ap
Asian Journal of Physics Vol. 23, Nos 1 & 2 (2014) 145-170

Early Astronomical Tests of General Relativity: the gravitational deflection of light

Keith John Treschman
51 Granville Street, Wilston 4051 Australia 61-7-38562262

One of three astronomical tests of the general relativity theory of Einstein was the gravitational deflection of light. The British total solar eclipse of 1919 is lauded in history as having decided the case in favour of Einstein. This conclusion is questioned in the light of the philosophy of Science and the method employed to analyse the results. The case is put that more emphasis ought be placed on the outcome of the 1922 total solar eclipse in Australia where eight parties attempted measurements of light deflection in the vicinity of the Sun. Importance is attached to Campbell of the Lick Observatory, camped at Western Australia. His results were not completed until 1928. Other leaders, their affiliation and place of observation were Spencer Jones of the Royal Greenwich Observatory on Christmas Island, Freundlich for a German-Dutch expedition to Christmas Island, Evershed of the Kodaikanal Observatory in India also set up in Western Australia, Chant of the University of Toronto measuring at Western Australia, Dodwell of the Adelaide Observatory in a remote part of South Australia and Cooke from the Sydney Observatory and Baldwin of the Melbourne Observatory both in Queensland.

1 Introduction

Einstein's theory of relativity is well established today by precision measurements based on sophisticated technology. On the other hand, when relativity theory was originally proposed, the limited equipment of the day favoured the use of astronomical observations to make critical comparisons between the forecasts of relativity theory and classical Newtonian physics. This paper reviews the early use of astronomical observations to test general relativity theory to make an objective assessment of their claimed successes.

Embedded within relativity theory, there were three predictions which could be tested astronomically and one of these was that starlight is bent by the Sun. However, what is perhaps little known is that the use of the bending of starlight to test gravitational theory predates relativity and was in fact discussed as a test of classical Newtonian physics.

In the early 1700s, Isaac Newton (1642-1727) had asked a rhetorical question "Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action … strongest at the least distance?" [1]. Later that century, Henry Cavendish (1731-1810) applied Newtonian principles and calculated this effect at the edge of the Sun. His work appeared in an unpublished manuscript in 1784 [2] and eventually in publication in 1921 [3]. Johann Georg Soldner (1776-1833) performed a similar calculation that was in print in 1801 [4].

The results of Cavendish and Soldner differ slightly since Cavendish treats a light ray emanating at infinity, whereas Soldner works with a beam from the surface of the body. In both cases, the general analysis is based on the corpuscular theory so that light has mass. However, a value is not required as a derived equation has this mass on both sides of the equality. The force from the Sun is presented as being related to the acceleration due to gravity at the surface g and distance r from the centre of the Sun. Acceleration is written as the second derivative of the displacement. The velocity of light is v, x and y are geometrical coordinates and with a diagram, suitable spatial relationships, integration and manipulation of equalities, Soldner arrived at

$$y^2 = \frac{v^2}{g}\,x + \frac{v^2\,(v^2 - 4g)}{4g^2}\,x^2.$$

Corresponding author :
e-mail: treschmankm@bigpond.com; (Keith John Treschman)

This equation is that of a conic section. For $v^2 = 4g$, the result is a parabola; $v^2 = 2g$, a circle; $v^2 < 4g$, an ellipse; $v^2 > 4g$ a hyperbola. It is noted that the hyperbolic situation exists for all known celestial bodies. The light ray at a great distance follows the asymptote of the hyperbola with the concave part towards the Sun and the angle of deviation ω at the edge of the Sun is given by

$$\tan \omega = \frac{2g}{v\sqrt{v^2 - 4g}}.$$

This equation was used by Soldner to produce an angle of 0".84.

This angle may be approximated to $\frac{2GM}{c^2\, r}$ and if modern figures of the universal gravitational constant, $G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}, mass of the Sun, $M = 1.99 \times 10^{30}$ kg, the speed of light, $c = 3.0 \times 10^8$ m s^{-1} and the radius of the Sun, $r = 6.96 \times 10^8$ m are used, the amount of deflection is 4.24×10^{-6} radians which is equivalent to 0′′.87.

In 1905 Albert Einstein (1879-1955) proposed what is known today as the Special Theory of Relativity. This theory rests on two postulates: firstly, that the laws of physics take the same form in all inertial frames and secondly, in any given inertial frame, the velocity of light is the same whether the light is emitted by a body at rest or in uniform motion [5]. In a review paper on special relativity in 1907 Einstein indicated that his principles may be applied in the presence of gravitation and crucially he invoked an equivalence principle where acceleration and gravitation are identical [6]. So, while he had deduced in 1907 that light could be bent, it was not until 1911 that he realised that this property could be detected experimentally in the region of the Sun [7]. Einstein computed the angular deviation to be $\frac{2GM}{c^2\, r}$ as above and his result was 0′′.83, a figure almost identical with the Newtonian one. Therefore, it would be more important to demonstrate an inverse distance relationship away from the Sun than the actual limb deviation to dismiss any other opposing explanation [8].

The General Theory of Relativity, which includes accelerated frames of reference, was developed by Einstein in 1915 and published in 1916 [9]. The general theory is a unification of space and time and a geometric interpretation of how bodies move in the presence of a mass. Using the general theory, Einstein computed the deviation to be $\frac{4GM}{c^2\, r}$, which amounts to a doubling of his 1911 reckoning. This latter increased deviation is due to a combination of time curvature, which was approximately equivalent to Newtonian theory, and space curvature which was added to relativity theory. Einstein's conclusion was that light passing the limb of the Sun would thus be deflected by 1".7.

2 The aim of this paper

From the preceding introduction this paper aims to examine the early history of attempts to settle the differentiation between the Newtonian and Einsteinian views of space. There are grounds to reappraise the initial tests based on the availability of the records and the modern security of Einstein's theory compared to Newton's.

3 Unsuccessful Efforts: 1911 – 1918

The first astronomer to show interest in the measurement of the displacement of starlight was Erwin Finlay-Freundlich (1885-1964) of the Berlin Observatory. Communicating with Einstein from 1911 he suggested attempting to detect the bending near Jupiter to eliminate issues with refraction from the solar atmosphere. Einstein opined that he thought the shift would be too small and encouraged Freundlich to search photographic plates from past total solar eclipses. This he did from a number of sources, in particular, from William Walter Campbell (1862-1938) (section 8) of the Lick Observatory in California for the 1905 and 1908 expeditions but the images were not sharp enough for meaningful measurements. Campbell encouraged Charles Dillon Perrine (1867-1951) to attempt a measurement of light deflection at the 1912 eclipse in Brazil but rain prevented the taking of any images [10]. Freundlich decided to take his own measurements at the

Russian eclipse of 1914 and Campbell mounted a Lick campaign but Frank Watson Dyson (1868-1939) of the Greenwich Observatory declined an invitation from Freundlich as there was no impetus from Britain to pursue any light bending phenomenon. There were two British expeditions to Russia, however, they did not propose to tackle this problem [11]**.** The outbreak of the world war negated any chance of results from any of these ventures. Indeed, Freundlich's party was captured by the Russians. The older members were deported while Freundlich and the younger members were held as prisoners of war in Odessa until they were exchanged later for Russians caught in Germany.

The secretary of the Royal Astronomical Society and Director of Cambridge Observatory, Arthur Stanley Eddington (1882-1944) received a copy of Einstein's paper in 1916 and became interested in the possibility of testing this theory.

The 1916 eclipse in Columbia and Venezuela passed without any group's endeavour to investigate light bending [12]. A number of parties in the United States of America made an attempt on the 1918 eclipse in their own country. Most groups experienced cloud cover and Campbell had to contend with inferior equipment as the Lick supplies were still finding their way back from the 1914 disaster. Also, as a result of this debacle, comparison plates of the same field of stars when the Sun was not present had not been made beforehand. There were large errors in the measurements and lack of support for Einstein was announced in 1919. Campbell had decided to await the 1923 eclipse across California and Mexico for another attempt and Freundlich had wished to travel for the eclipse of 1919 but his instruments, which had been impounded in Odessa, were not returned to Germany until 1923.

4 Total Solar Eclipse of 1919

This absence of results from prior eclipses left the British with an opportunity in 1919. The upcoming eclipse to occur on 29 May 1919 was to have a maximum time of 6 minutes 51 seconds. Two sites were chosen, one at Sobral, Brazil and the other on the island of Príncipe off the west coast of Africa.

The purpose of the expedition was outlined as an investigation to discriminate between three possibilities: zero influence from gravitation, an effect in accordance with Newtonian law of $0''.87$ or one determined by Einstein's general relativity of $1''.75$ [13]. A more open plan would have been to measure the deflection of light, if any, rather than be constrained by these options.

4a. The Brazilian Expedition of 1919

The South American component had as observers Andrew Claude de la Cherois Crommelin (1865-1939) and Charles Rundle Davidson (1875-1970), both of the Royal Greenwich Observatory. Crommelin had experience in four previous eclipse excursions planned by the British Astronomical Association. This organisation had been founded in 1890 and their first endeavour was with 58 persons to Vadsöya, Norway in 1896. Here, Crommelin was in charge of naked eye drawings of the outer corona with the use of a disc screen but cloud interfered with any observations [14]. At the 1900 occasion in Algiers, Algeria, Crommelin was in control of the time department and used a three inch (7.6 cm) aperture refractor for prominence observation [15]. His third stint was on board a ship near Palmo, Spain in 1905 where he used a telescopic projection of Baily's Beads, took two photographs with a portrait lens of prominences, the inner corona and streamers, followed by binocular observation of the corona [16]. Crommelin observed the 1912 eclipse from the neighbourhood of Paris [17]. Davidson had previously travelled to Brazil with Eddington for the 1912 eclipse [18], and to Russia with Harold Spencer Jones (section 9a) for the 1914 eclipse [19]. In 1912 Davidson had intended using a coronagraph but rain interfered and in 1914 he operated a spectroscope for the flash spectrum and the corona.

A coelostat is a flat mirror turned by a motor to reflect the Sun into a fixed telescope. This allows substantial mounting for the telescope and easier movement of a smaller device to capture sunlight over a period of time. Preliminary testing at the eclipse site showed that the drive attached to their 16 inch (41 cm) coelostat was creating some oscillation in the images. To attempt to lessen this effect they opted for shorter exposures. For the 1919 eclipse Crommelin and Davidson controlled two instruments [20]. With the 41 cm coelostat feeding a 13 inch (33 cm), 3.43 m focal length astrographic telescope which was stopped to eight inches (20 cm), they managed 19 photographs of alternating 5 and 10 second exposures. From the relationship, plate scales in arcseconds = 206 265/focal length, 1 mm on the photographic plate represented one arcminute displacement. As deviations of the order of one arcsecond were being countenanced, measurements of 1/60 mm would be required [21].

Their second piece of equipment was a four inch (10 cm), 19 foot (5.8 m) focal length telescope served by an 8 inch (20 cm) coelostat. The scale was 1 mm ≡ 36″. From this telescope, eight images, each of 28 seconds duration, were obtained.

The astrograph showed 12 stars on a number of plates and seven stars on all but three. Comparison plates were made at the same locality over eight days some six weeks later. As the plates were being developed, it was noticed that the images were diffuse and there had been a change of focus. It was thought that this poor focus was due to an unequal expansion of the mirror from the heat of the Sun. However, focus was restored without any adjustment when the comparison plates were taken. Nevertheless, all the stars were measured.

For the 10 cm telescope one plate could not be used as it was taken through cloud but the other seven plates revealed seven stars. The images were superior to those taken with the astrograph but were still not perfect.

Crommellin and Davidson developed the plates, took a break a short distance away and returned to secure comparison plates at Sobral from 10-17 July 1919.

