Astronomical Tests of General Relativity

A ůKŜăłă for the award of

Doctor of Philosophy

Keith John TRESCHMAN

BSc, DipEd, BEdSt, BA, MEd, MSc

2015

Abstract

This thesis is an in depth investigation of the history of the acceptance of Einstein's Theory of General Relativity by scientists and by the public through the media. It emphasises the key role that Australia played in that acceptance and in the verification of General Relativity. This contribution came from the 1922 total solar eclipse across the continent as well as the discovery in 2003 at Parkes Radio Telescope of the first, and to this date only, pair of pulsars in mutual orbit. This system provides a unique opportunity to plumb the theory in a much stronger gravitational field regime than previously. This historical scrutiny provides an insight into scientific revolutions in general. The examination of this particular development may then act as a template for the study of other scientific revolutions. One of the key findings is that the Theory of General Relativity was prematurely accepted. The main argument of the thesis is for 1928 being the year when sufficient evidence existed for scientists to begin accepting the theory based on gravitational deflection of light instead of the commonly accepted date of 1919. Emphasis is given to the explorations of the 1922 eclipse parties in Australia and the activities of the eight groups measuring light deflection at this eclipse. This work is gathered together here for the first time. The upshot is that it was 1928 before the results were published in full and a conclusion could be drawn. It is also established that the situation for Mercury needed a much longer time period to near the end of the twentieth century before a decisive verdict could be made. Similar to the situation for light deflection, it is found that 1928 is also the year in which spectroscopic data from spectral line frequency shifts of the Sun and white dwarfs had accumulated sufficiently so that a strong conclusion on the third of the classical tests of General Relativity could be made. From the late 1960s the radio region of the spectrum was employed more frequently to investigate gravitational deflection. As a result of a subsequent extension of this application to interferometry, the increased precision of experiments provided a greater level of testing. No astronomical test yet has refuted General Relativity and agreement has been reached at the 0.05% level with one parameter involving the double pulsar. In line with the emphasis of the 1922 eclipse in Australia, the Australian newspapers were gleaned up to 1928 to see how the 1919 British total solar eclipse results were regarded by the media and the public and to ascertain how the media explained the purpose for those 1922 expeditions in Australia. It is found surprisingly that the newspapers performed admirably in explaining difficult concepts in simple terms for the public during this time. This work provides an historical account of the astronomical tests of General Relativity. More broadly, this thesis demonstrates how the acceptance of a scientific revolution depends on the constant accumulation of data by many scientists and the communication of those results to the wider community. A century after it began, Einstein's revolution in thinking provides a suitable model for space and time in the Universe.

Certification of Thesis

I certify that the work contained in this dissertation is the bona fide work of the candidate, not previously submitted for an award. The ideas, results, analyses and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged

K. J. Treschman

Signature of Candidate

23/09/2015

Date

Endorsement

B. Carter

Signature of Primary Supervisor

24 Sep 2015

Date

Signature of Associate Supervisor

24 Sep 2015

Date

Acknowledgements

The title of this ůKŜăłă is ‘Astronomical Tests of General Relativity’. However, it had its origin with the theme ‘The Contribution to Physics of the Total Solar Eclipses in Australia 1830 – 1930’ and my supervisor was Dr Wayne Orchiston who guided me at James Cook University 2011-12.

After Astronomy was discontinued at this institution, I transferred to the University of Southern Queensland where I was welcomed by Dr Brad Carter. He had been my supervisor for my Master of Science 2006-10. With him the topic morphed to the present one. From 2013-15 Brad has been my enthusiastic conductor. He has the ability to draw from me the crux of an issue when I am immersed in a lot of detail. After his reading of my work at many junctures during this period, his suggestions resulted in improvement in my communication. He is at his best in a brainstorming session when I am thrashing about attempting to find a direction. He has the keen ability to make links between different areas of research to develop a central theme. During the times when I wondered whether continuing with this study was worthwhile, his humanity was at the fore as he gently guided me to see the end game and what was necessary to achieve this. Brad’s positive support has been instrumental in my reaching this destination. When I commenced my Masters in Science in 2006 he had the vision for my achieving a Doctorate even though I did not have this in mind until I completed that Degree. My gratitude is extensive for my following his baton for a total of eight years throughout both qualifications.

I experienced the skill of Dr John Mainstone as an associate supervisor for only a short time until his death in 2013. He was a master of the English language, had a broad level of knowledge and possessed a command of writing.

From then I came under the influence of Dr Nick Lomb. His listening abilities are very skilful before he picks up a required thread and can weave this into a connection of ideas. Over time I have witnessed his capacity to supply gems of thought in this continuing saga. His ideas have been very welcomed and he has provided a new point of direction for me on many occasions. The feedback from Nick has been exceptionally prompt and he provides nuggets in his responses. I have valued his creative flair in our discussions.

My wife Madonna has been a constant source of support throughout my many years of study. Whenever I encountered a brick wall, she had the ability to ask the right questions to redirect my efforts. She was able to look at things from a different perspective and encouraged me to continue this journey. Her emotional support has been outstanding.

Our children Ursula, Monica and Paul have been patient and understanding as they saw me devote many hours to my study during their childhood and adolescence. For their positive attitudes, I am truly thankful. Now, as adults, they still display an interest in my academic pursuits and value the importance of learning.

I have also received encouragement from my own high school students who exhibited a curiosity in my study. Anthony Lumsden has been of tremendous assistance with technical computer issues.

Contents

Papers for ¢KŜăĺă

Paper 1

Y W ¢NŜăŎKϒl·yΣ Early astronomical tests of General Relativity: the gravitational deflection of light, *Asian Journal of Physics*. (2014) 23 (1 & 2): 145-170.

Paper 2

Y W ¢NŜăŎKϒl·yΣ Early astronomical tests of General Relativity: the anomalous advance in the perihelion of Mercury and gravitational redshift, *Asian Journal of Physics*. (2014) 23 (1 & 2): 171-188.

Paper 3

Y W ¢NŜăŎKϒl·yΣ Recent astronomical tests of General Relativity, *International Journal of Physical Sciences*. (2015) 10 (2): 90-105.

Paper 4

Y W ¢NŜăŎKϒl·yΣ General Relativity support from the double pulsar, *International Journal of Physical Sciences*. (2015) 10 (15): 456-465.

Paper 5

Y W ¢NŜăŎKϒl·yΣ General Relativity in Australian Newspapers: The 1919 and 1922 Solar Eclipse Expeditions, *Historical Records of Australian Science*. (2015) 26: 150-163.

These are single authored papers.

Paper 1: Early astronomical tests of General Relativity: the gravitational deflection of light

List of Tables

Graph

Paper 2: Early astronomical tests of General Relativity: the anomalous advance in the perihelion of Mercury and gravitational redshift

List of Tables

Paper 3: Recent astronomical tests of General Relativity

List of Tables

Paper 4: General Relativity support from the double pulsar

List of Figures

List of Tables

Paper 5: General Relativity in Australian Newspapers: The 1919 and 1922 Solar Eclipse Expeditions

List of Figures

List of Tables

Introduction

One of the great cornerstones of Physics is the Theory of General Relativity. This was published by Albert Einstein (1879-1955) essentially in 1915, although he made a correction to his paper in 1916. Now, 100 years later, it is possible to provide an historical perspective to see both how the scientific community responded to this new idea and how the public have been included in its worldview.

General Relativity is regarded as a revolution in Science. If so, then it would be expected to bear the characteristics of other scientific revolutions. At the outset, the theory challenged the thinking of the time so that interplay existed between this new concept and the culture within which it emerged. In addition, one ought to be able to trace its historical development and see how it became accepted by scientists and the public. Hence, this progress may demonstrate Science in action.

The motion of a body is described relative to something else called a frame of reference. If this frame is stationary, it is known as an inertial frame and the description of the motion is, as a result, in fairly simplified terms. Then, the mathematics of the motion in another reference frame may be given as a result of transformations. This was the situation in the Physics of Isaac Newton (1643-1727). Thus, Einstein was not the first to propose that the laws of Physics should be the same in all frames of reference which had uniform motion. However, his special insight in 1907 was that this should apply to any measurement of the speed of light. Consequently, he followed a path that differed from Newtonian Physics. In the Physics that preceded Einstein, if light were moving towards or away from a person who was also moving, then simple addition or subtraction of relative motion would result in changes to the speed of light. This would counteract his first premise. He solved this conundrum by challenging the notions of an absolute position for space and absolute time. In his depiction, space and time were relative to the observer. The outcomes which followed from his thoughts were that as the speed of an object increased, any clock being carried with this entity would run slower and the length of the object in the direction of travel would become shorter. In addition, if two events occurred simultaneously in one frame of reference, this would not be the case with one frame moving relative to the other. These quirky ideas provided a consistency in his two postulates.

Einstein subsequently wrote a number of equations to describe his concept of the Universe. Gravitation arose as a geometric property of space and time (referred to as spacetime) to show that they are not independent quantities but are related to the gravitational field of any mass. Whereas previously gravity had been an inexplicable force acting between bodies at a distance, Einstein envisaged that any acceleration in the vicinity of a massive body was due to the curvature of spacetime around it. One of his inferred consequences in 1907 was that light emitted from the Sun would display an alteration of its frequencies since time in its neighbourhood would affect this light. From his equations, he produced a figure of 2.12×10^{-6} as the ratio of the change in wavelength at the surface of the Sun compared with the wavelength measured on Earth for this gravitational shift towards the red end of the spectrum in this environment. This became one of the three classical astronomical tests of General Relativity.

A second classical astronomical test ensued in 1911 when Einstein calculated a value for the amount of bending of starlight in spacetime at the edge of the Sun. He revised this calculation upwards in 1916 in the flowering of his ideas in the General Theory of Relativity. He postulated that the amount of displacement of the light at the edge of the Sun would be 1".75 and that this quantity would decrease proportionally as the distance from the centre of the Sun increased. This was a very small measurement for the instrumentation of the day and could only be quantified by taking photographs of a region of stars during a total solar eclipse and then of the same region at night months before or after the event.

The third of the three classical astronomical tests of General Relativity involved a solution to the motion of the planet Mercury. In a two bodied interaction, such as that of the Sun and Mercury, the orbit of the planet was described by Johannes Kepler (1571-1630) in 1609. His investigation of the orbit of Mars led him to suggest that any planet would trace out an ellipse and that it would return to the same position in each orbit. However, the presence of the other planets would cause the orientation of the ellipse to swing around the Sun. In the Physics of Newton involving many bodies, astronomers attempted to calculate the change that would be expected in the perihelion position of Mercury in space. After accounts of all the forces believed to exist, there was still an unexplained anomaly. This was interpreted, in one scenario, as evidence for a planet closer to the Sun and this fictional body even received the name Vulcan. However, in 1915 Einstein reasoned that spacetime would affect the orbit and he predicted a value of the movement of this perihelion position in space of 45" ± 5 century^{-1} which very closely matched the measured anomaly of 43" century^{-1} [42.98 ± 0.1]. In a letter about this to the theoretical physicist Paul Ehrenfest (17 January 1916) Einstein described that he was beside himself with joy.[1]

These three classical astronomical tests of General Relativity, then, are predictive in nature and are known as gravitational redshift, gravitational displacement of light and the anomalous advance in the perihelion of Mercury in its orbit.

