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Early Astronomical Tests of General Relativity: the anomalous advance in the perihelion of Mercury and gravitational redshift

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There were three astronomical tests of general relativity. Besides the gravitational bending of light, there were the anomalous advance of the perihelion of Mercury and gravitational redshift. The early history of these latter two tests is addressed here. For Mercury, data for its position were obtained principally from transit phenomena. Le Verrier was the first to account for the known perturbation effects on the elliptical orbit of Mercury and calculated an unexplained discrepancy. This was supported by Newcomb who revised the figure. With the use of his general theory of relativity, Einstein appeared to calculate this disagreement from Newtonian principles. Yet, other avenues needed to be explored before an acceptance of general relativity as a reasonable paradigm. This is part of a more general query of when should scientists endorse a theory.

For the test of the redshift of radiation in the presence of a gravitational field, support for this phenomenon followed a winding route. Many factors, which could contribute to the redshift of spectral lines needed to be nominated, and their individual contribution, if any, had to be teased from the rest. Very small measurements had to be effected. This situation received some respite when measurements moved from the Sun to large mass objects such as white dwarfs which theory suggested should have a much larger redshift. 1928 was taken as the year in which the results could be interpreted as supporting general relativity. However, developments opened up subsequently and further confirmation has continued to the present day. The story is threaded with a theme that new ideas in science follow anything but a straightforward course and that real history is much more interesting.

1 Introduction

The General Theory of Relativity reached its climax in the publication by Albert Einstein (1879-1955) in 1916. There were three astronomical tests which could lend support to the new world picture: the amount of bending of starlight as it passes the Sun, the anomalous advance of the perihelion of Mercury and the gravitational redshift of light from the Sun.

Storytelling involving scientific advances appears to present a simplistic rendering of events. The retelling of Archimedes rushing from his bath naked into the street shouting "Eureka!" captures the imagination of a scientist achieving an inspirational idea and all falls into place. Yet, the history of science is anything but a spontaneous breakthrough and ready acceptance by the scientific community.

The 1919 British total solar eclipse is hailed by biographers as confirmation of Einstein's ideas. A comprehensive account of Einstein's life and science by Pais gives the public reaction to this event but does not pursue the continuing scientific path before acceptance [1]. A strong case can be made that it was the 1922 total solar eclipse in Western Australia and the final publication in 1928 by the Lick Observatory that provided the clinching argument. The same mythology of the 43" per century for the unaccounted for advance of the perihelion of Mercury arising from Einstein's concepts with immediate acceptance is far from the truth.

This paper treats the second and third astronomical tests, namely the orbit of Mercury (sections 2-6) and the gravitational redshift (sections 7-14). It investigates the history of scientific understanding regarding the orbit of Mercury and how its accurate fitting provided key support for Einstein's revolutionary concept of general relativity. The questions scrutinised are at what point was there enough evidence for scientists to endorse this theory and was there a premature acceptance of general relativity? For the gravitational

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redshift, the aim is to show the tortuous route followed by any new idea in Science before the majority of scientists are swayed to accept it.

2. Transits of Mercury

Johannes Kepler (1571-1630) completed the Rudolphine Tables in 1623 based on what are now known as his three laws of planetary motion. These tables were printed in 1627 [2]. From these indices, in 1630, Kepler published ephemerides for the years 1629-39. As a result he predicted a transit of Mercury for 07 November 1631. Having died in 1630, Kepler did not witness the transit. The Mercury occurrence was noted by Pierre Gassendi in Paris. It was 4 hours 49 minutes and 30 seconds ahead of Kepler's prediction. There was an error of 13' in longitude and 1' 5" in latitude. As a comparison, tables reliant on Ptolemy and Copernicus were typically out by 5° [3]. Gassendi was, for a while, unsure whether he was observing a transit or sunspot as the black dot was estimated by him to be 20". From the movement across the Sun over several hours, Gassendi was convinced he witnessed a transit. His value was on the high side as at inferior conjunction, Mercury's apparent diameter is 11".0. Importantly, the transit allowed astronomers to correct Kepler's elements of Mercury, with the inclination of the orbit to the ecliptic and the position of orbital nodes in particular being measured with greater accuracy than before [4].

The aim of planetary positional astronomy is to describe six Keplerian elements with respect to the mean ecliptic and equinox at a set epoch and the rate of change of these quantities over an extended period of time. The fundamentals are ***a*** the semi-major axis distance, ***e*** the eccentricity, (these two describing the size and shape of the orbit), ***i*** the inclination of the planetary orbit to the ecliptic measured at the ascending node, **Ω** the longitude of the ascending node measured as an angle from the March equinox in the direction of motion of the planet, (the latter two components define the orientation of the orbital plane of the ellipse), ϖ the longitude of perihelion is a compound angle measured as the heliocentric longitude along the ecliptic to the planetary node and thence along the orbit to the perihelion point and ***L*** the mean longitude at a set epoch.

In order for these values to be determined for Mercury, observations of meridian transit coupled with transit timings across the face of the Sun need to be accumulated over a significant period of time. Also, as Mercury does not have a moon, a determination of its mass was performed in the first half of the nineteenth century from perturbations on the comet 2P/Encke [5].

Transits of Mercury exhibit a recurring pattern. At the present time, all transits of Mercury fall within several days of May 07 (descending node) and November 09 (ascending node) when Earth has the same heliocentric longitude as that of Mercury, 228° and 48° respectively [6]. In 2013, the perihelion and aphelion dates for Mercury were 16 May and 21 December. Thus, for May transits the planet is near aphelion (257°), so its slower orbital motion at 38.9 kms^{-1} makes it less likely to cross the node during the critical period. In contrast, November transits are near perihelion (77°) so the combination of closer proximity to the Sun and the more rapid motion at 59.0 kms^{-1} produces nearly twice as many transits compared with May timings. At apparent diameters of 12" and 10" for May and November transits respectively, visibility requires a telescope.

