Physics Before and After Einstein
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Chapter 7

Testing Relativity

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1. Introduction: Einstein's Attitude towards Experiments

This chapter covers various experimental tests of special and general relativity, with an emphasis on those conducted during Einstein's lifetime.[1] But what was Einstein's own attitude toward this activity? As the popular image would have it, Einstein would dismiss any empirical result contradicting his predictions, preferring to follow his own intuition.

One origin of this myth is the apocryphal story reported by a neo-Kantian philosopher, Ilse Rosenthal-Schneider.[2] Reminiscing in a memoir dated 23 July 1957 (which finally appeared in 1981, i.e. decades after Einstein's death in 1955) about meetings as a student in Berlin in 1919 with Einstein, von Laue and Planck, she recounted witnessing how Einstein received the first telegram from Lorentz[3] about the provisional results of his light deflection measurements. She purportedly asked Einstein what he would have done if the results had turned out otherwise and his alleged reply was: 'Then too bad for the observations; my theory is right anyway.'

If Rosenthal-Schneider's story were construed as implying that Einstein was indifferent to empirical verifications, then this would contradict what we know from several other sources. Letters to his mother and his colleagues from the time reveal that he was quite excited about Eddington's results as well as about his earlier success in calculating the previously unexplained slight motion of Mercury's perihelion, which agreed so well with the anomalies recorded since the mid-nineteenth century.

Einstein – at least until his epistemological shift in the early 1920s – was very keen on empirical verification of the three testable predictions of general relativity. In 1917 he even went so far as to hire an astronomer, Erwin Finlay Freundlich (1885–1964) to pursue this issue as the first full-time staff member of the Kaiser Wilhelm Institute for

[1] Because of space limitations, my footnotes will generally only refer to a few key papers and secondary sources. Surveys of the vast primary literature are given in Tonnelat [90], Will [94,99] and Hentschel [56].

[2] On the following, see Hentschel [50] and further references to primary documents given therein.

[3] Actually Rosenthal-Schneider refers to *Eddington*'s telegram even though Eddington did not send any telegrams to Einstein. Einstein was first informed by a telegram sent by H.A. Lorentz from The Hague on Sept. 22, 1919, then by a more detailed letter dated Oct., 7, 1919, and then by another Lorentz-telegram dated Nov. 14, 1919 soon after the famous joint meeting of the Royal Society and the Royal Astronomical Society on Nov. 6, 1919. Eddington first sent a letter to Einstein on Dec. 1, 1919 expressing his great pleasure to be now in personal communication with Einstein. The fact that Rosenthal-Schneider does not know the name of the telegram's sender puts her account further into question.

Physical Sciences, which Einstein headed as the founding director.[4] And in December 1919, right after congratulating and thanking Eddington for his attempts to test the deflection of light on the 1919 solar eclipse expedition (see below), he went even further, emphasizing the still open issue of gravitational redshift: 'If it were proven that this effect did not exist in nature, then the whole theory [of gravitation and relativity] would have to be abandoned.'[5]

However, as Einstein saw it, such 'proof' would not result from any single experiment or observation, but rather from a cluster of experiments all pointing in one direction and barring feasible alternatives.[6] As we shall see in the following, testing the theories of relativity was no easy matter and in most cases his predictions were only satisfactorily confirmed after his death in 1955.

2. Experimental Tests of Special Relativity

All testable deviations of Einstein's special theory of relativity from classical mechanics and classical electrodynamics are very small. They are usually second-order effects, that is $\sim v^2/c^2$, with v being the velocity of the observer (for instance, c. 30 km/sec for aether–wind experiments relating to the Earth's motion around the Sun), and c, the velocity of light, which is c. 30 million km/sec in vacuo. So $v^2/c^2 \sim 10^{-8}$ is a very small ratio indeed.

Einstein's 1905 paper on the electrodynamics of moving bodies was *not* written with the Michelson–Morley experiment in mind but with entirely different motives.[7] Nevertheless, the negative outcome of that experiment, of which Einstein was certainly aware from Lorentz's 1895 essay or Wien's 1898 survey, for instance, was also naturally explained in terms of the constancy of light. The velocity of light was independent of the velocity of its emitter (which eliminated all emission theories of light such as Ritz's),[8] and also independent of the direction in which the two arms of the Michelson interferometer were turned (isotropy).[9] Thus experiments such as the Michelson–Morley ones could not detect any relative motion of the Earth and the aether, not just because of the experimental accuracy then obtainable, but in principle. The Fizeau drag coefficient, known empirically since Fresnel's interpretation of Fizeau's experiment of 1851 involving a relative motion of light and water, could also be derived by inserting c/n and the

[4] On Freundlich's efforts to find avenues for testing general relativity, see Hentschel [53] and [55] with references to Freundlich's many articles regarding particularly gravitational redshift and light deflection.

[5] A. Einstein to A.S. Eddington, 15. Dec. 1919, Collected Papers of Albert Einstein, call no. 8 263–2: 'Wenn bewiesen wäre, dass dieser Effekt in der Natur nicht existiert, so müsste die ganze Theorie verlassen werden.'

[6] Einstein's quasi-holistic attitude towards experiments was most likely inspired by Pierre Duhem's philosophy of science and explains why Einstein could very well reject *singular*, isolated experiments in conflict with his theories such as Kaufmann's 1906 data that seemed to contradict Einstein's formula for relativistic mass increase: see Einstein [25, p. 439].

[7] On this point, cf. Holton [58]. For a detailed analysis of Einstein's path to special relativity and a contrast to Lorentz's and Poincaré's approaches, see Miller [68]. On the Michelson experiment of 1881 and its many repetitions by Michelson and Morley in 1887, and then by Morley and others, see Swenson [87].

[8] On this point see de Sitter [13]; on other early experiments and observations relevant for special relativity, even though many of them had been conducted before 1905, see Laub [62] and Lenard [63, pp. 498 ff].