4b. The Principe Expedition 1919

The Príncipe sojourn was undertaken by Eddington and Edwin Turner Cottingham (1869-1940), a clockmaker. They had in their possession a similar astrographic telescope to the one taken to Brazil and this one was supplied by Oxford Observatory. 16 plates were obtained with exposures ranging from 2-20 s for the eclipse observations but the first 10 photographs were taken through cloud. The remaining six had no more than five stellar images on any plate. Nevertheless, 11 stars in total were measured from these six exposures.

Ideally, comparison plates should be taken from the same locality with the star field at the same altitude. Instead, as travel to eclipse localities is generally difficult with regard to transportation, comparison is often made in the predawn sky about a month or more later. This gives time for the Sun to have moved sufficiently further east through the zodiac. Adjustment is then required between the plates. As the Principe location had an afternoon timing as opposed to a morning one for Brazil further east, comparison plates would need to wait several months for a predawn exposure that would have the same altitude as that for the comparison plates for Sobral. However, after the eclipse a transport strike at Principe threatened, so the eclipse party decided to leave the island and hence comparison plates were obtained back in Oxford in August and September 1919 for an initial comparison and during the following January and February 1920 for a subsequent analysis.

4c. Combined Results 1919

The micrometer at the Royal Greenwich Observatory was not precise enough to take direct comparison measurements for the plates. An intermediary known as the scale plate was used and this was another photograph of the same region procured directly through a lens and not by reflection from a mirror so that a reversed image was obtained. Thus, measurements were made separately through the glass of the scale plate clamped on the eclipse and comparison plates.

Davidson and a Mr Furner carried out independent measurements on the Sobral plates with no discernible difference in their results. For the astrograph their outcome was 0″.93 at the limb of the Sun. From the 10 cm telescope, their calculated figure was 1″.98 ± 0.12. Meanwhile, Eddington used the Cambridge measuring machine on the Principe plates. As the sky was not completely clear of cloud during the eclipse, the brightness of the stars varied across parts of a plate and the diffusion was similarly erratic. By placing a weighting to each star in terms of its reliability, Eddington whittled the six plates with stellar images to two with which he held some confidence. Calculations derived from the use of one such plate against two comparison plates yielded deviations of stellar angles of 1″.94 and 1″.44, respectively. When the other accepted eclipse plate was checked against the same two comparison plates, Eddington obtained slightly different deviations of 1″.55 and 1″.67. These four values were then averaged to obtain a mean stellar deviation of 1″.65. With the 1920 comparison plates, Eddington revised his figure for the displacement at the limb of the Sun to 1″.61 ± 0.30 [22].

It was then up to Astronomer Royal Dyson to combine the results from Sobral and Principe.

While Dyson did not attend the 1919 eclipse, he had previously used a quartz spectroscope at total solar eclipses at Ovar, Portugal in 1900, Sumatra in 1901 and S fax, Tunis in 1905 [23] and had witnessed the 1912 eclipse in Paris [24].

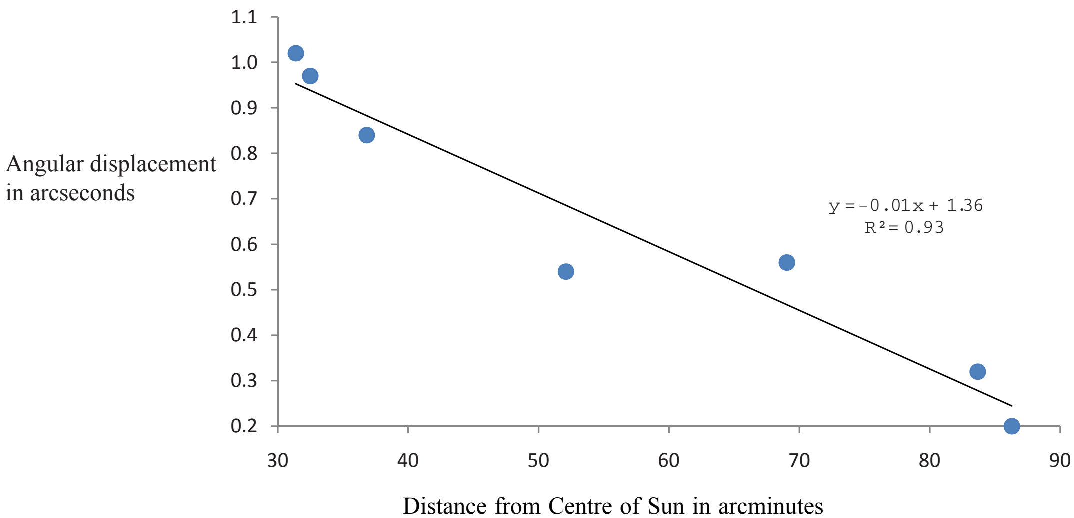
Dyson made a decision to eliminate the Sobral figures found with the astrograph on the basis of systematic errors. He acknowledged that the images were far superior to those on the similar instrument at Principe in terms of number of stars (12 versus 5) and the quality of the images. He argued that the nearly two orders of magnitude of brightness of the stars are actually a negative as this would mean a longer exposure. This does not necessarily follow as Sobral was almost cloud free at the time of the eclipse except for one minute in the middle of totality where a thin veil of cloud appeared. In contrast, Principe was troubled by cloud. The Sun was seen through drifting cloud although this thinned during the last third of totality. Dyson attempted to build the case further along lines of the comparison plates and temperature stability at Principe. It could be construed that he knew what value he wanted to obtain and wished to clear any value that would negate this. Because of the longer focal length of the 10 cm telescope at Sobral, the scale on the plates would give a lower uncertainty than for the astrograph. Dyson concluded that the remaining two values, 1″.98 ± 0.12 and 1″.61 ± 0.30, point to the 1″.75 proposed by Einstein. He also indicated that the experiment would probably be repeated at future eclipses.

A more telling effect would be whether the angular displacement was inversely proportional to the distance from the centre of the Sun. The authors addressed this expected dependence by choosing the seven stars selected from the 10 cm telescope, placing the observed displacement against calculated figures and graphing the observed figure against the distance from the centre of the Sun.

Table 1. For the 7 stars from the 10 cm telescope at Sobral, Brazil the observed angular displacement and distance from the centre of the Sun where the radius is 15″.78 are shown along with the calculated figure based on the Einstein value of 1″.75 at the limb and an inverse relationship with distance.

Star	Calculated Angular Displacement in arcseconds	Observed Angular Displacement in arcseconds	Distance from the Centre of the Sun in arcminutes
1	0.32	0.20	86.30
2	0.33	0.32	83.68
3	0.40	0.56	60.04
4	0.53	0.54	52.10
5	0.75	0.84	36.82
6	0.85	0.97	32.49
7	0.88	1.02	31.38

To reproduce this graph, Table 1 gives new labels to the stars as 1 to 7. The authors used the distance from the centre of the Sun in the graph but did not display it. It is calculated in the fourth column by the use of the Einstein value of 1″.75 at the limb of the Sun, the inverse law and the radius of the Sun as 15′.78 [25] at the time of the eclipse. The ensuing graph is one of observed angular displacement versus distance from the centre of the Sun.



Graph of observed angular displacement versus distance from the centre of the Sun.

One question to answer is how well the experimenters performed in 1919? Firstly, the measurements are very small. For 1 mm ≡ 36″, a value of 1″ involves a measurement of 0.028 mm on the plate and many angular measurements were even smaller. So, the measurement of displacements on the plates is a technically challenging task.

In spite of the eclipse being surrounded by bright stars of the Hyades cluster, no star within one solar radius of the edge of the Sun was selected and measured. These would have been expected to give a larger displacement and thus have a smaller uncertainty.

Other factors came into play. Temperature differences can affect eclipse and comparison photographs, refraction effects could be involved for lower parts of the plates, latitude and elevation may alter comparison and the scales from a series of images to the next month later may be different. There was an attempt to address some factors and then dismiss them as not being significant or incorporate adjustments into the calculations. It could be argued, as Dyson did, that the astrographic values from Sobral should not be included in the measurements due to poor images. On this basis, then, one could also question whether the two stars that were given the major weight from Príncipe should also have been excluded. In this case the result would be the one from the 10 cm Sobral data of 1″.98 ± 0.12. Given that the predicted deviation angle from Einstein's theory has a precise value of 1″.75 with no associated uncertainty, it could be concluded that the rejection of the poor Principe data indicates a disagreement between theory and observation. As the author's aim was to discriminate between three possibilities, they opted for Einstein.

As discordant plate scales and inadequate treatment of atmospheric refraction might pose issues, the determination of the relationship of the amount of bending to distance was an important factor. This shows an inverse correlation with an R^2 value of 0.93.

In 1979 a reanalysis of the Sobral data was performed at Greenwich with a modern plate-measuring machine and data reduction software [26]. This had good agreement for the 10 cm instrument of 1″.90 ± 0.11. Compared with the 1919 result the value for the astrographic lens was higher at 1″.55 ± 0.34 which more closely matched the figure for Einstein. The data from Príncipe have not survived from their return to Cambridge. Given the equipment that the British had to deal with and the meticulous nature of the measurements, the results were remarkably good.

5 Communication of the 1919 Results

Eddington and Dyson arranged for a joint meeting of the Royal Society and the Royal Astronomical

Society for 06 November 1919 to present the results from the eclipse. The paper was not received until 30 October [27]. So there was no time for critical analysis to be made by anyone other than the experimenters. The prestige of Dyson, the Astronomer Royal 1915-20, and Eddington, secretary to the Royal Society, allowed them to call this meeting and for their paper to be read as the first on the agenda [28].

After the presentation of the data by Dyson, Crommelin and Eddington, "in spite of the poor accuracy and the uncertainties surrounding the results, it was announced that the evidence was decisively in favour of the value of the displacement that had been predicted by Einstein" [29]. The stature of the speakers was impressive. Dyson, knighted in 1915, was followed by another awardee from 1908 in the person of Joseph John Thomson (1856-1940). His Nobel Prize in 1906 was for his experimental work on the conduction of electricity by gases and he was responsible for the concepts of the electron and isotopes and the invention of the mass spectrometer. Before calling for questions or alternative views, Thomson, as Chair of the meeting and President of the Royal Society 1915-20, proposed

"It is difficult for the audience to weigh fully the meaning of the figures that have been put before us, but the Astronomer Royal and Prof. Eddington have studied the material carefully, and they regard the evidence as decisively in favour of the larger value of the displacement. This is the most important result obtained in connection with the theory of gravitation since Newton's day, and it is fitting that it should be announced at a meeting of the Society so closely connected with him. ... If it is sustained that Einstein's reasoning holds good – and it has survived two very severe tests in connection with the perihelion of Mercury and the present eclipse – then it is the result of one of the highest achievements of human thought [30].

Given the flourish with which the meeting had been conducted, it would have been difficult to counteract the exciting atmosphere. Nevertheless, Ludwik Silberstein (1872-1948), who had written a textbook on the theory of relativity in 1914, countered that while there was probably a deflection of sunlight, this did not support Einstein's suggestion of a gravitational effect since the third astronomical prediction of the shift of spectral lines had not been measured. A month later, after he had digested some of the results, he objected that two stars deviated in the opposite direction from that predicted [31]. He also pondered what result would have been obtained if the astronomers did not have Einstein's value in front of them.

6 The world response to Einstein

The world response was exceptionally swift. The next day in The Times of London the caption read "Revolution in Science – New Theory of the Universe – Newtonian Ideas Overthrown" [32]. The newspaper referred to the meeting at the Royal Society the previous afternoon and quoted the sentiments of Thomson. The following day a short biography of Einstein was provided. The article seemed to be at pains to describe Einstein as fighting for the cause of those who resisted the war intentions of Germany [33].