It was claimed by some that General Relativity was 'proven' based on

(i) the Mercury calculation from 1915,

(ii) the two British expeditions at the 1919 total solar eclipse where starlight deflection measurements were attempted for the first time and

(iii) experimental work on the frequencies of lines in the solar spectrum conducted up to the year 1923.

Indeed, on the 100 year anniversary of General Relativity, the popular science magazine, Scientific American, devoted its entire September 2015 edition to Einstein. Within it, lies a summary of his work which is typical of that in many books and reports. "On November 6, 1919, four years after Einstein completed the general theory of relativity, newspapers the world over trumpeted just released astronomical measurements establishing that the positions of stars in the heavens were slightly different than what Newton's laws would have us expect, just as Einstein had predicted. The results triumphantly confirmed Einstein's theory and rocketed him to icon status overnight. He became the man who had toppled Newton and who, in the process, had ushered our species one giant step closer to nature's eternal truths."[2]

So, this great revolution is portrayed as resting on one defining moment, that of the measurements of the deflection of starlight during a total solar eclipse in 1919. This is often the way that Science is depicted publicly and how the populace customarily understands the operation of Science. Three other examples attest to this perception of an immediate and monumental breakthrough in the advancement of scientific knowledge. There is the often told story of the Eureka moment of Archimedes as he observed the water rising when he entered a bathtub and he transferred this to a method for measuring the volume of irregular solids. Then, there is the narrative of Newton watching an apple fall and being thus inspired to produce the Universal Law of Gravitation. The third illustration comes from the history of Astronomy. The geocentric representation of Claudius Ptolemy (90-168) of Alexandria stood for 1500 years and was overthrown by Nicolaus Copernicus (1473-1543) of Poland who proposed a heliocentric model in his published work of 1543. The retrograde motion of the planets could now be explained easily as a consequence of a moving Earth and so the heliocentric version won the day. Since this was so simple, it was not explained why it took so long for intelligent people to come to this viewpoint.

From a reading of the history of scientists and their work, one comes to realise that there is a departure between the popular perception and the real situation. The flowering of many scientific ideas involved a more convoluted track. The actual historical development of the third example of the heliocentric model may now be taken to criticise the simplistic presentation of one defining point in time.

The heliocentric idea was written about much earlier by Aristarchus (c310-c230 BCE), a Greek astronomer and mathematician from Samos. He had the planets in their correct order, believed the stars were suns and that they were at a very great distance from the Earth. His proposal probably rested on his measurements of the angle between Moon-Earth-Sun at quarter moon and the almost equality between the angular size of the Sun and Moon in the sky. His angle was on the low side at 87˚.

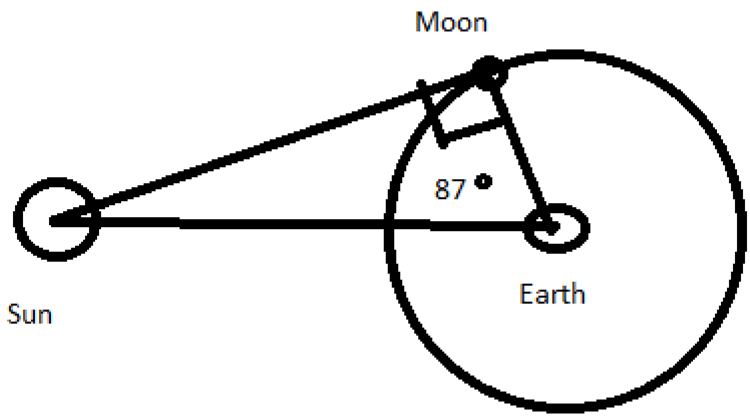


Figure 1. Diagram of Sun, Earth and Moon with the Moon at first quarter.

He did not use trigonometry but since 1/cos 87˚ = Earth-Sun distance / Earth-Moon distance = 19 (Figure 1), he indicated that the Earth-Sun distance was 18-20 times the Earth-Moon distance. He reasoned that as the Sun and Moon had the same angular size, the Sun must be 18-20 times larger than the Moon. He had an approximate ratio of the size of the Earth to the Moon from the arc of the Earth's shadow on the Moon during a lunar eclipse. So, he deduced that the Sun was much larger than the Earth. Therefore, the Earth was more likely to orbit the Sun than vice versa. The Ptolemaic geocentric proposal was disparaged on the basis of the introduction of epicycles in Ptolemy's attempt to align observations with theoretical predictions. Yet, Copernicus eventually had to adjust his model with epicycles just like Ptolemy had and his system was just as complicated and was no better at predicting the position of the planets. Rather than the idea of Copernicus having an immediate impact, the heliocentric proposal was still not well accepted until near the end of the life of Galileo Galilei (1564-1642). In 1610 Galileo had found that some objects did not have Earth as their centre, namely four moons of Jupiter, but the debate continued to divide scholars into opposite camps. This was certainly a scientific revolution in action. Yet, the real revolutionary of the period was Kepler. In his work for Tycho Brahe (1546-1601), Kepler was instructed to pursue his master's model that the Earth was stationary, the Sun and Moon orbited the Earth and the five known planets orbited the Sun. Historically, few people have heard of this Tychonic system. Nevertheless, it answered the questions of why the Earth does not feel as if it is moving and it allowed the stars to be much closer since no parallax could be measured of their positions six months apart as ought to be the case if the Earth were moving. In 1609 Kepler, interpreting the data of positions of Mars produced by Tycho, published his theory of elliptical movement of the planets. It was still some time, 1627, before he used his ideas to circulate predictions for the positions of the planets. Since his tables were significantly more accurate than those based on Ptolemy or Copernicus, more scientists were swayed to accept his worldview. While Kepler's planetary law described the orbits of the planets, it had no theoretical basis. This was provided 60 years later by Newton who showed mathematically that if the force of attraction between two bodies varied with distance as the square of the inverse, then the resulting shape would need to be one of the conic sections. As a result, an ellipse was one possibility.

So, if this revolution followed such a tortuous path, could another revolution, namely General Relativity, proceed in a similar way? This thesis seeks to challenge that there was one defining moment which overthrew what had gone before and ushered in the acceptance of General Relativity. The thrust of these papers is summarised in the following.

Hypotheses

1. Australia played a key role in the acceptance and verification of General Relativity from the 1922 total solar eclipse across the continent as well as the discovery in 2003 at Parkes Radio Telescope of the first, and to this date only, pair of pulsars in mutual orbit.

2. The Theory of General Relativity was accepted prematurely.

The emphasis given in the previously quoted Scientific American article is one of immediacy. It will be contended in these papers that this is far from the actual methodology of Science. In contrast to an acceptance at one instant, this investigation of the history of General Relativity seeks to conclude that, from a scientific point of view, this revolution does not rest on one defining moment. Rather, it is a long, slow process. There is argument and counterargument. A proliferation of retesting and new investigations is necessary. Results need to be accumulated.

In order that a conclusion may be made concerning the hypothesis, it is necessary to examine the nature of proof in Science. To gain acceptance, any theory has to run the gauntlet of scientific procedures. The ideas need to be couched in language which could look at the falsifiability of the proposals. Within the philosophy of Science, hypotheses take the form 'If A, then B.' This statement could be falsified if A existed but B did not. However, the reverse, 'If B, …' could only lead to the logical deduction that 'A might exist.' since other reasons may also lead to B being the result. Hence, Science operates with a specific methodology. Other explanations always need to be pursued. Nevertheless, there does come a time when each scientist interprets the evidence and makes a judgement call. It is similar to the situation when a 12 person jury in a criminal case offers an opinion based on the evidence. Truth is not necessarily the result but the public accepts the decision since this is how our societal system is organised. Similarly, Science, through the majority of its practitioners, decides on accepting or rejecting the elements of a theory. A new paradigm ought to be only tentatively held. There is a conclusion held until more evidence may accrue to sway that opinion. Historically, this follows a pattern of a number of early adopters, then more scientists become adherents as the weight of arguments mounts until, finally within the realm of study, a critical mass of those in the field believe that enough experimental support exists to hold that the theory contains the best explanations of the observed data.

In the first four of five papers, relevant journals in the fields of Physics and Astronomy are examined to marshal the arguments for the hypothesis that General Relativity was prematurely accepted. The first two papers encompass the three classical astronomical tests of General Relativity.

Paper 1: Early astronomical tests of General Relativity: the gravitational deflection of light

The first paper explores the historical context of the classical test of the gravitational deflection of light up to the year 1928. In 1919, the British sent parties to Brazil and the island of Príncipe off the coast of west Africa. The Einstein prediction was 1".75 of starlight deflection at the edge of the Sun. This exceedingly small measurement was at the extreme edge of capabilities at the time with the photographic apparatus, telescopic equipment and measuring instruments available. Nevertheless, the 1919 expeditions performed an admirable service in securing measurements at a total solar eclipse [147-51].

The paper includes some critical analyses of the hypothesis that was used, the manner with which contributing factors were dealt, the selection of the data obtained, the interpretation of the results and the way in which the results were communicated initially to scientists [147-51]. A case is made that there was insufficient evidence to support Einstein at this juncture based on the astronomical test of gravitational deflection. This led to the need to obtain further measurements and this was the major focus during a subsequent total solar eclipse in 1922.

An assault was made on this problem in 1922 when eight parties dispersed across Australia and Christmas Island to attempt observations with an aim to provide either supporting confirmation or a refutable result. Another five groups were seeking information other than light deflection so that a total of 13 assemblies were devoted to observations at this event [152-65]. The event was a significant occurrence in both Australian and scientific history, yet little of it resides in the current public consciousness. This paper is the first assemblage of the work of these eclipse parties into one piece of writing. For the eight of the 13 parties that congregated in the Australian region for the eclipse to determine a measure of light deflection, there were representatives from (1) Royal Greenwich Observatory [155] and (2) a German-Dutch party [156] which set up stations on Christmas Island in the Indian Ocean between Western Australia and Indonesia. At a remote station called Wallal near Broome in Western Australia there was a group from (3) Kodaikanal Observatory in southern India [156-7], (4) a Canadian troupe from the University of Toronto and Dominion Astrophysical Observatory [157] and members of (5) Lick Observatory from the USA [152-5]. In a remote part of South Australia, a gathering from (6) Adelaide Observatory trained their telescope [158-61]. Further east at Goondiwindi in Queensland, personnel under the banners of (7) Sydney Observatory [162-3] and (8) Melbourne Observatory [163] set up a station each. The other five groups which were involved in matters other than light deflection were (1) an English party [157-8] and (2) Perth Observatory [158] both at Wallal, (3) the University of Sydney camped at Goondiwindi [161-2], (4) the Carnegie Institution of Washington at Coongoola in the far south west of Queensland [163] and (5) the New South Wales Branch of the British Astronomical Association at Stanthorpe in southern Queensland [163-4].

Results from the eight institutions are presented but the major emphasis is placed on the outcomes from Lick Observatory. Preliminary data from this establishment were published in 1923 but it was to be 1928 before all of the calculations were completed. The argument is that 1928, rather than 1919, ought to be the year when General Relativity had sufficient support from the sole criterion of gravitational deflection.

