Testing the relativistic theories of gravity

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20.06.2019

Sfetcu, Nicolae, "Testing the relativistic theories of gravity", SetThings (20 iunie 2019), URL = https://www.setthings.com/en/testing-the-relativistic-theories-of-gravity/

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A partial translation of
Sfetcu, Nicolae, "Epistemologia gravitației experimentale – Raționalitatea științifică", SetThings (1 august 2019), MultiMedia Publishing (ed.), ISBN: 978-606-033-234-3, DOI: 10.13140/RG.2.2.15421.61925, URL = https://www.setthings.com/ro/e-books/epistemologia-gravitatiei-experimentale-rationalitatea-stiintifica/

Clifford M. Will describes, in *Theory and Experiment in Gravitational Physics*, [1] the emergence of a new era for general relativity, testing and checking at very high levels of accuracy.

In 1959, scientists at Lincoln Laboratories in Massachusetts bombarded the planet Venus with radio waves from Earth, hoping to detect the echo of reflected waves. They did not detect any echoes. On further analysis, they detected an echo on September 14, this being the first radar echo recorded on a planet.

In 1960, astronomers Thomas Matthews and Allan Sandage and colleagues at Mount Palomar used a telescope to record the star field around the 3C48 radio source on a photo plate. They were expecting to find a group of galaxies, but at the exact location of the radio source an object was observed as a star but with an unusual spectrum and variable brightness with the frequency of 15 minutes[2]. This was the first observed quasar. [3]

The Pound-Rebka experiment (1960) verified the principle of equivalence and gravity redshift and demonstrated the utility of quantum technology (atomic clocks, laser measurements, superconducting gravimeters, gravitational wave detectors) in high precision gravitational experiments. [4]

Radiations recorded from Venus made the solar system a laboratory for testing relativistic gravity[5]. The interplanetary space program developed in the early 1960s, and the discovery in 1964 of the relativistic effect of delay[6], offered new and accurate tests of general relativity. Until 1974, the solar system was the only way for high accuracy tests of general relativity.

In developing general relativity, Einstein was led by theoretical criteria of elegance and simplicity. His theory initially encountered "three classic tests": perihelion precession of Mercury's orbit, deflection of light by the Sun, and gravitational redshift of light.

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[1] Clifford M. Will, *Theory and Experiment in Gravitational Physics, Revised Edition*, Revised edition (Cambridge England ; New York, NY, USA: Cambridge University Press, 1993).

[2] Thomas A. Matthews and Allan R. Sandage, "Optical Identification of 3C 48, 3C 196, and 3C 286 with Stellar Objects.," *The Astrophysical Journal* 138 (July 1, 1963): 30–56, https://doi.org/10.1086/147615.

[3] Will, *Theory and Experiment in Gravitational Physics, Revised Edition.*

[4] R. V. Pound and G. A. Rebka, "Apparent Weight of Photons," *Physical Review Letters* 4, no. 7 (April 1, 1960): 337–41, https://doi.org/10.1103/PhysRevLett.4.337.

[5] W. B. Smith, "Radar Observations of Venus, 1961 and 1959," *The Astronomical Journal* 68 (February 1, 1963): 15–21, https://doi.org/10.1086/108904.

[6] Irwin I. Shapiro, "Fourth Test of General Relativity," *Physical Review Letters* 13, no. 26 (December 28, 1964): 789–91, https://doi.org/10.1103/PhysRevLett.13.789.

At the end of the 1950s it was suggested that the gravitational redshift of light is not, however, a real test of general relativity. It is a pure consequence of the principle of equivalence and does not test the field equations of gravitational theory. Schiff suggested that the Eotvos experiment is more accurate than the gravitational redshift of light, which it replaced as importance, the Eotvos experiment verifying to what extent the bodies of different composition have the same acceleration. [7]

Subsequently, other tests for general relativity were proposed, such as the Lense-Thirring effect, the orbital disturbance due to the rotation of a body, and the Sitter effect, a secular movement of the perigee and the node of the orbit of the moon, [8] [9] but the perspectives for detecting them were still weak. [10]

Another test area for observing general relativity was cosmology, foretelling the primordial explosion called the "Big Bang" and the subsequent expansion of the Unive, but by the end of the 1950s cosmological observations could not distinguish between different theories of gravity. [11]