Other newspapers quickly joined in the adulation. Pais even described the response in terms of canonisation [34]. Instead of attempting to explain the theory of relativity, several editors distanced the public from Einstein by suggesting that very few people could ever understand what was being proposed. This added to the unique realm occupied by Einstein. It would be difficult to pinpoint the factors that contributed to the esteem generated towards Einstein. One could conjecture that a devastating world war had just ended and many people needed a lift. Einstein could fit the bill of everyone's benign family member, he was removed from the war and he seemed to fit the stereotype of the absent minded professor.

Nevertheless, there were words raised in objection subsequently. Some disliked the overthrow of their hero Newton. Others saw that due process was not followed in settling disputes in Science and some believed more work needed to be done. Campbell summed up a view when he wrote "Professor Eddington was inclined to assign considerable weight to the African determination, but, as the few images on his small number of astrograph plates were not so good as those on the astrograph plates secured in Brazil, and the results from the latter were given almost negligible weight, the logic of the situation does not seem entirely clear" [35]. He was supported by another astronomer from the United States of America who penned "… the results of the eclipse of 1919, although highly lauded at the time, carried but little conviction in favour of

Relativity to conservative scientific opinion [36]. He questioned why two-thirds of the plates were rejected as inferior yet they supported the figure of Newton.

7 Philosophy of Science

In order to reach a verdict on the method, analysis and conclusions from 1919, it is necessary to delve into the operation of the scientific process.

A criticism that could be levelled at the public statements after the 1919 expedition, the acceptance of many other scientists and the glorification of Einstein by society at this juncture rests on an understanding of the philosophy of Science.

Judgement of support for a theory will make use of the words written by Karl Popper [37] in 1935. One of his major thrusts was that a speculation needed to be couched in a form such that verification and falsification were both possible. Further, he held that it was the falsifiability of a system that was more important than verifiability. “If this decision is positive, that is, if the singular conclusions turn out to be acceptable, or *verified*, then the theory has for the time being, passed its test: we have no reason to discard it. … It should be noted that a positive decision can only temporarily support the theory, for subsequent negative decisions may always overthrow it” [38]. His stance was encapsulated in “I too hold that hypotheses cannot be asserted to be ‘true’ statements, but they are provisional conjectures …” [39].

Thus, Science proceeds via a statement “If A, then B.” If it rains, the grass is wet. This could be seen to be false if it rained and the grass were not wet. However, if the grass is wet, other possibilities could exist apart from rain. There may have been an overflow from a tank, a burst water pipe, a sprinkler and so on. A tentative conclusion is “If B, then A may have occurred.” This is the conditional stance that Popper asserts. So, Science may disprove an idea but cannot prove it.

Science is a powerful instrument designed to gain a comprehension of reality. It does not find reality but produces models we can appreciate as an aid in fathoming something we cannot understand. Things are not discovered but invented. The justification for Science is the fruitfulness of its methods.

One unfortunate consequence is that scientists speak of models as if they are reality. Our language is such that it is simpler to follow this path. However, of all people, scientists should be aware of the methods they are employing and, when pushed, ought to acknowledge the way of their discipline. The public are not always aware of this distinction and use statements such as “scientifically proven”, “it is *only* a theory” or “there are some scientists who disagree”. This is very evident today in the public perception of the human contribution to climate change. Scientists have taken much evidence, made decisions based on the evidence and reached what is rightly within the profession, a tentative conclusion. Opponents who are not scientists misunderstand the provisional nature of the discipline and use this to suggest that no conclusion has been drawn.

The 1919 result was tentative. Those involved did recognise that supporting experiments were needed and the fact that the British mounted another expedition in 1922 for this purpose does indicate their upholding of the mechanism of Science. However, the genie was not going to be put back into the bottle. The British scientific establishment of the day, as well as perhaps a public tired of the war and buoyed by an uplifting idea, need to bear some ownership of this runaway effect. There was a much too immediate acceptance of Einstein’s theory.

8 Campbell and the Total Solar Eclipse of 1922

While 1919 was the first time that some results of light bending were obtained, much more credit needs to be given to Campbell (section 3) for his expedition planning and execution for the 21 September 1922 total solar eclipse.

The path of this total solar eclipse began at sunrise in Ethiopia (then known as Abyssinia), moved easterly across the Maldives in the Indian Ocean, through Christmas Island, met Australia near Broome, crossed that continent in a south-easterly direction just into South Australia, covered a section of south-east Queensland, departed at the Pacific coast at Ballina in New South Wales and ended at sunset north of New Zealand.

The options for observation were summed up in a lecture delivered by Campbell [40]. Christmas Island had the advantage of a small zenith distance of 12°. The north-western coast of Western Australia was difficult to reach, however, its advantages were that the zenith distance was still a respectable 32°, the duration of totality was expected to be 5 minutes 19 seconds and the weather predictions based on 25 years of records were favourable. In that time it had only rained on two September days and on each occasion that precipitation was less than one-tenth of an inch (2.5 mm). Little or no wind would be anticipated at the eclipse time of 1.40 pm. The location in South Australia presented problems of access and the Sun would be low. Places in south-east Queensland admitted railway convenience but the negatives were the chance of adverse sky and wind conditions, a low altitude of the Sun at 4.15 pm and a shorter surveillance time of 3.5 minutes.

The Lick Observatory opened in 1888 as a result of US $700 000 donated in 1874 by James Lick (1796-1876). With the advantage of the world's largest refractor [41]. The observatory had embarked on a program of eclipse work and already had experience in 11 total solar eclipses: two separate ones in 1889, 1893, 1896, 1898, 1900, 1901, three localities in 1905, 1908, 1914 and 1918 [42]. Phoebe Elizabeth Hearst (formerly Apperson, 1842-1919) had financed the 1893 sojourn. Funds for the eclipse expeditions of 1898-1922 were provided by two brothers Charles Frederick Crocker (1854-1897) and William Henry Crocker (1861-1937) who inherited US$ 25 million from their railroad investor father Charles Crocker (1822-1888) [43].

Before 1922, Campbell had already gained expertise from his eclipse work at Jeur, India in 1898, Thomastown, Georgia, USA in 1900, Alhama, Spain in 1905, Flint Island, Pacific Ocean in 1908, Brovarý, Russia in 1914 and Goldendale, Washington, USA in 1918. During these six eclipses Campbell had the use of the 40 foot (13 m) Schaeberle camera for coronal studies and on three expeditions other cameras were employed in searching for the possibility of a planet closer to the Sun than Mercury.

While on his sojourn to India, his place at the Lick Observatory was filled by a substitute at the expense of C F Crocker. Campbell took nine instruments all for photographic use [44]. John Martin Schaeberle (1853-1924) on staff at the Lick Observatory had planned a long focal length camera after his 1889 solar eclipse trip to Cayenne, French Guiana and used his design at Mina Bronces, Chile in 1893 and in 1896 at Akashi, Japan. Campbell saw the advantages of this instrument as allowing collimation in a precise position, eliminating issues that would have been inherent with the use of a coelostat and a driving clock, providing a constant focus mechanism, shielding from the wind and being further away from ground radiation. He pioneered the use of a large tower 24 feet (7.3 m) high to hold the lens objective inside the telescope tube with the lower end of the tube mounted on another tower and fixed rigidly to the ground. The photographic plate carriage was mounted separately from the tube in a pit dug into the ground. The system allowed for the taking of steady images. Concentration at this eclipse was on spectroscopy [45].

For the 1900 event closer to home Campbell built a tower based on his Indian eclipse observatory construction style and obtained eight excellent photographs with the Schaeberle instrument as well as capturing superb images with the other 11 devices [46]. The eclipse excursions were becoming a much bigger affair. W H Crocker financed three stations from the Lick Observatory at Labrador, Spain and Egypt as the astronomers attempted to notice changes along the eclipse path. In Spain, Campbell now had 18 instruments and coordinated 24 volunteers. The focus was on spectroscopic work on the corona and ten photographs of good quality were taken with the Schaerberle camera [47].

The Flint Island experience of 1908 had 20 instruments and 11 observers with transport to and from Tahiti provided by the United States Navy. Campbell had become quite an expert in logistics and total solar eclipse instrumentation. "All of the instruments were in perfect focus and adjustment" [48]. Six exposures of duration 2, 4, 16, 32, 32 and 64 seconds were secured with the Schaerbele telescope [49].

The Russian attempt with 12 instruments was thwarted by cloudy skies and complicated by the outbreak of war [50]. The instruments were held up by the hostilities [51] and a more modest campaign ensued in 1918 in spite of the eclipse being on home soil. This was the first attack by the Lick Observatory on the Einstein problem. The result was inconclusive due to both a lack of equipment which was not returned until the end of the world war as well as the borrowing of some items which were not up to the usual standard. Nevertheless, excellent negatives with the large telescope were obtained [52].

This, then, was the experience from Campbell personally and the Lick Observatory personnel prior to mounting the 1922 operation to see if the Einstein effect existed.

A modest expedition had been planned from the Lick Observatory for Wallal that acted as a combined telegraph and postal station on the north-western coast of Western Australia. Edward Francis Pigot (1858-1929) of Riverview College Observatory prevailed upon the Australian government to provide financial assistance to Campbell. The form this took was the offer of a naval vessel to transport the personnel and equipment from Fremantle, the port for Perth in Western Australia, to the eclipse site, near Broome, and return. Once Campbell knew this was in place, he was able to convince his benefactor William Crocker to enlarge the enterprise.

Campbell was a meticulous planner. Even before he departed for the Australian eclipse, he experimented with exposure times near the full Moon to obtain good star fields without fogging the plates. As well, he intended the developing to take place in Australia and so he had refined darkroom techniques.

The ideal scenario would have been to occupy the Wallal site several months in advance to obtain the comparison plates. As the naval ship would not be available until August and alternative transportation to the region would be very difficult, Campbell sent his Lick Observatory colleague Robert Julius Trumpler (1886-1956) to Tahiti ahead of time as this locality had a similar latitude 17° 32′ S and elevation as Wallal 19° 45′ S. Trumpler's expertise had been in the precise determination of proper motion of the stars belonging to the Pleiades cluster.

Campbell and Trumpler designed four new special purpose cameras.These were completely manufactured in the observatory workshops except for the lenses. Two cameras had quadruplet lenses from Hastings-Brashear. They had 5 inch (13 cm) aperture, 15 foot (4.6 m) focal length and had a common horizontal mount. The scale was 1 mm ≡ 45″. The field of view encompassed 5° × 5° and the plates were 17 inches (38 cm) square. Another two cameras, mounted similarly, carried quadruplet lenses from Ross-Brashear. They were smaller with 4 inch (10 cm) aperture and 5 foot (1.5 m) focal length. The scale of 1 mm ≡ 135″ allowed a 15° × 15° view on the same size plate. Collectively, these four items were referred to as the Einstein cameras.

By June 1922, with the use of the shorter focal length Einstein cameras, Trumpler had secured plates of the star fields where the eclipse would be in September. As an aid in comparison with the intended Wallal photographs, Trumpler obtained images of another star group with a similar declination to the eclipse field but six hours larger in right ascension. The intention was to do the same in Western Australia before and after the eclipse.

Further eclipse equipment left San Francisco in June 1922 and the two shipments reached Sydney a few days apart but Trumpler was delayed in combining the shipments to travel as one package to Fremantle. Further setbacks occurred there. Also, as a result of alterations in logistics from the Australian Government, the five weeks of intended analysis of the pre-eclipse data at the Perth Observatory were foregone. While transportation from Fremantle was brought forward a week and was changed to a commercial steamer, the Australian Government did provide a raft of helpful measures. These included duty free entry of apparatus and supplies, complimentary rail travel from Sydney to Fremantle return for the party, 10 personnel from the Australian Navy to accompany the group and assist the movement of the astronomers and goods from Fremantle to Broome return. They were to provide further aid in the changeover to a vessel to land at the beach, movement to the eclipse site, performing the heavy labour duties and delivering free services for sleeping and dining on site [53].