The regularity of the transits of Mercury is determined by a division of the sidereal periods of Earth 365.256 363 d and Mercury 87.969 256 d to give 4.152 091. Once a transit has occurred, the next one at that node will necessitate integer orbits of each planet where the ratio is close to 4.152. For May transits, this is usually 13 or 33 years, where 54/13 = 4.154 and137/33 = 4.152. For transits in November, the frequency may be 7, 13 or 33 years where 29/7 = 4.143. All the transits of Mercury are shown in *Table 1* from the first predicted by Kepler in 1631 until the most recent in 2006. There are two rare intervals of 6 years, 25/6 = 4.167, and another of 20 years, 83/20 = 4.150. There are more regular patterns at 46 years (13 + 33) as 191/46 = 4.152 and 217 years as 901/217 = 4.152.

Table 1. November and May transits of Mercury 1631-2006 along with intervals. Transit Predictions by Fred Espenak National Aeronautics and Space Administration/Goddard Space Flight Center [7].

November Transits						May Transits		
year	**day**	**y**	**year**	**day**	**y**	**year**	**day**	**year**
1631	07	–	1822	05	7	1661	03	-
1644	09	13	1835	07	13	1674	07	13
1651	03	7	1848	09	13	1707	05	33
1664	04	13	1861	12	13	1740	02	33
1677	07	13	1868	05	7	1753	06	13
1690	10	13	1881	08	13	1786	04	33
1697	03	7	1894	10	13	1799	07	13
1710	06	13	1907	14	13	1832	05	33
1723	09	13	1914	07	7	1845	08	13
1736	11	13	1927	10	13	1878	03	33
1743	05	7	1940	11	13	1891	10	13
1756	07	13	1953	14	13	1924	08	33
1769	09	13	1960	07	13	1937	11	13
1776	02	7	1973	10	13	1957	06	20
1782	12	6	1986	13	13	1970	09	13
1789	05	7	1993	06	7	2003	07	33
1802	09	13	1999	15	6			
1815	12	13	2006	08	7			

Analysis of *table 1* gives 52 transits of Mercury in this 375 year period with 36 (69%) in November and 16 (31%) in May. For November the respective numbers for the intervals 6, 7 and 13 years are 2, 10, 23 and for May 13, 20, 33 years 7, 1, 7.

In May, the apparent diameter of the Sun is 1 902". With a 46 year time span, Mercury shifts its position with respect to the Sun by approximately 200". Hence, there may 10 transits that can be viewed as a series, spanning 9 intervals × 46 years = 414 years. For November, the Sun is 1 937" and Mercury shifts by about 100", giving 19 transits in a series which may span 18 intervals × 46 years = 828 years. There may be six transit series running concurrently [8].

3 Lindenau, Le Verrier, Newcomb

The next step of progress in the fit of Mercury's orbit was taken by a German, Bernhard August von Lindenau (1780-1854) who, in 1802, became director of the Gotha Observatory. Planning for this observatory began in 1787 and in the early part of the nineteenth century it became an international centre for Astronomy principally due to its instruments. These consisted of an eighteen inch (46 cm) quadrant, a two foot (61 cm) transit instrument, three Hadley sextants, an achromatic heliometer, a two foot (61 cm) achromatic refractor, a Gregory reflector and many clocks [9]. Lindenau also had impetus for publishing results as a new journal from the observatory commenced in 1800 and he was the editor from 1807 until it ceased in 1813. He used data from 17 transits of Mercury and introduced perturbations to publish more up to date tables on the orbit of Mercury in 1813 [10]. He applied a considerable increase to the mass of Venus to reconcile theory with observations [11].

The next significant contribution was from Urbain Jean Joseph Le Verrier (1811-1877) who was director of the Paris Observatory 1854-1870 and 1873-1877. His first work on Astronomy was about the stability of the solar system which he presented to the Académie des Sciences in 1839 [12]. Following a suggestion from the director of the Paris Observatory in 1840 that Le Verrier work on Mercury's orbital motion, he produced a research paper in 1843 [13].

Le Verrier had also been applying mathematics to perturbations in the orbit of Uranus and calculated a 40" discrepancy. In response to a proposition that the disturbance may be due to an exterior planet, he used a new method of inverse perturbations to produce 13 unknowns. Assuming a noncircular orbit, a tentative distance from the Sun and little inclination, he reduced the unknowns to nine. He informed Johann Gottfried Galle (1812-1910) at the Royal Observatory in Berlin where to search for an eighth magnitude planet with a disc of 3".3. On the first evening of his pursuit in 1846, Galle located Neptune 55" from the point and of the magnitude predicted. It had a disc of 3".2. Uranus and Neptune had been in conjunction in 1821 so they were still near each other in the line of sight [14].

Flushed with success, however, his 1843 work was found wanting during the transit of Mercury in 1848, when his theory was shown not to match the observation. He collected data on 397 meridian observations of Mercury at the Paris Observatory as well as 21 second and third contact timings from 14 passages across the Sun, nine November ones 1697-1848 and five May transits 1753-1845, and produced a revised theory in 1859 [15].

Under a two body situation of the Sun and Mercury, the planet would be expected to trace out an elliptical orbit with its perihelion fixed relative to the stars. However, the presence of other planets causes the perihelion to trace out an advance in the direction of motion. This was such a small figure at a little over 500" per century. At approximately four orbits per year, this amounts to 1".25 per orbit. One precession would require 260 000 years [16].

Le Verrier produced calculations of the contribution of planetary perturbations on the perihelion advance of Mercury in arcseconds per century: Venus 280.6, Earth 83.6, Mars 2.6, Jupiter 152.6, Saturn 7.2, Uranus 0.1 to give a total of 526.7 but the measured amount was 39" century^{-1} more [17]. This unaccounted datum became known as the anomalous advance of the perihelion of Mercury.

