relativity. Although its authors never referred to it this way, it came to be known as the Brans–Dicke theory.

On September 26, 1960, just over a year after the recorded Venus radar echo, astronomers Thomas Matthews and Allan Sandage and co-workers at Mount Palomar used the 200-in. telescope to make a photographic plate of the star field around the location of the radio source 3C48. Although they expected to find a cluster of galaxies, what they saw at the precise location of the radio source was an object that had a decidedly stellar appearance, an unusual spectrum, and a luminosity that varied on a timescale as short as 15 min. The name quasistellar radio source or "quasar" was soon applied to this object and to others like it.

These disparate and seemingly unrelated events of the academic year 1959–60, in fields ranging from experimental physics to abstract theory to astronomy, signaled a new era for general relativity. This era was to be one in which general relativity not only would become an important theoretical tool of the astrophysicist, but would have its validity challenged as never before. Yet it was also to be a time in which experimental tools would become available to test the theory in unheard-of ways and to unheard-of levels of precision.

The optical identification of 3C48 (Matthews and Sandage, 1963) and the subsequent discovery of the large red shifts in its spectral lines and in those of 3C273 (Schmidt, 1963; Greenstein and Matthews, 1963), presented theorists with the problem of understanding the enormous outpourings of energy (10^{47} erg s^{-1}) from a region of space compact enough to permit the luminosity to vary systematically over timescales as short as days or hours. Many theorists turned to general relativity and to the strong relativistic gravitational fields it predicts, to provide the mechanism underlying such violent events. This was the first use of the theory's strong-field aspect (outside of cosmology), in an attempt to interpret and understand observations. The subsequent discovery of pulsars and the possible identification of black holes showed that it would not be the last. However, the use of relativistic gravitation in astrophysical model building forced theorists and experimentalists to address the question: Is general relativity the correct relativistic theory of gravitation? It would be difficult to place much confidence in models for such phenomena as quasars and pulsars if there were serious doubt about one of the basic underlying physical theories. Thus, the growth of "relativistic astrophysics" intensified the need to strengthen the empirical evidence for or against general relativity.

The publication of Penrose's spinor approach to general relativity (Penrose, 1960) was one of the products of a new school of relativity theorists that came to the fore in the late 1950s. These relativists applied the elegant, abstract techniques of pure mathematics to physical problems in general relativity, and demonstrated that these techniques could also aid in the work of their more astrophysically oriented colleagues. The bridging of the gaps between mathematics and physics and mathematics and astrophysics by such workers as Bondi, Dicke, Sciama, Pirani, Penrose, Sachs, Ehlers, Misner, and others changed the way that research (and teaching) in relativity was carried out, and helped make it an active and exciting field of physics. Yet again the question had to be addressed: Is general relativity the correct basis for this research?

The other three events of 1959–60 contributed to the rebirth of a program to answer that question, a program of experimental gravitation that had been semidormant for 40 years.

The Pound–Rebka (1960) experiment, besides verifying the principle of equivalence and the gravitational red shift, demonstrated the powerful use of quantum technology in gravitational experiments of high precision. The next two decades would see further uses of quantum technology in such high-precision tools as atomic clocks, laser ranging, superconducting gravimeters, and gravitational-wave detectors, to name only a few.

Recording radar echos from Venus (Smith, 1963) opened up the solar system as a laboratory for testing relativistic gravity. The rapid development during the early 1960s of the interplanetary space program made radar ranging to both planets and artificial satellites a vital new tool for probing relativistic gravitational effects. Coupled with the theoretical discovery in 1964 of the relativistic time-delay effect (Shapiro, 1964), it provided new and accurate tests of general relativity. For the next decade and a half, until the summer of 1974, the solar system would be the sole arena for high-precision tests of general relativity.

Finally, the development of the Brans–Dicke (1961) theory provided a viable alternative to general relativity. Its very existence and agreement with experimental results demonstrated that general relativity was not a unique theory of gravity. Many even preferred it over general relativity on aesthetic and theoretical grounds. At the very least, it showed that discussions of experimental tests of relativistic gravitational effects should be carried on using a broader theoretical framework than that provided by general relativity alone. It also heightened the need for high-precision experiments because it showed that the mere *detection* of a small general relativistic effect was not enough. What was now required was measurements of these effects to accuracy within 10%, 1%, or fractions of a percent and better, to distinguish between competing theories of gravitation.

To appreciate more fully the regenerative effect that these events had on gravitational theory and its experimental tests, it is useful to review briefly the history of experimental gravitation in the 45 years following the publication of the general theory of relativity.