Campbell, his wife Elizabeth (Bessie) Ballard (formerly Thompson,1868-1961) and Joseph Haines Moore (1878-1949), a Lick Observatory staff member who had previously attended the 1918 eclipse, left

San Francisco in July 1922. At Wellington, New Zealand the party expanded to include Charles Edward Adams (1870-1945), his wife Eleanor Robina (formerly Jacobson, - 1941) and their daughter Elizabeth. Adams was appointed first Government Astronomer of New Zealand in 1911 and was a fellow at the Lick Observatory for the year 1915 [54]. The group arrived in Sydney on 05 August 1922.

The party swelled as they progressed to Perth. They were joined by J B O Hosking of the Melbourne Observatory. In Adelaide, those from Canada were Clarence Augustus Chant (1865-1956) from the University of Toronto, his wife Jean (Laidlaw), their daughter Elizabeth and Reynold Kenneth Young (1886-1977) of the Dominion Astrophysical Observatory in Victoria, British Columbia who had spent three years at the Lick Observatory. At Perth, they were joined by Alexander David Ross (1883-1966), Professor of Astronomy and Physics at the University of Western Australia and the expedition from the Perth Observatory included C Nossiter an astronomer in charge, G M Nunn a surveyor, V J Matthews a principal of a private school, J J Dwyer and C S Yates. Two others from the vicinity of Cambridge, England were J Hargreaves and G S Clark Maxwell [55].

Following the eight day boat trip of 2 600 km to Broome, the coalition was transferred to another craft and was combined with John Evershed (1864-1956) from the Kodaikanal Observatory from southern India along with his wife. They were escorted to Wallal latitude 19° 46' S, longitude 8 h 2 m 43.7 s E. Here, the Lick entourage was given first choice of a site, the Canadian unit was a short distance to the south, the Indian group to the west, the English contingent north east and the Perth band three miles (5 km) distant at a station.

A time of 5 minutes 15.5 seconds of totality was experienced during which the Lick assemblage obtained photographs with the Schaeberle camera and the four Einstein cameras. The negatives arrived back in California in late December. It was to be 1928 before the last results were published. This story will be continued after the outcomes from the other 1922 expeditions have been explored.

There were eight teams that made an attempt on measuring light deflection and another five groups that had other aims. So that the quality of the Lick Observatory operation may be gauged by comparison with other efforts in 1922, the performances of other campaigns attempting eclipse observations are presented before a return to Campbell's results (section 20).

9 Royal Greenwich Observatory and German-Dutch Observations on Christmas Island 1922

The two groups on Christmas Island were unsuccessful in their efforts to measure the deflection of light near the Sun.

9a. Royal Greenwich Observatory Encounter on Christmas Island 1922

Harold Spencer Jones (1890-1960) led the Royal Observatory Greenwich party with the aid of the Joint Permanent Committee of the Royal Society and the Royal Astronomical Society. He was accompanied by his wife and Philibert Jacques Melotte (1880-1961) and they went to Christmas Island off the coast of Western Australia. They travelled to Christmas Island via Java.

The main instrument was the 33 cm, 3.4 m focal length astrographic telescope which was used in Brazil in 1919. However, this time it was intended to take images directly and dispense with the coelostat.

The result here was nil due to clouds [56]. Anyone, no matter how well prepared, can experience cloud at the crucial time of an eclipse. However, the selection of Christmas Island was not a sound one. Cloud is almost a constant factor on this small island. The month with most cloud is October, followed by September when the eclipse occurred. For September, the median cloud cover is above 90%. None of the days spent here by Spencer Jones was ever cloud free. He did realise that Wallal would be a better site but he believed this was inaccessible from the direction of his journey. Counter to this was that Evershed (section 10) had joined the Wallal group at Broome from Singapore.

9b. German-Dutch Party Observations on Christmas Island 1922

Cloud was also the fate of a joint German-Dutch excursion on the same island and the same comments may be made here about the site selection.The group was headed by Freundlich (section 3). Campbell had met him in Germany in August 1913 and they discussed the Einstein test [57]. Other members included August Kopff (1882-1960) from the Königstuhl-Heidelberg Observatory, Josef Hopmann (1890-1975) of Bonn Observatory, Joan George Eradus Gijsbertus Voûte (1879-1963) of the Weltevreden Meteorological and Magnetic Observatory in Java, Dr Weber, a Swiss engineer, a Dutch naval lieutenant, two mechanics and others [58].

The main pieces of equipment were an astrographic telescope and an 8.50 m focal length camera with a coelostat. The intention was to take comparison plates with re-erected equipment later in Java.

10 Indian Results from Wallal 1922

John Evershed (section 8) is noted more for his work on another astronomical prediction of relativity, namely the redshift of spectral lines from the Sun. On this occasion, he was attempting to obtain an improved value for a green coronal line but his major thrust was measuring the displacement of light near the Sun.

Accompanying Evershed was his wife Mary Ackworth (formerly Orr, 1867-1949). Both were English astronomers who had met on the total solar eclipse excursion to Norway in 1896. At the 1900 event John travelled to Algeria near Maelma. His intention was to take a long series of photographs of the chromosphere and flash spectrum. He did obtain some results but was outside the limit of totality [59]. Mary witnessed the eclipse in Algiers.

The intention in 1922 had been to go to the Maldive Islands but, as transportation there was not an easy arrangement, they approached the Australian Government and this resulted in an invitation to join Campbell's group [60]. Ross (section 8), of the University of Western Australia, deputised Don W Everson, a technician in his own department, to assist Evershed. His role was to provide mountings for the instruments and align the special cameras [61].

Evershed did not consider that the Einstein issue had been settled. He wrote "The expedition was organised mainly for the purpose of obtaining photographs of the star-field surrounding the eclipsed Sun, in order to determine the deflection of light near the Sun. It appeared to be of great interest and importance because of a certain ambiguity in the results of previous eclipse expeditions …" [62].

Even though his preparations commenced one year before the eclipse, Evershed was plagued with mechanical problems. Two coelostats were not perfect and he decided to apply them to the spectrographic work where it would not be as large a problem. Dyson (sections 3,4a,5) supplied him with a 16 inch (41 cm) coelostat to counter criticism of this technique by Campbell. It had been tested at the National Physics Laboratory but the report was unsatisfactory with regards to both the mirror and the driving mechanism. This was to provide light for the Einstein camera, a 12 inch (30 cm) photovisual lens. Evershed bought a new driving clock. Upon testing the arrangement in India, he found that instead of star trails appearing as a straight line, there was a sine curve plus numerous other irregularities. Days were spent grinding new screws and teeth for the driving apparatus but testing was not done until he had arrived at Wallal. As a result, comparison plates could not be taken at Madras before the eclipse. An order was placed for a mirror to replace this one but it was not received in time.

Evershed and his wife arrived at Broome after travelling via Singapore from Madras and awaited the arrival of the other parties from Fremantle. Once at Wallal, much time was spent in erecting the instruments so that no rehearsals were conducted. Preparatory tests showed that star images were blurred due to faults in the mirror. The aperture was reduced to improve the situation. While the new screws operated better, performance was still below par. The focus of the lens was subject to temperature change.

Five images were collected with the Einstein camera and these were necessarily of short exposure, 5 – 15 seconds, due to problems with the equipment. Glitches occurred with the taking of the first and last photographs. The coronal and spectrographic plates were developed that evening. The coronal plate had fog and other defects and the other plates did not show any coronal lines due to their faintness at this eclipse. It was decided to develop the other plates under better conditions at Broome. Further disappointment followed when these showed unexplained fog on some, along with movement of the star images and poor definition. Despondency appears in Evershed's summary: "This completed the failure of our eclipse expedition" [63]. He had a scathing attack on British manufacturing, believing it should have abandoned the old methods and used ball bearings or rollers on all moving parts and done away with gears in the driving mechanism to produce smooth changes. He was able to see the contrast from the Lick Observatory operation nearby. "Our admiration for the American installation was perhaps tinged with envy" [64].

11 Canadian Results from Wallal 1922

The fifth of eight groups to tackle an Einstein effect was from Canada. The four members of this party (section 8) sailed the Pacific to Auckland and then Sydney. Here, they met Cooke (section 16), Pigot (section 8) and Gale (section 19). They entrained via Melbourne to Adelaide where they met Grant (section 14) who had arranged to have some of the apparatus for the Canadians made in the University of Adelaide workshop. Once the entourage of Campbell caught up with them, the entire assemblage moved through Kalgoorlie to Perth. From nearby Fremantle they took a boat up the coast, eventually to Wallal [65].

Campbell was viewed as being in charge of the entire operation. The Canadian group set up a little to the south of Campbell's spot so that both groups could hear the same timing being shouted [66]. The ten men from the Australian Navy were the commander Harold Leopold Quick and J W Barker, S Cushing, H Hutchins, James R Kean, W Kenny, W S Rhoades, T Roberts, F Sinclair and L W Starling. They assisted in transporting the group from Fremantle to Wallal return, loading and unloading the equipment, helping in the erection of the camps, assisting with the arrangement of the equipment and aiding in some astronomical measurements.

The main piece of equipment of the Canadian group was an Einstein camera of clear aperture six inches (15 cm) and focal length 11 feet (3.4 m) giving a plate scale of 1 mm ≡ 61″. Two cameras of focal lengths 36 and 33.75 inches (91 and 86 cm) as well as two ordinary cameras and a movie camera to take pictures of shadow bands on sheets were to be used. Seven comparison plates had already been secured by Trumpler in Tahiti (section 8) where the Canadians had forwarded their camera. There was time for rehearsals before the major event. Jean Chant observed shadow bands before and after totality visually but no success ensued with photographing them [67].

Developing of the main plates took place at Broome where two were discerned to be of good quality and a third less so. It was November before the personnel were back in Canada and Young commenced measurements at the Dominion Astrophysical Observatory. On the two plates selected there were 25 stellar images but due to the faintness of some, 19 were chosen and a further three were rejected later [68]. Young followed the method used by the English from the 1919 eclipse and his results were 1″.30 and 2″.17 at the limb, with an average of 1″.73 compared with Einstein's prediction of 1″.75. No uncertainty value is given in the article but from two values a precision uncertainty is 0″.45. He displayed a graph of displacement in arcseconds versus distance from the centre of the Sun in arcminutes with the Einstein relationship drawn. Inspection shows that of the 16 stars displayed, seven are within 0″.1 of the line, a further 3, 1, 1, 1, 3 respectively within 0.2, 0.3, 0.4, 0.5 and 0.6 arcseconds. The Canadian results, subsequently, were taken as having confirmed Einstein's theory relating to light displacement. However, there is a significant variability between the figures of 1″.30 and 2″.17 they obtained.

12 English Party at Wallal 1922

The English party had a different agenda from light bending. Hargreaves and Clark Maxwell (section 8) excavated a cellar and placed within it a piece of self-recording magnetic apparatus. Their results were collected over a fortnight [69]. In addition to their magnetic readings, they obtained photographs of the corona and the shadow bands [70].

13 Perth Observatory Team at Wallal 1922

The Perth team, also, did not attempt an Einstein test. The five members under the auspices of the Perth Observatory (section 8) succeeded in determining the coordinates of the site. Their programme entailed spectrographic work, photographs of the Moon's shadow, observation of shadow bands, images of coronal streamers and the corona. A particular focus was the comparison of illumination levels [71].

14 South Australian Expedition to Cordillo Downs 1922

A sixth Einstein endeavour was ambitious in setting up in a remote part of Australia. Further along the eclipse track the path of totality only just cut a swathe in the north eastern section of South Australia but State pride set the wheels in motion for a slice of history in this difficult to access region. In November 1921 an eclipse committee was formed with George John Robert Murray (1863-1942) as president. As a judge, lieutenant-governor of the State and lecturer in the law school at the University of Adelaide where he was elected Chancellor six times between 1916-1942 [72], Murray was a man of competent organisational ability. He harnessed the abilities of Grant, Dodwell and Kennedy.