[9] For the latest limit on the anisotropy of the velocity of light $\delta c/c_0 < 3 \times 10^{-15}$ and for the independence of c from the velocity of the emitter $\Delta c/c_0 < 6 \times 10^{-12}$, obtained by comparing the resonance frequency of two cyrogenic resonators over a period of more than a year, see Peters and Müller [71].

water's velocity w into Einstein's formula for the relativistic addition of velocities. The slight correction factor $1/(1 + v_1 v_2/c^2)$ to the classical superposition rule automatically led to the Fizeau drag coefficient $1 - 1/n^2$ without any need for special assumptions:

$$v_{\text{rel}} = \frac{v_1 + v_2}{1 + v_1 v_2/c^2} \to v = c/n + w\left(1 - \frac{1}{n^2}\right) + \text{negligible terms} \sim v^2/c^2.$$

Einstein's reinterpretation of the Lorentz transformation also led to testable predictions such as the contraction of bodies moving relative to the observer's frame of reference ($\sim 1/\gamma$) and the corresponding dilation of time intervals ($\sim\gamma$). Because of the closeness to 1 of the relativistic factor $\gamma = 1/(1 - v^2/c^2)^{1/2}$, however, any practical testing of these second-order effects was difficult.

The time dilation was confirmed after the discovery of unstable particles, so-called muons or μ-leptons, among cosmic rays reaching Earth. Their decay time of 2.2×10^{-6} sec is very well determined from laboratory experiments. It was also known that they are generated by impacts of protons from extraterrestrial cosmic rays with atoms in the outer regions of the terrestrial atmosphere. Even at the maximum speed, the velocity of light c, this would only allow them to travel about 0.66 km before decaying, far less than the c. 16 km needed to reach sea level. The only explanation for their abundant presence on the Earth's surface is that their decay time, invariant in their own frame of reference, had been stretched by the γ-factor of 20 or 30 relative to our frame of reference because of their extremely high speed of about $0.99c$. Similar effects of the lengthening of decay times of artificially created unstable particles could later also be observed in high-energy physics experiments, where muons were accelerated in a circular accelerator ring to 99.7% of c. The observed 12-fold increase in their lifetimes agreed with relativistic predictions to an accuracy of 2% in the first measurement of this kind at CERN in 1966. The reliable measurements of particle velocities and decay times make these tests today among the best means to test the special theory of relativity.[10]

3. On $E = mc^2$

Einstein's mass–energy relationship, $E = mc^2$, has probably become the most famous equation in physics. When he derived it in 1905, Einstein suggested that it might be testable by measuring changes in mass after the decay of radioactive substances, such as radium salts.[11] Two years later, Max Planck pointed out that the loss of mass of one gram mole of radium within one year of decay would be too small to be measured by the limited techniques then available. It took another 25 years until the relation could be directly confirmed experimentally.[12]

In 1937, a German review article on the issue could conclude that the equivalence of mass and energy had turned into 'an empirically-based fundamental law of physics'.[13]

[10] On the preceding see Rossi *et al.* [77,78] and further references in Marder [65, Sec. 2.7 and Chap. 5].

[11] See Einstein [24], especially towards the end of the short note (p. 71 of the English translation).

[12] On the rather intricate story about Bainbridge's realization that Cockroft and Walton's experiment actually afforded a direct test of Einstein's formula, see the excellent survey article of Stuewer [86] and refs therein.

[13] See Braunbek [6, p. 11]; on Fritz Hasenöhrl's 1904 paper and on alternative interpretations of mass–energy equivalence within classical physics see e.g. Lenard [63, pp. 510 ff., 549 ff] and the editor's critical comments on pp. 366–369.

Even though Einstein's name was not once mentioned in this article, the validity of his formula could no longer be denied, even in Nazi Germany. Further tests of the special theory of relativity arose from combining it with quantum theory in what is called quantum electrodynamics (which is beyond the scope of this chapter). As far as the mass–energy equivalence is concerned, special relativity can be regarded as one of the most reliably confirmed theories of modern physics.

4. General Remarks about Experimental Tests of General Relativity

Even more so than special relativity, general relativity is exceedingly difficult to verify, as all relativistic effects deviating from Newtonian gravitational theory are proportional to GM/c^2R, with G the gravitational constant, c again the velocity of light, and M the mass of the body massive enough to create curvature effects in space–time, R the distance from it. On the surface of the Sun, this factor equals 10^{-6}, on the surface of the Earth it is just 10^{-9}, and on the surface of a ten-ton block of aluminium it is 10^{-22}. Only for exotic astronomical objects, such as black holes, does this factor approach unity, but experimenters too close to black holes would have other problems. For all terrestrial experiments and astronomical observations within our solar system, the relevant solution of Einstein's gravitational field equations is the one published in 1916 by the astronomer Karl Schwarzschild (1873–1916), valid for the spherically symmetric space around a mass point or a spherically shaped fluid in space such as the Sun (cf. Chap. 5, §15).

$$ds^2 = -\frac{dr^2}{1 - 2m/r} - r^2\left(d\Theta^2 + \sin^2\Theta\, d\phi^2\right) + \left(1 - \frac{2m}{r}\right)dt^2.$$

The main features of this solution in terms of experimentally testable effects (all of which will be dealt with in detail below) are: (i) a redshift of spectral lines, (ii) a light deflection of twice the amount as derived from Einstein's 1911 Prague theory (cf. below), (iii) a perihelion motion of Mercury of about 43", and (iv) a time delay for signals passing close by the Sun. Also note that the system has a coordinate singularity at $2m/r = 1$, i.e. for the radius r equalling the so-called 'Schwarzschild radius' $r \cong 2m$ in natural units of measure ($c = 1$) and a true singularity at $r = 0$. For a long time this was regarded as a mere mathematical artifact, but the work of Subrahmanyah Chandrasekhar, Robert Oppenheimer and Hartland Snyder and (later) Stephen Hawking (all beyond the scope of this chapter) has shown that such singularities should be interpreted as black holes: collapsed systems of extremely compressed mass cause the formation of singularities in space–time from which no material body, not even a light ray, can escape.