In 1882 as Director of the Nautical Almanac Office in the United States of America, Simon Newcomb (1835-1909) reexamined Le Verrier's results. Newcomb had data on four extra transits of Mercury since 1848 and he decided to include only those results from known viewers at observatories where the longitude would be established precisely and the results had been published. In addition, he included data on first and fourth contacts. To fit periodic perturbations on the motion of Venus he reduced the mass of Mercury from 3.333 $\times 10^{-7}$ that of the Sun used in 1859 to 1.333×10^{-7} and for Venus, from its perturbations on other planets, from $2.488\,5 \times 10^{-6}$ to 2.469×10^{-6}. He agreed with Le Verrier on a discordance between observation and theory for the motion of the perihelion of Mercury but raised the value to 43" century^{-1} (42".95) [18]. "In seeking a possible explanation of this excess of motion, the author [Newcomb] considers several arguments which have been brought forward – such as a possible term of very long period; Le Verrier's hypothesis of a planet or group of planets between Mercury and the Sun; the Zodiacal Light; a possible ellipticity of the Sun or its atmosphere; a ring around the Sun; any modification of the law of gravitation; Weber's electro-dynamic theory; all of which he rejected …" [19].

. In 1895 Newcomb published the result of 20 years of his work devoted to the motion of planetary bodies and the fundamental constants of Astronomy [20]. Analysing 62 000 meridian observations at Washington for Mercury, Venus and Mars alone, he took into account some long term fluctuations in the Earth's motion. He constructed tables of the motions of the planets which were adopted by the annual almanacs of the US Naval Observatory and the Royal Greenwich Observatory. Newcomb incorporated four secular variations for Mercury, Venus and Mars: $\boldsymbol{e}$ eccentricity of the orbit, $\boldsymbol{i}$ inclination of the orbit, $\boldsymbol{\Omega}$ longitude of the ascending node and ϖ longitude of the perihelion. For Earth, $\boldsymbol{e}$ and ϖ were included as well as the obliquity of the ecliptic [21]. Newcomb identified four anomalies remaining: perihelion motion of Mercury, node motion of Venus, perihelion of Mars and the eccentricity of Mercury [22]. While the tables have been superseded, they are accurate to within a few arcseconds even today.

4 Einstein

Many lines of enquiry to unravel the anomalous advance of the perihelion were pursued. Slight adjustments were made to the $1/R^2$ Newtonian relationship with distance. This could account for the discrepancy but then aspects of the motion of nearby planets were altered in an incorrect direction. The pursuit of Vulcan or a host of planetesimals continued mainly during total solar eclipse expeditions. During the Lick Observatory expeditions of 1901, 1905 and 1908, Charles Dillon Perrine (1867-1951) searched photographically for any evidence of such bodies. 506 stars were captured on a glass plate at the 1908 Flint Island eclipse in the Pacific Ocean and these images were compared with ones taken earlier at Mount Hamilton where the Lick Observatory was located. “These observations make it practically certain that there are no intra-mercurial bodies of 8.0 visual magnitude, or brighter, in or near the plane of the Sun’s equator, with elongation of 12°, or less, as viewed from Earth” [23]. The hunt was abandoned as it was calculated that a million objects of lesser brightness with the density of Mercury would be necessary.

On his way to developing the general theory of relativity in 1915 from his special theory of 1905, Albert Einstein (1879-1955) collaborated with Marcel Grossmann (1878-1936). It was Grossmann who pointed out to Einstein the relevance to general relativity of tensor calculus and the use of the non-Euclidian geometry of Riemann. They wrote a joint paper in 1913, the first on the general theory of relativity [24]. Einstein then invited Michele Besso (1873-1955) to assist him in solving the equations in this joint paper, particularly those equations involving the perihelion advance of Mercury. Their work of 1913-1914 has survived in what is known as the Einstein-Besso manuscript. Their first attempt yielded an answer of 1 821" = 30', which was a devastating blow [25]. However, their input for the mass of the Sun was in error by a factor of 10 too high and as the motion was proportional to the square of the mass, the obtained value was 10^2 higher, so their revised value was 18". They next calculated the effect due to the rotation of the Sun and found 0".1, which once the error for the solar mass was found, was 0".001 retrograde.

On 04 November 1915 Einstein, now more confident in the mathematics he was using, presented a new version of general relativity to the Prussian Academy. A week later on 11 November, a short addendum to the paper followed in which he changed the field equations. In another week, 18 November, Einstein presented the paper with a calculation of 45" ± 5 century^{-1} for the anomalous advance of the perihelion of Mercury. He altered equations again in a paper another week later, 25 November, but this did not alter his Mercury value [26]. His final work was published in 1916 [27]. Here, the calculation for the change in angle $\Delta\phi$ in radians per orbit due to general relativity is expressed as

$$\Delta\phi = \frac{6\pi GM}{c^2 a\,(1 - e^2)}$$

where ***G*** the universal gravitational constant = 6.673×10^{-11} m^{3}kg^{-1}s^{-2}, ***M*** the mass of the Sun = 1.989×10^{30} kg, ***c*** the speed of light = 2.998×10^8 ms^{-1}, ***a*** the mean distance from the Sun in m and ***e*** the eccentricity of orbit. Conversion factors of $180/\pi$ to give °, 3 600 for " and 100/orbital period in tropical years produce an answer in " century^{-1}. With these data and the following in table *2* from a modern almanac [28], the anomalous precession for each planet can be calculated.

Table 2. Anomalous advance in the perihelia of the planets.

planet	**a** × 10^{10} m	**e**	**orbit** in tropical years	$\Delta\phi$ in " per century
Mercury	5.791	0.205 6	0.240 844 45	42.98
Venus	10.821	0.006 8	0.615 182 57	8.625
Earth	14.960	0.016 7	0.999 978 62	3.839
Mars	22.794	0.093 4	1.990 711 05	1.276
Jupiter	77.830	0.048 5	11.856 525 02	0.062
Saturn	142.939	0.055 5	29.423 510 35	0.014
Uranus	287.504	0.046 3	83.747 406 82	0.002
Neptune	450.445	0.009 0	163.723 204 5	0.000 8

From Table 2, it can be seen that the value of 42".98 century^{-1} for Mercury is within the uncertainty range of 45" ± 5 century^{-1} calculated by Einstein. Mercury has the highest eccentricity of orbit so its perihelion position is distinguishable. As well, being closest to the Sun, it would experience the greatest effect of spacetime.