Kerr Grant (1878-1967) had been acting Professor of Physics in 1909 and then Professor since 1911 at the University of Adelaide [73]. He received an invitation from the managers of Beltana Pastoral Company to set up an eclipse post on their sheep station Cordillo Downs 9 h 22 min 32.0 s E, 26° 43′ S [74]. The chief director of the company, Peter Waite, offered to provide transport from the nearest railway siding Farina to the Downs (640 km each way), hospitality and assistance at the homestead, the transport of instruments by camel and observers by car. The Greenwich band (section 9a) had also been invited but by this time their preparations for Christmas Island were too far advanced.

The Director of the Adelaide Observatory from 1909 was George Frederick Dodwell (1879-1963). He had served as an assistant at the observatory 1899-1909 and then Government Astronomer 1909-1952 [75]. He took charge of this enterprise as it became the mission of the Adelaide Observatory. His previous eclipse encounters were to Bruny Island, Tasmania in 1910 and Vava'u, Tonga in 1911 [76]. At the former his role was to photograph the corona but was prevented by cloud. In 1911 he used a mirror and coelostat to obtain images of the lower corona.

In preparation, Dodwell discussed the eclipse program at the May 1922 Rome Congress of the International Astronomical Union where he presented his recent longitude determination work at Adelaide. He sought out, among others, Oliver Justin Lee (1881-1964) of Yerkes Observatory and Herbert Doust Curtis (1872-1942), Director of the Allegheny Observatory, University of Pittsburgh, Pennsylvania. From there he had exchanges at Greenwich with the Astronomer Royal Dyson and Davidson from their experience of the 1919 expeditions. Returning via the USA, Dodwell paid a call to the Allegheny Observatory and Curtis loaned him a quadruplet camera. He visited another Pennsylvania establishment in Sproul Observatory at Swarthmore, the Mount Washington Observatory in New Hampshire, Mount Wilson Observatory in California and in the same State the Lick Observatory. Campbell provided him with the polar axis mounting, driving clock and driving arm for the quadruplet camera. In addition, Campbell wanted a comparison of photographs of the corona with the same type of instrument from widely separated places to see any rapid change in the corona. Wallal and Cordillo Downs were 35 minutes apart for the timing of the eclipse. Since Cordillo Downs would have a lower Sun altitude compared with Wallal, Campbell loaned the larger and better of the coronagraph lenses. Dodwell was also supplied with fittings for this instrument to mount it according to the Schaeberle method. A gift of US$100 was afforded by Louis Agricola Bauer (1865-1932) who was the first Director between 1904-1929 of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. The aim was to build up a picture of the magnetic field of the Earth.

Chief Assistant at Adelaide Observatory between 1921-1924, Alexander Lorimer Kennedy (1889-1972) [77] had been a member of Douglas Mawson's Australasian Antarctic Expedition 1911-1914 where his occupation is listed as magnetician [77]. He was to effect the magnetic observations at Cordillo Downs.

The equipment reached Adelaide in early May 1922 [79] and with some ancillary parts manufactured locally, Kennedy departed on 31 May 1922 in charge of all the apparatus. When he arrived at Lyndhurst Siding, he was informed that camel wagons were not available as there was concern about flooding in the Cooper River. The alternative was a team of pack camels and this required the daily loading and unloading of heavy and delicate equipment. During the latter part of the journey and at the terminus he was assisted by A G Appleby. Once at his destination on 20 July 1922 Kennedy laid concrete foundations to support the instruments and the Allegheny camera was ready for use by 08 August 1922.

By mid August Dodwell had returned to Adelaide and set out by car. He was delayed for a few days in the sandhills in the vicinity of the aptly named Mount Hopeless until his vehicle was extricated by camels. He arrived at Cordillo Downs on 29 August 1922 with E A Thrum. Grant appeared on the scene on 06 September and some helpers pitched in to ready proceedings. These included the managers C F Murray and his wife, as well as T E Barr Smith, Chief Director of Beltana Pastoral Company, since Waite had died, Ive the Managing Director, Adamson, the Secretary of the company, and P Riddell of Broken Hill. A party led by Walter George Woolnough (1876-1958), a Professor of Geology [80] arrived one week before the event and K Dixon was a member of the party also. Woolnough had lectured at the University of Adelaide 1901-04, then the University of Sydney 1905-1911 and was the founding Professor of Geology at the University of Western Australia 1913-1919.

With the assistance that he had received from a large group of astronomers, Dodwell had set himself four tasks: to test the Einstein prediction, to photograph the corona, to make use of the spectroscope and to perform magnetic work.

The Allegheny camera [81] had an objective made by the Brashear Company of four lenses where each pair fit together as achromatic components. The separation between the duplicates was 30.0 cm. While the diameter of each lens was 10.4 cm, the existence of a diaphragm at the optical centre reduced this to an effective 7.6 cm. The focal length of the camera was 163.1 cm and the field of view was 10°. This arrangement resulted in a scale of 1 mm ≡ 126". The camera produced a compact, circular stellar image of 3×10^{-3} cm within 2°.5 of the axis. Beyond this, elongation occurred in the radial direction but the advantage was that there was a dense centre to the images.

The plate holder could be adjusted to present a perpendicular orientation to the incoming light. Measuring 17.8 cm × 20.3 cm, the plates provided a 7° × 8° field. On this occasion, 0.3 cm thick glass doubly coated with Seed 30 emulsion from the Eastman Kodak Company was used. In addition to the two brass holders provided, two of wood and metal were constructed on site. The longer side of the plate was aligned with declination. Attached to a wooden frame, the assembly pointed along the polar axis but the camera was bolted at an angle to correspond with the declination of the Sun at eclipse time. Hence, the operation of the camera was restricted to a range in right ascension only.

The Lick Observatory had supplied roller bearings for attachment of the frame to the piers which were wooden and these were sunk into concrete footings. A driving arm over 3 m long controlled the northern part of the polar axis with its far end having two pulley wheels on an inclined track fixed in concrete. Regulation of the arm was via a clock that was on loan from the Lick Observatory.

Two guiding telescopes were attached to the camera. One pointed 1° 11′ north and 1° west of the axis to use Beta Virginis as the finder star. The other was designed to centre on Spica.

Campbell had supplied a 15.2 cm aperture, 12.2 m focal length coronagraph lens with fittings and mountings to be operated by the Schaeberle method. As well, the Lick Observatory gave them a 5.4 cm aperture, 152.4 cm focal length lens to obtain long exposure photographs of the corona.

The weather consisted of warm, sunny and clear days with a mean maximum shade September temperature of 27.9 °C and clear, pleasant nights of mean 10.8 °C. The telescopic seeing was excellent. The one downside was that a change of weather would bring in copious amounts of dust. This, together with a lack of facilities, necessitated developing the plates back in Adelaide.

Dodwell had sent a cablegram to Kennedy while the latter was en route to the site to take a number of test photographs half an hour after sunset. Several preliminary photographs captured on 12 and 13 August 1922 of 60 s each of the eclipse field served as a guide to the required exposures during the eclipse.

A strong wind threatened on the morning of the eclipse but this became calm by the afternoon and the eclipse was observed in a clear sky with the Sun at an altitude of 32°. The duration was 3 min 52 s, 3.33.17 – 3.37.09 pm Adelaide standard time. For the camera, plate I was exposed for 20 s on the eclipse followed by 20 s on the check fields, plate II 30 s on the check field then 60 s on the eclipse field, plate III 55 s on the eclipse field only and plate IV 20 s on the eclipse field only. Totality ended earlier than expected. After an initial call, the first slide was drawn and 5 s was allowed for any vibration to settle. Subsequently, 10 s was allocated for any change and dampening of vibration. Instead of the use of a shutter, an exposure screen unattached to the camera was employed and Dodwell remarked how this should be used in any future undertaking. Since the camera could only be moved in right ascension, the check field chosen was 24′.4 east of the Sun. Dixon had suggested a stop device between the extremes and this simplified the procedure.

On the day, the corona was of a type typical of sunspot minimum with a streamer extending about two solar diameters above the Sun and two comparable streamers below. The corona and chromosphere were described as moderately bright. There was only one large prominence and this was on the southwest portion of the Sun and other small ones on the upper limb.

Cordillo Downs only had very weak signals from Australian radio stations and E A Thrum and V D Bowers constructed an amplifier in situ. During the eclipse they observed a marked decrease in the radio signal from the Sydney transmitter [82].

The return journey by car was via Broken Hill.

In Adelaide the plates were developed with solutions of hydrokinone/sodium sulfite/sulfuric acid and potassium carbonate/sodium sulfite/potassium bromide for 12 minutes each. Grant attended to this and he and A L Nairn tackled a preliminary investigation. Comparison plates were the ones taken by Kennedy at Cordillo Downs and those by Dodwell on his return to the eclipse site six months later in March 1923. These encompassed 90 s each of eclipse and comparison fields taken on 12 March, 60 s each of 4 eclipse regions and 2 comparison ranges from 18 March and 60 s for each of two plates for each zone photographed on 19 March. These were taken during early morning when the field stars were at the same altitude and position in the sky as for the eclipse. Dodwell used the same Allegheny camera which had been stored at the homestead in the intervening period.

The eclipse and comparison plates were sent to Greenwich in two shipments as the measuring device in Adelaide was not accurate enough. Probable errors of the camera from the Allegheny Observatory had been supplied by that institution as ± 0″.171 in right ascension and ± 0″.176 in declination. It fell to Davidson (section 4a) to tease out the effects of scale from the proposed Einstein contribution. The theory is that the star positions at the time of the eclipse need to be compared to their locations six months apart so that the same altitude is used. As a further comparison, an exposure of a second field of stars away from the Sun during the eclipse could be judged against this field subsequently. This, however, does not guarantee similar conditions such as temperature. An alternative procedure is to photograph this second field on the same plate as the eclipse field at the time of the eclipse and then compare this with a photograph six months apart. Thus, any effect due to scale can be subtracted.

The Einstein effect is inversely proportional to distance. Davidson gave examples that a star at 15′ from the limb of the Sun was predicted to give 0″.87 displacement and at 45′, 0″.44. With the diameter of the Sun being 30′, the radius of 15′ + 45′ = 60′ = 1°. Hence, two stars at 1° from the centre of the centre on opposite sides would be forecast to be 2 × 0″.44 = 0″.88 further apart.

Davidson determined that there were too few stars on plate IV to give a meaningful result and after measuring the other three, he concluded that the scale on plate III was different from that for the other two. This plate had been exposed in the improvised wood carrier and a difference of only 0.05 cm from the supplied brass ones would be sufficient to explain the discrepancy.

Nine comparison plates had been taken, two before the eclipse and seven subsequently. Of the latter group, two were of the eclipse field only and the other five contained both fields. Davidson relied on this set of five mainly with only a slight contribution from the other four.

The method employed for measurement had been used previously at Greenwich to ascertain stellar parallaxes. Two plates had diamond rulings etched into them in the position of the stars to be measured, one for the eclipse field and the other for the comparison field. They were then placed over each photograph in turn. Departures from the positions were then recorded with the use of a microscope.

19 stars in the eclipse domain and 17 in the comparison realm were investigated. Even under magnification, some of these stars were too indistinct for accurate measurements and Davidson whittled this to 11 stars in the eclipse field on plate I, 14 on plate II in the eclipse region and 16 in the comparison region on both plates. The comparison stars were assumed to be far enough away from the Sun not to experience a gravitational effect. As the altitude of the Sun at Cordillo Downs during the eclipse was below 30°, Davidson applied a second order correction for refraction and used a proper motion amendment to bring the stars to the same epoch.