In deriving general relativity, Einstein was not particularly motivated by a desire to account for unexplained experimental or observational results. Instead, he was driven by theoretical criteria of elegance and simplicity. His primary goal was to produce a gravitation theory that incorporated the principle of equivalence and special relativity in a natural way. In the end, however, he had to confront the theory with experiment. This confrontation was based on what came to be known as the "three classical tests."

One of these tests was an immediate success – the ability of the theory to account for the anomalous perihelion shift of Mercury. This had been an unsolved problem in celestial mechanics for over half a century, since the discovery by Leverrier in 1845 that, after the perturbing effects of the planets on Mercury's orbit had been accounted for, and after the effect of the precession of the equinoxes on the astronomical coordinate system had been subtracted, there remained in the data an unexplained advance in the perihelion of Mercury. The modern value for this discrepancy is 43 arc seconds per century (Table 1.1). A number of ad hoc proposals were made in an attempt to account for this excess, including, among others, the existence of a new planet, Vulcan, near the Sun; a ring of planetoids; a solar quadrupole moment; and a deviation from the inverse-square law of gravitation (for a review, see Chazy, 1928). Although these proposals could account for the perihelion advance of Mercury, they either involved objects that were detectable by direct optical observation, or predicted perturbations on the other planets (for example, regressions of nodes, changes in orbital inclinations) that were inconsistent with observations. Thus, they were doomed to failure. General relativity accounted

Table 1.1. *Perihelion advance of Mercury*

Cause of advance	Rate (arc s/century)
General precession (epoch 1900)	5025″.6
Venus	277″.8
Earth	90″.0
Mars	2″.5
Jupiter	153″.6
Saturn	7″.3
Others	0″.2
Sum	5557″.0
Observed Advance	5599″.7
Discrepancy	42″.7

for the anomalous shift in a natural way without disturbing the agreement with other planetary observations. This result would go unchallenged until 1967.

The next classical test, the deflection of light by the Sun, was not only a success, it was a sensation. Shortly after the end of World War I, two expeditions set out from England: one for Sobral, in Brazil; and one for the island of Principe off the coast of Africa. Their goal was to measure the deflection of light as predicted by general relativity – 1.75 arc seconds for a ray that grazes the Sun. The observations had to be made in the path of totality of a solar eclipse, during which the Moon would block the light from the Sun and reveal the field of stars behind it. Photographic plates taken of the star field during the eclipse were compared with plates of the same field taken when the Sun was not present, and the angular displacement of each star was determined. The results were 1.13 ± 0.07 times the Einstein prediction for the Sobral expedition, and 0.92 ± 0.17 for the Principe expedition (Dyson et al., 1920). The announcement of these results confirming the theory caught the attention of a war-weary public and helped make Einstein a celebrity. But Einstein was so convinced of the "correctness" of the theory because of its elegance and internal consistency that he is said to have remarked that he would have felt sorry for the Almighty if the results had disagreed with the theory (see Bernstein, 1973). Nevertheless, the experiments were plagued by possible systematic errors, and subsequent independent analyses of the Sobral plates yielded values ranging from 1.0 to 1.3 times the general relativity value. Later eclipse expeditions made very little improvement (Table 1.2). The main sources of error in such optical deflection experiments are unknown scale changes between eclipse and comparison photographic plates, and the precarious conditions, primarily associated with bad weather and exotic locales, under which such expeditions are carried out. By 1960, the best that could be said about the deflection of light was that it was definitely more than $0''.83$, or half the Einstein value. This was the amount predicted from a simple Newtonian argument, by Soldner in 1801 (Lenard, 1921),[1] or from an extension of the principle of equivalence, by Einstein (1911). Beyond that, "the subject [was] still a live one" (Bertotti et al., 1962).

The third classical test was actually the first proposed by Einstein (1907): the gravitational red shift of light. But by contrast with the other two

[1] In 1921, the physicist Philipp Lenard, an avowed Nazi, reprinted Soldner's paper in the *Annalen der Physik* in an effort to discredit Einstein's "Jewish" science by showing the precedence of Soldner's "Aryan" work.

tests, there was no reliable confirmation of it until the 1960 Pound–Rebka experiment. One possible test was a measurement of the red shift of spectral lines from the Sun. However, 30 years of such measurements revealed that the observed shifts in solar spectral lines are affected strongly by Doppler shifts due to radial mass motions in the solar photosphere. For example, the frequency shift was observed to vary between the center of the Sun and the limb, and to depend on the line strength. For the gravitational red shift the results were inconclusive, and it would be 1962 before a reliable solar red-shift measurement would be made. Similarly inconclusive were attempts to measure the gravitational red shift of spectral lines from white dwarfs, primarily from Sirius B and 40 Eridani B, both members of binary systems. Because of uncertainties in the determination of the masses and radii of these stars, and because of possible complications in their spectra due to scattered light from their companions, reliable, precise measurements were not possible [see Bertotti et al. (1962) for a review].