Paper 2: Early astronomical tests of General Relativity: the anomalous advance in the perihelion of Mercury and gravitational redshift

The other two classical tests of the anomalous advance in the perihelion of Mercury and gravitational redshift are the subject matter of the second paper.

An unexplained advance in the perihelion of Mercury's orbit had been known since the time of Urbain Le Verrier of Paris Observatory in 1843 [173-4]. The curvature of spacetime proposed by Einstein in 1915 seemed to provide a fit for the missing quantity [175]. However, before a theory gains acceptance, other proposals need to be explored. Some of these suggestions were that the inverse square law of Newton may have to be tweaked; there could be a planet or a ring of planetesimals orbiting the Sun closer than Mercury; perhaps the Sun or its atmosphere may have an elliptical shape [174-5]. Also, Mercury was a case of one. It was 1956 before similar, but smaller, measurements of this anomalous phenomenon were obtained for Venus and Earth [176]. Embedded in this historical development is the difficulty of predicting orbital parameters as soon as one removes the restriction of only a two body problem and includes the influence of the other planets [172-9]. Indeed, parameters for Mercury and its orbit needed refinement. Since the planet does not have a moon, its mass had been determined by the passage of a comet [172]. The launch of spacecraft to Mercury from 1974 has continued to provide alterations to the mass of Mercury. Long term fluctuations of its orbit to sufficient accuracy required the use of numerical integration and computers which were applied to this issue in the 1980s. Thus, it will be contended that confidence in this classical test being used did not really exist until the 1980s.

For the third classical astronomical test of gravitational redshift, judgements were historically influenced by thoughts from the field of gravitational light displacement. While debate ensued over the interpretation of results from solar frequency measurements, this field of endeavour took an unexpected detour with values obtained from a double star system where one of the pair was a very dense object. Arthur Eddington (1882-1944) of Cambridge Observatory was able, in 1924, to tease out some of the factors contributing to the displacement in the frequencies of spectral lines as there were much larger frequency shifts in the region of a white dwarf compared with those at the Sun [182-3]. It took extensive toil, particularly from two experimenters, Walter Adams (1876-1956) and Charles St. John (1857-1935) both of Mount Wilson Observatory, before the influences on solar line displacements were attributed to the relevant diverse factors and the Einstein value surfaced [183]. It is opined that 1928, the same year as for the classical astronomical test of starlight deflection, was the time where gravitational redshift could reasonably support General Relativity.

Paper 3: Recent astronomical tests of General Relativity

The story of General Relativity did not cease with the three classical tests. After 1928, a flowering of applications of new ideas, improved technical equipment, the extension of light measurements to the radio region of the spectrum, longer time periods for measurements, the proliferation of spacecraft and the discovery of exotic objects beyond the solar system allowed General Relativity to be tested to greater precision, in stronger gravitational fields and in a myriad number of ways not envisaged at its inception. In particular, the discovery in 2003 of a double pulsar, two pulsars orbiting each other, at Parkes Radio Telescope opened up an unprecedented possibility of extreme precision. These applications beyond the three classical tests are the 13 topics numbered following and presented in the third paper.

(1) Einstein's proposal contained an equivalence of inertial and gravitational mass, that is, that acceleration is independent of the nature of the body [91-2]. Experiments along these lines preceded the publication of General Relativity. From 1885 Loránd Eötvös (1848-1918) of Hungary performed tests on torsion balances to determine any correspondence between these two quantities. His work was continued by his coworkers presented in publications in 1922 and 1935. By 1964 the baton had passed to other experimenters with improved equipment so that greater accuracy ensued. An extension of this equivalence principle was possible when it was realised that, since the Earth and Moon both accelerate in the gravitational field of the Sun, a comparison could be made between these accelerations to ascertain if they had matching values. To this end, the position of the Moon relative to the Earth required greater accuracy. This was possible from 1969 when retroreflectors were placed on the Moon and laser beams were sent from and received at the Earth via these devices. Enhancements over time were more reflectors on the Moon, telescopes specifically dedicated to this venture, enlargement of the aperture size of the telescope, the placement of these telescopes at a higher altitude, technological advances in lasers and a greater capture of photons.

(2) The paths on which experiments on the classical test of gravitational redshift followed after 1928 took some interesting turns [92-3]. Appearing to be a tangent, one intriguing setup involved the emission and absorption of gamma rays over a vertical distance and then interchanging the positions of emitter and receiver. Results were achieved throughout the 1950s and 1960s where a frequency change was expected because of a gravitational potential difference in altitude at the surface of the Earth. With the emergence of planetary spacecraft, an extension could be conducted on gravitational redshift as these vessels could be manoeuvred into special alignments. Voyager 1 sent its signal past Saturn in 1980, Galileo past Venus in 1990 on its journey to Jupiter and Cassini in 2002 past the Sun as it proceeded to its destination of Saturn. Signals were received by three 64 m radio telescopes on Earth to determine the frequency shift. While the topic of the next paper is entirely devoted to the only double pulsar discovered to date, it is included under this phenomenon as the pulse of one body is influenced by the gravitational field of the other so any frequency change may be monitored.

(3) Over time the classical test of the Mercury anomaly was seen as but one example of the orbital precession of a body in a gravitational field. By 1943, Gerard Clemence (1908-1974) had at his disposal many more meridian observations and transits of Mercury than were available in 1915. With altered figures for the eccentricity and perihelion of Earth, as well as a revised figure for the mass of Venus (another planet without a moon), he altered the anomalous advance for Mercury slightly from that of Einstein. Another experimenter in 1956 made a number of corrections to planetary data after analysing meridian observations of Venus. He was able to produce a figure for an anomaly for Venus to check against the relativistic amount. In the same year, this was also performed for the Earth after almost 200 years of solar data were scrutinised and an adjustment made to the eccentricity of our planet [93-4].

(4) These figures for the planets are extremely small and in the relatively weak gravitational field of the Sun. In contrast, after the discovery in 1974 of the first binary pulsar, it was then possible to compare changes in the radio frequency from a pulsar in the gravitational field of its companion,

where each member had a larger gravitational field than that of the Sun, with atomic clocks on Earth. Such monitoring enabled a measurement of periastron advance of the binary system and this was of the order of 1000 times more than that for Mercury [94-6]. By 1992, 21 binary pulsars had been studied to add to the measurements of orbital precession of a body in a gravitational field. Another component of Einstein's work could also be investigated as he deduced in 1918 that there would exist an orbital decay since a binary system would emit gravitational wave energy. Studies of a binary system over an extended period are able to determine the rate of decay.

(5) Yet another avenue under the banner of orbital precession emerged when Willem de Sitter (1872-1934) realised in 1916 that since the Moon was falling in the gravitational field of the Sun and it was orbiting the Earth, it ought to undergo what was eventually called geodetic precession [96]. This challenge was pursued by Irwin Shapiro (1929-) when, in 1998, after 17 years of data from the retroreflectors on the Moon, he was able to pronounce on this phenomenon. A similar experiment was conducted after the launch of Gravity Probe B in 2004. Shifts in the axis of gyroscopes placed on board were monitored over 12 months as the spacecraft orbited over the poles of the Earth.

(6) A still smaller effect than geodetic precession is frame dragging [96-7] which was recognised in 1918 by Josef Lense (1890-1985) and Hans Thirring (1888-1976). This arises as a precession due to a rotating body dragging its local spacetime around with it. Results have accumulated from Mars Global Surveyor in 1996, the twin satellites LAGEOS in Earth orbit in 2004 and Gravity Probe B in 2012.

(7) The deflection of starlight in the optical region [97-8], one of the three classical astronomical tests, has been conducted over five total solar eclipses. However, the technique has been superseded since the launch of Hipparcos in 1989. This satellite can now monitor the position of over 10^5 stars with a precision of the order of 10^{-3} arcsecond. Over a three year period the distances between any pair of stars were monitored. Hence, there was no longer any need for a total solar eclipse as measurements could be taken at large angles from the Sun due to the precision of the well calibrated instrument on board and the sensitivity that could be achieved. This eliminated any involvement from the solar corona. Results were published in 1997.

(8) Gravitational light deflection was no longer restricted to the visible wavelengths. There was much promise in the use of the radio spectrum as angular resolution with interferometry was much improved relative to that within the optical band [98-9]. The deflection of light by the Sun from a very bright object known as a blazar was measured in 1969. This was followed by measurements on three radio sources with a 35 km baseline in 1974, four radio emitters with the Very Long Baseline Array in 1990, 74 radio sources collected by 29 observatories over a decade with the baseline eventually up to 10 000 km in 1991 and 541 radio sources over 87 sites for 20 years published in 2004. Accuracy has progressed in this field to the extent that the use of radio waves from quasars deflected as it passes the planets may now be employed, as happened with Jupiter in 2002 and 2008 and Saturn in 2009.

(9) In 1912 Einstein mused that a foreground star might produce a double image of a source due to gravitational light bending [99]. This idea was extended by Fritz Zwicky (1898-1974) in 1937 when he theorised that the objects could be nebulae and later, in 1964, the proposal was that a supernova could be lensed by a galaxy. In 1979 this was achieved with a quasar lensed by a galaxy. 70 similar systems have since been investigated by the Hubble Space Telescope.

(10) In 1964 Irwin Shapiro introduced another test for General Relativity. He indicated that a time delay [100] could be measured between the emission and detection of radar pulses bounced off Mercury and Venus when they were near superior conjunction and this was achieved by 1970. As in many of these proposals, the use of spacecraft allowed other possibilities. Echoes from Mariner 6 and Mariner 7 at Mars were implemented in 1969 and accuracy was improved in 1971 with Mariner 9. In 1976 further accuracy was achieved with Viking 1 and Viking 2 in orbit around Mars and a lander from each on the surface of that planet.

(11) In 1971 four atomic clocks were flown easterly and westerly around Earth and compared with a reference atomic scale on Earth as another example of what could be measured for light propagation in gravitational fields [100].

(12) If Einstein were not supported, the higher mass Earth should accelerate towards the Sun at a different rate from that of the Moon. This Nordtved effect [100], after Kenneth Nordtved (1939-), has been investigated up to 2008 by lunar lasing measurements operated by the Apache Point Observatory in New Mexico.

(13) As the mass of the Sun compared with some extrasolar objects is small, its weak gravitational field regime is unlike that of the very strong fields in the presence of neutron stars. With very strong fields as mentioned previously with binary pulsars, the orbital decay is predicted to produce gravitational waves [100] but this energy is still quite small. However, since binary systems are dissipating energy, the two components would be expected to collide eventually and this should result with a large burst of energy according to the theory. Search is underway with VIRGO, GEO600, TAMA and LIGO.

Paper 4: General Relativity support from the double pulsar

The fourth paper traces the history of the theory of neutron stars, their association with a supernova, the theory of a rapidly spinning neutron star, the discovery of the first pulsar in 1967, pulsar surveys, classification of pulsars and the discovery in 2003 of the only double pulsar to date [457-61]. The special nature of having two pulsars in mutual orbit provides a unique astronomical test for General Relativity as two signals are passing through the strong gravitational field of a companion. Measurements are effected on the time of arrival of the pulse energy.

