Classic gravitational tests of post-Einsteinian theories

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With the help of PPN formalism, gravity theories are confronted with the results of experiments in the solar system. The *γ* parameter in this formalism highlights the light deflection and the light delay. By calculations according to PPN, light deflection is obtained with respect to local straight lines, compared to rigid rods; due to the curvature of space around the Sun, determined by the parameter *γ*, the straight local lines are bent relative to the asymptotic straight lines away from the Sun. The development of very-long-baseline radio interferometry (VLBI) has improved the measurement of light deformation, allowing transcontinental and intercontinental VLBI observations of quasars and radio galaxies to monitor the rotation of the Earth[1]. Hipparcos optical astrometry satellite has led to improved performance. [2]

The *light delay* tests are based on a radar signal sent over the solar system along the Sun to a planet or satellite, and upon returning to Earth it suffers an additional non-Newtonian delay. Irwin Shapiro discovered this effect in 1964. Targets used include planets like Mercury or Venus, as passive radar signals (passive radar), and artificial satellites, such as Mariner 6 and 7, Voyager 2, Viking Mars, and the spacecraft. Cassini to Saturn, used as active transmitters of radar signals (active radar) [3]. Kopeikin suggested, in 2001, to measure the delay of light coming from a quasar when passing through the planet Jupiter[4], thus measuring the speed of gravitational interaction. In 2002, precise measurements of the Shapiro delay[5] were made. But several authors have pointed out that this effect does not depend on the speed of gravity propagation, but only on the speed of light. [6]

Explaining the *anomalies of Mercury's orbit* has long been an unresolved issue half a century since Le Verrier's announcement in 1859. Several *ad-hoc* hypotheses have been tested to explain this inconsistency with the theory, including the existence of a new planet Vulcan near the Sun, a

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[1] S. S. Shapiro et al., "Measurement of the Solar Gravitational Deflection of Radio Waves Using Geodetic Very-Long-Baseline Interferometry Data, 1979--1999," *Physical Review Letters* 92, no. 12 (March 26, 2004): 121101, https://doi.org/10.1103/PhysRevLett.92.121101.

[2] François Mignard and F. Arenou, "Determination of the Ppn Parameter with the Hipparcos Data," 1997.

[3] Clifford M. Will, "The Confrontation between General Relativity and Experiment," *Living Reviews in Relativity* 17, no. 1 (December 2014): 4, https://doi.org/10.12942/lrr-2014-4.

[4] Sergei M. Kopeikin, "Testing the Relativistic Effect of the Propagation of Gravity by Very Long Baseline Interferometry," *The Astrophysical Journal* 556, no. 1 (2001): L1–5, https://www.academia.edu/18481905/TESTING_THE_RELATIVISTIC_EFFECT_OF_THE_PROPAGATION_OF_GRAVITY_BY_VERY_LONG_BASELINE_INTERFEROMETRY.

[5] E. B. Fomalont and S. M. Kopeikin, "The Measurement of the Light Deflection from Jupiter: Experimental Results," *The Astrophysical Journal* 598, no. 1 (November 20, 2003): 704–11, https://doi.org/10.1086/378785.

[6] Fintan D. Ryan, "Gravitational Waves from the Inspiral of a Compact Object into a Massive, Axisymmetric Body with Arbitrary Multipole Moments," *Physical Review D* 52, no. 10 (November 15, 1995): 5707–5718, https://doi.org/10.1103/PhysRevD.52.5707.

planetoid ring, a quadrupolar solar moment, and a deviation from the inverse square in the law of gravity, but all these assumptions failed. General relativity has naturally solved this problem.

Another class of experiments in the solar system for gravity verifies the *strong equivalence principle* (SEP). The SEP violation can be tested by violating the principle of low equivalence for gravitational bodies leading to disturbances in Earth-Moon orbit, preferred location and the preferred frame effects in locally measured gravitational constancy that could produce observable geophysical effects, and possible variations in gravity constant at cosmological level.[7]

Nordtvedt[8] also stated that many metric theories about gravity predict that massive bodies violate the *weak equivalence principle* (falling with different accelerations, depending on their gravitational energy). Dicke[9] notes that this effect (the "Nordtvedt effect") occurs in theories with a spatially variable gravitational constant, such as scalar-tensor gravity. The Nordtvedt effect is not noticed in the results of the laboratory experiments, for objects of laboratory dimensions. The data analyzes did not find evidence, within the experimental uncertainty, for the Nordtvedt effect[10]. In the general relativity (GR), the Nordtvedt effect disappears[11].