Aside from Einstein's general theory of relativity and gravitation, about 25 alternative theories of gravitation were proposed between 1905 and 1960. In order to relate the many different types of experiments to these theories, the so-called parametrized post-Newtonian (PPN) formalism was developed. It contains a set of about 10 parameters to describe any conceivable metric theory of gravitation in its respective post-Newtonian approximations. With most of them already excluded by experiment, Einstein's theory has so far withstood every test.[14]

[14]For surveys of the PPN formalism see Thorne and Will [89], Will [93], Misner *et al.* [69, pp. 1068 ff], Will [95, pp. 86 ff]. For updates on the limits on the ten PPN parameters set by various experiments, see Will

5. Equality of Inertial and Gravitational Mass

In Newton's *Principia*, inertial and gravitational mass appear as separate entities, one of them endowed with the strange property to resist all changes of motion (inertia), the other responsible for the mutual attraction of two masses according to Newton's inverse square law. Newton was aware of this duality and actually tested the equality of these two types of mass in experiments involving pendulums consisting of empty containers into which various materials of identical weight could be mounted. The resulting periods seemed not to depend on the material composition, thus confirming his assumption of the equality of mass and weight to one per mille. Friedrich Wilhelm Bessel (1784–1846) improved upon Newton's accuracy by a factor 10 in 1832, and in 1923 this rose to a factor 100.

Further advances had to await a different type of instrument: a special torsion balance designed by the Hungarian geophysicist Baron Roland von Eötvös (1848–1919).[15] Basically this consisted of two weights suspended at the two ends of a horizontally hung rod, isolated from vibrations. Because of the Earth's rotation, two different forces act on these two masses: gravitation, pulling both of them downward, and a centrifugal force pulling the masses away from the axis of the Earth's rotation. Even though this centrifugal force is about 470 times smaller than gravity, it leads to a considerable tilting of the angle of the suspended masses against the vertical. If inertial and gravitational mass were not exactly equal, the centrifugal force would act differently on these two masses and a small torsion would emerge, tilting the horizontal bar along the vertical axis. Turning the whole set-up by 180 degrees would make the torsion act in the other direction, thus enabling a highly sensitive null experiment. By comparing the torsion in both orientations, the torsion should cancel out only if the equality of inertial and gravitational mass is valid.

In several series of measurements between 1889 and 1920, Eötvös and his colleagues Desidirius Pekár and Eugene Fekete carried out this test using various materials, including copper, water, asbestos, aluminium, etc., and did not find any anomalous torsion. Thus they concluded that both types of masses were identical at least up to a few parts at 10^8. Even though Einstein only learned about these experiments in 1912, he often cited them as confirmation of his principle of equivalence which he first expounded in 1907.

The Eötvös experiments set the standard for this type of test for roughly 50 years. It was only in the early 1960s and 1970s that two groups of experimentalists managed to achieve even higher accuracy.[16] They replaced terrestrial gravitation and the centrifugal force exerted by the Earth's rotation around its axis by its attraction towards the Sun and by the force induced by the Earth's motion around the Sun. This had the advantage that experimenters did not have to turn the balance since that was automatically achieved by the Earth's axial rotation, thus allowing the whole apparatus to be mounted in a vacuum with sensitive temperature and optical control systems in place. The group led by Robert H. Dicke (1916–1997) at Princeton University achieved an accuracy of $1 : 3 \times 10^{11}$, while a Russian team headed by Vladimir Braginski (*1931) claimed to have reached $1 : 10^{12}$.

[95, pp. 204 ff], [99,100], [101, p. 546]. On measurements of the Newtonian gravitational constant, see Gillies [45].

[15] On the following, see Eötvös *et al.* [37] and the earlier literature cited therein.

[16] See Dicke [15], Braginski in Bertotti (ed.) [3], Will [95, pp. 24 ff] and [97, Chap. 2 with clear diagrams].

In the second half of the 1980s, a reanalysis of Eötvös's data led Ephraim Fishbach and a few others to claim that certain residuals in these data could be understood as indicating a fifth fundamental force in nature, having a strength in between the long-range gravitational and electromagnetic forces and the ultra-short-range weak and nuclear strong forces, and a range of a kilometre or less.[17] Fishbach's reanalysis of Eötvös's data seemed to indicate that there was a correlation between differences in acceleration of various test bodies on Eötvös's balance and their respective baryon-number-to-mass ratio. Unlike gravity, which acts similarly on all masses regardless of their (sub)atomic composition, a repulsive fifth force would cause an acceleration depending upon baryon number or isospin, that would vary with the material and thus violate the principle of equivalence. But subsequent experiments carried out at various locations with very sophisticated torsion balances showed no evidence for the fifth force, down to a level of $1/1000$ and less. Nor did such a fifth force show up in Galilean-type experiments with falling masses of different compositions in a high-vacuum chamber. Ultimately, the preponderance of negative evidence with increasing constraints on the strength of such a fifth force at one hundred-thousandth of the strength of gravity led to the rejection of such an additional force of nature by the scientific community.

The Einstein equivalence principle (EEP) has been differentiated into a number of closely related assumptions.[18] One of them, the weak equivalence principle (WEP), states that test bodies fall with the same acceleration independently of their internal composition and is thus verified by the Eötvös-type experiments just discussed. It can also be put as follows:

The outcome of any local non-gravitational experiment is (i) independent of the velocity of the freely falling reference frame in which it is performed (that is local Lorentz invariance, LLI), or: the outcome is (ii) independent of where and when in the universe it is performed (local position invariance, LPI).

The EEP has been shown to be at the core of general relativity in the sense that, once valid, it implies that gravitation must be described by *metric* theories of gravitation, hence ruling out many competing, non-metric theories. Another consequence of Einstein's EEP is gravitational redshift, discussed below.

6. Gravitational Redshift

Minute shifts of solar spectrum lines, as compared with the position of these same lines in terrestrial emission spectra, had already been observed by Lewis E. Jewell, the personal assistant of Henry A. Rowland (1848–1901) at Johns Hopkins University in Baltimore around 1890. While Rowland himself tried to explain them away as a mysterious artefact of his newly invented concave gratings, Jewell persevered and proved they were real.[19]

Even though gravitational redshift is one of the simplest consequences and also, historically speaking, the first that Einstein derived, in 1907, just from the principle of equivalence as opposed to the full field equations of 1915, it remained one of the most difficult effects to test empirically. The reason is that in the solar spectrum this gravitational shift of spectral lines is superimposed by many other physical effects also leading

[17] On the following see e.g. Will [97, 2nd ed., 1993, Chap. 11], and Franklin [41].

[18] For a survey of the various versions of EEP see e.g. Haugan [47].

[19] See Hentschel [52], [56, Chaps 2–3], where I also discuss the early interpretations of these spectrum shifts.

to shifts in varying amounts, such as Doppler shifts induced by convection currents in the convective layer of the solar atmosphere, scattering and pressure effects. With other astronomical objects it is hard to discriminate between redshifts induced by gravitational fields and those originating from a motion of the object away from the observer, such as cosmological redshift (proportional to the object's distance according to Edwin Hubble's law of 1929).

