Tests and Anomalies of Post-Newtonian Gravitational Theories

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Tests of post-Newtonian theories

Newton's proposed tests

In the first edition of *Principia*, Newton considered that the experiments with the **pendulum** would allow him to decipher the different types of resistance force and their variation with speed. It recognizes the failure of these experiments, in the second and third editions, then appealing to the vertical fall of objects with the forces of resistance due to the inertia of the environment. His intention was to approach the other types using the differences between observations and this law[1]. But this approach was also wrong, since there is no distinct species of resistance force, but only a result of the interaction with the inertial and viscous environment. This interaction being very complex, Newton could not deduce a law for the force of resistance, it only determined empirically relations for bodies of different forms. [2]

Newton argues in the law of gravity the strict proportionality of the "quantity of matter" with weight, but the pendulum experiments only indicate that the inertial mass is proportional to the weight. [3] The mass of an object is an intrinsic feature of it, while the weight is an extrinsic feature, depending on the gravitational fields generated by other objects. The experiments with the pendulum are described in detail in Book III, Proposition 6, where Newton states: "All bodies gravitate toward each of the planets, and at any given distance from the center of any one planet the weight of any body whatever toward that planet is proportional to the quantity of matter which the body contains," [4] and then describes his experiments. [5]

Newton states, in contradiction with the Cartesian view, that each of the universal and essential properties of matter - i.e. extension, mobility, hardness, impenetrability and mass - is known "only through the senses". But from his assertion that the properties of matter are known "only through experiments," it follows that Newton does not accept a naive-empirical view, but rather a sophisticated double conception of the epistemology of matter, [6] denying the Cartesian view that we can determine the universal properties of matter only *a priori* or only by reason, and arguing that conceptually guided experiments in physical theory are necessary to determine the properties of matter: "It [mass] can always be known from a body's weight, for – by making very accurate experiments with pendulums – I have found it to be proportional to the weight." [7] Newton's

[1] Isaac Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," *Science* 177, no. 4046 (1726): 749, https://doi.org/10.1126/science.177.4046.340.

[2] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics: Volume 6*, 2 edition (Amsterdam u.a: Butterworth-Heinemann, 1987), 31–36, 168–79.

[3] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 701, 806–9.

[4] Newton, 806.

[5] Newton, 806–7.

[6] Andrew Janiak, *Newton as Philosopher* (Cambridge University Press, 2010).

[7] Newton, "Philosophiae Naturalis Principia Mathematica, III Ed.," 404.

concept of matter involved a fundamental rejection of mechanistic philosophy. The experiments with the pendulum are also described in Proposition 24 of Book 2, in corollaries five and seven.

In the experiments with the pendulum, comparing the number of oscillations of the bob of the solid pendulum and the empty pendulum, Newtom tried to determine how an ether that acts not only on the surface of a body but also on its interior parts, affects these pendulums. This is how Newton came to believe that there is no ether and he favored the idea in the Preface of *Principia* of the universality of gravity. [8]

To discuss the effects that distinguish absolute motion from relative motion, Newton uses the "**water bucket**" thinking experiment, described in a paragraph on the effects that distinguish absolute motion from relative motion. Newton states here that "the true and absolute circular motion of the water, which is here directly contrary to the relative, becomes known, and *may be measured by this endeavor*." [9] Hang a bucket of water with a rope and twist the bucket in one direction; then let the rope recover. The bucket is rotating now, and the water surface will initially be flat, but in relation to the bucket it rotates. By rubbing with the rotating bucket, the water gradually starts to rotate, eventually balancing the speed of the bucket, so that the movement towards the bucket gradually reaches zero. But, as the relative rotation of the water relative to the bucket decreases, "endeavor to recede from the axis of motion" increases accordingly. Newton observes that acceleration (for example, rotation) is empirically detectable by the presence of inertial effects, even in the absence of a change in object relations. Also, Newton argues, contrary to Descartes, that we cannot understand the true movement of water in the bucket as a change in the relationship between water and the surrounding body (in this case, the bucket). The relationship between the water and the bucket remains the same, even though the water has a real movement, as indicated by the presence of inertial effects. So, the true movement of a body cannot be understood in terms of changes in its relations with other objects. Absolute space allows us to capture what is the true movement, according to Newton. [10]

For Newton, it seems that centrifugal force is the criterion and measure of absolute rotation. He defines absolute rotation as producing such an effect, criticizing Descartes' definition of "motion in the philosophical sense" as a movement of a body in relation to neighboring bodies. The experiment shows that the dynamic effect is independent of the relative motion between the water and the bucket. [11] Newton finally demonstrates that, because it depends on identifiable physical forces, its definition can be applied consistently even in the absence of observable reference bodies,

[8] Newton, 382–83.