The result of the deviation at the limb of the Sun was determined at Greenwich to be a 2″.36 average displacement (2″.31 in the x coordinate and 2″.40 in y) for plate I and 1″.18 mean for plate II (1″.64 and 0″.71 for *x* and *y,* respectively). These two plates give an average of 1″.77 with an estimated range of ± 0″.3. While there was general agreement with the Einstein value, Davidson opined that there was "considerable discordance" in the separate results.

15 University of Sydney Mission to Goondiwindi 1922

Opting for the relative convenience of train travel, four companies honed in on Goondiwindi in Queensland, namely, the University of Sydney, Sydney Observatory, Melbourne Observatory and the Carnegie Institution of Washington, United States of America, while a fifth group, the New South Wales Branch of the British Astronomical Association, ventured to nearby Stanthorpe.

The contingent from the University of Sydney was specified by one of the participants, Edgar Harold Booth [83] (1893-1963), who was lecturing in Physics at the University of Sydney [84]. The Senate of the University approved the expedition and the equipment changes that were considered necessary and the troop had nine months to prepare. Selected as the original leader, James Arthur Pollock (1865-1922) had been appointed in 1886 as second astronomical assistant to the government astronomer of New South Wales. His professorship of Physics at the University of Sydney ensued in 1889 [85]. There was disarray when he died on 24 May 1922.

The new leader was Oscar Ulrich Vonwiller (1882-1972). Having taken over the Chair of Physics on the death of Pollock, he was subsequently appointed Professor in 1923 [86]. Other members were James Nagle, Superintendent of Technical Education and a member of the Senate of the University, Edward Francis Pigot (section 8), founder of Riverview Observatory in Sydney, George Henry Briggs (1893-1987) [87] and Norman Abraham Esserman (1896-1982) [88], both lecturers in Physics at the University of Sydney, H J Swain, Superintendent of Mechanical Engineering at the Department of Technical Education, and A B Ranclaud, lecturer in Physics at The Teachers' College in Sydney. Described as attached to this work force were Barnes, mechanician to the Department of Physics, R L Aston and Gordon Vonwiller, the son of the Professor. Pigot had been to the 1910 total solar eclipse in Bruny Island and the 1911 event in Tonga [89].

The equipment was sent by rail to Goondiwindi three weeks prior to the eclipse. On 07 September 1922 the main body entrained. Swain, Booth and one other person left on 14 September 1922 as they had to organise to make up classes at their respective institutions on the party's return. In his rendition of the event, Booth took the Sydney Express to Warwick and changed to a mixed train onto Goondiwindi taking 31 hours and 10 minutes for the complete journey.

The first week of the first wave was devoted to manual labour in digging holes and setting up stands for the equipment. They operated out of the back of a vacant shop. In the second week they erected and checked the apparatus. Nagle had the job of determining the location of Goondiwindi. The observers were drilled in the operation of the eclipse by day and then at night to simulate the eclipse conditions for the 3.5 minutes of totality.

They had unfavourable weather conditions right through until the day of the eclipse which was then clear and cloudless.

They also had local assistance. Mention was made of Mr Fletcher, solicitor of the district, as photographer of shadow bands along with Miss Doreen Fletcher.

A coelostat was used to reflect light into a telescope and photographs were taken by Nagle and developed by Briggs. Two photoelectric cells with active surfaces of potassium and containing helium secured light intensity measurements throughout the eclipse. Aston observed with cell number two. Maxima were measured at the beginning and end of the eclipse and a minimum at mid-eclipse [90].

The afternoon was spent gathering readings and dismantling the equipment. Some stayed to pack the gear for its return to Sydney. The others in the eclipse party were provided by the government with a special sleeper carriage on the train to Warwick.

Photographs of the corona were obtained but no results on light bending were attempted.

16 Sydney Observatory Experience at Goondiwindi 1922

The leader of the Sydney Observatory expedition to Goondiwindi for the seventh company investigating the Einstein effect was William Ernest Cooke (1863-1947). He worked as an astronomical assistant at the Adelaide Observatory beginning in 1878 before being appointed in 1896 as the first government astronomer at Perth Observatory. One of his major interests was mapping the sky photographically and he became quite competent in this field. In 1912 Cooke transferred to the position of government astronomer of New South Wales as well as holding the station of foundation chair of Astronomy at the University of Sydney [91].

At the site of the Goondiwindi racetrack an astrograph was mounted on two pillars, one of a concrete base with well-seasoned timber and the other was of iron casting which was specially made. “The observatory was built of wood and galvanised iron, with a meridian opening in the roof extending from the zenith to the Pole, and a large opening in the western wall, protected by a stout canvas blind” [92]. Eight exposures each of 10 s duration were taken during the eclipse with three of these used for a region 5° south of the eclipse but with the same right ascension.

A Grubb chronograph controlled the driving mechanism. In the collection of comparison photographs pre-eclipse, all worked perfectly but the system encountered difficulties at a critical time so that only two eclipse plates were obtained under a steady drive condition. For these the definition was too diffuse to allow precise measurements for the task in hand. Cooke indicated that the astrograph was worth some perseverance. The seeing conditions were steady close to the horizon but less clear at 40° altitude so that Cooke concluded that altitudes above 50° or 60° would be required for this type of astrographic work.

Photographs were obtained by a photoheliograph mounted on an old 6-inch (15 cm) Grubb equatorial stand. Partial phase images as well as some around the four contact times were secured. Campbell from Lick Observatory had arranged for Trumpler (section 8) to forward equipment to Sydney for the use of this group after he had taken comparison photographs in Tahiti in readiness for the eclipse.

The times of the four contacts were observed by eye and the use of graphical and computational methods. The stopwatch failed at the second contact time by eye. While there was excellent agreement between these three techniques, the values by computation were compared with the times that had been predicted for this eclipse. The four contacts were all early by 25.5 s, 13.0 s, 10.3 s and 12.2 s, respectively.

One requirement was to determine the latitude and longitude of Goondiwindi. A Reichenbach repeating circle that had belonged to Thomas Brisbane was resurrected and had a new telescope and transit micrometer attached. Static rendered wireless transmission from Washington and New York inoperable so that P Shaw, a local, depended on signals from Sydney. Later, signals from Lyon that were received in Greenwich, Paris and Sydney led Moore to believe that the longitude of Sydney needed to be adjusted downwards by 0″.5. He deduced that the location of Goondiwindi was 28° 32′ 46″.9 south and 10 h 01 min 13.07 s east.

W C Graham of the Sydney Observatory and Dr Thomson used timekeepers and watched the shadow bands on a white sheet on the ground. Graham was first assistant at this institution and retired in 1939 after 47 years work there [93]. Other personnel were W E Raymond, first assistant at the Sydney Observatory, H Cranney, astronomical assistant, J Short, astronomical photographer, D A Trigg, mechanician, and F F Cook [94].

A summation for the displacement results was “Bad atmospheric definition and poor performance of the driving clock of the telescope led to failure of an attempt to measure the deflection of sunlight passing near the Sun for comparison with the values predicted by Einstein’s Theory of Relativity …”[95]. 74 photographs were secured with the astrograph and heliograph but only two of the eight taken with the astrograph were free of distortion [96].

17 Melbourne Observatory Party at Goondiwindi 1922

Joseph Mason Baldwin (1878-1945) had been a research assistant at the Royal Observatory Cape of Good Hope and Potsdam Observatory Germany. He became chief assistant at the Melbourne Observatory 1908-1915, acting director 1915-1920 and government astronomer 1920-1944. He led the Melbourne Observatory expedition to Goondiwindi [97]. This was the eight unit which intended taking measurements of the deflection of light.

The excursion was financed and organised by Wilfred Russell Grimwade (1879-1955) who acted as a photographer for the scenes surrounding the camp. Present [98] also were W M Holmes of Melbourne University, Kidson, supervising meteorologist at the Central Weather Bureau, Thomas Parnell (1881-1948), Professor of Physics at the University of Queensland, Edward Montague Wellish (1882-1948), a lecturer in Applied Mathematics who had studied Einstein’s theory at Cambridge and in the USA [99], J G Mann and Z A Merfield.

The result was summarised “This time it was the equipment rather than the weather that was uncooperative, and they failed to take precise photographs” [100].

18 Carnegie Institution Representative at Coongoola 1922

Donald G Coleman from the Carnegie Institution of Washington selected Coongoola 250 miles (400 km) west of Goondiwindi in the Cunnamulla district as it was on the centreline of the eclipse and had more likelihood of cloud free conditions than other places in Queensland. This was the end of the western railway line from Brisbane. It was also selected by an official photographer aiming to capture the corona and an astronomical observer from the Queensland government [101].

Coleman had been doing magnetic work for the Institution in the Society Islands. He intended checking for magnetic variation from two days before to two days after the eclipse. His itinerary was then to proceed to Thursday Island and the most northerly parts of Australia. He would come back through Sydney and onto Washington after being away from his headquarters for about two and a half years [102].

19 New South Wales Branch of the British Astronomical Association at Stanthorpe 1922

Walter Francis Gale (1865-1945) was the leader of the New South Wales branch of the British Astronomical Association party to Stanthorpe in 1922 to observe the eclipse. In 1893 he visited Chile with the Lick Observatory eclipse expedition as well as travelling to observatories in the United States of America.

Gale was a founder of the New South Wales branch of the British Astronomical Association in 1894 [103]. Personnel were H Brown, J Scanlon, J J Richardson, E W Esdaile, R W Schuch, Marshall Andrew, C Barr, J Brown, F Swinburne, A P Macherras, J C Jenkinson, G H Hoskins, H H Edwards, L Melville, A W Gale, W Best, E Gardiner and Thomas Brindley.

The group dispersed to a few localities around Stanthorpe and a number of local residents joined to assist observations. They viewed themselves as an amateur organisation and their published aims were to observe a number of phenomena: the contact timings, the passage of the Moon over any sunspots, shadow bands, corona with drawings, prominences, photograph Baily's Beads, effect on animal life, colouring of the landscape and sky and anything unusual [104]. A great many observations were recorded and while many telescopes were in operation, no attempt was made to measure the Einstein effect.

20 Results from the Lick Observatory Expedition to Wallal 1922

Even though Campbell had planned his expedition in minute detail, his schedule was thwarted by events beyond his control. He had arranged for Trumpler to proceed from Tahiti after obtaining reference plates and carry out measurements of the brightest stars on these plates for five weeks at the Perth Observatory. Trumpler had shipping delays getting to Perth, arrangements for the transport of the equipment from Perth were brought forward and there was a delay returning to Fremantle after the eclipse (section 8).

As Trumpler had made arrangements to visit family in Switzerland before returning to the USA, he and Campbell effected measurements on one plate in an incomplete and time rushed manner at Broome. Their preliminary result was a light deflection but with a value between that of Newton and Einstein.

There was great interest and pressure for Campbell to publish his results. However, he withheld these and the eclipse negatives did not reach him back at his observatory until 16 December 1922. It was February 1923 before Trumpler returned. Meanwhile, Campbell was offered the presidency of the University of California. He accepted on condition he remain director of Lick Observatory. The extra workload added to the stress of finalising the results.

There were two plates each from each pair of Einstein cameras and a large number of stars was recorded because Campbell had decided on longer exposures with good tracking. For the longer focal length pair of cameras, 120 s exposures were followed by 125 s and Beta Virginis was tracked with a guiding telescope by Trumpler. These cameras were more suited to stars near the limb of the Sun. The brighter stars had well defined images but the fainter ones near the edges of the plates were diffuse. There were 92 stars recorded and as many stars as possible in each eclipse field were measured against 37 stars in the check field with an intermediate plate. Campbell and Trumpler released preliminary results from the larger two Einstein cameras on 11 April 1923 and on 23 April 1923 Campbell gave details at a meeting of the Academy of Sciences in Washington. At this point, having worked independently, Trumpler had results for three plates and Campbell two. By May 1923 when the results were submitted for publication, there were some slight modifications to their five results and Trumpler had finalised measurements for the four plates and Campbell had completed three. They agreed with the inverse distance relationship and thus calculated the deflection at the limb as shown in Table 2 [105].