Furthermore, by the late 1950s, it was being suggested that the gravitational red shift was not a true test of general relativity after all. According to Leonard I. Schiff and Robert H. Dicke, the gravitational red shift was a consequence purely of the principle of equivalence, and did not test the field equations of gravitational theory. Schiff took the argument one step

Table 1.2. *Optical measurements of light deflection by the Sun*[a]

Eclipse	Approximate number of stars	Minimum distance from center of Sun in solar radii	Result in units of Einstein prediction	Results from different analyses
1919	7	2	1.13 ± 0.07	1.0 to 1.3
1919	5	2	0.92 ± 0.17	
1922	92	2.1	0.98 ± 0.06	1.3 to 0.9
1922	145	2.1	1.04 ± 0.09	1.2
1922	14	2	0.7 to 1.3	
1922	18	2	0.8 to 1.2	
1929	17	1.5	1.28 ± 0.06	0.9 to 1.2
1936	25	2	1.55 ± 0.15	1.55 ± 0.2
1936	8	4	0.7 to 1.2	
1947	51	3.3	1.15 ± 0.15	1.0 to 1.4
1952	10	2.1	0.97 ± 0.06	0.82 ± 0.09
1973[b]	39	2	0.95 ± 0.11	

[a] See Bertotti et al. (1962) for details.
[b] Texas Mauritanian Eclipse Team (1973), Jones (1973).

further and suggested that the gravitational red-shift experiment was superseded in importance by the more accurate Eötvös experiment, which verified that bodies of different composition fall with the same acceleration (Schiff, 1960a; Dicke, 1960).

Other potential tests of general relativity were proposed, such as the Lense–Thirring effect, an orbital perturbation due to the rotation of a body, and the de Sitter effect, a secular motion of the perigee and node of the lunar orbit (Lense and Thirring, 1918; de Sitter, 1916), but the prospects for ever detecting them were dim.

Cosmology was the other area where general relativity could be confronted with observation. Initially the theory met with success in its ability to account for the observed expansion of the universe, yet by the 1940s there was considerable doubt about its applicability. According to pure general relativity, the expansion of the universe originated in a dense primordial explosion called the "big bang." The age of the universe since the big bang could be determined by extrapolating the expansion of the universe backward in time using the field equations of general relativity. However, the observed values of the present expansion rate were so high that the inferred age of the universe was shorter than that of the Earth. One result of this doubt was the rise in popularity during the 1950s of the steady-state cosmology of Herman Bondi, Thomas Gold, and Fred Hoyle. This model avoided the big bang altogether, and allowed for the expansion of the universe by the continuous creation of matter. By this means, the universe would present the same appearance to all observers for all time.

But by the late 1950s, revisions in the cosmic distance scale had reduced the expansion rate by a factor of five, and had thereby increased the age of the universe in the big bang model to a more acceptable level. Nevertheless, cosmological observations were still in no position to distinguish among different theories of gravitation or of cosmology [for a detailed technical and historical review, see Weinberg (1972), Chapter 14].

Meanwhile, a small "cottage industry" had sprung up, devoted to the construction of alternative theories of gravitation. Some of these theories were produced by such luminaries as Poincaré, Whitehead, Milne, Birkhoff, and Belinfante. Many of these authors expressed an uneasiness with the notions of general covariance and curved spacetime, which were built into general relativity, and responded by producing "special relativistic" theories of gravitation. These theories considered spacetime to be "special relativistic" at least at a background level, and treated gravitation as a Lorentz-invariant field on that background. As of 1960, it was possible to enumerate at least 25 such alternative theories, as found in the primary research literature between 1905 and 1960 [for a partial list, see Whitrow and Morduch (1965)].

Thus, by 1960, it could be argued that the validity of general relativity rested on the following empirical foundation: one test of moderate precision (the perihelion shift, approximately 1%), one test of low precision (the deflection of light, approximately 50%), one inconclusive test that was not a real test anyway (the gravitational red shift), and cosmological observations that could not distinguish between general relativity and the steady-state theory. Furthermore, a variety of alternative theories laid claim to viability.

In addition, the attitude toward the theory seemed to be that, whereas it was undoubtedly of importance as a fundamental theory of nature, its observational contacts were limited to the classical tests and cosmology. This view was present for example in the standard textbooks on general relativity of this period, such as those by Møller (1952), Synge (1960), and Landau and Lifshitz (1962). As a consequence, general relativity was cut off from the mainstream of physics. It was during this period that one young, beginning graduate student was advised not to enter this field, because general relativity "had so little connection with the rest of physics and astronomy" (his name: Kip S. Thorne).