At first blush, one can understand the excitement in Einstein's response. There had been a problem in celestial mechanics since 1859 when Le Verrier (section 3) put forward an anomalous advance of the perihelion of Mercury of 39" century^{-1}. In 1882 Newcomb (section 3) agreed with the existence of an anomaly but calculated the value as 43" century^{-1}. Now, Einstein seemed to have solved the situation nicely. There were two other astronomical tests that Einstein's theory needed to satisfy, namely, the amount of bending of starlight in the vicinity of the Sun and the gravitational redshift of spectral lines. The ready acceptance of the solution of the Mercury problem by Einstein and others influenced the conclusions drawn from a 1919 total solar eclipse aimed at measuring the deviation of starlight.

The scientific method rests on examining the falsifiability of any result. Support for a theory rests on how well predictions match observations. The achievement of Le Verrier was extraordinary. Without the advantage of modern computers, he attempted to account for all the forces on Mercury's orbit in a Newtonian framework. The number of bodies involved was large and he adjusted masses, deemed in proportion to that of the Sun, to make a better fit to a series of observations. Indeed, some later attempts, which also met with some success, distributed the matter of the planets evenly around their orbit to simplify calculations [29]. Nevertheless, given the unknowns in masses and eccentricities of the planets, the result of Le Verrier needed to be held as tentative. The anomalous figure is such a small angle, namely, 1.2% of a degree and it represents only 7.5% of the total precession of Mercury. Le Verrier's fame in directing the finding of the new planet Neptune from his mathematics, no doubt, added weight to the result he produced for Mercury.

Newcomb was a prolific writer and a giant for his time in calculations within the solar system. His agreement with the anomaly as real carried considerable support. However, he produced this anomaly when he was using the motion of Mercury to test changes in the rotation of the Earth. In reverse, this factor itself could affect the value obtained for the anomalous advance. Also, at this time there was another major unsolved anomaly, that of the secular acceleration of the Moon. Could these have the same cause or were they independent?

There were questions raised about Newton's ideas. Some astronomers played with a slight adjustment to the $1/R^2$ relationship. With a suitable value, improvements could be made in some of the tables but it generally made others less reliable. Was $\boldsymbol{G}$ constant? There were endeavours to lessen its value with increasing distance. A major alternative proposed was the presence of one or several bodies inside Mercury's orbit or perhaps a large number of very small particles. The more massive bodies could be discredited when photographic searches at total solar eclipses did not reveal them. Suppose, though, that there were a number of much smaller particles that could account for not the full anomaly of 43" century^{-1} but say 10" century^{-1}. Then, Einstein's figure of 45" ± 5 century^{-1} would not be in agreement.

Values for any anomalies of the other planets did not exist when Einstein published his general relativity thesis. However, one could argue that if the figure for Venus also matched theory, then this would build a stronger case for acceptance of general relativity. It was not until 1956 when the results for the three inner planets were published as in Table 3.

Table 3. Comparisons between the observed discrepancy and relativistic prediction for Mercury, Venus and Earth [30].

Quantity	Mercury (" cy^{-1})	Venus (" cy^{-1})	Earth (" cy^{-1})
observed discrepancy	43.11 ± 0.45	8.4 ± 4.8	5.0 ± 1.2
relativistic prediction	43.03	8.6	3.8

In November 1915 Einstein presented his paper on four occasions, each time making corrections, some of which involved his field equations. At the time, this should have invited caution on the part of Einstein's followers even if it were thought the issue of Mercury had been solved.

Furthermore, another problem in measurement was highlighted in 1947. "According to general theory of relativity, the elliptical orbit of a planet referred to a Newtonian frame of reference rotates in its own plane in the same direction as the planet moves... The observations cannot be made in a Newtonian frame of reference. They are affected by the precession of the equinoxes, and the determination of the precessional motion is one of the most difficult problems of observational astronomy. It is not surprising that a difference of opinions could exist regarding the closeness of agreement of observed and theoretical motions..." The current figure for this precession is 574" century^{-1}. This is compared with the values of the contributions framed by Clemence in Table 4 [31].

Table 4. Sources of the precession of the perihelion of Mercury.

Amount (" cy^{-1})	**Cause**
531.63 ± 0.69	gravitational tugs from the other planets
0.025 4	oblateness of the Sun
42.98 ± 0.04	general relativity
574.64 ± 0.69	total
574.10 ± 0.65	observed

The anomalous advance is not smooth over time. From a 1987 graph [32] of the position of the heliocentric longitude of the perihelion of Mercury between 1983 and 1988, a number of fluctuations and irregularities are displayed. The deviation of the orbit of Mercury from that of an ellipse is due principally to Venus, then Jupiter, followed by Earth, with these three planets accounting for 99% of the fluctuation. Large changes in Mercury's advance occur when Mercury is near aphelion and Venus is close by. Smaller ripples reflect the 88 day orbital periodicity of Mercury. The relativistic effect may only be revealed once the periodic influences of these three planets are subtracted.

The major reason for the initially slow acceptance of general relativity was that no experiment could be performed that could test the anomalous advance. The observed figure rested on a large series of observations over a span of time and Einstein also relied on new and difficult mathematics in challenging the Newtonian view of the Universe, successful for over 200 years. Science does advance when the current paradigm no longer fits observation. However, evidence is built through rigorous analysis and attempts to falsify the new proposal before it does take its rightful place as the best currently accepted theory.

5 Modern Methods

The secular variations of planetary orbits is a concept describing long-term changes in the orbits of the planets Mercury to Neptune. While a general theory approach, which provides an equation of motion as a function of time, was used and a progressive increase in accuracy was achieved as first order, then second order and, with the use of computers, third order, effects were incorporated, perturbation phenomena are now computed by numerical integration. "The initial conditions for the numerical integration are adjusted to fit available observational data by a least squares fit and a second numerical integration is performed based on that correction. This process is repeated until the numerical integration represents the observational data to the required accuracy" [33].