In 2003, Ingrid Stairs of the University of British Columbia provided five equations to determine parameters for this double pulsar system and to test predictions of General Relativity [461-2]. Each equation is in terms of the combined mass or the individual masses. The parameters are (1) the relativistic advance of periastron from the ascending node, (2) gravitational redshift as a combination of the time delay and gravitational redshift, (3) the derivative of the orbital period, that is, the change in this value over time, (4) a Shapiro delay due to the medium of transmission and (5) the shape of the Shapiro delay which is dependent on the orbital inclination angle. The first two equations have two unknowns and a solution provides the masses of the individual pulsars. Then, the next three equations may be used to determine how tightly constrained are the masses based on General Relativity. In this way, a percentage departure from Einstein's predictions may be ascertained [461-2]. Even though the double pulsar scenario can provide the most accurate figure for General Relativity, further constraints will be available from X-ray data from Chandra, ultraviolet imaging with the Hubble Space Telescope, a 500 m radio telescope in China due to commence operating in 2016 and the Square Kilometre Array which may start in a reduced mode in 2018.

Paper 5: General Relativity in Australian Newspapers: The 1919 and 1922 Solar Eclipse Expeditions

The previous four papers belong to the realm of scientists. Yet, if a revolution occurs within Science, it interacts not only with the practitioners but interplays with the culture of the period. In the fifth paper a different direction is taken to see how the early development of General Relativity was communicated to the Australian population. Communication to the public in the early years of the development of General Relativity was via newspapers. However, the public were not versed in the mathematical underpinnings required to understand the emerging concepts of Einstein. Newspapers offer a rich vein of material to probe in order to ascertain the state of scientific thinking and the manner of imparting this knowledge to the public. The recent availability of digitised newspapers through TROVE at the National Library of Australia allowed locating and collating this information for the first time. The expectation was the newspapers might reflect a view that General Relativity was prematurely accepted.

An analysis of the Australian newspapers from 1911-1928 was conducted. There were 266 distinct newspaper pieces which responded to the input of “Einstein” AND “relativity”. Statistics could be produced for the number of articles per year in that time period [152] to gauge when the interest in Einstein was at its height. The peak coincided with 1922 when the total solar eclipse occurred across Australia and Christmas Island and 13 parties were operating in the region observing the event. A further breakdown was performed for each month in 1922 to see if September, the month of the eclipse, were highlighted [152]. There were major themes mentioned in print throughout this period and statistics were forthcoming to ascertain what the major themes throughout this time were. The topics discerned were the 1922 total solar eclipse, relativity, Einstein, 1919 total solar eclipse, gravitational redshift, ether, perihelion advance of Mercury and energy-mass equivalence [152]. As much had been made of the three classical astronomical tests during the first years following the publication of Einstein’s theory, the relative importance of gravitational light deflection, perihelion advance of Mercury and gravitational redshift were ascertained [153].

There were eight parties that attempted a measurement of the amount of light deflection in 1922. The leader of each party, their affiliation and place of observation were:

Wallace Campbell (1862—1938), Lick Observatory USA, Wallal in Western Australia;

Harold Spencer Jones (1890—1960), Royal Observatory Greenwich England; Christmas Island;

Erwin Finlay-Freundlich (1885—1964), Berlin Observatory Germany, joint German-Dutch party; Christmas Island

John Evershed (1864—1956), Kodaikanal Observatory India, Wallal;

Clarence Chant (1865—1956), University of Toronto Canada, Wallal;

George Dodwell (1879—1963), Adelaide Observatory, Cordillo Downs in South Australia;

William Cooke (1863—1947), Sydney Observatory, Goondiwindi in Queensland;

Joseph Baldwin (1878—1945), Melbourne Observatory, Goondiwindi.

Another five groups carried out investigations that did not include light displacement in their operation:

J. Hargreaves, England, Wallal;

Alexander Ross (1883—1966), Perth Observatory, Wallal;

Oscar Vonwiller (1882—1972), University of Sydney, Goondiwindi;

Donald Coleman, Carnegie Institution of Washington, Coongoola in Queensland;

Walter Gale (1865—1945), New South Wales Branch of the British Astronomical Association, Stanthorpe, Queensland.

The newspaper articles were probed to see the relative importance placed on each group as well as to contrast the eight groups attempting a measurement of gravitation detection with the five assemblies devoted to other pursuits at the eclipse [155]. In a similar vein, the proportion of articles mentioning each of the six localities of Wallal, Goondiwindi, Christmas Island, Cordillo Downs, Stanthorpe and Coongoola could be used in conjunction with the importance of the leader or institution [155].

It is instructive to see the language used by the journalists as they interpret some of the scientific pronouncements as well as translate a complex topic into words that could be understandable to the general public. In addition, some reason needed to be given for why the 1922 total solar eclipse was so important since in some quarters Einstein was being hailed as having his theory vindicated by the results from the eclipse of 1919 [156]. Since, in the philosophy of Science and the logic of hypotheses, 'proof' cannot be forthcoming, analysis was conducted on articles concerning the 1919 event to see how the distribution existed between support for Einstein's theory, more evidence being required and not supporting his concept [157].

The aim of these five papers is to seek a conclusion to the hypotheses:

1. Australia played a key role in the acceptance and verification of General Relativity from the 1922 total solar eclipse across the continent as well as the discovery in 2003 at Parkes Radio Telescope of the first, and to this date only, pair of pulsars in mutual orbit.

2. The Theory of General Relativity was accepted prematurely.

References

1. Referenced in A. Pais, *'Subtle is the Lord': The Science and the Life of Albert Einstein* (1982), Oxford University Press, 253.

2. B. Green 'Why He Matters', *Scientific American* (2015 September), 26.

List of Figures

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 : Keith John Treschman
e-mail: treschmankm@bigpond.com

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 Wallace 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].

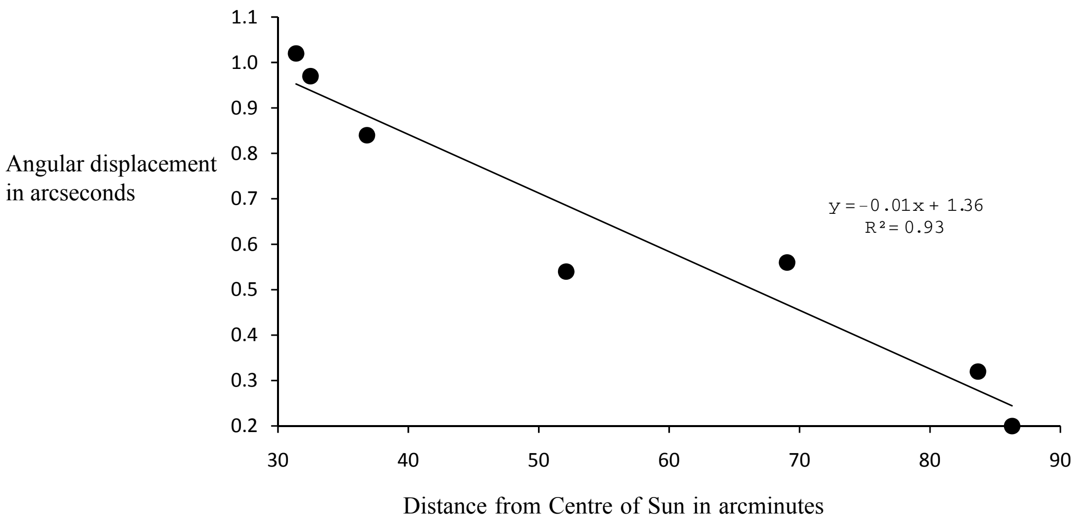
Dyson made a decision to eliminate the Sobral figures found with the astrograph on the basis of systematic errors. He acknowledged that the images were far superior to those on the similar instrument at Principe in terms of number of stars (12 versus 5) and the quality of the images. He argued that the 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 [78]. 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 $1''.75 \pm 0.09$ 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]

Asian Journal of Physics Vol. 23, Nos 1 & 2 (2014) 0-00

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

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

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

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

Total Refs : 78

1 Introduction

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

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

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

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

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

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

2. Transits of Mercury

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

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

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

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

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

Table 1. November and May transits of Mercury 1631-2006 along with intervals. Transit Predictions by Fred Espenak National Aeronautics and Space Administration/Goddard Space Flight Center.[6]

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

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

In May, the apparent diameter of the Sun is 1 902". With a 46 year time span, Mercury shifts its position with respect to the Sun by approximately 200". Hence, there may 10 transits that can be viewed as a series, spanning 9 intervals × 46 years = 414 years. For November, the Sun is 1937" and Mercury shifts by about 100", giving 19 transits in a series which may span 18 intervals × 46 years = 828 years. There may be six transit series running concurrently.[8]

3 Lindenau, Le Verrier, Newcomb

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

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

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

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

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

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

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

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

4 Einstein

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5. Modern Methods

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

In the case of the USA and the United Kingdom, the fundamental planetary and lunar ephemerides are based on a program that was developed at the Jet Propulsion Laboratory in 1980 and prepared by the United States Naval Observatory. As a result of 362 observations over the span 1966-1974 from radar stations at Arecibo in Puero Rica, Haystack Observatory in Massachusetts and Goldstone in California, the mass of Mercury has been refined.This is essential as a major problem in any theory is that the amplitudes of the perturbations are a function of the masses of the planets. 175 explicit unknown parameters and 50 424 observations, which involved 39 579 Washington transits of the Sun, Moon and planets to 1”.0 standard deviation for Mercury over 1911-1977, formed the basis of the original program.[34]

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

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

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

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

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

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

6 Conclusion for the Anomalous Advance in the Perihelion of Mercury

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

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

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

7 Einstein and Gravitational Redshift

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

8. Solar Spectral Research to 1918

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

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

In an attempt to disentangle effects which may have different conditions between the Sun and an electric arc, J. Halm in 1904 compared the spectrum of two neutral iron lines from the centre of the Sun's disc with points at distances out to the extremity. He interpreted that there was a gradual increase, reaching 12 mÅ at the limb once a correction for Doppler differences was performed.[45] This so-called limb effect was supported by Maurice Paul Auguste Charles Fabry (1867-1945) of the University of Marseille and Henri Buisson (1873-1944), a French physicist, with their interferometer in 1909 for 14 spectral lines, other than those of iron.[46]

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

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

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

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

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

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

9 Significance of 1919 Total Solar Eclipse

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

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

10 Results 1920-24

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

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

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

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

11 The Case of Sirius B

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

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

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

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

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

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

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

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

12 1928

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

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

13 Post 1928

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

However, disquiet followed this time period. It was suggested that much of the light that had been studied by Adams (sections8,10,11) was scattered from the much brighter Sirius. In 1954, Daniel Magnes Popper (1913-1999) measured a redshift on another white dwarf, 40 Eridani B, as 21 km s^{-1} which was within the uncertainty range attached to 17 km s^{-1} predicted by general relativity with the values of mass and radius then attributed to the star.[71] The value for Sirius B was extensively revised upwards in 1971 by Greenstein, Oke and Shipman[72] to 89 ± 16 km s^{-1} with revised data for its mass and radius. Publications in 1967[73] on 53 white dwarfs and in 1972[74] on 74 white dwarfs by Trimble and Greenstein produced, from a selection of these, respective averages of +51 and +54 km s^{-1} and provided further confirmation of both general relativity and an understanding of white dwarfs. Confidence in the measurement of redshift has reached a stage where researchers use the data as part of an investigation into the mass-radius relationship in white dwarfs as in Koester and Weidemann[75] for 40 Eridani B in 1991 and Weidemann et als[76] in their study of members of the Hyades cluster in 1992.