When Einstein's astronomer Freundlich tried to find redshift in stellar spectra based on statistics in 1915/16, this cosmic expansion (another effect of general relativity dealt with in Chapter 6 of this volume) was not yet known, so he was bound to fail. The first efforts to find gravitational redshift in the solar spectrum were fraught with problems. They were expected to amount to a relative shift of 2×10^{-6} (i.e., a mere 0.01 Å difference for spectral lines in the visible range of the spectrum when compared against terrestrial spectra).[20] From 1919 to 1922, Einstein supported the efforts of two physicists from Bonn, Albert Bachem (1888–1957) and Leonard Grebe (1883–1967), to explain away the discrepancies with his predictions as due to unresolved fine structure or to stronger neighboring spectrum lines, but their photometric work remained inconclusive.[21] In the US, the spectroscopist Charles Edward St John (1857–1935) invested several years of work in a thorough search for redshift in the solar spectrum. His results from 1917 until 1921 were mostly negative (as was his predisposition against relativity theory), but in 1923 he announced that the more extensive data sets he had subsequently analysed seemed to speak in favour of gravitational redshift in the amount predicted by Einstein since 1907.[22]

The first non-controversial confirmation of gravitational redshift eventually came from Robert V. Pound (*1919) and his assistant Glen A. Rebka from a terrestrial experiment performed in 1959. They utilized the recently discovered Mössbauer effect, a recoil-less emission of low-energy gamma rays, to measure the minute frequency shift of 2.45×10^{-15} of a 14.4 keV gamma ray falling in the Earth's gravitational field at the 22.5 m elevation of the Harvard Jefferson Laboratory.[23] Soon afterwards, James William Brault (*1932) also managed to validate gravitational redshift of the strong D_1-line of sodium in the solar spectrum using a newly developed photoelectric spectrometer with its slit vibrating mechanically back and forth across a narrow region of the spectrum. That way, the position of the line peak was defined independently of subjective judgment and with a precision improved by a factor of 10 over conventional visual methods. He chose the sodium line because it was known to be emitted high in the Sun's atmosphere, above the regions strongly disturbed by pressure and convective shifts, yet deeper than the chromosphere.[24]

When Josef Carl Hafele (*1933) and R.E. Keating made a comparison of caesium atomic clocks at different altitudes in 1971, they actually measured a complex com-

[20] On the following, cf. Hentschel [56] for a detailed analysis of seven decades of work toward understanding the slight shifts in the solar spectrum when compared against terrestrial emission spectra.

[21] For a study on this photometric analysis see Hentschel [1992a].

[22] On this spectacular about-face of an experimenter against his own predisposition see Earman and Glymour [17], Hentschel [51].

[23] See Pound and Rebka [73]; in a refined experiment of similar type, Pound and Snider [74] verified gravitational redshift with an accuracy of less than 1%; for details cf. also Pound [72], Misner *et al.* [69, pp. 1056–1058], Hentschel [54, pp. 270 ff], [56, pp. 682–701] (also on parallel endeavours by the British team of J.P. Schiffer and W.C. Marshall and others).

[24] See Brault [5], Misner *et al.* [69, pp. 1058 ff], Hentschel [54, pp. 281 ff], and [56, Sec. 11.3, pp. 703 ff].

posite effect of gravitational redshift (proportional to the differences in altitude ranging up to the 10,000 m reachable by the commercial jet aircraft of the time) and the kinematic time dilation of special relativity (proportional to the velocity of the jet relative to our terrestrial inertial frame). Because of the Earth's rotation, the velocity differs for west-bound and east-bound flights, so they decided to take two round trips, one in each direction, and compare the resulting time gains of the flying clocks against an identical one stationed on the ground.[25] For both directions, the observed time gains, e.g., $(273 \pm 7) \times 10^{-9}$ sec for the westward direction, could be fully accounted for by the kinematic correction in the special theory of relativity $(96 \pm 10) \times 10^{-9}$ plus the gravitational redshift $(179 \pm 18) \times 10^{-9}$. As an aside: given the simple instrumentation needed for this experiment, this was likely the cheapest high-precision test of relativity theory ever conducted. An improved variation with atomic clocks carried in aircraft tracked by radar and with laser pulse time comparison was performed between May 1975 and January 1976 by Carrol O. Alley and collaborators from the University of Maryland together with Hewlett-Packard and support from the US Navy.[26] The measured effect related to the calculated effect as 0.987 ± 0.016. Further improvement beyond this 15% confidence level was only possible by altering the experimental design. Robert F.C. Vessot and Martin W. Levine (both from the Center for Astrophysics at Harvard College Observatory) used a space-bound portable version of a hydrogen maser as a clock, to be compared with two identical stationary oscillators on Merrit Island, Florida, at a precision of 1 to 1 billion. The maser was mounted on a Scout D rocket, propelled to an altitude of 10,000 km and then decoupled from the rocket and subjected to free fall. By 1976 – after two years of data reduction and systematic elimination of Doppler effects of the clock on its ballistic trajectory from Wallops Island to a spot in the Atlantic Ocean east of the Bermuda islands – the two Cambridge astrophysicists were able to say that the observed redshift was equal to that predicted by the equivalence principle $\pm 2 \times 10^{-4}$. By 1980 they improved their data analysis to an agreement of 70×10^{-6}, including the final parts of the trajectory.[27]

If gravitational redshift is accepted as a real effect, it can serve as a tool to determine the mass of the system emitting radiation. In the earliest such study, Walter Adams (1876–1956) from Mt Wilson Solar Observatory, measured the redshift of the H_β line of hydrogen in the spectrum of Sirius B, a strange companion of Sirius with very low luminosity. Its faint spectrum indicated that it was a white-hot star, and Eddington came to believe that Sirius B was a very dense star, a so-called white dwarf. Adams's measurement of the redshift made it possible to calculate its mass. At the time this was highly controversial because gravitational redshift still remained to be verified.[28] While Einstein's formula for the dependency of gravitational redshift on the differences of gravitational potential remained unscathed, Adams's spectroscopic measurements – indicating an average redshift equivalent to a Doppler shift of 19 to 21 km/s – did not. In the late 1960s, new measurements of Sirius B's gravitational redshift yielded over 80 km/s, with an estimated error of no more than 16 km/s. Retrodictive adaptation of the relativity theory to the new finding was easy: one just had to lower the estimated radius of Sirius

[25] See Hafele and Keating [46].