In the case of the USA and the United Kingdom, the fundamental planetary and lunar ephemerides are based on a program that was developed at the Jet Propulsion Laboratory in 1980 and prepared by the

United States Naval Observatory. As a result of 362 observations over the span 1966-1974 from radar stations at Arecibo in Puero Rica, Haystack Observatory in Massachusetts and Goldstone in California, the mass of Mercury has been refined. This is essential as a major problem in any theory is that the amplitudes of the perturbations are a function of the masses of the planets. 175 explicit unknown parameters and 50 424 observations, which involved 39 579 Washington transits of the Sun, Moon and planets to 1".0 standard deviation for Mercury over 1911-1977, formed the basis of the original program [34].

The French equivalent is a planetary theory called VSOP (*Variations Séculaires des Orbites Planétaires*) which began in 1982. It is developed and maintained by scientists at the Bureau des Longitudes in Paris, France. For the 1987 version, which uses periodic series as a function of time, a precision of 1" is claimed for the position of Mercury 4 000 years before and after epoch 2000 [35].

In 100 years Mercury completes 100 y/0.240 844 45 orbit in tropical years = 415.2 orbits. The Keplerian elements at epoch 2000 with respect to the mean ecliptic and equinox of J2000 and the rate over 415 revolutions are given in Table 5.

Table 5. Keplerian elements for Mercury and their change over 100 years at epoch 2000 [36].

Keplerian Elements	Value	Rate
a semi-major axis	0.387 098 93 AU	0.000 000 66 AU/415 revs
e eccentricity	0.205 630 69	0.000 025 27 per 415 revs
i inclination of orbit to ecliptic	7°.004 87	–23.51" century^{-1}
Ω longitude of the ascending node	48°.331 67	–446.30" century^{-1}
ϖ longitude of perihelion	77°.456	45 573.57" cy^{-1}
L mean longitude	252°.250 84	261 628.29" cy^{-1}

The approximate maximum errors for Mercury over the interval 1800-2050 are 20" or 6 000 km in heliocentric right ascension, 5" or 1 000 km in declination and 5" or 1 000 km in distance [37].

Robotic spacecraft have given a better figure for the shape, mass and composition of Mercury. Mariner 10, throughout 1974-1975, effected three flybys of the planet and photographed 40-45% of the surface. MESSENGER, launched in 2004, made use of course corrections from Earth, twice from Venus and three flybys of Mercury before orbital insertion in 2011. By May 2013 it had completed 2 000 orbits. The mass of Mercury is now accepted as 3.301 04 × 10^{23} kg or as a fraction of the Sun's mass as 1.660 × 10^{-7} (compared with Le Verrier's value of 3.333 × 10^{-7} in 1859 and Newcomb's 1.333 × 10^{-7} in 1882, section 3).

6 Conclusion for the Anomalous Advance in the Perihelion of Mercury

An understanding of the orbit of Mercury provides an opportunity to trace the development of scientific thought. More refined ephemerides gleaned from its meridian crosses and transits across the Sun with more sophisticated instruments were produced. Tables of its position at anytime improved until it seemed that the ellipse itself moved. This amount of perihelion advance was a major stumbling block to elucidate the motion of Mercury.

Einstein proferred a solution which was accepted rapidly in a number of circles. Yet, time was necessary before general relativity could compete with alternatives. His proposal was not proof but a "provisional conjecture" [38]. As well, this was one of three astronomical tests that needed to run the gauntlet of scientific opinion.

Computers and spacecraft have been employed to revise data for Mercury and its orbit. Numerical integration, incorporating perturbation theory, is now the tool with which one may locate the position of Mercury with confidence and unprecedented accuracy.

7 Einstein and Gravitational Redshift

Following his 1905 publication on what is now called the Special Theory of Relativity, Einstein wrote a review paper in 1907 where he applied his notions to gravitation [39]. He postulated that acceleration and gravitation were identical, his equivalence principle. From this idea he deduced that gravitation would have an effect on light. Specifically, Einstein proposed that, compared with an atom on Earth, light from an atom at the Sun's surface would have a lower frequency, that is, that a clock in this position would run slower than on Earth. As a consequence, his work led him to predict that all lines in the solar spectrum ought to be shifted to the red end relative to the situation of a source on Earth. The value of the displacement was given as a ratio of the change in wavelength relative to the wavelength of 2.12×10^{-6}. This was referred to the gravitational redshift. In 1911 [40], Einstein returned to these thoughts and derived the gravitational redshift of spectral lines from a new perspective. Thus, although the gravitational redshift is often treated as a consequence of general relativity, it can be derived from gravity in a Newtonian framework, the particle theory of light and the equivalence principle. Willem de Sitter (1872-1934) from the Leiden Observatory had been responsible for introducing the work of Einstein to England. In 1916, in a paper investigating the astronomical consequences of Einstein's theory [41], he calculated the displacement towards the red as equivalent to a radial velocity of 2.12×10^{-6} times the speed of light. This translated to 6.34×10^{-1} km s^{-1}. He also produced an amount of displacement in km s^{-1} for any star based on its mass M and density ρ both in terms of the Sun $6.34 \times 10^{-1} M^{2/3} \rho^{1/3}$.

8 Solar Spectral Research to 1918

Commencing in 1887, Henry Augustus Rowland (1848-1901) of Johns Hopkins University utilised high quality diffraction gratings and with his experimentalist Lewis E. Jewell (c1863-after 1926) produced, by 1895, a comprehensive list of wavelengths of the solar spectrum [42]. When they noticed that the solar lines appeared displaced by several units at the scale of 10^{-9} m, mainly towards the red end of the spectrum, compared with those of an electric arc, Rowland opined that the equipment was not up to the task, or the light through the slit was not from the centre of the solar disc thereby resulting in a Doppler effect or it resulted from turbulent conditions on the Sun. However, Jewell disagreed. After effecting a new set of measurements in 1896, he ruled out a Doppler effect as the amount of the shift was not directly proportional to the wavelength [43]. Furthermore, he analysed that the displacement differed between elements, between lines from the same element, of the same line on different photographic plates and seemed to be related to line intensity.

To complicate the situation further, William Jackson Humphreys (1862-1949), also at the Johns Hopkins University, and John Frederick Mohler (1864-1930) of Dickinson College published the results of their experimentation in 1896. They found that arc lamp spectral shifts were proportional to the pressure when increased above atmospheric conditions and that the lines tended to broaden in an asymmetrical pattern. They also uncovered that the amount of displacement differed for various lines [44].