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

14 Conclusion on Gravitational Redshift

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

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

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

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

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

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

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

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

References

1. Pais A, *Subtle is the Lord … the science and life of Albert Einstein*, (1982), chapter 16.
2. Kepler J, *Tabulae Rudolphinae*, (1627).
3. Baum A and Sheehan W, *In search of Planet Vulcan – the ghost in Newton's clockwork universe*, (1997).
4. van Helden A, "The importance of the Transit of Mercury of 1631", *Journal for History of Astronomy*, vii (1976), 7.

5. Richardson R S, "Encke's Comet", *Astronomical Society of the Pacific Leaflets*, v (1948), 297-304.
6. Meeus J, *Mathematical Astronomy Morsels III*, (2004), 279.
7. Espenak F, *Seven century catalog of Mercury transits: 1601 CE to 2300 CE*, NASA/GSFC.
8. *Ibid.*
9. Wolfschmidt G, "Gotha – the instruments of the observatory", *Acta Historica Astronomiae*, iii (1998), 89-90.
10. de Lindenau B, "*Investigatio nova orbitae a Mercurio circa solem descriptae; accedunt tabulae planetae ex elementis recens repertis et theoria gravitatis*", (*new research on the orbit of Mercury around the Sun described; the approach of the planetary tables recently devised from a famous theory of gravity*), (1813).
11. G.B. Airy, "Report on the progress of Astronomy during the present century" in *Report of the first and second meetings of the British Association for the Advance of Science*, (1825), second report for Oxford 1832, 125-89.
12. U.J.J. Le Verrier, *Sur les variations séculaires des orbites des planētes* (*On the secular variations of the orbits of the planets*) to Académie des Sciences, (1839).
13. U.J.J. Le Verrier, *Détermination nouvelle de l 'orbite de Mercure et de ses perturbations* (*A* n*ew determination of the orbit of Mercury and its perturbations*), (1843).
14. A. Baum and W. Sheehan, *In search of Planet Vulcan – the ghost in Newton's clockwork universe*, (1997).
15. U.J. Le Verrier, "Theorie du mouvement de Mercure" (Theory on the motion of Mercury), *Annales L'Observatoire Impérial de Paris*, xv (1859).
16. N.T. Roseveare, *Mercury's perihelion from Le Verrier to Einstein*, (1982).
17. Le Verrier, *op. cit.* (ref13), 99.
18. S. Newcomb, "Discussions and results of observations on transits of Mercury from 1677 to 1881', *Astronomical Papers of the American Ephemeris and Nautical Almanac*, I (1882) 367-487, 473.
19. Report of the council to the sixty-fourth annual general meeting, "Transits of Mercury, 1677-1881", *Monthly Notices of the Royal Astronomical Society*,xliv (1884), 184.
20. S. Newcomb, "The elements of the four inner planets and the fundamental constants of Astronomy", *Supplement to the American Ephemeris and Nautical Almanac 1897* (1895).
21. Roseveare, *op. cit.* (ref 16), 45.
22. *Ibid*, 45.
23. W.W. Campbell, "Publications of the report of observations", *Publications of the Astronomical Society of the Pacific*, xxii (1910), 216-41, 223.
24. A. Einstein and M. Grossmann, "Entwurf einer verallgemeinerten Relativitätstheorie und einer Theorie der Gravitation" (Outline of a generalised theory of relativity and of a theory of gravitation),*Zeitschrift für Mathematik und Physik*,lxii (1913), 225–261.
25. M. Janssen, "The Einstein-Besso manuscript: a glimpse behind the curtain of the wizard", *Introduction to the Arts and Sciences*, (2002).
26. Pais, *op. cit.*, 250-5.
27. A. Einstein, "The Foundations of the General Theory of Relativity", *Annalen der Physik*, xlix (1916), 769-822.
28. P.K. Seidelmann ed., *Explanatory Supplement to the Astronomical Almanac,* (2006), 704.
29. M.P. Price and W.F. Rush, "Non relativistic contribution to Mercury's perihelion", *American Journal of Physics*, xlvii (1979), 6, 531-4.
30. D.C. Norton, "Notes and Queries – Relativistic Advances of Perihelion", *Journal of the Royal Astronomical Society of Canada*, l (1956), 223.
31. G.M. Clemence, "The relativity effect in planetary motions", *Reviews of Modern Physics*, xix (1947), 361-4.
32. N.C. Rana, "An investigation of the motions of the node and perihelion of Mercury", *Astronomy and Astrophysics*, clxxxi (1987), 195-202.
33. P.K Seidelmann and G.A. Wilkins, "Introduction to positional Astronomy" in *Explanatory Supplement to the Astronomical Almanac*, ed. P.K. Seidelmann704.

34. E.M. Standish, X.X. Newhall, J.G. Williams and D.K. Yeomans, “Orbital ephemerides of the Sun, Moon, and planets”, in *Explanatory Supplement to the Astronomical Almanac,* ed.K. Seidelmann (2006), 296-7.
35. P. Bretagnon and G. Francou, “Planetary theories in rectangular and spherical variables. VSOP87 solutions”, *Astronomy and Astrophysics*, ccii (1988), |format= requires |url= (help)309–15.
36. Standish, *op. cit.*, (ref 34), 316.
37. *Ibid.*, 316.
38. K. Popper, *The Logic of Scientific Discovery*, (2005, 1935 first publication).
39. A. Einstein, [in German} “On the relativity principle and the conclusions drawn from it”, *Jahrbuch für Radioaktivität und Elektronik*, iv (1907), 411-62.
40. A. Einstein, [in German] “On the influence of gravitation on the propagation of light”, *Annalen der Physik*, xxxv (1911), 898-908.
41. W. de Sitter, “On Einstein’s theory of gravitation, and its astronomical consequences”, *Monthly Notices of the Royal Astronomical Society*, lxxvi (1916), 9, 49-699-728.
42. H. Rowland, “Preliminary table of solar spectrum wavelengths”, *Carnegie Institute of Washington* (1895).
43. L.E. Jewell, “The co-incidence of solar and metallic lines”, *Astrophysical Journal*, viii (1896), 89.
44. W.J. Humphreys and J.F. Mohler, “Effect of pressure on the wave-lengths of lines in the arc spectra of certain elements”, *Astrophysical Journal*, iii (1896), 114.
45. J. Halm, “Spectroscopic observations of the rotation of the Sun”, *Transactions of the Royal Society of Edinburgh*, xvi (1904), 89.
46. C. Fabry and H. Buisson, “Comparaisons des spectres du centre et du bord du Soleil”, *Comptes Rendus de l’Académie des Sciences*, cxvviii (1909), 1 741.
47. R. Rossi, “The effect of the pressure on the band spectra of the fluorides of the metals of the alkaline earths”, *Proceedings of the Royal Society A*, lxxxii (1909), 518.
48. W.S. Adams, “An investigation of the displacements of the spectrum lines at the Sun’s limb”, *Astrophysical Journal*, xxxi (1910), 30.
49. J. Crelinsten, *Einstein’s Jury – The Race to Test Relativity* (2006), 321.
50. K. Schwarzschild, “Ueber die Verschiebungen der Bande bei 3,883 Å im Sonnenspektrum”, *Königlich Preussische Akademie der Wissenschaften*, (1914), 1 201.
51. J. Evershed and T. Royds, “On the change of wavelength of the iron lines in passing from the centre of the Sun’s disc to the limb”, *Bulletin of the Kodiakanal Observatory*, xvix (1916).
52. C.E. St. John, “The principle of generalized relativity and the displacement of the Fraunhofer lines towards the red”, *Astrophysical Journal*, xlvi (1917), 249.
53. E.G.Forbes, “A history of the solar red shift problem”, *Annals of Science*, xvii (1963), 3, 139.
54. M. Stanley, “An expedition to heal the wounds of war”, *Isis*, xciv (2003), 57-89.
55. “Joint eclipse meeting of the Royal Society and the Royal Astronomical Society”, *TheObservatory*, dxlv (1919), 391.
56. L. Grebe and A. Bachem, [in German} “About the Einstein effect in the gravitational field of the Sun”, Journal for Physics, I (1920), 51-4.
57. Forbes, *op. cit.* (ref 53), 141.
58. C.E. St. John, “”The displacement of solar spectral lines”, *TheObservatory*, xliii (1920), 260-2.
59. J. Evershed, “Displacement of the lines in the solar spectrum and Einstein’s prediction”, *TheObservatory*, xliii (1920), 153-7.
60. C.E. St. John, “ Displacement of solar lines and the Einstein effect”, *TheObservatory*, xliii (1920), 158-62.
61. C.E. St. John, “On gravitational displacement of solar lines”, *Monthly Notices of the Royal Astronomical Society*, lxxxiv (1923), 93-96.
62. W.S. Adams, “Summary of the year’s work at Mount Wilson”, *Proceedings of the Astronomical Society of the Pacific*, xxxvi (1924), 313-9.

63. A.S. Eddington, “On the relation between the masses and luminosities of the stars”, *Monthly Notices of the Royal Astronomical Society*, lxxxiv (1924), 308-32.
64. *Ibid*, 322.
65. W.S. Adams, “The relativity displacement of the spectral lines in the companion of Sirius”, *The Observatory*, xlviii (1925), 618, 337-8.
66. *Ibid*, 338-42.
67. J.H. Moore, “Recent spectrographic observations of the companion of Sirius”, *Proceedings of the Astronomical Society of the Pacific*, xl (1928), 229-33.
68. C.E. St. John, “Evidence for the gravitational displacement of lines in the solar spectrum predicted by Einstein’s theory”, *Contributions from the Mount Wilson Observatory*, cccxlviii (1928), 1-45.
69. *Ibid*, 1.
70. W.W. Campbell and R. Trumpler, “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.
71. D.M. Popper, “Red shift in the spectrum of 40 Eridani B”, *Astrophysical Journal*, cxx (1954), 316-21.
72. J.L. Greenstein, J.B. Oke and H.L. Shipman, “Effective temperature, radius and gravitational redshift of Sirius B”, *Astrophysical Journal*, clxix (1971), 563-6.
73. J.L. Greenstein and V.L. Trimble, “The Einstein redshift in white dwarfs”, *Astrophysical Journal*, cxlix (1967), 283-98.
74. V. Trimble and J.L. Greenstein, “The Einstein redshift in white dwarfs. III”, *Astrophysical Journal*, clxxvii (1972), 441-52.
75. D. Koester and V. Weidemann, On the mass of 40 Eri B, *Astrophysical Journal*, cii no 3 (1991), 1 152-5.
76. V. Weidemann, S. Jordan, I. Iben and S. Castertano, White dwarfs in the halo of the Hyades Cluster: the case of the missing white dwarfs, *Astrophysical Journal*, c1v no 5 (1992), 1 876-91.
77. J.H. Taylor and J.M. Weisberg, “Further experimental tests of relativistic gravity using the binary pulsar 1913 + 16”, *Astrophysical Journal*, cccxlv part 1 (1989), 434-50.
78. V. Weidemann, “Reflections on Binarity”, *Astronomical Society of the Pacific Conference*, lvii (1994), 214.