[9] Isaac Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*, 1713, 21, https://www.e-rara.ch/zut/338618.

[10] Janiak, *Newton as Philosopher*.

[11] Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*, 21.

because if two bodies connected by a cord are alone in an otherwise empty universe, the tension on cable still offers a criterion and a measure of the amount of true circular motion. [12]

Another Newtonian thought experiment involved **two bodies connected by a cord**, [13] which rotate around their center of common weight, in the absence of other bodies that can influence their movements. "The endeavor of the balls to recede from the axis of motion could be known from the tension of the cord, and thus the quantity of circular motion could be computed." Respectively, the absolute rotation of a body is not only independent of its rotation with respect to the contiguous bodies but is independent of any relative rotation.

According to Ernst Mach, two hundred years after Newton, if Newton neglected neighboring bodies, he referred all movements to "fixed stars." But if we can deduce from Newton's laws how bodies will behave in the absence of fixed stars, we cannot deduce whether, in these circumstances, they will remain valid anyway. For Einstein, under Mach's influence, Newton's argument illustrates the "epistemological defect" inherent in Newtonian physics. [14]

In Propositions 26-29, Book 3, of *Principia*, 1687, [15] Newton developed a special treatment of the influence of the Sun's gravitational force on the **motion of the Moon** around the Earth. Tycho Brahe had discovered a bi-monthly variation in lunar velocity after an expected lunar eclipse disappeared. Remarkably, Newton did not consider the actual motion of the Moon, which is known to be approximated by Horrocks' model of an ellipse precession with the Earth in one focus. He considered an idealized model in which the Moon rotates in a circular orbit around the Earth in the absence of solar disturbance. He calculated the orbit change due to this disturbance and obtained results that were in accordance with Brahe's observation. This was one of the great triumphs of Newton's gravitational theory, further developed by Euler[16], and G. Hill[17].

Newton's theory was most successful when it was used to predict **Neptune**'s existence based on Uranus movements, which could not be explained by the actions of other planets. The calculations

[12] Newton, 22.

[13] I. Bernard Cohen and George E. Smith, *The Cambridge Companion to Newton* (Cambridge University Press, 2006), 44.

[14] Cohen and Smith, *The Cambridge Companion to Newton*.

[15] Isaac Newton, "Philosophiæ Naturalis Principia Mathematica, I Ed.," The British Library, 1687, https://www.bl.uk/collection-items/newtons-principia-mathematica.

[16] Leonhard Euler, *Sol et Luna I: Opera Mechanica Et Astronomica Vol 23*, ed. Otto Fleckenstein, 1956 edition (Basileae: Birkhäuser, 1956), 286–289.

[17] G. W. Hill, "The Collected Mathematical Works of G. W. Hill," *Nature* 75, no. 1936 (December 1906): 284–335, https://doi.org/10.1038/075123a0.

of John Couch Adams and Urbain Le Verrier predicted the general position of the planet, and the calculations of Le Verrier led Johann Gottfried Galle to the discovery of Neptune. [18]

Newton's theory of gravity is better than Descartes's theory because Descartes's theory has been refuted (proved to be false) in explaining the motion of the planets. Newton's theory was in turn refuted by Mercury's abnormal perihelion. Even if the Keplerian ellipses rejected Cartesian vortex theory, only Newton's theory forced us to reject it; and even though Mercury's perihelion rejected Newtonian gravity, only Einstein's theory made us reject it. A refusal merely indicates the urgent need to revise the current theory, but it is not a sufficient reason to eliminate the theory.

Tests of post-Newtonian theories

Usually, the "laboratory" of gravitational tests was the celestial bodies, the astrophysical systems. But such tests are disturbed by non-gravitational effects. The most used such "laboratory" was the solar system. Recently, scientists have focused on observing binary pulsars for the verification of gravitational theories, by observing the variations of the orbital period, thus providing indirect evidence for the emission of gravitational radiation.