Some theories violate strong equivalence principle by predicting that the results of local gravitational experiments may depend on the speed of the laboratory in relation to the average resting frame of the universe (the *effects of the preferred frame*, corresponding to PPN parameters a_1, a_2 and a_3) or to the location of the laboratory in relation to a gravitational body nearby (*preferred location effects*, some being governed by the PPN parameter ξ)[12]. The effects consist of variations and anisotropies in the locally measured value of the gravitational constant leading to the occurrence of abnormal values of the Earth and variations of the rate of rotation of the Earth, abnormal contributions to the orbital dynamics of the planets and the Moon, self-accelerations of the pulsars,

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[7] Will, "The Confrontation between General Relativity and Experiment."

[8] Kenneth Nordtvedt, "Equivalence Principle for Massive Bodies. I. Phenomenology," ResearchGate, 1968, 1014–16, https://www.researchgate.net/publication/243706608_Equivalence_Principle_for_Massive_Bodies_I_Phenomenology.

[9] P. G. Roll, R. Krotkov, and R. H. Dicke, "The Equivalence of Inertial and Passive Gravitational Mass," *Annals of Physics* 26 (February 1, 1964): 26, 442–517, https://doi.org/10.1016/0003-4916(64)90259-3.

[10] James G. Williams, Slava G. Turyshev, and Dale H. Boggs, "Progress in Lunar Laser Ranging Tests of Relativistic Gravity," *Physical Review Letters* 93, no. 26 (December 29, 2004): 261101, https://doi.org/10.1103/PhysRevLett.93.261101.

[11] Kenneth Nordtvedt, "The Relativistic Orbit Observables in Lunar Laser Ranging," ResearchGate, 1995, 51–62, 114, https://www.researchgate.net/publication/223758280_The_Relativistic_Orbit_Observables_in_Lunar_Laser_Ranging.

[12] Will, "The Confrontation between General Relativity and Experiment."

and anomalous torques on the Sun which would determine the random orientation of its axis of rotation towards the ecliptic. [13]

Most theories that violate the strong equivalence principle predict a variation of the Newtonian gravitational constant measured locally, as a function of time.

Other tests to verify gravitational theories are based on *gravitomagnetism* (moving or rotating matter produces an additional gravitational field analogous to the magnetic field of a moving charge or magnetic dipole). The relativistic effects that can be measured involve the Earth-Moon system and the binary pulsar systems. [14]

Gyroscope experiments attempt to detect this frame dragging or Lense-Thirring precession effect. Another way to test the frame dragging is to measure the precession of the orbital planes of the bodies that rotate on a rotating body, measuring the relative precession[15]. The Earth-Moon system can be considered a "gyroscope", with the axis perpendicular to the orbital plane.

A non-zero value for any of the PPN parameters ζ_1, ζ_2, ζ_3, ζ_4 and α_3 would result in a violation of *conservation* of momentum or Newton's third law conservation in gravitational systems. A test for Newton's third law for gravitational systems was conducted in 1968 by Kreuzer, in which the gravitational attraction of fluorine and bromine was compared with accuracy. A planetary test was reported by Bartlett and van Buren[16]. Another consequence of the violation of conservation of momentum is a self-acceleration of the mass center of a stellar binary system.

The PPN formalism is no longer valid for strong gravitational fields (neutron stars, black holes), but in some cases post-Newtonian approximations can be made. Systems in strong gravitational fields are affected by the emission of gravitational radiation. For example, relativistic orbital motion (fusion or collapse of binary systems of neutron stars or black holes in the final phase) can be detected by a network of observers with gravitational interference waves with a laser interferometer, but the analysis is done using different techniques.

Only two parameters can be used in observing the generation of gravitational waves: the mass momentum and the angular momentum. Both quantities can be measured, in principle, by

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

[14] K. Nordtvedt, "Gravitomagnetic Interaction and Laser Ranging to Earth Satellites," *Physical Review Letters* 61, no. 23 (December 5, 1988): 61, 2647–2649, https://doi.org/10.1103/PhysRevLett.61.2647.