[*Received*; *accepted:* 2014]

academicJournals

Vol. 10(2), pp. 90-105, 30 Janaury, 2015
DOI: 10.5897/IJPS2014.4236
Article Number: 26552F450052
ISSN 1992 - 1950

http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Review

Recent astronomical tests of general relativity

Keith John Treschman

51 Granville Street Wilston 4051 Australia.

Received 16 November, 2014; Accepted 22 December, 2014

This history of experimentation relevant to general relativity covers the time post-1928. Classes of investigation are the weak equivalence principle (equivalence of inertial and gravitational mass and gravitational redshift), orbital precession of a body in gravitational fields (the relativistic perihelion advance of the planets, the relativistic periastron advance of binary pulsars, geodetic precession and Lense-Thirring effect), light propagation in gravitational fields (gravitational optical light deflection, gravitational radio deflection due to the Sun, gravitational lensing, time dilation and atomic clocks) and strong gravity implications (Nordtved effect and potential gravitational waves). The results of experiments are analysed to conclude to what extent they support general relativity. A number of questions are then answered: (a) how much evidence exists to support general relativity, (b) is it a reasonable way of thinking and (c) what is the niche it may occupy?

Key words: general relativity, equivalence principle, orbital precession, gravitational fields.

INTRODUCTION

The special theory of relativity came from the mind of Albert Einstein (1879-1955) in 1905 (Einstein, 1905). In it he proposed that the laws of physics take the same form in all inertial frames and that the velocity of light is constant irrespective of the motion of the emitting body. Previously, Isaac Newton (1642-1727) had supplied the term inertial mass when treating his three laws of motion and gravitational mass in the context of his universal law of gravitation. While Newton had attempted to pursue if these conceptual terms were the same, it was Einstein in 1907 who extended his own notions and declared that acceleration and gravitation were identical, that is, objects of different composition would have identical accelerations in the same gravitational field (Einstein, 1907). This idea is now referred to as the equivalence principle. In a publication in 1916 Einstein broadened his concepts to include an accelerated frame of reference (Einstein, 1916). Within his general theory of relativity he united space and time and presented gravity as a geometrical interpretation of how bodies move in the presence of a mass.

It was claimed that there were three astronomical tests which could act as a litmus examination of general relativity: the anomalous advance of the perihelion of Mercury, the extent to which starlight could be bent as it passes the Sun and the gravitational redshift of light from the Sun. In truth, the gravitational light deflection and the gravitational redshift are derived from the equivalence principle and the Mercury situation from general relativity. This distinction will not be invoked in this paper and the term general relativity will be used to encompass the equivalence principle.

E-mail: treschmankm@bigpond.com, Tel: 61-7-38562262.

Former work by the current author questioned the early acceptance of the results of these tests of gravitational light deflection in one paper (Treschman, 2014a) and Mercury and gravitational redshift in another (Treschman, 2014b). It was argued in those articles that insufficient evidence existed until the year 1928 for acceptance of general relativity as a reasonable explanation of the data that had been gathered.

AIM OF THIS PAPER

This paper picks up the thread post-1928. It does include the extension a number of other scientists made to general relativity from as early as 1916 and even some experiments that were conducted prior to Einstein's publications which can be interpreted within the worldview of general relativity. The history of several themes is examined to gauge at what level they support general relativity.

In order to ascertain reality, science rests on models, namely, using something known as a proxy for the unknown. Truth is not the issue but how useful is the construct in explaining phenomena and predicting outcomes. The aim in this paper is to place the theory of general relativity in the context of its suitability as a description of the cosmos.

Scientific breakthroughs are often presented as before and after. Yet, acceptance takes a long period of time. Aristarchus (c310-c230 BCE) recorded a heliocentric model which was published much later in 1543 by Nicolaus Copernicus (1473-1543). This was in contrast to the geocentric rendition of Claudius Ptolemy (90-168). Yet, even after the telescopic observations of Galileo Galilei (1564-1642) commencing in 1609, scientists correctly needed more evidence before their world picture was better presented by the earth orbiting the Sun. Interestingly, there are still vestiges of the alternative model today in terms such as "sunrise" and "sunset". The ideas of Isaac Newton (1643-1727) put to print in 1687 had initial difficulty with the notion of action at a distance which had a whiff of magic about it. It is still a practical worldview if one limits the picture to speeds much below that of light and to masses the size of the planets. So, the questions are:

(i) How much evidence exists to support general relativity,
(ii) is it a reasonable way of thinking and
(iii) what is the niche it may occupy?

Answers to these queries are attempted by tracing some selections from the historical record separated into classes based on the type of investigation. The survey of the literature is restricted mainly to journals printed in English.

WEAK EQUIVALENCE PRINCIPLE

Equivalence of Inertial and Gravitational Mass

To elucidate any difference between inertial mass and gravitational mass the Hungarian physicist, Loránd Eötvös (1848-1918), commenced measurements in 1885. He used a torsion balance which consisted of a horizontal rod suspended by a thin fibre and having two masses of different composition but the same gravitational mass at the ends of the rod. He worked firstly with copper and platinum. The rod was oriented parallel with the meridian and had an attached mirror which reflected light into a telescope so that any small twist in the fibre could be observed more easily. The rotation of the Earth created forces on the masses proportional to their inertial masses. The vector sum of the tension in the fibre, the gravitational force and the reaction to the centripetal force would result in a zero torque (beyond the rotation of the rod at the same rate as that of the Earth). For a null movement of the rod, Eötvös could claim a proportionality constant between inertial and gravitational mass.

Continuing with different materials he published his results in 1890 (Eötvös, 1890) in which he claimed an accuracy of 1 in 2 x 10^7. In 1891 he refined the model to have one of the masses suspended by its own fibre from the rod so that the system could now have measurements in two dimensions. His coworkers from 1906-1909 were Dezsö Pekár (1873-1953) and Jenö Fekete (1880-1943). The later publication by Eötvös (1909) declared an improved accuracy to 1 in 10^8. The final results (Eötvös, 1922) were printed after his death.

Later János Renner (1889-1976) (Renner 1935) who had worked with Eötvös took the results to 2-5 in10^9 and in another three decades Robert Henry Dicke (1916-1977), Peter G. Roll and R. Krotkov (Roll et al., 1964) had used improved equipment to conclude an accuracy of 1 in 10^{11}. Another avenue for testing the equivalence principle was to probe the motions of the Earth and Moon. Both bodies accelerate in the gravitational field of the Sun. To establish whether the accelerations were different, it was necessary to obtain a more accurate position of the Moon relative to the Earth. It had been proposed to bounce a laser beam off the Moon but the topography would conspire to produce spurious results. Hence, in 1969 on the first human lunar landing, the astronauts of Apollo 11 embedded a retroreflector array on the Moon. This consisted of 100 corner cube prisms in a 10 x 10 array 0.45 m square with each cube made of quartz and dimension 3.8 cm. The design of each prism had a trio of mutually perpendicular surfaces such that an incoming ray is totally internally reflected from three surfaces to generate a deviation of 180°. The array from Apollo 14 in 1971 is similar but the one also in 1971 from Apollo 15 had 300 cubes in a hexagonal array. The Soviet Union landed two rovers on the Moon: Lunokhod 1from Luna 17 in 1970 and Lunokhod 2 from Luna 21 in

1973. Each of the rovers carried 14 cubes in a triangular formation with 11 cm size apiece in an array 44 x 19 cm (Dickey et al., 1994).

A number of Earth stations have observed a reflected pulse but long term dedication belongs to the Observatoire du CERGA (Centre d'Etudes et de Recherches Géodynamiques et Astronomiques) near Cannes in France with a 1.5 m telescope and the McDonald Laser Ranging System in Texas using a 2.7 m system. The latter was replaced by a dedicated 0.76 cm instrument in 1985. The laser adopted was a neodymium-yttrium-aluminium-garnet one firing a 2 x 10^{-10} s pulse 10 times per second. In the early 1970s accuracies were at the 25 cm level. This was reduced to 15 cm in the mid 1970s as a result of improvements to the timing system and from 1985 to 2-3 cm. The findings were consistent with general relativity to 1 in 10^4 as well as determining the recession of the Moon from Earth by 3.8 cm yr^{-1} (Gefter, 2005). An improvement to 1 mm accuracy between the Earth and the Moon has been achieved by the 3.5 m arrangement at Apache Point Observatory in New Mexico (Murphy et al., 2008). This requires a 3.3 x 10^{-12} s exactitude in the one way trip or 6.7x 10^{-12} s both ways. The major uncertainty in the distance is due to the libration of the Moon which, on its own, contributes to a spread of 15-36 mm in distance, equivalent to 1.0-2.4 x 10^{-11} s round trip time. Accuracy has improved due to the aperture size of the telescope, altitude of 2880 m, a greater capture of photons and a timing mechanism of atomic standards to 10^{-7} s. Any violation of the equivalence principle would produce a displacement of the lunar orbit along the earth-Sun line with a variation coinciding with the 29.53 days synodic period. This has not occurred to the 0.1% level (Williams et al., 2009).

Gravitational Redshift

Measurements of the gravitational redshift of lines from the Sun followed a tortuous journey. From an apparent tangent of using the lines from Sirius B and then other white dwarfs, scientists unravelled the many factors from which the relativistic redshift emerged. Pursuing another tack, Robert Vivian Pound (1919-2010), Glen Anderson Rebka, Jr (1931-) and Joseph Lyons Snider conceived an imaginative experiment.

Pound and Rebka (1959) reported that a fraction of gamma rays could be emitted from the nuclei of a solid without recoil momentum of the nuclei. They hypothesised that gravitational redshift could be measured from an emitter to a source at a different altitude and register the situation for maximum scattering (Pound and Rebka 1959). The emitter they chose was Co-57 electroplated onto one side of an iron disc. To ensure diffusion of the cobalt into the iron, the disc was heated up to 1000°C for one hour. The absorber was seven units of iron enriched in Fe-57 to 32% electroplated onto a beryllium disc. The absorption level was one third of the emitted gamma rays. Placed inside a space at the Jefferson Physical Laboratory of Harvard University, the source and absorber were 22.6 m apart. To reduce the absorption of gamma rays by air, helium was run through the tower continuously. The fractional change in frequency was proportional to gh/c^2 where g = 9.8 m s^{-2} is the acceleration due to gravity, h = 22.6 m is the altitude and c = 3.0 x 10^8 m s^{-1} is the speed of light. The ingenious aspect was to measure the change in energy instead by having gamma rays move against gravity and then with gravity by interchanging the emitter and absorber. Thus, the change in energy down less the change in energy up = $2gh/c^2$ = 4.9 x 10^{-15}. The authors reported that their experimental result was 1.05 ± 0.10 times the theoretical value (Pound and Rebka, 1960a) for a frequency change of 3.27 x 10^{-8} s^{-1} for this altitude difference in the gravitational potential of the Earth (Pound and Rebka, 1960b) where the gradient (Hirate, 2012) is 1.1 x 10^{-16} c^2 m^{-1}. Improvements were effected in 1964 by Pound and Snider and their result was published as 0.999 0 ± 0.007, 6 times the predicted relativistic frequency (Pound and Snider, 1965).