[26] On the following see Alley [2, pp. 17–26].

[27] See Vessot and Levine [91], Vessot *et al.* [92] and Alley [2, pp. 26 ff].

[28] See Adams [1] and Hetherington [57] for a historical analysis of this interesting case.

B and thus increase its mass density accordingly, but what went wrong in Adams's very careful earlier measurements could never be clarified satisfactorily.

7. Light Deflection

In 1911 Einstein also predicted the deflection of starlight by heavy masses like the Sun. Because of light scattering, this minute effect could only be observed during an eclipse when the brilliant solar disk is obstructed by the Moon and stellar images near the solar rim become visible. Einstein's Prague theory of 1911 predicted a shift of $0.85''$ for light rays grazing the solar rim, which decreased by $1/r$ as the distance r from the Sun increased.[29] This effect was derived from the assumption of equality of inertial and gravitational mass according to which light with energy E should also have a mass $m = E/c^2$ and thus be attracted to the Sun like any other small test body. As a matter of fact, in the late eighteenth and early nineteenth centuries similar quasi-ballistic calculations had already been carried out by Henry Cavendish and Georg von Soldner on the basis of Newton's particle theory of light, but both had only verified that the resulting effect would be too small to observe with contemporary visual observation techniques. When Einstein's papers drew attention to this issue again, rabid anti-relativists intent on charging Einstein with plagiarism dug up the much older papers from 1921 – overlooking Einstein's totally new approach to the question.[30] Einstein's Prague theory still comprehended a pseudo-Euclidean space–time, with the gravitational potential $\Phi = -GM/R$ replaced by the velocity of light as a new scalar potential $c = c_0 + \Phi/c^2$, so the deflection of the light rays near the Sun could also be interpreted as a minute change in the refractive index $n = c/c_0 = 1/(1+\Phi/c^2) \sim 1-\Phi/c^2$, with $\Phi < 0$. But efforts to find this minute shift in stellar positions on existing eclipse photographs were in vain. A new chance to take more photographs with this specific purpose in mind came with the eclipse of 1914. The Berlin astronomer Erwin Finlay Freundlich prepared to go on an expedition to the Crimea that summer, but their team unfortunately got detained as potential spies at the outbreak of World War I. By November 1915 Einstein had found the correct field equations for his general theory of relativity and gravitation, which yielded a light deflection of $1.75''$ for stellar rays just grazing the solar rim, decreasing as $1/r$ with increasing distance r of the star position from the solar rim. This new prediction is approximately twice that of the Prague theory because the old prediction was augmented by a contribution from the curvature of space induced by the solar mass, an effect not accounted for in the earlier theory.

Even though England had been cut off from official academic exchange with the Continent since 1914, news of the interesting effect reached the Dutch astronomer Willem de Sitter (1872–1934), who privately passed on copies of Einstein's papers to his British colleagues and then wrote a widely read survey article, 'On Einstein's theory of gravitation and its astronomical consequences'. In 1917, the Astronomer Royal Frank Watson Dyson (1868–1939) drew attention to the fact that 29 May 1919 would be an exceptionally good opportunity for testing Einstein's theory, as the image of the Sun would be in the richly populated region of the Hyades full of bright stars which would be visible

[29] See Einstein [26, p. 908]; cf. also Earman and Glymour [18] and Hentschel [55] on the early reception.

[30] For the classical derivations see Jaki [59], Will [98] and Eisenstaedt [36]; on the later anti-relativist plagiarism charges issued foremost by the anti-Semite Philipp Lenard, see also Hentschel [48, pp. 155–161, 570].

during an eclipse even against the solar corona. Arthur Stanley Eddington (1882–1944) was keen to lead an expedition to one of the two remote places expected to have good visibility conditions: Principe Island in the Gulf of Guinea on the West African coast, or Sobral in Brazil. Being a Quaker, Eddington was a conscientious objector, so the option to send this distinguished scientist on an expedition provided the authorities with a face-saving alternative to internment, which would otherwise have been unavoidable.[31] But the day of the eclipse was overcast on Principe where Eddington and his assistant Cottingham went, so several of his photographs did not show any stellar images at all. One, however, did permit tracing about a dozen star images through the clouds. A comparison of this photograph with one of the same region taken without the Sun supported Eddington's claim of a systematic deflection of the stellar positions with the extrapolated value at Principe being $1.61'' \pm 0.30''$. Thus the quasi-Newtonian scalar-potential models were excluded. The observational estimate agreed with Einstein's modified prediction of late 1915.

Another British expedition headed by Andrew de la Chérois Crommelin (1865–1939) and Charles Rundle Davidson (1875–1970) had been sent to Sobral, where the weather was perfect. It was found, though, that the focal length of the astrograph had changed due to the rapid temperature differences during the eclipse. Thus the stellar images on all 16 photographs were blurred and it was only with great difficulty that they could arrive at an estimate for the light deflection of $0.93'' \pm 0.05''$. The seven photographs from another coelostat in Sobral yielded $1.98'' \pm 0.12''$, hence slightly larger than Einstein's prediction but of the right order of magnitude.[32]

Despite considerable difficulties in the reduction of the data and the problematic weather conditions under which these data were collected, they were advertised as a decisive confirmation of Einstein's theory of gravitation. On 6 November 1919, immediately after the official presentation of these findings at an overcrowded joint meeting of the Royal Society and the Royal Astronomical Society, *The Times* reported: 'Revolution in Science. Newtonian Ideas Overthrown', and other major newspapers throughout the world struck the same exuberant note. Overnight Einstein became a world celebrity and relativity a household word, which – incidentally – did not mean that people knew what they were talking about.[33]

Contrary to this public perception of a clear confirmation, the scientific debate continued. Eddington's observations remained controversial: for some, they became a model of how *not* to do an experiment. For others, 'the quality and the utility of the photographs were very carefully considered.'[34] Later eclipse expeditions likewise yielded somewhat inconclusive evidence.[35] Several expeditions were launched at the next opportunity on 21 September 1922. William Wallace Campbell (1862–1938) and Robert Julius Trumpler (1886–1956) from Lick Observatory obtained $1.72'' \pm 0.15''$ with a double astrograph

[31] For more material on this political and religious background see Stanley [85]; on the contemporary press campaign see Sponsel [83]; on earlier (failed) expeditions cf. also Earman and Glymour [18]; Brush [7] deals with the issue of prediction *vs*. retrodiction.