Meanwhile, a "proliferation" of competing alternative gravity theories of general relativity has appeared. By 1960 there were at least 25 such alternative theories. [12]

According to Will, by 1960 general relativity was empirically supported by a moderate accuracy test (change of perihelion, about 1%), a low accuracy test (light distortion, about 50%), an inconclusive test (gravitational redshift) and cosmological observations that could not distinguish between different theories. This was what Lakatos called the "stationary period". Due to its limited experimental confirmations, general relativity was even removed from basic physics. [13]

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[7] L. I. Schiff, "On Experimental Tests of the General Theory of Relativity," *American Journal of Physics* 28, no. 4 (April 1, 1960): 340–43, https://doi.org/10.1119/1.1935800.

[8] Josef Lense and Hans Thirring, "Über Den Einfluß Der Eigenrotation Der Zentralkörper Auf Die Bewegung Der Planeten Und Monde Nach Der Einsteinschen Gravitationstheorie," *Physikalische Zeitschrift* 19 (1918): 156–63, http://adsabs.harvard.edu/abs/1918PhyZ...19..156L.

[9] W. de Sitter, "On Einstein's Theory of Gravitation and Its Astronomical Consequences. Second Paper," *Monthly Notices of the Royal Astronomical Society* 77 (December 1, 1916): 77, 155–84, https://doi.org/10.1093/mnras/77.2.155.

[10] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

[11] G. J. Whitrow and G. E. Morduch, "Relativistic Theories of Gravitation : A Comparative Analysis with Particular Reference to Astronomical Tests," *Vistas in Astronomy* 6 (1965): chap. 14, https://doi.org/10.1016/0083-6656(65)90002-4.

[12] C. DeWitt, *Experimental Relativity, in Relativity Groups and Topology. Lectures Delivered at Les Houches During the 1963 Session of the Summer School of Theoretical Physics*, Second Printing edition (Gordon & Breach, 1965), 165–313.

[13] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*.

The period from 1960 to 1980 was the period of maturity of general relativity: new high-precision test methods were developed that included new tests, such as gyroscopic precession, light delay and the "Nordtvedt effect" in the moon motion, including astrophysical observations and artificial satellites.

Due to the proliferation of alternative theories, the best theoretical framework was needed to compare the checks of the different experiments, to classify the theories and to compare their predictions with the results of the experiments in a systematic way.

Year	Experimental or observational results	Theoretical results
1960	Hughes-Drever mass anisotropy Pound-Rebka experiment of gravitational redshift	Penrose's work on spinors Gyroscopic precision (Schiff) Brans-Dicke theory
1962	Discovery of non-solar X-ray sources Discovery of the quasar redshift	Bondi formula for mass loss Discovery of the Kerr metric
1964	Eotvos Experiment, Princeton Pound-Snider experiment of gravitational redshift Discovery of the 3K microwave background	Delay in time of light (Shapiro) Singularity theorems in general relativity
1966	Detection of solar flattening Pulsar discovery	Production of elements in the Big Bang
1968	Planetary radar measurements for time delay Launch of *Mariners* 6 and 7 Acquisition of lunar laser echo First radio deflection measurements	Nordtvedt effect and early PPN framework
1970	CygXl: a black hole candidate *Mariners 6* and 7 time-delay measurements	Preferred frame effects Refined PPN framework Increasing the domain of black holes in general relativity
1972	Eotvos Experiment, Moscow	
1974	Discovery of binary pulsars	Quantum evaporation of black holes Dipolar gravitational radiation in alternative theories
1976	Experiments of gravitational ewsahift with rockets Moon test of the Nordtvedt effect	

	Time delay results obtained with *Mariner 9* and *Viking*
1978	Measurements of decreasing orbital period of binary pulsar SS 433
1980	Discovery of gravitational lenses

Table 2.2 A chronology of the tests for verifying the theory of general relativity between 1960-80. Source: Clifford M. Will, *Theory and Experiment in Gravitational Physics*[14]

Robert Dicke performed several high-precision nullity experiments to confirm gravity theories. [15] Dicke concludes that gravitational experiments can be divided into two classes:

1. one that tests the *basis of gravity theory* (eg, the principle of equivalence): the Eotvos experiment, the Hughes-Drever experiment, the gravitational redshift experiment, etc.), verifying that gravity is a curved spacetime phenomenon (described by a "metric theory" of gravity). General relativity and Brans-Dick's theory are examples of metric theories of gravity.
2. a second class that tests the *metric theories of gravity*: the parameterized post-Newtonian formalism, or PPN, initiated by Kenneth Nordtvedt, Jr., [16] and expanded and improved by Will. [17] PPN takes into account low velocities and weak fields (post-Newtonian limit) of metric theories, based on a set of 10 real parameters. PPN was used to analyze the gravitational experiments of the solar system, to discover and analyze new tests of gravity theory, such as the Nordtvedt effect, the preferred frame effects and the preferred location effects, and to analyze and classify alternative metric theories of gravity becoming the standard theoretical tool for these experiments, searches and studies.

By the mid-1970s, many alternative theories of gravity were upheld by experiments at the solar system level, but not at the cosmological level. In 1974, Joseph Taylor and Russell Hulse discovered the binary pulsar, [18] whose extremely stable pulses were monitored radiotelescopically, allowing accurate measurement of astrophysical parameters. In 1978 the rate of change of the orbital period

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[14] Will.

[15] DeWitt, *Experimental Relativity, in Relativity Groups and Topology. Lectures Delivered at Les Houches During the 1963 Session of the Summer School of Theoretical Physics*, 165–313.

[16] Kenneth Nordtvedt, “Equivalence Principle for Massive Bodies. II. Theory,” *Physical Review* 169, no. 5 (May 25, 1968): 1017–25, https://doi.org/10.1103/PhysRev.169.1017.

[17] C. M. Will, “Theoretical Frameworks For Testing Relativistic Gravity. Ii. Parametrized Post-Newtonian Hydrodynamics, And The Nordtvedt Effect.,” *Astrophys. J. 163: 611-28(1 Feb 1971).*, January 1, 1971, 163, 611–28, https://doi.org/10.1086/150804.

[18] R. A. Hulse and J. H. Taylor, “Discovery of a Pulsar in a Binary System,” *The Astrophysical Journal Letters* 195 (January 1, 1975): L51-53, https://doi.org/10.1086/181708.

of the system was measured, which was confirmed by general relativity but not by most alternative theories.

In the **Michelson-Morley experiment**, Michelson started from an experiment to test Fresnel and Stokes's contradictory theories about the influence of ether. [19] [20] Stokes initially believed that the two theories are observationally equivalent, both theories explaining the aberration of light. Michelson argued that his 1881 experiment was a crucial experiment that demonstrated Stokes' theory. Lorentz pointed out that Michelson "misinterpreted" the facts, and Michelson's calculations were wrong. Michelson, along with Morley, decided to repeat the experiment "at intervals of three months and thus avoid all uncertainty," [21] their conclusion rejecting Fresnel's explanation. Lorentz also questioned the new experiment: "the significance of the Michelson-Morley experiment lies rather in the fact that it can teach us something about the changes in the dimensions." In 1897 Michelson made a new experiment, concluding that the result of the experiment was an "improbable" one and decided that in 1887 he was wrong: Stokes' theory had to be rejected, and Fresnel's had to be accepted.

Fitzgerald, independent of Lorentz, produced a testable version that was rejected by Trouton, Rayleigh and Brace's experiments as it was theoretically progressive, but not empirical, Fitzgerald's theory being considered *ad-hoc* (that there is no independent (positive) evidence for it). [22] Einstein, ignoring these experiments, but stimulated by Mach's criticisms of Newtonian mechanics, arrived at a new progressive search program,[23] which "predicted" and explained the result of the Michelson-Morley experiment, but also predicted a huge range of undiscovered facts previously, that have obtained dramatic corroborations. Thus, only twenty-five years later, the Michelson-Morley experiment came to be seen as a crucial experiment, considered to be "the largest negative experiment in the history of science," [24] [25] demonstrating Lakatos's methodological tolerance.