Table 2: Light deflection at Sun's limb from Lick Observatory published in 1923

Plate	Trumpler	Number of Stars	Campbell	Number of Stars	Plate Mean
1	1″.88 ± 0.27	69	1″.72 ± 0.32	62	**1″.80**
2	1″.62 ± 0.22	81	1″.35 ± 0.22	77	**1″.48**
3	1″.91 ± 0.19	84	1″.78 ± 0.22	80	**1″.85**
4	1″.76 ± 0.22	85		85	**1″.76**
Mean for each observer	**1″.78 ± 0″.11**	-	**1″.60 ± 0.14**	-	-

The mean value for the four plates was published as 1″.745 but the value for plate 4 in Table 2 was given a 0.9 weighting relative to 1.0 for the other three. Thus, the conclusion for the Einstein value was lower at 1″.72 ± 0.11.

It was another five years to 1928 before publication of the results from the pair of shorter focal length cameras occurred [106]. Campbell had directed the production of six plates at the eclipse with four of 60 s duration and two of 102 s. The first two plates had been exposed to the check field the night before and remained in the cameras. The last two plates stayed in the cameras after the eclipse and were opened to the check field during that evening. These cameras had a larger field of 15° × 15° so that, in all, 550 stars were imaged. Trumpler was the sole astronomer who measured these plates. He produced calculations for 147 stars of which he eventually used 145 stars. His comparison group of stars was 75 in number. His method of comparison was new as he lined up both plates directly without an intermediate plate so that the accuracy was improved for this pair of cameras. These plates had a scale of 135″ to the mm and the images were sharp and well defined.

Results from the four plates with the check field were ready by 1924 and delivered by Campbell on 26 April 1924 to the American Philosophical Society in Philadelphia. The data supported the Einstein effect.

The publication of the full set of results in 1928 again gave support that an inverse distance relationship was the best fit for the deflection. The Einstein extent at the limb of the Sun was 1″.82 ± 0.15. This value was given a weighting of 1 relative to a 2 for the longer focal length result of 1″.72 ± 0.11. The conclusion, with a weighting of 3, was 1″.75 ± 0.09, in agreement with the figure predicted from the Theory of General Relativity.

21 Discussion

The 1919 expedition by the British is to be lauded as the first where measurements pointed to light deflection in the vicinity of the Sun. The amount of displacement is very small and the astronomers performed well in obtaining photographs and comparison plates to plot the differences between the two. These British parties needed to discount differences in scale, temperature and refraction effects and their major contribution was to show the inverse distance relationship from the limb of the Sun.

However, criticism has already been levelled at establishing an hypothesis directed to discriminating between three possibilities (section 4). An attempt at measuring the deflection, if any, ought to have been the aim. Thus, there appear to be some dubious decisions made as which plates should be included and which omitted. The elimination of the 0″.93 value for the astrograph used in Brazil is unconvincing. There were enough questions that could be raised to be more tentative in declaring a result.

Judged against the manner in which Science operates, the conclusion was presented in too positive a manner. The status of the personnel involved in both the eclipse and the meeting to hear the results appeared to attempt to carry the day rather than countenance objections.

The press, without an understanding of the scientific method, seized upon the pronouncements and heralded a new world in Science. Perhaps this was a world in need of an uplift after four years of devastating war and gloomy news.

At the very least, the result needed to be treated as speculative. The procedure of Science required another attempt to ascertain whether there was support for the measurements or a contrary indication.

In 1922 eight different groups made an attempt to measure the deflection of light. The problems encountered give perspective to the difficulties of this procedure. The Royal Greenwich Observatory party and the Dutch-German one can be criticised for their poor selection of a small island subject to cloud most of the year and in a month leading up to the most cloud experienced on the island each year. On the other side of the continent, the choice of Goondiwindi had improved access but a low altitude Sun at the time of the eclipse and unpromising weather prospects were strong negatives. Although poor atmospheric definition was cited by the Sydney Observatory team, it and the Melbourne Observatory band acknowledged equipment issues in their lack of success. Similarly, the contingent from India was apparently furious with the poor standard of apparatus needing to be in peak operational condition for some delicate measurements.

This left three groups which did obtain measurable results on light bending. There can be no doubt about the tenacity of the South Australian contingent. However, even though dryness would be expected for the eclipse, the choice of location could be questioned. The locality had the Sun in eclipse below 30° elevation. Thus, more correction was required with the analysis due to refraction effects. The motive for the site selection had more to do with State pride than placing the results as paramount. Measurements were processed on 11 stars and the two results had a variation of 1″.18 and 2″.36. It is interesting to note that this average was 1″.77 yet Davidson, who measured the movements on the plate declared them to be discordant. Davidson was involved in the 1919 eclipse but the same conclusion was not reached for his and the other data, even though the results carried a similar spread to Dodwell's numbers.

The Canadian group selected Wallal but relied on Trumpler for comparison plates. Young used data from 16 stars on two plates to obtain 1″.30 and 2″.17, average 1″.73. There were more stars than the number exploited by Dodwell and the range was narrower at 0″.87 versus 1″.18. However, this is still a significant discrepancy.

What of the Lick Observatory results? With the two 4.57 m focal length Einstein cameras, four plates were measured by Trumpler and three of the same by Campbell. For this set of seven, the minimum number of stars was 62. Trumpler executed a variation of 0″.29, Campbell 0″.43. The average for each plate varied by 0″.37 and the two astronomers provided an average which differed from each other by only 0″.18. Their result was published as 1″.72 ± 0.11. The two smaller Einstein cameras of focal length 1.52 m would not be as good a scale but this was partly compensated for by a more precise technique. The result was 1″.82 ± 0.15, a difference of 0″.10 and in agreement with each other within the uncertainty values. The combination with weighting produced 1″.75 ± 0.09, in excellent agreement with Einstein's prediction of 1″.75.

Campbell's result is by far the one with the most confidence in support of the Einstein effect. However, this does not constitute proof. Instead, according to Karl Popper's view of the philosophy of Science, one does not conclude from the results that Einstein's theory is correct but that these observations do not disprove him and scientists can look favourably on the usefulness of his model of the Universe.

What factors contributed to the success of Campbell's venture? The Lick Observatory was well funded with instruments at its locality due to its wealthy founder. Expeditions were well resourced principally through two very wealthy siblings who supported what became known as Crocker expeditions over a sustained period of time. Thus, a great deal of proficiency was built into these excursions. Campbell himself gained much experience with six eclipses prior to 1922. Some other players also travelled to a number of eclipses. However, not only had he been to more eclipses but the work he undertook on some was similar to what he used in 1922. Other observers had been involved in things like spectroscopy and then changed to photographic techniques.

Campbell was a great organiser. He planned each phase of the trip with precision. He had no bias with any expected outcome so he can be viewed as impartial. Even though he wanted to publish earlier than he did, he was not rushed into pronouncements. By comparing his attempt with those of the other seven in 1922 and the 1919 precursor, one could conclude him as the most authoritative of the observers.

22 Conclusion

The work presented here suggests that the 1919 British solar eclipse expedition results and conclusions ought to have been more tentatively presented rather than announced to the world so definitively. The aim of the expedition was misguided in being a choice between three possibilities instead of an attempt to find a measure of deflection. As a result, the selection of which data to eliminate carries some apparent arbitrariness. In addition, the way in which the results were combined can be questioned and the variations in the measurements were readily apparent. All of this indicates that any conclusions drawn at this time should have been more cautious. Supporting results were required and fortunately this was what the British attempted in 1922.

The published accounts from the 1919 eclipse indicate that the world press, acting on the British announcement, hailed Einstein prematurely. In particular, the wholehearted support from a person with the stature of Thomson appears to have interfered with the correct procedure in Science for examining the evidence and presenting an outcome with an appropriate level of caution. Thus, it seems there was a clear departure at the time from openness regarding a conclusion towards seeing a specific hypothesis being immediately proven. This approach is at odds with the philosophy of Science.

Examination of the results also suggests that principal credit for the first eclipse observations that convincingly support Einstein should be given to Campbell for his 1922 measurements performed in Australia and whose analyses continued to 1928. Here it is seen that four sets of results, measured independently by two people, yielded precise and closely consistent figures and a conclusion of 1″.75 ± 0.09 which neatly encompassed Einstein's prediction of 1″.75.

The reasons for Campbell's success are clear. He had substantial financial support for his work, superior equipment compared with other expeditions, more extensive experience and a meticulous mode of operation. The Lick Observatory had been engaged in eclipse expeditions before Campbell became involved and the 1922 total solar eclipse expedition was the seventh such undertaking by Campbell. Thus, Campbell had the capacity to use the previous experience of the Lick personnel as well as hone his own skills. Additionally, it seems that Campbell was open to any result and did not favour a particular outcome. The difficulties experienced by the other solar eclipse expedition efforts in 1922, as outlined in this paper, highlight some flaws compared with Campbell's successful enterprise.

This paper has analysed the history associated with early tests of one of the three predictions from the General Theory of Relativity which could be measured astronomically, that of the amount of bending of starlight in the vicinity of the Sun. On the other hand, Einstein's theory could be tested further due to its predictions regarding the anomalous perihelion precession of Mercury's orbit and the gravitational red shift of spectral lines. Thus, the 1919 pronouncement was based on only one of the three tests, a situation which could be interpreted as another sign of premature acceptance of what was then a completely revolutionary theory.

In conclusion, the accolades that were given to what was then considered an observational demonstration of general relativity from the 1919 solar eclipse would have been better accorded to Campbell for his measurements resulting from the 1922 eclipse.

References

1. Newton I, *Opticks* or *A Treatise of the Reflections, Refractions, Inflections & Colours of Light*, 4th ed (1704, 1979), 339.
2. Treder J, Jackisch G, "On Soldner's value of Newtoniandeflection of light, *Astronomische Nachrichten*, cccii (1981), 275-7.
3. Dyson F (ed.), *The scientific papers of the honourable Henry Cavendish,* (1921).
4. Soldner J, "On the deflection of a light ray from its rectilinear motion, by the attraction of a celestial body at which it nearly passes by", *Berliner Astronomisches Jahrbuch,* (1804), 161-72, (translated into English).
5. Einstein A "On the electrodynamics of moving bodies", *Annalen der Physik*, xvii (1905), 891-921.
6. Einstein A, "On the relativity principle and the conclusions drawn from it", *Jahrbuch der Radioaktivität und Elektronik*, iv (1907), 411-62.
7. Einstein A, "On the influence of gravitation on the propagation of light", *Annalen der Physik*, xxxv (1911), 898-908.