In an attempt to disentangle effects which may have different conditions between the Sun and an electric arc, J. Halm in 1904 compared the spectrum of two neutral iron lines from the centre of the Sun's disc with points at distances out to the extremity. He interpreted that there was a gradual increase, reaching 12 mÅ at the limb once a correction for Doppler differences was performed [45]. This so-called limb effect was supported by Maurice Paul Auguste Charles Fabry (1867-1945) of the University of Marseille and Henri

Buisson (1873-1944), a French physicist, with their interferometer in 1909 for 14 spectral lines, other than those of iron [46].

R Rossi in 1909 had shown that shifts still existed for lines in the cyanogen bands even though they did not respond to pressure [47]. He offered the explanation that ascending radial currents at the Sun's centre were responsible for the effect. At this point, astronomers were attempting to explain the observed effects by teasing out the contributions from pressure, motion in the line of sight, refraction and scattering. On top of this, Einstein had thrown in a consideration of gravitation.

Instrumentation received a boost with the erection of a 60 foot (18 m) tower telescope in 1908 at Mount Wilson Observatory. From this, Walter Sydney Adams (1876-1956) used a high-dispersion grating spectrograph and compared centre-limb shifts for 470 lines of neutral and ionised elements. He eliminated rotational effects by comparing east and west limbs at the same latitude simultaneously. He concluded in 1910 that any shift was proportional to wavelength and the displacement for ionised lines was greater than for neutral species of the same element [48]. In 1912 a 150 foot (46 m) tower telescope came on line at Mount Wilson.

In his work on Einstein Crelinsten wrote, "At Mount Wilson the challenge was accurate measurements of solar spectral lines and identification of various laboratory and solar phenomena that shifted spectral lines. The astronomers involved did not question relativity's validity at first, since they had no adequate understanding anyway: their skills were in precision measurement. Once specific results began to emerge from this specialized research, the participants began to view the whole enterprise in a different light. Those debating the validity of the underlying theory began to cast the astronomical work as determining the truth of a controversial theory. For the astronomers conducting the research, it was actually about precise measurement of astronomical phenomena" [49].

With specific reference to Einstein, in 1914 Karl Schwarzschild (1873-1916) of the Astrophysical Observatory in Potsdam found his measurements to be smaller than the gravitational redshift [50]. John Evershed (1864-1956) and Thomas Royds (1884-1955) at the Kodaikanal Observatory in India were able to fit a mathematical relation to the displacements by measuring the relative translations at small intervals along the radius of the Sun [51]. In 1917 Charles Edward St. John (1857-1935) at Mount Wilson Observatory indicated his results did not support Einstein [52].

At this juncture, no clear picture had emerged. A summary of the situation is provided by Forbes.

"The first person to recognize in the observations of the solar red shifts a possible verification of Einstein's prediction was Freundlich [Erwin Finlay-Freundlich (1885-1964) of the Berlin Observatory], who noticed that the results of Fabry and Buisson for iron lines at the centre of the Sun's disk, and those of Evershed, corresponded very closely with the predicted values. He was also aware, however, that Evershed, Royds and St. John had clearly shown that the shifts of iron lines varied with intensity by an amount too large to be accounted for by differential pressure effects in the various layers of the solar atmosphere throughout which the spectral lines are formed. In addition, measurements by Royds … had yielded similar results for nickel and titanium, and thus verified Jewell's original discovery that the shifts varied from element to element. They also showed that the Sun-arc shifts are not directly proportional to wavelength, and that their values at the centre of the disk were generally smaller than Einstein's prediction requires – facts which suggested that some other effect was producing anomalies in either solar or terrestrial wavelengths, or both. Indeed, the observed increase in all these displacements in going from the centre to the limb was a feature of the solar lines only which was independent of the existence of the Einstein effect. Consequently, the observations at that time [1914] could not be regarded as constituting a decisive verification of this prediction” [53].

9 Significance of 1919 Total Solar Eclipse

A definite change in approach was noticeable following the May 1919 British total solar eclipse expedition to measure the amount of bending of starlight by the Sun, another prediction from Einstein’s ideas.

In his summation of the results to a special joint meeting of the Royal Astronomical Society and the Royal Society in November 1919, one of the eclipse expeditioners, Arthur Stanley Eddington (1882-1944), declared for Einstein in the displacement of starlight. However, he noted that the “relativistic displacement of solar spectral lines” had up to this point been unsuccessful [54]. Eddington then proceeded to draw a distinction between Einstein’s law and his theory. He pressed the point that Einstein had made a prediction on a law of gravitation and the two British eclipse excursions had confirmed this. However, this did not automatically imply that the underlying thinking of Einstein was supported [55]. This appears extraordinary from Eddington at this point of time. He was the lone voice in England popularising relativity. The one tactical advantage of this demarcation was that a claim could be given immediately for the British results and it did not matter if gravitational redshift were shown to be non-existent.

10 Results 1920-24

Flushed now with apparent support for some prediction of their fellow German scientist, Leonhard Grebe (1883-1967) and Albert Bachem (1888-1957), Bonn physicists, produced results in 1920 [56] which not only supported the gravitational redshift but they also gave an opinion why earlier investigators had not found the Einstein effect. “The feature of Grebe and Bachem’s work which distinguishes it from all previous researches is that the relativity effect was assumed to be implicit in the observed values of the absolute (Sun-arc) shifts, and the problem under consideration was not to decide whether this effect exists, but rather to explain why the measured displacements are smaller than the theoretical prediction demands” [57]. St John criticised their results since he claimed the spectrograph they used had insufficient dispersion, they had not ensured that the slit of the spectrograph was parallel to the solar axis, an accurate guiding mechanism was not employed and did not use mirrors to compare the solar and arc lines simultaneously [58].