In this context, a typical signal of the degeneration of a program is the proliferation of contradictory "facts". Using a false theory as an interpretive theory, one can obtain - without committing an

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[19] A Fresnel, “Lettre a Francois Arago Sur L’Influence Du Mouvement Terrestre Dans Quelques Phenomenes Optiques, in Annales de Chimie et de Physique - 98 Years Available - Gallica,” 1818, https://gallica.bnf.fr/ark:/12148/cb343780820/date.r=Annales+de+chimie+et+de+physique.langEN.

[20] George Gabriel Stokes, *On Fresnel’s Theory of the Aberration of Light* (London, 1846), 76–81.

[21] Hendrik A. Lorentz, “Considerations on Gravitation,” in *The Genesis of General Relativity*, ed. Michel Janssen et al., Boston Studies in the Philosophy of Science (Dordrecht: Springer Netherlands, 2007), 1038–52, https://doi.org/10.1007/978-1-4020-4000-9_13.

[22] Joseph Larmor, *On the Ascertained Absence of Effects of Motion through the Aether, in Relation to the Constitution of Matter, and on the FitzGerald-Lorentz Hypothesis*, 1904, 624.

[23] Karl Raimund Popper, *The Logic of Scientific Discovery* (Psychology Press, 2002).

[24] J. D. Bernal, *Science in History J. D. Bernal*, 3rd edition (M.I.T Press, 1965).

[25] Imre Lakatos, *The Methodology of Scientific Research Programmes: Volume 1: Philosophical Papers* (Cambridge University Press, 1980).

"experimental error" - contradictory factual proposals, inconsistent experimental results. [26] Michelson himself was frustrated by the inconsistency of "facts" resulting from his measurements.

Carlton Morris Caves proposes six possible laboratory experiments for non-Newtonian gravity: three use a torsion balance as a detector, and three use a high-sensitivity dielectric crystal. [27] Caves' idea is to demonstrate that technology will soon make possible a new class of experiments, exclusively laboratory tests. Caves' conclusion is that none of these experiments would be easy to do, because of the limitations of current technology. But most are feasible in the near future.

The strong effects of gravity are observed astrophysically (white dwarfs, neutron stars, black holes), in which case there are used, as experimental tests, the stability of the white dwarfs, the spin-down rate of the pulsars, the orbits of the binary pulsars, the existence of a black hole horizon, and so on.

Recently, a series of cosmological tests have been developed for theories of dark matter, using for constraints the rotation of the galaxy, the Tully-Fisher relation, the speed of rotation of dwarf galaxies, and gravitational lenses.

For the theories related to cosmic inflation, the most rigorous test is by measuring the size of the waves in the spectrum of cosmic microwave background radiation. [28]

For dark energy theories, the results of supernova brightness and age of the universe can be used as tests.

There are large differences in predictions between general relativity and classical physics, such as gravitational time dilation, gravitational lensing, gravitational redshift of light, and so on. And there are many relativistic theories of gravity, bifurcated or independent, but Einstein's general theory of relativity has upheld all predictions and is the simplest of such theories.

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[26] Lakatos.

[27] Carlton Morris Caves, "Theoretical Investigations of Experimental Gravitation" (phd, California Institute of Technology, 1979), http://resolver.caltech.edu/CaltechTHESIS:03152016-161054898.

[28] The potential function, which is crucial for determining the dynamics of inflation, is simply postulated, and not derived from an underlying physical theory.

Tests proposed by Einstein

Einstein states, in *Relativity Theory - Special Relativity and General Relativity*, [29] that theories evolve through observation-based decalations, in the form of empirical laws, from which general laws are obtained. Intuition and deductive thinking play an important role in this process. After the initial stage, the investigator develops a thinking system guided by empirical data, logically constructed from fundamental assumptions (axioms). The "truth" of a theory results from its correlation with a large number of unique observations. For the same empirical data there may be several theories that differ.

Einstein speaks, in *Relativity Theory - Special Relativity and General Relativity*, of the confirmed prediction of general relativity for the motion of Mercury's perihelion, with a precision far greater than that predicted by Newton's law of universal gravity. [30]

Another confirmed prediction discussed by Einstein is the deflection of light by a gravitational field, which admits an experimental test by photographic recording of stars during a total solar eclipse, thus: stars in the vicinity of the Sun are photographed during a solar eclipse. The second photo of the same stars is taken when the sun is in a different position on the sky, a few months earlier or later. By comparing the positions of the stars, there should appear radially outward. The British Royal Society and the Royal Astronomical Society performed these tests on two expeditions, on Sobral (Brazil) and Principe Island (West Africa), confirming the prediction.