[32] The most detailed analysis of Eddington's data was presented in Dyson, Eddington and Davidson [16]; cf., however, also Freundlich [44] and Hentschel [53] for a critical reanalysis of Eddington's data, claiming that Eddington should rather have reported a result of $2.2''$.

[33] On some aberrations and misinterpretations of relativity theory, cf. Hentschel [48].

[34] These are quotes from Everitt [39, p. 533] and Stanley [85, p. 89], respectively.

[35] On the following see the detailed surveys provided in Mikhailov [67], *vs*. Klüber [60], Hentschel [53], [55, Chaps 9, 12], and the extensive primary literature listed there.

and $1.82'' \pm 0.2''$ with a quadruple astrograph, both set up in Wallal, Western Australia; G.F. Dodwell and C.R. Davidson from Adelaide and Greenwich obtained $1.77'' \pm 0.4''$. C.A. Chant and R.K. Young from Victoria Observatory preferred to quote separately the different results from their three plates: $1.75''$, $1.42''$ and $2.16''$. At the eclipse on 9 May 1929 in Sumatra, Erwin Finlay Freundlich was finally successful in taking careful measurements with a double coelostat, which incorporated the first independent scale checks by means of a grid projected onto the field of view. Strictly speaking, though, his result of $2.24'' \pm 0.10''$ ruled out Einstein's prediction as beyond his margin of error, and so did various other later eclipse photographs, such as Mikhailov's in 1936, yielding $2.73'' \pm 0.31''$, or van Biesbroeck from the Yerkes Observatory on a Brazil expedition in 1947, yielding $2.01'' \pm 0.27''$. In 1974, a reanalysis of all known measurements of the deflection of light using modern computing methods[36] yielded satisfactory agreement for those stars further away from the solar image, with deviations shrinking from $+0.139 \pm 0.033''$ for an average distance of 3.43 solar radii $R_\circ$, to just $+0.013 \pm 0.029''$ for $11.6 R_\circ$.

Better agreement with Einstein's general theory of relativity and gravitation could thus far only be obtained by resorting to other frequencies. Using long baseline radio-interferometric techniques for the precise localization of powerful sources of radio waves, so-called quasars, it is now possible to trace their apparent change due to the proximity of the Sun along their paths.[37] In the first such measurement in 1968, Richard Anthony Sramek (*1943) obtained an agreement of $\pm 7\%$, and in the mid-1970s, Fomalont and Sramek even obtained agreement up to $\pm 1.5\%$. By the mid-1990s, agreement had been improved to 0.9996 ± 0.0017, using Very Long Baseline Interferometry (VLBI) between the Haystack observatory and the Owens Valley Observatory in California.[38]

Furthermore, various good examples of gravitational lensing have been found. They are called such in analogy to optical lenses, with multiple, semicircular or even completely circular images of an emitter deflected by a very heavy mass positioned somewhere in the optical path between the emitter and us. While the dark heavy mass absorbs all the direct light rays, it deflects those grazing by in our direction so we see a smeared image of the same cosmic object from other directions very nearby.[39] Thus finally, gravitational deflection can also count as fully confirmed, albeit not for light, but for other forms of electromagnetic radiation only.

8. Mercury's Perihelion Motion

Kepler's laws describe the path of the planets around the Sun as perfect ellipses with the Sun at one of the two focal points. Newton's theory of gravitation with its $1/r^2$ law of attraction allowed incorporation of these Keplerian ellipses into the theory, but only for a single planet. Other bodies present in the solar system would disturb this perfect path and lead to deviations from closed ellipses, as would any deviation from the strict $1/r^2$-law. Because there are other planets nearby, Mercury's orbit deviates from a perfect

[36] See Merat *et al.* [66].

[37] On the following see e.g. Sramek [84], Fomalont and Sramek [40] and Will [95, p. 172].

[38] See Maddox [64] for references and commentary.

[39] On the earliest discovery of gravitational lensing which Einstein [34, p. 507] himself had considered to be very unlikely ever to be observed, see Chaffee [8]; for more recent examples of such gravitational lenses including a nearly complete Einstein ring, see Ehlers [23, pp. 44 ff].

ellipse, with the perihelion, i.e., the point of the orbit closest to the Sun, moving by as much as 531 arc-seconds/century around the Sun. In 1859, the French astronomer Jean Joseph LeVerrier (1811–1877) announced that there was an unresolved discrepancy of c. $38''/c$ between Newtonian theory and increasingly precise observations. By 1882, Simon Newcomb (1835–1909) had recalculated and rechecked the observations, obtaining an unresolved difference between Newtonian theory and observation of $43''/c$, which was very close to today's value of $43.11'' \pm 0.45''$.

Various alternative explanations were put forward, such as an increase by 10% in the mass of Venus, the existence of intramercurial planets or asteroids or an undetected moon of Mercury, or finally, deviations of the Newtonian $1/r^2$-law. But none of these hypotheses were fully satisfactory, in particular since each would have led to new problems and discrepancies with observations elsewhere. So the advance of Mercury's perihelion remained an unresolved, if innocuous, anomaly in the classical scheme.[40]

Einstein realized early on in his endeavour to generalize relativity and gravitation that this issue would also be affected. In 1913 one of Einstein's candidates for the gravitational field equations yielded a mercurial perihelion motion of $\sim -50''$/century, that is, even in the opposite direction from the known discrepancies between observations and Newtonian theory. In October 1915, another candidate came to $18''$, i.e. only one-third of the amount needed. But a month later his modified field equations finally produced a perihelion advance of $45'' \pm 5''$/century, just the amount needed to explain the anomaly known since half a century. (Today's calculations yield $43.03''$/century, i.e., an even better fit between theory and observation!)