[15] John C Ries et al., "Prospects for an Improved Lense-Thirring Test with SLR and the GRACE Gravity Mission," n.d., 7.

[16] D. F. Bartlett and Dave Van Buren, "Equivalence of Active and Passive Gravitational Mass Using the Moon," *Physical Review Letters* 57, no. 1 (July 7, 1986): 21–24, 57, https://doi.org/10.1103/PhysRevLett.57.21.

examining the external gravitational field of the bodies without any reference to their internal structure. Damour[17] calls this an "effacement" of the internal structure of the body.

Another way to verify the agreement with GR is by comparing the observed phase of the orbit with the theoretical phase of the model as a function of time.

The observation of gravitational waves can provide the means to test GR forecasts for polarization and wave velocity, for damping of gravitational radiation and for gravity of strong field, using gravity wave detectors with interferometer or resonant band. Broadband laser interferometers are particularly sensitive to the evolution of gravitational wave phases, which carry information about the evolution of the orbital phase.

Another possibility involves gravitational waves from a small mass orbiting and inspiralling into a spinning black hole. [18]

One of the problems considered by physicists in testing GR in the strong field is the possibility of contamination with an uncertain or complex physics. For example, a few seconds after the Big Bang, physics is relatively clear, but some theories of gravity fail to produce cosmologies that meet even the minimum requirements for big-bang nucleosynthesis or the properties of the cosmic microwave background[19]. But, within modest uncertainties, one can evaluate the quantitative difference between predictions and other theories under strong field conditions by comparing with observations. [20]

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[17] T. Damour, "The Problem of Motion in Newtonian and Einsteinian Gravity.," in *Three Hundred Years of Gravitation*, 1987, 128–98, http://adsabs.harvard.edu/abs/1987thyg.book..128D.

[18] Ryan, "Gravitational Waves from the Inspiral of a Compact Object into a Massive, Axisymmetric Body with Arbitrary Multipole Moments," 52, 5707–5718.

[19] Will, *Theory and Experiment in Gravitational Physics, Revised Edition*, chap. 13.2.

[20] Clifford M. Will, *Was Einstein Right?: Putting General Relativity To The Test*, 2 edition (New York, NY: Basic Books, 1993).

Classic tests

Albert Einstein proposed[21] three tests of general relativity, later named the **classic tests of general relativity**, in 1916:

1. the precession of the perihelion of Mercury's orbit
2. Sun light deflection
3. the gravitational redshift of the light.

For gravitational testing, the indirect effects of gravity are always used, usually particles that are influenced by gravity. In the presence of gravity, the particles move along curved geodesic lines. The sources of gravity that cause the curvature of spacetime are material bodies, depending on their mass. But in relativity the mass relates to the energy through the formula $E = mc^2$, and the energy with the momentum, according to the special relativity.

Einstein's equations give the relation between the spatial geometry and the properties of matter, using Riemannian geometry, the geometrical properties being described by a function called metric. In general relativity, the Riemann curvature metric and tensor take values defined at each point in spacetime. The content of matter defines a size called the energy-momentum tensor **T**. These quantities are related to each other by Einstein's equations, in which the Riemann curvature tensor and the metric define another geometric magnitude **G**, called the Einstein tensor, which describes some aspects of how spacetime is curved. Einstein's equation thus states that

$$\mathbf{G} = (8\pi G/c^4)\mathbf{T},$$

where **G** measures curvature and **T** measures the amount of matter. *G* is the gravitational constant of Newtonian gravity, and *c* is the speed of light in special relativity. Each of the quantities **G** and **T** are determined by several functions of the spacetime coordinates, thus resulting in more equations, in fact. Each solution of these equations describes a certain geometry of spacetime.

Precision of Mercury's perihelion

Urbain Le Verrier discovered, in 1859, that the orbital precession of the planet Mercury does not correspond to the theory: the ellipse of its orbit rotated (precessing) slightly faster, the difference being about 38 (subsequently corrected to 43) arcseconds of rotation per century[22]. Several *ad-hoc* hypotheses have been proposed, such as interplanetary dust, the Sun's unobserved oblation, a

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[21] A. Einstein, "The Foundation of the General Theory of Relativity," in *The Principle of Relativity. Dover Books on Physics. June 1, 1952. 240 Pages. 0486600815, p. 109-164*, 1952, 769–822, http://adsabs.harvard.edu/abs/1952prel.book..109E.