Throughout the 1920s, the two main experimenters on gravitational redshift were Evershed and St. John. By 1920 Evershed was able to conclude from his measurements on 42 iron lines that there was a shift to the red and the amount increased from the centre to the limb. At the centre any radial motion of the solar atmosphere would be in the line of sight whereas at the limb, it was expected to have a component of zero. In fact, this was the rationale behind performing these measurements. Evershed had at this stage eliminated pressure effects from his thinking. He found an excess value over Einstein’s prediction at the limb and agreement at the centre although he was concerned about the variation with the intensity of the lines [59].

St John acknowledged that the 1919 eclipse result was an impetus to his work on gravitational displacement. He pointed out how difficult the analysis was. He itemised the conditions that were necessary: stable equipment, simultaneous observations of the comparison sources, a long focus spectrograph, high resolving power, a large solar image to eliminate errors in guiding, the use of lines separated from others and corrections made for the rotation of the Earth and its eccentricity when measuring terrestrial lines. He took into account the rotation of the Sun which would Doppler shift the lines one way or the other, depending on from what side of the Sun he was measuring. His average result was 0.005 Å compared with an Einstein figure of 0.013 Å [60]. By 1923 St. John analysed data for some 200-300 lines and leaned towards the displacements being caused by general relativity combined with small Doppler shifts [61].

Evershed, who had generally been supporting Einstein, had worked on strong lines while St. John had produced zero shift employing weak lines. A breakthrough had occurred when, as summarised by Adams [62], over 330 lines were examined between the Sun and an arc in a vacuum. Displacements were shown to increase in a progressive way with intensity. The intensity of lines was related to the level in the solar atmosphere where absorption lines originated, with convection currents moving upwards at low levels and downward at high levels, causing line shifts. Once a correction was made for these line shifts, St. John was able to confirm gravitational shift.

11 The Case of Sirius B

The astronomers at Kodaikanal and Mount Wilson Observatories struggled at measuring accurately such small deviations and separating the various components that might contribute to these displacements. The story appeared to take a complete change of direction when measurement moved away from the Sun to another star.

With regard to Einstein's general relativity, Eddington (section 9) is known principally for the part he played obtaining the first set of results on gravitational displacement of starlight in the vicinity of the Sun. However, he made a significant contribution to gravitational redshift from his investigations into stellar relationships.

In 1924 Eddington published a paper where he was attempting to ascertain the connection between masses and luminosities of stars [63]. As the number of stars with a determination of their mass and absolute magnitude was limited at this time, Eddington wanted candidates that were double stars with a known orbit, large parallax between them and a ratio for the masses of the components. Sirius and its companion white dwarf now known as Sirius B fitted his requirements. Its spectral analysis pointed to an effective temperature of 8 000 K and this, with its absolute magnitude of 11.3, suggested a radius of 19 600 km, less than that of Uranus. Eddington determined its mass range to be 0.75 to 0.95 the mass of the Sun and he adopted the figure of 0.85. The consequence of these figures was that its calculated density was 53 000 times that of the Sun.

While a number of scientists regarded this result as impossible, Eddington was not fazed. With such a large density, he calculated a gravitational redshift of 20 km s^{-1} [64]. He looked for support of his conclusion and prevailed upon Adams (sections 8,10) to effect a spectral analysis of Sirius B.

Adams took up the challenge. He outlined in 1925 the general procedure of Eddington. "From the elements of its orbit its mass and velocity relative to the principal star may be derived, and the well-known parallax of Sirius in combination with the apparent magnitude of the companion provides a knowledge of its absolute magnitude. The spectral type of the star is a matter of direct observation, and results for surface brightness, size, and density follow as a consequence of what is known regarding stars of similar spectral class" [65].

The 100 inch (2.5 m) Hooker Telescope on Mount Wilson produced a spectrum of Sirius B overlaid with scattered light from Sirius. The hydrogen beta line was reasonably free of stray light. The displacements in km s^{-1} ranged over 8 plates from 17-31. Corrections were applied depending on the intensity and according to which of two devices was used in the measurement. The average then was 26 km s^{-1}. With a division of 62 at this wavelength, the equivalent Å value was 0.42. The hydrogen gamma line had pronounced superposition. The 7 plates gave a range 2-17 and a weighted average after correction of 21 km s^{-1}. A division factor of 69 for this wavelength equates this to 0.30 Å. 10 plates covered the species Fe, Fe^{+}, Sr^{+}, Mg^{+} and Ti^{+} giving a range 4-37 and a weighted mean of 22 km s^{-1}. The computed average for all lines was 23 km s^{-1} towards the red. Adams wrote his concluding sentence: "The results may be considered … as affording direct evidence from stellar spectra for the validity of the third test of the theory of general relativity, and for the remarkable densities predicted by Eddington for the dwarf stars of early type of spectrum [66].

Even though Eddington was thoroughly pleased with the result, he awaited some confirmation. This was provided by Joseph Haines Moore (1878-1949). Throughout 1926-28 Moore experimented with the 36 inch (91 cm) refractor at the Lick Observatory. Even though this was contrasted with the large reflector used by Adams, its one advantage was that it minimised the amount of scattering. Moore also used the hydrogen alpha and gamma lines and some others. His series of results were 22, 10, 29 and 21 km s^{-1} [67]. Corrections were not applied as Adams had done but the lowest figure was discarded as clouds that evening had added to the amount of scattered light. This gave a mean of 24 km s^{-1} and as Sirius B was receding from Sirius at 5 km s^{-1}, Moore concluded a shift to the red of 19 km s^{-1} or 0.29 Å. When he did apply the same corrections as had Adams, Moore obtained 21 km s^{-1} or 0.32 Å.

What was exciting about this result was that, with a larger displacement to measure, it not only supported the gravitational redshift as predicted by Eddington but here was a case for a practical application of the Einstein effect in confirming Eddington's proposal of the very large density of a dwarf star. Astronomers now had confidence in returning to their measurements on the Sun.