The *redshift of the spectral lines* was also predicted by the general relativity and discussed by Einstein in the same book, but when this book was written it had not yet been confirmed. Experiments were carried out on cyanogen bands, but the results were not conclusive during that period. Einstein proposed a verification of the average displacement of the lines towards the less refractory edge of the spectrum, through statistical investigations of the fixed stars.

In the second edition of the book *Relativity Theory - Special Relativity and General Relativity*, [31] Einstein states that in developing his theory for the "cosmological problem" he relied on two hypotheses:

1. There is an average density of matter throughout the space, which is everywhere the same and different from zero.
2. The size ("radius") of the space is independent of time.

The hypotheses proved to be in line with the general theory of relativity after the introduction of a hypothetical term in the field equations ("the cosmological term of the field equations"). Subsequently, Einstein came to the conclusion that one can keep the hypothesis (1) without

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[29] Albert Einstein, *Teoria relativității: Relativitatea specială și relativitatea generală* (Nicolae Sfetcu, 2017), https://books.google.ro/books?id=aMtNDwAAQBAJ.

[30] Einstein.

[31] Einstein.

appealing to that term, if one can renounce the hypothesis (2), respectively the initial equations of the field admit a solution in which the "radius of the world" depends on time (space expansion), thus allowing space expansion.

Hubble, through an investigation of extra-galactic nebulae, confirmed that the emitted spectral lines showed a redshift proportional to the distance between the nebulae.

For Einstein, the epistemological approach of thought experiments was of particular importance. These experiments, by the way they were developed, offered a new understanding of the discussed phenomena.

At sixteen, Einstein imagined what would happen if a *light beam is followed with the speed of light.*[32] The experiment is more difficult than it seems at first sight. Einstein was, at that time, searching for a "universal principle" that could lead to true knowledge. The experiment starts with the hypothetical situation of tracking a light wave at speed c. In this case of equal magnitude of speeds, the "surfer" will observe a "frozen" light wave, with light radiation as a static spatially oscillating electromagnetic field, and the properties of the wave would disappear. But this time-independent field does not exist, because it is not in line with Maxwell's theory. His conclusion would be that an observer can never reach the speed of light, the hypothesis being false by modus tollens in classical logic. Einstein said that this experiment contains a paradox in that the two assumptions included (the constancy of the speed of light and the independence of the laws (so also the constancy of the speed of light) of the choice of the inertial system (the principle of special relativity) are "mutually incompatible (despite the fact that both, taken separately, are based on experience)".

In September 1905, Einstein attempted to extend the principle of relativity to accelerated reference systems by introducing a new and powerful physical principle in 1907, the "principle of equivalence" (the laws of physics take the same form in a uniform system of accelerating coordinates as in a system which is at rest relative to a homogeneous gravitational field), with a very high heuristic value.[33] He argued this principle through the "*elevator thought experiment*", sometimes considered Einstein's most important thought experiment. Einstein assumes an accelerated frame of reference with a constant acceleration in the x-direction, and a second frame at rest in a homogeneous gravitational field that gives all objects an acceleration in the same x-direction. Observationally, there is no distinction between the two frames. All bodies are accelerated in the same gravitational field. Thus, the principle of equivalence allows a homogeneous gravitational field to be replaced by a uniformly accelerated reference system. This hypothesis of the exact physical equivalence of the two frameworks has two important theoretical consequences:

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[32] Albert Einstein, "Autobiographische Skizze," in *Helle Zeit — Dunkle Zeit: In memoriam Albert Einstein*, ed. Carl Seelig (Wiesbaden: Vieweg+Teubner Verlag, 1956), 9–17, https://doi.org/10.1007/978-3-322-84225-1_2.

[33] Abraham Pais, *Subtle Is the Lord: The Science and the Life of Albert Einstein* (Oxford ; New York: Oxford University Press, 2005), 179–80.

we cannot speak of an absolute acceleration of the reference system, and the equal fall of all bodies in a gravitational field.

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