From 1976, spacecraft were involved in this particular test of general relativity. Carrying a hydrogen maser, a 100 kg spin stabilised spacecraft, jointly organised by the National Aeronautics and Space Administration (NASA) and the Smithsonian Astrophysical Observatory, was launched to 10000 km almost vertically. The output frequency of 1.420 405 751 x 10^9 Hz, accurate over 100 s averaging time to 1 in 10^{14}, was compared with another maser on Earth. The agreement with general relativity was calculated to the 7 x 10^{-5} level (Vessot et al., 1980).

Voyager 1 was launched in 1977, flew by Jupiter in 1979 and reached Saturn in 1980. It carried an ultrastable crystal oscillator. As a result of its close approach to Saturn, a redshift of several hertz was predicted to its 2.3 x 10^9 Hz downlink sent by its 3.7 m antenna. Comparison was made against the three 64 m stations on Earth which are part of the Deep Space Network: Goldstone in California, near Madrid in Spain and near Canberra in Australia. Each of these stations was referenced to a hydrogen maser frequency standard. The result was in agreement with general relativity to 0.995 6 ± 0.000 4 as a formal uncertainty and ± 0.01 as a realistic uncertainty (Krisher et al., 1990).

Similar communication channels were set for Galileo which was launched in 1989 on a trajectory which included a gravity assist from Venus in 1990 and Earth in 1990 and 1992 before arriving at Jupiter in 1995. During the phase from launch to the first Earth gravity assist, regular frequency measurements of the spacecraft clock were conducted. Personnel from the Jet Propulsion Laboratory reported a 0.5% agreement with general relativity for the total frequency shift and a 1% concord with the solar gravitational redshift (Krisher et al., 1993).

However, it was the Cassini spacecraft on its way to

Saturn which has provided the closest match to general relativity at 0.0023% (Williams et al., 2004). Jointly coordinated by NASA and the Italian Space Agency, Cassini was launched in 1997, and flew by Earth, Venus and Jupiter to orbit Saturn in 2004. In 2002 it was near superior conjunction, with the Earth situated 8.43 astronomical units distant. Interference from the solar corona and the Earth's troposphere could be accounted for by two different uplink frequencies and three different downlink signals with use of Cassini's 4 m antenna. Measurements were conducted on the 18 passages of signals between Earth and Cassini (Bertotti et al., 2003). Each pulsar in a binary system is influenced by the strong gravitational field of the other. From PSR J0737 – 3039 A/B (see later), a redshift parameter of 3.856 x 10^{-4} s is compared with a relativistic calculation of 3.841 8 x 10^{-4} s to give a ratio between them of 1.003 6 (Kramer et al., 2006).

ORBITAL PRECESSION OF A BODY IN GRAVITATIONAL FIELDS

Relativistic Perihelion Advance of the Planets

Between the publication of special relativity in 1905 and general relativity in 1916, Einstein received assistance from Marcel Grossmann (1878-1936) (Einstein and Grossmann, 1913) and Michele Besso (1873-1955) (Janssen, 2002). Grossmann alerted Einstein to how tensor calculus and Riemannian geometry could be applied to general relativity and Besso worked with Einstein on solving some equations which were relevant to the perihelion advance of Mercury. Einstein incorporated into his equations Lorentz transformations named for Hendrik Antoon Lorentz (1853-1828). These involved *c* the speed of light independent of a reference frame. They showed how measurements of space and time taken by two observers were related. Thus, they gave meaning to how two observers travelling at different relative velocities may make different measures of distance and elapsed time. The Lorentz factor ***γ*** (gamma) was defined as

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \qquad (1)$$

where v is the relative velocity between inertial reference frames. In Einstein's work he used for time dilation for length contraction in the x direction.

$$\Delta t' = \gamma \, \Delta t \qquad (2)$$

and

$$\Delta x' = \frac{\Delta x}{\gamma} \qquad (3)$$

for length contraction in the x direction.

In later experimentation, to ascertain how closely results may be interpreted in the worldview of general relativity, the Lorentz factor was a part of a number of equations and the closer this value is to unity, then general relativity is more supported.

It was in 1916 that Einstein wrote his gravitational field equations applying within a vacuum and chose the Sun as the origin of his coordinate system (Vankov, 1915). He made use of Huygens' principle to formulate the angular deflection of a ray of light at a certain distance from the Sun. Through a series of approximations, he derived a planetary motion equation. As long as the speed of a particle was much less than **c** the speed of light, Newton's equation could be obtained as a first approximation.

With a switch to planar orbit equations with the polar coordinates **r** and **ϕ** as the radius vector and angle respectively, the equations led to the known energy and Kepler's planetary law of areas. One result was:

$$r^2 \frac{d\phi}{ds} = \text{a constant} \qquad (4)$$

where **s** is displacement. If orbital motion were described, the equation was in agreement with Kepler's third law portraying the relationship between the period of a planet and its distance from the Sun. The curvature of spacetime envisaged by Einstein was an explanation of the Mercury advance as it had further to travel than in flat space due to the distortion created by the mass of the Sun.

To obtain the secular advance of an elliptical orbit Einstein next integrated the equation containing **ϕ** over the ellipse so that **Δϕ**, the change in angle in radians per orbit, is found in terms of **a** the semi major axis and **e** the eccentricity. If this is extended to an entire passage, the result in the direction of motion for the period **T** in s is

$$\Delta\phi = 24\pi^3 \frac{a^2}{T^2 c^2 (1 - e^2)} . \qquad (5)$$

With conversion factors of $180/\pi$ to give °, 3 600 for ", a change of period from s to 0.240 844 45 tropical years and 100/orbital period in tropical years producing an answer in " century^{-1}, Einstein calculated a figure of 45" ± 5 century^{-1} for Mercury, the then accepted value for the anomalous advance of the perihelion of Mercury being 42".95 century^{-1}.

By 1943 Gerald Maurice Clemence (1908-1974) had examined meridian observations of Mercury totalling 10 400 in right ascension and 10 406 in declination over the period 1765-1937 and 24 transits of Mercury across the Sun spanning 1799-1940 (Clemence, 1943). From this analysis he adjusted figures for the eccentricity and perihelion of the Earth as well as for the mass of Venus. His new value for the anomalous perihelion advance of Mercury was 43".11 ± 0.45 century^{-1} against the Einstein figure at this time of 43".03 century^{-1}.

With his attention on another planet, Raynor Lockwood Duncombe (1917-2013) scrutinised meridian observations of Venus across 1750-1949 (21009 in right ascension and 19852 in declination) (Duncombe, 1956). After applying corrections to some elements of Venus and the Earth and the mass of Mercury, he deduced, for the first time, results accurate enough for the anomalous advance of the perihelion of Venus. In 1956 this was determined as 8".4 ± 4".8 century^{-1} while the relativity figure was 8".6 century^{-1} (Morton, 1956).

For Earth, HR Morgan dissected studies of the Sun over 1750-1944 from a number of observatories and applied a correction in 1945 to the eccentricity of the planet (Morgan, 1945). He combined with Clemence and Duncombe to determine by 1956 the anomalous advance of the perihelion of Earth as 5".0 ± 1".2 century^{-1} while the Einsteinian amount was 3".8 century^{-1} (Morton *op. cit.*). Kepler's third law of planetary motion for Mercury may be expressed as

$$T^2 = \frac{4\pi^2 a^3}{G(M+m)} \tag{6}$$

for **G** the universal gravitational constant, **M** is the mass of the Sun and **m** the mass of Mercury. As **m**<<**M**, it may be omitted. If, then, T^2 is substituted into equation (5), one may express the Einstein derivation into a similar one (Gamalath, 2012) as

$$\Delta\phi = \frac{6\pi GM}{c^2 a\left(1 - e^2\right)}. \tag{7}$$

For **c** = 2.998 x 10^8 m s^{-1}, ***G*** = 6.673 x 10^{-11} m^3 kg^{-1} s^{-2}, ***M*** = 1.989 x 10^{30} kg, and data from a modern almanac (Seidelmann, 2006) the calculations for Mercury, Venus and Earth are juxtaposed against the observed values in Table 1. The calculated values are within the range of the observed figures.

For % difference between the calculated and observed values, the central value gives (43.11 – 42.98)/42.98 x 100 = 0.19%. However, the extreme difference is (43.11 + 0.45 – 42.98)/42.98 x 100 = 1.4%. In a similar way, the values respectively for Venus are 2.3 and 58% and Earth 32 and 62%.

One of the assumptions in Einstein's derivation was that the orbital plane of the planets coincided with the rotational equator of the Sun. This is incorrect but the technology to measure what became known as the quadrupole moment of the Sun did not exist until the 1980s and particularly into the 1990s. The splitting of spectral lines due to solar oscillations in the 1980s revealed that, with the precision of the measurements, the assumption in the derivation of Mercury's anomalous perihelion advance was acceptable (Campbell and Moffatt, 1983).

A Global Oscillations Network Group GONG was formed in 1995 to produce continuous solar velocity imaging with an aim to ascertain the spherical harmonic functions of the Sun related to its radius and latitude. Six solar observatories in the Canary Islands, Australia, California, Hawaii, India and Chile combined to analyse 33169 splits of spectral lines (Pijpers, 1998). The conclusion was that the results are currently consistent with the figure accepted for Mercury's perihelion advance determined by general relativity. This decision is also supported by the first six months of data obtained from helioseismology measurements taken by the Michelson Doppler Imager aboard SOHO, the Solar Heliospheric Observatory, launched in 1995. An interesting extension to this concept is the use of exoplanets (Zhao and Xie, 2013). Data from the Kepler space observatory launched in 2009 and future missions may give improved accuracy so the periastron advance to these other systems may be added to the information on the solar system planets.

Relativistic Periastron Advance of Binary Pulsars

There are many factors involved in determining the orbits of the planets and the positions of the perihelia. In addition, the *total* change per year in the location of the perihelion of Mercury is as small as 5".7. Fortunately, the same property applicable to the relativistic perihelion advance of the planets may be applied outside the solar system. In addition, within the solar system, the gravitational fields are comparatively weak whereas outside the solar system there are opportunities for some very strong fields. The target is a stellar binary system where at least one of the stars is a pulsar so that the periastron advance may be monitored.

The term binary pulsar is used if one or both objects are pulsars. The first such system was discovered in 1974 by Russell Alan Hulse (1950-) and Joseph Hooton Taylor, Jr (1941-) while conducting a survey at the 305 m Arecibo Observatory in Puerto Rico (Hulse and Taylor, 1975). The technology that existed at this time enabled a computer "to report on any pulsar suspects above a certain sensitivity threshold" (McNamara, 2008). The pulsar had a very short pulsation period of 5.9 x 10^{-2} s in a highly eccentric orbit of e = 0.615 with a period of 0^d.323 0. Its companion is believed to be a neutron star. The pulsar is designated PSR 1913 + 16.

The measurement technique is a comparison between the phases of the radio pulses from the pulsar and those of atomic clocks on the Earth (Will, 1995) to register the

Table 1. Anomalous advance in the perihelia of Mercury, Venus and Earth.