In a letter to Arnold Sommerfeld dated 28 November 1915, Einstein called this surprisingly good match of his calculation with the known anomaly 'the most magnificent thing that ever happened to me' ('das Herrlichste, was ich erlebte'). Soon afterwards he wrote enthusiastically to his friend Michele Besso: 'The boldest of dreams have now been fulfilled. *General* covariance. Mercury's perihelion motion wonderfully precise.'[41] To his colleague Wander J. de Haas he even confessed that he was so excited that he was unable to work for days. Both light deflection and mercurial perihelion advance are direct effects of the slight changes of space–time metrics near large masses, but the derivation of the perihelion advance depends on the fully-fledged gravitational field equations. In this sense, it was the first test of the fully developed general theory of relativity – which might well explain Einstein's exaltation.

Later recalculations and improved observations have not substantially altered this excellent match. In the 1960s, there was some discussion about a possible discrepancy of 10% due to the effects of solar oblateness, suggested by Robert Dicke. Optical studies of the shape of the Sun by Dicke and Goldenberg seemed to confirm this in 1968, but others came to the conclusion that the optical shape of the Sun fluctuates and cannot be taken as a reliable indicator of the shape of its mass.[42] Considering this issue of solar

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[40] For a survey of the literature on Mercury's perihelion advance, see Roseveare [76].

[41] Einstein to Besso, 10 December 1915, as quoted from the *Collected Papers of Albert Einstein*, Vol. 8, English translation volume, Princeton: Princeton University Press, 1998, p. 160.

[42] For surveys of these later discussions see Everitt [39, p. 531 ff], Will [95, pp. 176 ff], [97, Chap. 5]. The editor, Marco Mamone Capria, pointed out to me that the standard textbook argument depends essentially on using, on the one hand, Newtonian physics for the n-body perturbative calculation of the $531''$ observed secular advance, and on the other hand, the relativistic one-body spherically symmetric Schwarzschild solution for the residual $43''$. Some theoreticians, such as J.L. Synge [88, pp. 296 ff], find this schizophrenic approach to save the phenomena 'intellectually repellent', but the scientific community at large has no problem with it.

oblateness still remains to be resolved definitely, one of the leading experts, Clifford Will from the McDonnell Center for Space Science at George Washington University in St Louis summarized the situation with respect to Mercury's perihelion motion: 'It is ironic that after seventy years, Einstein's first great success remains an open question, a source of controversy and debate.'[43]

9. Other Non-standard Tests of General Relativity after 1960

9.1. The Time-Delay Measurement

In 1964, Irwin I. Shapiro (*1929) pointed out that light passing by a very heavy body such as the Sun is not just deflected (see above) but also slightly delayed. This can best be understood on the basis of Einstein's Prague theory with its Ansatz for the change of the velocity of light (slowing down in the proximity of large masses, hence taking more time). Measurement of this time delay became feasible with sophisticated radar ranging techniques that have been available since the early 1960s. Shapiro's paper inspired a series of very successful measurements of time delays in radar echos from Mercury, Venus and Mars, all showing a clear maximum when the Sun's orbit is closest to the line connecting Earth and Venus.[44] Because the delay time amounts to no more than about 200 microseconds for echo signals from Venus travelling for about half an hour before reaching Earth, these determinations have to be exact to 10^{-7}: an impressive achievement. With the landing of the Viking probes on Mars in 1976, a new climax was reached for time-delay measurements because the unmanned stations, designed to work for 90 days on Mars, actually functioned for several years. The most recent test of this time delay used multi-frequency radio links with the Cassini spacecraft during a solar conjunction in 2002. By overcoming the solar plasma noise, Bertotti and his Italian co-workers reached a sensitivity approaching the level sensitive to deviations from some non-standard cosmological models inspired by string theory. The prediction of general relativity is now confirmed up to a factor $1 + (2.1 \pm 2.3) \times 10^{-5}$.

9.2. The Gyroscope Experiment

This experiment was devised in 1959 by the theoretical physicist Leonard Isaac Schiff (1915–1971) and implemented by some of his experimentalist colleagues at Stanford University.[45] The underlying idea is to measure the precession of a gyroscope's spinning axis relative to the distant stars as the gyroscope orbits the Earth. General relativity implies two minute effects pertinent to such an orbiting gyroscope: a geodetic precession as a consequence of the curvature of space near gravitating bodies, and the so-called Lense–Thirring effect, a kind of dragging of inertial frames by rotating masses. Both these consequences of general relativity had been known about for a long time. The first was pointed out by Willem de Sitter in 1916 in one of the earliest surveys of experimental consequences of general relativity. The second dates back to a paper by Austrian physicists Josef Lense and Bruno Thirring in 1918. But measuring a tiny perturbation of the

[43] Will [97, p. 107].

[44] See e.g. Shapiro [81], Shapiro *et al.* [82], Reasenberg *et al.* [75], Will [97, Chap. 6] and Bertotti *et al.* [4] for the latest measurement.

[45] See e.g. Schiff [80], Misner *et al.* [69, pp. 1117 ff], Fairbank *et al.* in Bertotti (ed.) [3], Everitt [38], [39, pp. 535 ff], Will [95, pp. 208 ff], [97, Chap. 11], Everitt *et al.* in Lämmerzahl *et al.* (eds) [61].

orbit caused by the spin of the attracting body only became feasible with the availability of satellites and sophisticated techniques of stabilizing gyroscopes (pushing the limiting drift rate below $0.001''$/year) in the wake of their use in guidance systems for rockets and submarines after World War II. In the terrestrial gravitational field, the disturbing influences on the gyroscope would be far greater than the few arc-seconds precession per year that have to be measured. In outer space, further from gravitating masses, it is barely feasible to measure the net effect of $6.9''$ geodetic precession per year of a gyroscope orbiting the Earth about 5000 times a year at an altitude of a few hundred kilometres. Even the smaller inertial dragging effect, amounting to no more than $0.1''$ or even only half that per year might be possible, depending on the orientation of the gyroscope and its orbit relative to the Earth's spinning axis.[46] The Stanford implementation of this idea consists of a set of four gyroscopes, each constituting a perfectly spherical ball about 4 cm in diameter made of optically selected fused quartz and coated with a thin film of superconducting niobium. The ball is electrically suspended and initially spun up to a speed of about 12,000 revolutions per minute by gas jets, then the gas is pumped out and the ball is allowed to spin freely in a vacuum. The direction of its spinning axis is read out by a very sensitive SQUID (superconducting quantum interface device) magnetometer, and any unforeseen sources of error are cross-checked by four identical gyroscopes side by side. This experiment, called Gravity Probe B, is currently undergoing final testing prior to launch: its weekly progress can be followed at http://einstein.stanford.edu.