But the experimenter cannot "arrange the lab" according to his needs, nor trigger certain events when he needs them. But the current technological development is beginning to allow pure laboratory experiments. Thus, resonant detectors (harmonic oscillators) with very low dissipation levels were reached. In these laboratory tests, one type of experiments is the one for checking the post-Newtonian gravitational effects. For this purpose, a body of laboratory dimensions is moved (by rotation or vibration) to produce in its vicinity a "post-Newtonian gravitational field" (Newtonian-type gravitational fields produced by kinetic energy or pressure). The movement of the mass is modulated so that the desired post-Newtonian signal resonantly drives the oscillations of the detector and the experimenter monitors the changes resulting in the movement of the detector. [19]

Through these experiments, only certain types of post-Newtonian effects can be examined. Some post-Newtonian effects (such as nonlinear gravitational effects) are completely negligible. But it is possible to check the gravitational influences of speed and pressure. In these post-Newtonian experiments, the elimination of "Newtonian noise", the Newtonian gravitational field effects of the laboratory source that are much larger than the largest post-Newtonian effects, is attempted.

[18] John Couch Adams, "On the Perturbations of Uranus (1841-1846). | StJohns," 1846, 265, https://www.joh.cam.ac.uk/w16-manuscripts-john-couch-adams-perturbations-uranus-1841-1846.

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

Newtonian gravity anomalies

Newton's law of gravity is precise enough for practical purposes. The deviations are small when the dimensional quantities $\varphi/c^2 << 1$ and $(v/c)^2 << 1$, where φ is the gravitational potential, v is the speed of the studied objects and c is the speed of light[20]. Otherwise, general relativity must be used to describe the system. Newton's law of gravity is the gravitational limit of general relativity under the conditions specified above.

Regarding Newton's law, there are still current theoretical concerns: there is still no consensus regarding the mediation of gravitational interaction (whether there is action at a distance). Also, Newton's theory involves an instantaneous propagation of gravitational interaction, otherwise an instability of planetary orbits would appear.

Newton's theory could not explain the exact precession of the orbit of the planets, especially for Mercury, which was detected long after Newton died. [21] The difference of 43 arcseconds per century appears from the observations of the other planets and from the precession observed with advanced telescopes in the 19th century.

The angular deflection of light rays due to gravity, calculated using Newton's theory, is half the deflection observed by astronomers. General relativity predicts values much closer to observational ones.

In spiral galaxies, the orbit of the stars around their centers seems to not exactly respect Newton's law of universal gravity. Astrophysicists have introduced some ad-hoc hypotheses to agree this phenomenon with Newton's laws, assuming the existence of large amounts of dark matter.

Newton himself was disturbed by the concept of "action at a distance" that his equations involved. In 1692, in his third letter to Bentley, he wrote:

> "That gravity should be innate, inherent, and essential to matter, so that one body may act upon another at a distance, through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it. Gravity must

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[20] Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler, *Gravitation* (W. H. Freeman, 1973), 1049.

[21] Max Born, *Einstein's Theory of Relativity*, Revised edition edition (New York: Dover Publications Inc., 1962), 348.

> be caused by an agent acting constantly according to certain laws; but whether this agent be material or immaterial, I have left to the consideration of my readers."[22] [23]

Newton failed to issue a phenomenological theory, to be confirmed experimentally, on how gravity acts, although he suggested two mechanical hypotheses in 1675 and 1717. In the General Scholium in the second edition of the *Principia* of 1713, he said: "I have not yet been able to discover the cause of these properties of gravity from phenomena and I feign no hypotheses...."[24]

[22] I. Bernard Cohen, "Isaac Newton's Papers & Letters on Natural Philosophy and Related Documents," *Philosophy of Science* 27, no. 2 (1960): 209–211.

[23] Nicolae Sfetcu, *Isaac Newton despre acțiunea la distanță în gravitație - Cu sau fără Dumnezeu?* (MultiMedia Publishing, 2018), http://doi.org/10.13140/RG.2.2.24577.97122.

[24] Newton, *Philosophiae Naturalis Principia Mathematica, II Ed.*

Saturation point in Newtonian gravity

At the end of the 20th century and the beginning of the 21st century, the contradictions between Newtonian mechanics and Maxwell's electrodynamics (between the Galilean invariance and the idea of the constant speed of light) became evident. An initially proposed solution was the ether concept. Einstein rejected this solution, interpreting Newton's and Maxwell's theories as so fundamental, each with its rival model, that the only solution was the development of a new unifying theory, with another hard core and a specific positive heuristic: special relativity.