8. Crelinsten J, *Einstein's Jury – The Race to Test Relativity,* (2006), 144.
9. Einstein A, "The Foundations of the General Theory of Relativity", *Annalen der Physik*, xlix (1916), 769-822.
10. Crelinsten J, *op. cit.* (ref 8), 55-58.
11. *Ibid.*, 76-77.
12. *Ibid.*, 113.
13. Dyson F W, Eddington A S and Davidson C, "A determination of the deflection of light by the Sun's gravitational field, from observations made at the total eclipse of May 29, 1919", *Philosophical Transactions of The Royal Society*, ccxx (1920), 291-333.
14. Marriott R A, "The BAA's first organized eclipse expedition", *Journal of the British Astronomical Association*, ci (1991), 3, 162-70.
15. Maunder E W, "Report of the expeditions organized by the British Astronomical Association to observe the total solar eclipse of 1900, May 28", Excerpts from the *Journal of the British Astronomical Association* (1901).
16. Levandek F W (ed.), "The total solar eclipse 1905: Reports of observations made by members of the British Astronomical Association of the total solar eclipse of 1905, August 30", Excerpts from the *Journal of the British Astronomical Association,* (1905).
17. Meeting of the British Astronomical Association April 24, 1912, *The Observatory*, xxxv (1912), 2, 224-7.
18. Eddington A S and Davidson C, "Total eclipse of the Sun, 1912 October 10. Report on expedition to Passa Quarto, Minas Geraes, Brazil", *Monthly Notices of the Royal Astronomical Society*, lxxiii (1913), 386-90.
19. Jones H S and Davidson C R, "Total eclipse of the Sun, 1914 August 21. Preliminary account of the observations made at Minsk, Russia", *Monthly Notices of the Royal Astronomical Society*, lxxvii (1915), 125-34.
20. Dyson F W, Eddington A S and Davidson C, *op. cit.* (ref 13), 331-2.
21. Eddington A S, "The total eclipse of 1919 May 29 and the influence of gravitation on light", *The Observatory*, xlii (1919), 119-22.
22. Dyson F W, Eddington A S and Davidson C, *op. cit.* (ref 13), 328.
23. Jones H S and Davidson C R, *op. cit.* (ref 19), 388.
24. "Obituary Notes. Frank Watson Dyson", *Monthly Notices of the Royal Astronomical Society*, c (1940), 238-45.
25. Dyson F W, Eddington A S and Davidson C, *op. cit.* (ref 13), 322.
26. Kennefick D, "Testing relativity from the 1919 eclipse – a question of bias", *Physics Today,* (March 2009).
27. McCausland I, "Anomalies in the history of relativity", *Journal of Scientific Exploration*, xiii (1999), 2, 271-90.
28. Wali K C, "Chandra: abiography of S Chandrasekar", (1984).
29. McCausland I, *op. cit.* (ref 27).
30. Thomson J, "[Chair of] joint eclipse meeting of the Royal Society and the Royal Astronomical Society", *The Observatory*, ii (1919), 389.
31. Fowler A, "[Chair of] meeting of the Royal Astronomical Society, Friday, December 12, 1919".
32. *The Times* (London), "Revolution in science", 07 November 1919, 12.
33. *Ibid.*, 08 November 1919.
34. Pais A, *Subtle is the Lord – The Science and the Life of Albert Einstein*, 1982, 305.
35. Campbell W W, "The total solar eclipse of the Sun, September 21, 1922", *Publications of the Astronomical Society of the Pacific*, xxxv (1923), 11-44.
36. Pickering W H, "Relativity Since 1922", *Popular Astronomy*, xxxi (1923), 31, 380-2.
37. Popper K, *The Logic of Scientific Discovery*, (London 2005, 1935 first publication).
38. *Ibid.*
39. *Ibid.*
40. Campbell W W, *op. cit.* (ref 35).
41. Osterbrock D E, Gustafson J R and Shiloh Unruh W J, *Eye on the Sky – Lick Observatory's First Century,* (1998), 130-3.
42. Pearson J, "The Role of the 40 foot Schaeberle camera in the Lick Observatory investigations of the solar corona", *Ph D thesis* (2009), 79-85.

43. New York Times, "*C F Crocker dead*", 17 July 1897.
44. Campbell W W, "A general account of the Lick Observatory-Crocker eclipse expedition to India", *Publications of the Astronomical Society of the Pacific*, x (1898), 126-40.
45. Campbell W W, "Some spectrographic results obtained at the Indian eclipse by the Lick Observatory – Crocker expedition", *The Astrophysical Journal*, xi (1900), 226-33.
46. Campbell W W and Perrine C D, "The Crocker expedition to observe the total solar eclipse of May 28, 1900", *Publications of the Astronomical Society of the Pacific*, xii (1900), 175-84.
47. Campbell W W, "The Lick Observatory-Crocker eclipse expedition to Spain", *Publications of the Astronomical Society of the Pacific*, xx (1908), 63-85.
48. Campbell W W, "The Crocker Eclipse expedition of 1908", *Lick Observatory Bulletin*, cxxxi (1908), 1-5.
49. Campbell W W, "The Crocker eclipse expedition of 1908 from the Lick Observatory, University of California", *Publications of the Astronomical Society of the Pacific*, xx (1908), 63-86.
50. Campbell W W and Curtis H D, "The Lick Observatory – Crocker eclipse expedition to Brovarý, Russia", *Publications of the Astronomical Society of the Pacific*, xxvi (1914), 224-37.
51. Campbell W W, "Return of eclipse instruments from Russia", *Publications of the Astronomical Society of the Pacific*, xxx (1918), 312.
52. Barnes V M, "Two eclipse expeditions of 1918. The Crocker eclipse expedition from the Lick Observatory University of California", *Publication of the Astronomical Society of Pomona College*, viii (1923), 29-30.
53. Campbell W W, *op. cit.* (ref 35).
54. *Ibid*.
55. *Ibid*.
56. Jones H S, "The total solar eclipse of 1922 September 21", *The Observatory*, xlvi (1923), 164-1.
57. Campbell W W, *op. cit.*, (ref 35), 16.
58. Jones H, "Christmas Island eclipse expedition", *The Observatory*, xlv (1922), 317-20.
59. Evershed J, "Solar eclipse of May 28, 1900. Preliminary report of the expedition to the south limit of totality to obtain photographs of the flash spectrum in high solar latitudes", *Proceedings of the Royal Society of London*, lxvii (1900), 370-85.
60. Evershed J, "Report of the Indian eclipse expedition to Wallal, West Australia", *Kodaikanal Observatory Bulletin*, lxxii (1923), 45-51.
61. Robins J L, "Mr DW Everson and the department's war work", *History of the Department of Physics at UWA*, vii (2006), 1-5.
62. Evershed J, *op. cit.* (ref 59), 45.
63. *Ibid.*, 50.
64. *Ibid.*, 51.
65. Chant C A, "The eclipse expedition to Australia – From Auckland to Port Headland", *The Journal of the Royal Astronomical Society of Canada*, xvi, 125 (1922), 281-3.
66. Chant C A, "The eclipse camp at Wallal", *The Journal of the Royal Astronomical Societyof Canada*, xvii (1923), 1,1-17.
67. Chant J L, "The shadow bands at the Australian eclipse", *The Journal of the Royal Astronomical Society of Canada*, xvii (1923), 379-81.
68. Young R K, "The Canadian eclipse expedition. The measurement of the Einstein plates", *The Journal of the Royal Astronomical Society of Canada*, xvii (1923), 4, 129-37.
69. *The Register* (Adelaide), "Awaiting the Eclipse", 13 Sept. 1922, 11.
70. *The Mercury* (Hobart), 21 Sept. 1922, 5.
71. Ross A D, "Observations of the Total Solar Eclipse, September 21, 1922", *Publications of the Astronomical Society of the Pacific*, xxxv (1923), 45-9.
72. Castles A C, "Murray, Sir George John Robert (1863-1942)", *Australian Dictionary of Biography,* (1986).
73. Tomlin S G, "Grant, Sir Kerr (1878-1967)", *Australian Dictionary of Biography,* (1983).
74. Dodwell G F and Davidson C R, "Determination of the deflection of light by the Sun's gravitational field from

observations made at Cordillo Downs, South Australia, during the total eclipse of 1922 September 21", *Monthly Notices of the Royal Astronomical Society*, lxxxiv (1924), 150-62.
75. McCarthy G J, "Dodwell, George Frederick (1879-1963)", *Encyclopedia of Australian Science,* (1993).
76. Edward P G, "The Adelaide Observatory after Todd", *Proceedings of Astronomical Society of Australia*, xi [2] (1994), 206-10.
77. Walker R, "Alexander Lorimer Kennedy (1889-1972)", *Encyclopedia of Australian Science*, (1995).
78. Mawson D, *The Home of the Blizzard,* (1938).
79. Tomlin S G, "Physics and physicists in the University of Adelaide – The first seventy Five years", *University of Adelaide Archives,* (1975).
80. Branagan D F, "Walter George Woolnough (1876-1958)", *Australian Dictionary of Biography,* (1990), 572-3.
81. Schlesinger F, Hudson C J, "The determination of star positions by means of a wide-angle camera", *Publications of the Allegheny Observatory of the University of Pittsburgh*, iii (1961), 9, 59-75.
82. Tomlin S G, *op. cit.* (ref 73).
83. Booth E H, "The Sydney University eclipse expedition to Goondiwindi, Sept. 1922" in *Hermes*, The Magazine of the University of Sydney, xxviii (1922), 1.
84. Mitchell B, "Edgar Harold Booth (1893 - 1963)", *Australian Dictionary of Biography,* xiii (1993), 218-9.
85. McCaughan J B T, "James Arthur Pollock (1865–1922)", *Australian Dictionary of Biography,* xi (1988), 253-4.
86. McCaughan J B T, "Oscar Ulrich Vonwiller (1882-1972)", *Australian Dictionary of Biography,* xii (1990), 333-4.
87. McCarthy G J, "Briggs, George Henry (1893-1987)", *Encyclopedia of Australian Science,* (1993).
88. McCarthy G J, "Esserman, Norman Abraham (1896-1982)", *Encyclopedia of Australian Science,* (1993).
89. Drake L A, "Pigot, Edward Francis (1858-1929)", *Australian Dictionary of Biography*, xi (1988).
90. Briggs G H, "Measurement of the intensity of the light of the corona at the eclipse of September 21, 1922", *The Astrophysical Journal*, lx (1924), 273-82.
91. Hutchison D E, "William Ernest Cooke (1863-1947)", *Australian Dictionary of Biography*, viii (1981), 102-3.
92. Cooke W E, "The Total Solar Eclipse of 1922 September 21. Observations by the Sydney Observatory expedition at Goondiwindi, Queensland", *Monthly Notices of the Royal Astronomical Society*, lxxxiii (1923), 511-5.
93. Nangle J, "Report of the proceedings of Sydney Observatory", *Monthly Notices of the Royal Astronomical Society*, xcix (1939), 362.
94. *The Argus (Melbourne)*, "Eclipse of the Sun. Goondiwindi parties. Scientists busy. Stormy conditions feared.", 13 September 1922, 12.
95. Wood H, "Sydney Observatory: 1858 to 1958", *Sydney Observatory Papers*, xxxi (1950), part 7.
96. *The Powerhouse Museum Collection*, Sydney.
97. Simon P, "Baldwin, Joseph Mason (1878-1945), *Australian Dictionary of Biography,* (1979).
98. The Argus (Melbourne), *op cit.* (ref 94).
99. *The Sydney Morning Herald*, 11 November 1919, 7.
100. *Museum Victoria*, "Eclipse expeditions from Melbourne Observatory", (retrieved 2013).
101. *Cairns Post*, "Official observations next week in the south", 15 September 1922.
102. *The Sydney Morning Herald*, "Solar eclipse", 06 September 1922, 12.
103. Wood H, "Walter Frederick Gale (1865-1945)", *Australian Dictionary of Biography,* viii (1981), 609-10.
104. Expedition for the observation of the total solar eclipse of Sept 21, 1922, by Members of the New South Wales Branch of the British Astronomical Association, *Memoirs, British Astronomical Association*, xxiv (1924), 92-4.
105. Campbell W W and Trumpler R, Observations of the deflection of light in passing through the Sun's gravitational field during the total solar eclipse of September 21, 1922, *Publications of the Astronomical Society of the Pacific*, xxxv (1923), 158-63.
106. Campbell W W and Trumpler R, "Observations made with a pair of five-foot cameras on the light-deflections in the Sun's gravitational field at the total solar eclipse of September 21, 1922", *Lick Observatory Bulletin* 397, xiii (1928), 130-60.

[*Received*; 28.10. 2013; *accepted*: 28.12. 2013]