[22] U. Le Verrier, *Lettre de M. Le Verrier à M. Faye sur la théorie de Mercure et sur le mouvement du périhélie de cette planète, in Comptes rendus hebdomadaires des séances de l'Académie des sciences* (Paris : Gauthier-Villars, 1859), 379–383, http://archive.org/details/comptesrendusheb49acad.

month undetected of Mercury, or a new planet called Vulcan. As no hypothesis has been confirmed, it was assumed that Newton's law of gravity is incorrect, trying to change the law, but new theories conflicted with other laws. In general relativity, this precession is explained by gravity mediated by the curvature of spacetime, in agreement with the observation.

Light deflection

The prediction of the light deflection was initially confirmed by observing the light of the stars (quasars) deviated while passing through the Sun[23]. In the PPN formalism, the light deflection is highlighted by the parameter γ, which encodes the influence of gravity on the geometry of spacetime. [24]

The deflection of light by a massive object has been predicted since 1784 by Henry Cavendish, and Johann Georg von Soldner in 1801, based on calculations from Newtonian gravity. This prediction was confirmed by Einstein in 1911, correcting the value of curvature in 1915 based on general relativity[25]. The first observation of light deflection was made by Arthur Eddington during the total sun eclipse of May 29, 1919, simultaneously in Sobral, Brazil and São Tomé and Príncipe on the west coast of Africa[26].

The light deflection in the general relativistic case is observed only for a stationary observer who sees the path of light in relation to a gravitational body. Einstein understood, using EEP, that mass or even energy in Eisntein's formula would follow geodesic paths in spacetime, in relation to an observer at rest with the gravitational body. This result highlights the essence of EEP, showing that gravity and acceleration cannot be differentiated from one another, in a small region. Shapiro et al. [27] reported the sun's curvature of radio waves emitted by extragalactic radio sources, between 1979 and 1999.

Gravitational redshift

The gravitational redshift appears when the electromagnetic radiation from a source in a gravitational field is observed from a region with a higher gravitational potential. It is a direct result of the gravitational time dilation. In a test to confirm this effect, the reception of light must be

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[23] Daniel Kennefick and Jürgen Renn, *Astronomers Test General Relativity: Light-Bending and the Solar Redshift, in Albert Einstein - Chief Engineer of the Universe: 100 Authors for Einstein Essays*, 2005, http://adsabs.harvard.edu/abs/2005alei.book.....R.

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

[25] Will, "The Confrontation between General Relativity and Experiment."

[26] Matthew Stanley, "'An Expedition to Heal the Wounds of War' The 1919 Eclipse and Eddington as Quaker Adventurer," *Isis* 94, no. 1 (March 1, 2003): 57–89, https://doi.org/10.1086/376099.

[27] Shapiro et al., "Measurement of the Solar Gravitational Deflection of Radio Waves Using Geodetic Very-Long-Baseline Interferometry Data, 1979--1999."

located at a higher gravitational potential. If the observer has a gravitational potential lower than the source, he will notice a gravitational shift towards blue.

Einstein predicted the effect from the equivalence principle in 1907, stating that it can be measured in the spectral lines of a white dwarf star that has a very large gravitational field. The first accurate measurement of a white dwarf was made by Popper in 1954. [28]

Global Positioning System (GPS) must take into account the gravitational redshift in synchronization[29]. Physicians analyzed GPS data to confirm other tests[30]. Other precision tests are the Gravity Probe A satellite, launched in 1976, and the Hafele-Keating experiment that used atomic clocks in navigation aircraft. [31]

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[28] N. S. Hetherington, "Sirius B and the Gravitational Redshift: An Historical Review," ResearchGate, 1980, 246–52,
https://www.researchgate.net/publication/234478409_Sirius_B_and_the_gravitational_redshift_An_historical_review.

[29] GPS is continuously tested by comparing atomic clocks on the ground and on orbiting satellites, for correlation with relativistic effects, cf. Neil Ashby, "Relativity in the Global Positioning System," *Living Reviews in Relativity* 6, no. 1 (January 28, 2003): 1, https://doi.org/10.12942/lrr-2003-1.

[30] Ashby.

[31] S Schiller, "Gravitational Physics with Optical Clocks in Space," 2015, 31.

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