Nicholas Maxwell[25] discusses six discrepancies in Newtonian mechanics highlighted by Einstein[26] (which might be called anomalies in the Lakatos program), namely:

1. the arbitrariness of inertial reference frames and the concept of absolute space;
2. two distinct fundamental laws, (a) the law of motion ($F = ma$) and (b) the expression of gravitational force ($F = Gm_1m_2/d^2$);
3. the arbitrariness of (b) being given (a), there being an infinite number of possibilities as good for (b);
4. the possibility that the law of force is determined by the structure of space and the failure to exploit this possibility;
5. the ad-hoc character of the equality of the inertial mass with the gravitational one; and
6. the unnatural nature of energy being divided into two forms, kinetic and potential.

Einstein explains why attempts to solve anomalies by ad-hoc hypotheses fail, and concludes: "Accordingly, the revolution begun by the introduction of the field was by no means finished. Then it happened that, around the turn of the century ... a second fundamental crisis set in," the crisis generated by the beginnings of quantum theory, the first being particle/field dualism in classical physics. [27]

In addition, Lorentz's classical program was progressive until 1905 - the year that Einstein published his theory of special relativity.

Nugayev claims that the research program supported by Einstein was much broader, including relativity, quantum theory and statistical mechanics, for the unification of mechanics and electrodynamics. [28]

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[25] Nicholas Maxwell, "The Need for a Revolution in the Philosophy of Science," *Journal for General Philosophy of Science* 33, no. 2 (December 1, 2002): 381–408, https://doi.org/10.1023/A:1022480009733.

[26] Albert Einstein, "Autobiographische Skizze," in *Helle Zeit — Dunkle Zeit: In memoriam Albert Einstein*, ed. Carl Seelig (Wiesbaden: Vieweg+Teubner Verlag, 1956), 27–31, https://doi.org/10.1007/978-3-322-84225-1_2.

[27] Einstein, 27–31.

[28] R. M. Nugayev, "The History of Quantum Mechanics as a Decisive Argument Favoring Einstein Over Lorentz," *Philosophy of Science* 52, no. 1 (1985): 44–63.

Most of the explanations for Einstein's victory over Lorentz's research refer to the Michelson-Morley experiment. [29] Elie Zahar[30], based on Lakatos' methodology[31], states that Lorentz's etheric theories and Einstein's special and general theories of relativity have been developed in different competing programs. According to Zahar, Lorentz's program was replaced by Einstein's relativity program only in 1915 by explaining the precession of Mercury's perihelion. But with the development of the GR, Einstein's program predicted observations that could not be derived from Lorentz's. [32]

Nugayev, arguing against Zahar's extension of Lakatos' methodology, intends to explain the success of Einstein's research program on Lorentz's by a different extension of Lakatos's methodology, including different ones proposed by me. Thus, for two different theories trying to explain the same experimental data, the process of jointly applying the two theories to solve a problem will be called a "theories' cross", while these will be called "cross-theories". The set of statements that describes the relationships between crossings will be called "crossbred theory"[33]. Nugayev also addresses the idea of a theory that I have called "unifying" when the theories go through "cross-contradictions". Nugayev calls the new theory "global". According to him, there would be two logical ways of elaborating the global theory: "reductionist" and "synthetic".

Nugayev states that Lakatos' hard nuclei are obtained by convention. I do not agree with him here. The hard core is established by the initiator of the research program which also establishes the strategy of program development according to the negative heuristic. The hard core is what it wants to remain unwavering, being absolutely convinced that it is right. When they would change the hard core, they would practically abandon that research program and start another program.

[29] Gerald Holton, "Einstein, Michelson, and the 'Crucial' Experiment," *Isis: A Journal of the History of Science* 60 (1969): 132–97.

[30] Elie Zahar, "Why Did Einstein's Programme Supersede Lorentz's? (II)," *British Journal for the Philosophy of Science* 24, no. 3 (1973): 223–262.

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

[32] Nugayev, "The History of Quantum Mechanics as a Decisive Argument Favoring Einstein Over Lorentz."

[33] Nugayev.

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