9.3. The Nordtvedt Effect

Like all planets, the Earth is held together by gravitational forces. From the equation $E = mc^2$, it is possible to calculate a gravitational self-energy of the Earth, corresponding to 1 part in 10^9 of its mass. In 1968, Kenneth L. Nordtvedt (*1939) realized that in certain gravitational theories satisfying the principle of equivalence in the ordinary sense, the Earth–Moon system would violate this principle. An empirically testable consequence would be a bimonthly oscillation in the distance between the Earth and Moon that might be as large as 10 m according to the Brans–Dicke theory. Laser ranging measurements between the Earth and the Moon would make such oscillations traceable, but thus far no such effects have been found.[47] This implies the equivalence of gravitational and inertial mass for the different materials of the Earth and Moon to a few parts in 10^{11}, a level of accuracy nearly as high as that reached by Dicke, Roll and Krotkov in the 1960s in laboratory experiments testing the principle of equivalence for gold and aluminium (see §5 above).

10. Gravitational Waves

Like all other signals and forces, gravitational action can only propagate with the velocity of light. According to Einstein's theory, gravitational waves as emitted by rapidly changing mass–energy distributions in space–time – for example, by collapsing stars – would propagate as disturbances in the space–time metric with properties somewhat similar to

[46] For a clear exposition of the Lense–Thirring effect, see Lämmerzahl and Neugebauer in Lämmerzahl *et al.* (eds) [61]; on its recent confirmation within 10% of what is predicted by Einstein's general theory of relativity (±20% total error), by means of two laser-ranged satellites, LAGEOS I and II, see Ciufolini *et al.* [9].

[47] See e.g. Nordtvedt [70], Nordtvedt in Bertotti (ed.) [3] and Will [95, pp. 185 ff], [97, Chap. 7].

radio waves emitted by oscillating charges. Einstein's first paper on gravitational waves dates from 1918,[48] yet no efforts were made to detect these feeble ripples in space–time before the pioneering investigations of Joseph Weber (1919–2000) began in 1959.[49]

Weber's idea was to suspend a large aluminium bar, about five feet long and over two feet in diameter, and measure any mechanical oscillations of this bar by attached pyroelectric strain gauges capable of detecting changes in length as small as 10^{-14} cm. These piezocrystals would translate any deformation into an electric signal. Just as electric oscillations are induced in a radio antenna, such an aluminium bar would exhibit mechanical vibrations if – and that is a big if – its eigenfrequencies happened to resonate with the frequency of the incoming gravitational wave. Since gravity waves emitted from terrestrial objects would be far too weak to be detectable, Weber's only hope were large signals from huge cosmic objects undergoing catastrophic changes in shape and mass radius, because such events would emit the most intense gravitational waves. Besides anti-vibrational mountings for these devices to reduce even further the likelihood of accidental signals, Weber installed two gravitational wave antennas 1000 km apart, one at the Argonne National Laboratory near Chicago and the other at the University of Maryland, limiting his search to simultaneous oscillations. Against all odds, Weber was able to announce statistically significant events in 1968: pulses reportedly occurring several times a day and originating from near the centre of the galaxy.

However, many attempts to replicate Weber's findings, even with improved designs that ought to have had a much higher sensitivity, carried out between 1970 and 1975, could not confirm his findings. More troublesome still is the fact that the other teams did not even manage to interpret these events in Weber's own data. Their computer programs for data analysis apparently differed on significant assumptions about the shapes of the signal and background and on the algorithmic strategies to isolate the signal. When Weber analysed data provided to him by other teams, he again found significant correlated events, only to learn later that the assumptions about the time zones in which these two sets of data were taken were incorrect: his candidates for correlated events were actually measurements taken hours apart – thus revealing a certain in-built tendency in his programs to 'find' events too easily. The sociologist of science Harry Collins has claimed that this stalemate exemplifies what he calls the 'experimenter's regress', i.e. a kind of vicious circle between theoretical assumptions built into an experiment and the instruments used in it, and the results you get with that set-up. But other historians and philosophers of experiments, such as Allan Franklin, have argued that there are strong neutral strategies available for testing the reliability of such results, and that these were effective in Weber's case, as in others.[50]

Even with the second generation of gravitational-wave antennas similar to Weber's aluminium bars, but more sensitive by a factor of 1000 to 10,000, no one has yet succeeded in finding direct evidence for gravitational waves. Detectors (such as GEO600) working with laser detectors and laser interferometry had problems with ground vibrations but are now in the sensitivity range of 10^{-22}–10^{-23} $\mathrm{Hz}^{-1/2}$. Other projects searching for very low-frequency gravity waves by radar ranging to spacecraft have thus far

[48] See Einstein [33] and Einstein and Rosen [35].

[49] For surveys of gravitational wave physics, see Misner *et al.* [69], Will [95, pp. 221 ff], [97, Chap. 12].

[50] On this controversy see Collins [10, Chap. 4] (mostly based on interviews) [11] and Franklin [42], also quoting the pertinent primary literature by Weber and the many teams that set out to check his results.

also yet to report positive results.[51] However, we do have good indirect evidence for the existence of gravitational waves originating from the energy loss of a certain binary pulsar labelled PSR 1913+16, which was discovered by Joseph H. Taylor (*1941) and Russell A. Hulse (*1950) in 1974. Soon after their discovery of this strong radiowave emitter, they realized that its pulsation period changed periodically. This could be interpreted as Doppler shifts due to orbital motion of the pulsar about a dark, but heavy, companion. Continuous radio tracking of this binary star allowed its orbital parameters to be calculated so precisely that it became clear that this system was continually losing energy. In December 1978 Taylor published a measurement of the rate of change of the orbital period of $-(2.425 \pm 0.010) \times 10^{-12}$ sec, which was fully consistent with the prediction of gravitational radiation damping in general relativity. This finding constitutes excellent indirect evidence for the existence of such gravity waves; the best we have to date. The Nobel Prize Committee must have thought so, too, since they awarded the 1993 Nobel prize to Taylor and Hulse:[52] the latest physics Nobel prize awarded in the field of experimental tests of general relativity, which has long since ceased to be 'a theorist's paradise but an experimenter's hell'.

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