However, the events of 1959–60 changed all that. The pace of research in general relativity and relativistic astrophysics began to quicken and, associated with this renewed effort, the systematic high-precision testing of gravitational theory became an active and challenging field, with many new experimental and theoretical possibilities. These included new versions of old tests, such as the gravitational red shift and deflection of light, with accuracies that were unthinkable before 1960. They also included brand new tests of gravitational theory, such as the gyroscope precession, the time delay of light, and the "Nordtvedt effect" in lunar motion, that were discovered theoretically after 1959. Table 1.3 presents a chronology of some of the significant theoretical and experimental events that occurred in the two decades following 1959. In many ways, the years 1960–1980 were the decades for testing relativity.

Because many of the experiments involved the resources of programs for interplanetary space exploration and observational astronomy, their cost in terms of money and manpower was high and their dependence upon increasingly constrained government funding agencies was strong. Thus, it became crucial to have as good a *theoretical* framework as possible for comparing the relative merits of various experiments, and for pro-

Table 1.3. *A chronology: 1960–80*

Time	Experimental or observational events	Theoretical events
1960	Hughes–Drever mass-anisotropy experiments	Penrose paper on spinors
		Gyroscope precession (Schiff)
	Pound–Rebka gravitational red-shift experiment	Brans–Dicke theory
1962	Discovery of nonsolar x-ray sources	Bondi mass-loss formula
	Discovery of quasar red shifts	Kerr metric discovery
	Princeton Eötvös experiment	
1964		Time-delay of light (Shapiro)
	Pound–Snider red-shift experiment	
	Discovery of 3K microwave background	Singularity theorems in general relativity
1966		
	Reported detection of solar oblateness	Element production in the big bang
	Discovery of pulsars	
1968	Planetary radar measurement of time delay	Nordtvedt effect and early PPN framework
	Launch of *Mariners 6* and *7*	
	Acquisition of lunar laser echo	
	First radio deflection measurements	
1970		
		Preferred-frame effects
	CygX1: a black hole candidate	Refined PPN framework
	Mariners 6 and *7* time-delay measurements	Area increase of black holes in general relativity
1972	Moscow Eötvös experiment	
1974		Quantum evaporation of black holes
	Discovery of binary pulsar	
		Dipole gravitational radiation in alternative theories
1976	Rocket gravitational red-shift experiment	
	Lunar test of Nordtvedt effect	
	Time delay results from *Mariner 9* and *Viking*	
1978	Measurement of orbit period decrease in binary pulsar	
	SS 433	
1980	Discovery of gravitational lens	

posing new ones that might have been overlooked. Another reason that such a theoretical framework was necessary was to make some sense of the large (and still growing) number of alternative theories of gravitation. Such a framework could be used to classify theories, elucidate their similarities and differences, and compare their predictions with the results of experiments in a systematic way. It would have to be powerful enough to be used to design and assess experimental tests in detail, yet general enough not to be biased in favor of general relativity.

A leading exponent of this viewpoint was Robert Dicke (1964a). It led him and others to perform several high-precision null experiments which greatly strengthened our faith in the foundations of gravitation theory. Within this viewpoint one asks general questions about the nature of gravity and devises experiments to test them. The most important dividend of the Dicke framework is the understanding that gravitational experiments can be divided into two classes. The first consists of experiments that test the foundations of gravitation theory, one of these foundations being the principle of equivalence. These experiments (Eötvös experiment, Hughes–Drever experiment, gravitational red-shift experiment, and others, many performed by Dicke and his students) accurately verify that gravitation is a phenomenon of curved spacetime, that is, it must be described by a "metric theory" of gravity. General relativity and Brans–Dicke theory are examples of metric theories of gravity.

The second class of experiments consists of those that test metric theories of gravity. Here another theoretical framework was developed that takes up where the Dicke framework leaves off. Known as the "Parametrized Post-Newtonian" or PPN formalism, it was pioneered by Kenneth Nordtvedt, Jr. (1968b), and later extended and improved by Will (1971a), Will and Nordtvedt (1972), and Will (1973). The PPN framework takes the slow motion, weak field, or post-Newtonian limit of metric theories of gravity, and characterizes that limit by a set of 10 real-valued parameters. Each metric theory of gravity has particular values for the PPN parameters. The PPN framework was ideally suited to the analysis of solar system gravitational experiments, whose task then became one of measuring the values of the PPN parameters and thereby delineating which theory of gravity is correct. A second powerful use of the PPN framework was in the discovery and analysis of new tests of gravitation theory, examples being the Nordtvedt effect (Nordtvedt 1968a), preferred-frame effects (Will, 1971b) and preferred-location effects (Will, 1971b, 1973). The Nordtvedt effect, for instance, is a violation of the equality of acceleration of massive bodies, such as the Earth and Moon, in an