12 1928

St John, having toiled on the issue of gravitational redshift for 14 years, published in 1928 a large paper detailing the state of affairs [68]. He dealt with other causes of the displacement of solar lines and examined 1 537 spectral lines at the centre of the Sun and 133 at the edge. Each of the 586 iron lines at the centre showed a displacement to the red with an average of 0.008 3 Å. Those at a median level defined as 520 km within the solar atmosphere had a mean of 0.009 Å compared with an Einstein value of 0.009 1 Å. Higher level lines at 840 km were 0.002 7 Å greater than a calculated figure and lower level lines at 350 km 0.002 6 Å greater than predicted. These values for iron were confirmed for 6 lines of silicon, 18 lines of manganese, 402 lines of titanium and 515 lines of cyanogen [69]. St. John went on to treat factors involved in the different levels within the solar atmosphere and concluded strongly in favour of Einstein.

The year 1928 may be regarded as a watershed for experimental confirmation of Einstein's theory of relativity. It provided confirmation from Moore (section 11) on the work of Adams on Sirius B (section 11). St. John punched home the conclusion from his analysis of a large number of lines and his provision of an historical record of the factors at play. Also, much credit was given to the 1919 eclipse results but just as Eddington wanted confirmation from Adams's results, the same standard ought to have been applied to the proclamation of Eddington. This was provided by the 1922 total solar eclipse expedition to Western Australia led by William Wallace Campbell (1862-1938) of the Lick Observatory. It was 1928 before the definitive results of the gravitational light bending were provided by Campbell and his colleague Robert Julius Trumpler (1886-1956) [70].

13 Post 1928

This paper concerns the early astronomical tests of general relativity. A case can be made that 1928 could be conceived as a time when sufficient support existed for gravitational light bending, an explanation of the anomalous advance in the perihelion of Mercury and for gravitational redshift.

However, disquiet followed this time period. It was suggested that much of the light that had been studied by Adams (sections 8,10,11) was scattered from the much brighter Sirius. In 1954, Daniel Magnes Popper (1913-1999) measured a redshift on another white dwarf, 40 Eridani B, as 21 km s^{-1} which was within the uncertainty range attached to 17 km s^{-1} predicted by general relativity with the values of mass and radius then attributed to the star [71]. The value for Sirius B was extensively revised upwards in 1971 by Greenstein, Oke and Shipman [72] to 89 ± 16 km s^{-1} with revised data for its mass and radius. Publications in 1967 [73] on 53 white dwarfs and in 1972 [74] on 74 white dwarfs by Trimble and Greenstein produced, from a selection of these, respective averages of +51 and +54 km s^{-1} and provided further confirmation of both general relativity and an understanding of white dwarfs. Confidence in the measurement of redshift has reached a stage where researchers use the data as part of an investigation into the mass-radius relationship in white dwarfs as in Koester and Weidemann [75] for 40 Eridani B in 1991 and Weidemann *et al* [76] in their study of members of the Hyades cluster in 1992.

Strong confirmation of relativity resulted in 1989 following 14 years of measurement of the binary pulsar PSR 1913 + 16 by Taylor and Weisberg [77]. Theory proposes that the eight hour orbit would decay as the result of the emission of gravitational radiation. The rate of decay was within 1% of the rate predicted by special and general relativity. The situation was summed by Weidemann [78], "… I want to refer to a fruit : the confirmation of General Relativity Theory by observations and theoretical evaluation of the pulse arrival times from binary pulsars, especially PSR 1913 + 16. It has now become possible to determine periastron advance, gravitational redshift, time dilation, and gravitational wave emission to such a high degree of consistence, that all masses of the two component neutral stars are given with three decimal accuracy … In comparison to alternative theories of gravitation Einstein's theory comes out unchallenged …"

14 Conclusion on Gravitational Redshift

Storytelling enjoys dramatic events: Newton's apple and his theory of gravitation, Copernicus's placing the Sun at the centre and all fell into place and the 1919 British total solar eclipse supposed verification of Einstein's theory of relativity. In fact, each of these proposals has a much longer history than one defining moment and the latter part of the paper has concentrated on the gravitational redshift measurement as an additional astronomical test of relativity.

The measurements required for the anomalous advance of the perihelion of Mercury, the gravitational bending of light and the gravitational redshift of absorption lines were all subtle and at the limits of the technical apparatus available at the time. Science proceeds by proposing an hypothesis, designing an experiment that can falsify such an idea, effect measurements and conclude either that the hypothesis can be rejected or support is lent to the suggestion. Science then requires that other researchers repeat the experiment or design different ones to provide further conclusions. A new result needs sensible criticism to determine the amount of credence that ought to be given. Addressing the criticisms and further testing are the proper order of events. Should the concept stand a number of tests, more scientists start to favour the proposition. When some undefined critical mass of scientists supports the new idea, it becomes part of the fabric of science. It is never proven but held tentatively as the future may link this with other ideas to provide a meaningful framework or it may be modified or superseded.

The three astronomical tests were not demarcated to the extent that one result was completely independent of the other two. In the case of the gravitational redshift, there was a tendency to try to prove Einstein right after the supposed support from the other two predictions of Einstein. However, these also ran a much longer development historically than the simplistic crucial test treatment generally received.

There were so many factors involved in what could contribute to the shifting of solar spectral lines relative to those on Earth. Much experimentation was necessary to determine the amount of contribution, if any, from each of these to see if the residual could be matched with gravitational redshift. The major two players, Evershed and St. John, obtained mixed results and also disagreed with aspects of each other's work. In the early 1920s they were both leaning towards acceptance that part of their measurements could be attributed to the proposal of Einstein.

Eddington's idea of the possibility of intense density in stars and thus a larger amount of gravitational redshift permitted more accurate experimentation. Gravitational redshift was confirmed from two sources initially on Sirius B and then found to be occurring, albeit at a much lower displacement, for normal stars.

This paper seeks to demonstrate that 1928 was the time when a third verification of Einstein's theory had run the gauntlet of analysis to allow sufficient support for tentative acceptance.

The major discussion in this paper ends at 1928 but this in no way suggests that the story is complete. Einstein's theory has been applied to other areas, particularly cosmology. Further tests continue to this day with the use of robotic spacecraft, effects with quasars, very accurate clock measurements of a frequency change over a small interval of distance and global positioning systems, to name a few.

The study of the history of science is much more interesting than the erroneous "one big moment" rendition. New ideas follow a meandering course along a tortuous pathway. This is actually the fascination that science provides and what has produced the success of this methodology.

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