Planet	**a** x 10^{10} m	**e**	**Orbit in tropical years**	$\Delta\phi$ **in " per century calculated**	$\Delta\phi$ **in " per century observed**
Mercury	5.791	0.205 6	0.240 844 45	42.98	43.11 ± 0.45
Venus	10.821	0.006 8	0.615 182 57	8.625	8.4 ± 4.8
Earth	14.960	0.016 7	0.999 978 62	3.839	5.0 ± 1.2

small changes over time with the pulse frequency. The Doppler effect alters the arrival time of the pulses. The variation was between $0^d.058\ 967$ and $0^d.069\ 045$ which amounts to 6.7 s over its cycle of $0^d.323\ 0$, that is, 7.75 h (Hulse and Taylor, *op. cit.*). The precision of measurement was such that an initial discrepancy of 2.7 x 10^{-2} s for the period of what was thought to be a single pulsar measured at different times was not considered a false value (McNamara, *op. cit.*). The speed of the orbit is highly relativistic being 10^{-3}c. The relativistic periastron advance of 4°.226 62 ± 0.000 01 yr^{-1} is 2.7 x 10^3 greater than the 5".7 y^{-1} for the perihelion advance of Mercury. This periastron advance is within 0.8% of the prediction from general relativity (Damour and Taylor, 1991). Also, this system will be revisited later in this paper as monitoring continues for how the companion's gravitational field affects the redshift of the pulses and how the relativistic time dilation is caused by the orbital motion.

A consequence of general relativity, the curvature of spacetime, is implicated in the periastron advance of binary pulsars in the same way as the perihelion advance of the planets. However, in 1918, Einstein proposed that a binary system would lose gravitational wave energy and provided a quadrupole formula for the subsequent damping on the orbital period (Einstein, 1918). However, his results are expressed here from a project which derives Einstein's conclusions (Valença, 2008). Firstly, for **E** energy, **t** time, a condition of **e** = 0, μ reduced mass where $\mu = m_1m_2/(m_1 + m_2)$ for the individual masses, **m** representing the same mass which would be the case if e = 0 and **r** the distance between the two objects, then the change in energy over time is given by

$$\frac{dE(e=0)}{dt} = \frac{32\mu^2 m^3 G^4}{5c^5 a^5}. \tag{8}$$

Then, a correction is applied for the case when e $\neq$ 0 so that

$$\frac{dE}{dt} = \frac{32\mu^2 m^3 G^4}{5c^5 a^5}\left(1+\frac{15}{2}e^2+\frac{45}{8}e^4\right)(1-e^2)^{-7/2}. \tag{9}$$

The change in energy per time may be extended to include a change in the period P denoted as $\dot{P}$ as

$$\frac{dE}{dt} = \frac{-2m_1m_2G}{3rP}\dot{P}. \tag{10}$$

From measurements on PSR 1913 + 16, the mass of the pulsar was determined as 1.441 0 ± 0.000 7 M_S (times mass of the Sun) and the companion as 1.387 4 ± 0.000 7 M_S (Will, *op. cit.*). The distance between the pair ranged from 1.1 to 4.8 solar radii. Armed with these data, Taylor, a codiscoverer, and Joel M Weisberg found, in 1989 after 14 years of measurement on the binary pulsar, that the rate of orbital decay was within 1% of that predicted by special and general relativity (Taylor and Weisberg, 1989). By 1995, improvement had reached 0.3% accuracy with a rate of (– 2.402 43 ± 0.000 05) x 10^{-12} ss^{-1}. Once a small effect caused by galactic rotation, the relative acceleration between the binary pulsar and the solar system, is subtracted, the result is (- 2.410 ± 0.009) x 10^{-12} s s^{-1} which is the prediction afforded by general relativity (Will, *op. cit.*). After 30 years of analysis in 1995, Weisberg and Taylor provided consistency between theory and observation at the (0.13 ± 0.21%) level (Weisberg and Taylor, 2005).

A further Arecibo survey operating at 4.30 x 10^8 Hz in 1990 detected another binary pulsar PSR 1534 + 12. The 3.79 x 10^{-2} s pulse of orbital period 3.64 x10^4 s has a rate of decay of 2.43 x 10^{-18} s s^{-1} and periastron advance of 1°.756 2 yr^{-1}. Due to the strong and narrow pulse, greater precision for this system was expected over time (Wolszczan, 1991). This had been achieved by 1998 with further timing observations with radio telescopes at Arecibo, 43 m Green Bank in West Virginia and 76 m Jodrell Bank and a conclusion that the results were in accord with general relativity to better than 1% (Stairs et al.,1998).

A third binary pulsar PSR 2127 + 11C (Prince et al., 1991) had its relativistic periastron advance measured at 4°.46 yr^{-1} in 1991 but more work was needed to compare this with general relativity. By 1992, 21 binary pulsars had been studied well enough for their basic parameters to be determined (Taylor, 1992).

A rare situation emerged in 2003. A pulsar discovered with the 64 m radio telescope13 beam receiver (Staveley-Smith et al., 1966) at Parkes Australia was found subsequently to have a companion which is also a pulsar. An improved position was determined with the use of the 20 cm band from interferometric observations with the Australia Telescope Compact Array (Burgay et al., 2003).

Results were published in 2006 after 2.5 years of measurements had been effected on PSR J0737 – 3039A and PSR J0737 – 3039B. Data were gathered at Parkes at 6.80 x 10^8, 1.374 x 10^9 and 3.030 x 10^{10} Hz, 76 m Jodrell Bank Observatory in the UK at 6.10 x 10^8 and 1.396 x 10^9 Hz, and 100 m Green Bank at 3.40 x 10^8, 8.20 x 10^8 and 1.400 x 10^9 Hz. A total of 131 416 arrival of pulse times for A with an uncertainty of 1.8 x 10^{-5} s were received and 507 for B with a maximum uncertainty of 4 x 10^{-3} s. The system has an orbital period of 0^d.102 251 563, respective pulse periods of 2.27 x 10^{-2} and 2.77 x 10 s and a periastron advance for A of 16°.90 yr^{-1} (Lyne et al., 2004).

Four independent tests of general relativity are obtainable with this system. The orbital decay derivative observed was - 1.252 x 10^{-12} s s^{-1}, shrinking the distance between the pulsars by 7 mm d^{-1}. The relativistic prediction was 1.247 87 x 10^{-12} s s^{-1} giving a ratio of observed to expected value of 1.003 (Kramer, op.cit.). Other results relate to gravitational redshift and time dilation.

Geodetic Precession

Yet another property was added to the list for testing general relativity soon after its inception. In 1916 Willem de Sitter (1872-1934) applied relativity theory to the Earth-Moon system. He realised the pair was freely falling in the gravitational field of the Sun. Since the Moon was also orbiting the Earth, he predicted that the Moon ought to undergo a non-Newtonian precession in its orbit (Sitter, 1916). His expected figure was a secular motion of the perigee and the node both of + 1".91century^{-1} (Sitter, 1917). This effect is referred to as geodetic precession.

Shapiro et al. (1988) mined the lunar laser ranging data collected over the period 1970-1986 from the retroreflectors on the Moon. A model of the Moon's motion consisted of two coupled sets of differential equations, one for its orbit and the other for its rotation. Perturbations from the gravitational fields of the Sun, Earth, and other planets as well as torques on the Moon from the Sun and Earth and the drag from tides on the Earth were factored to provide equations as a function of time. An introduced numerical factor ***h*** was related to any extra precession of the Moon's orbit about the ecliptic pole that was not included in the predicted relativistic geodetic precession. ***h*** would equal zero if it were consistent with general relativity and unity if there were 100% difference from the prediction. From the set of 4 400 echo measurements, their analysis resulted in ***h*** = 0.019 ± 0.010 (Shapiro et al., 1988).

According to general relativity the Moon should precess in its orbit by 1.9 x 10^{-2} s yr^{-1}. A data set of 8 300 lunar laser ranges over the period 1969-1993 yielded a deviation from this amount by – 0.3 ± 0.9% (Dickey et al., *op. cit.*). Gravity Probe B Relativity Mission was launched by NASA in 2004 and operated an experiment for 12 months. Its aim was to measure two effects predicted by general relativity: geodetic precession and frame dragging or Lense-Thirring effect. Geodetic precession may be described as a vector perpendicular to the orbital plane whereas frame dragging may be designated as a vector arising from rotation and acting orthogonally to the geodetic precession vector. As the two effects act at right angles to each other, the component vectors could be distinguished.

The satellite was placed in an orbit over both poles of the Earth. The mean altitude was 642 km and the orbital eccentricity was 0.001 4. A telescope was fixed on the bright star IM Pegasi, as were initially four super-conducting niobium coated, 38 mm spherical quartz gyroscopes. Each was surrounded by liquid helium at 2 K where some escaping gas caused the gyroscopes to commence spinning up to an average rate of 72 Hz. The devices were suspended electrically with two spinning clockwise and two counter clockwise. They were tested at maintaining their drift rate accuracy to 5" x 10^{-4} yr^{-1}.The gyroscope is a vector not aligned with the spin axis of the Earth. After one orbit of parallel transport of the Earth, any shift in the axis of a gyroscope would induce a current which enabled the changed to be measured (Will, 2006). The predicted Einstein drift rate was – 6".606 1 x 10^{-6} yr^{-1}. The four results were combined to give a weighted average of – (6".601 ± 0.018.3) x 10^{-6} yr^{-1}, giving an accuracy of 0.28% (Everitt et al., 2011). Across the span 1961-2003, 250 000 high precision radar observations from the USA and Russia to the inner planets and spacecraft have been examined. In addition to the perturbations of the planets and the Moon, those of 301 larger asteroids and a ring of small asteroids have been included. The result for γ was 0.999 9 ± 0.000 2 (Pitjeva, 2005). With binary pulsars, if the spin axis is not aligned with the angular momentum axis of the system, geodetic precession should occur. All the candidates that have been discovered so far need a much longer time period of measurement to arrive at definitive answers for this property.

Lense-Thirring Effect

Frame dragging refers to another effect arising from general relativity in which a massive celestial rotating body drags its local spacetime around with it. Whereas geodetic precession operates in the presence of a central mass, frame dragging is postulated to exist as a separate effect if the mass is rotating. This consequence was hypothesised by Josef Lense (1890-1985) and Hans Thirring (1888-1976) in 1918. However, Pfister (2007), in his treatment of the history of this effect, argues from evidence in the Einstein-Besso manuscript 1913, Thirring's notebook of 1917 and a letter from Einstein to

Thirring in 1917 that Einstein pointed to this phenomenon. Frame dragging is a secular precession of an orbiting object which has its orbital plane at an angle to the equator of a central entity which possesses angular momentum. The magnitude of the effect is extremely small compared with geodetic precession.

NASA launched Mars Global Surveyor in 1996 and it was inserted into its orbit in 1997. In the five year period 2000-2005, the orbital plane of the spacecraft was predicted to shift by 1.5 m due to frame dragging and the measured result was 1.6 m, giving a difference from general relativity of the order of 6% (Iorio, 2006).

Twin satellites, Laser Geodynamics Satellite (LAGEOS) launched by NASA in 1976 and LAGEOS II a joint NASA and Italian Space Agency in 1992, are passive reflectors in Earth orbit. Each contains 426 corner cube reflectors, all but four of these made of fused silica glass with the others of germanium for infrared measurements. Their respective orbital parameters are: semi-major axis 12 270 and 12 163 km; eccentricity 0.004 5 and 0.014; inclination to Earth's equator 110° and 52°.65. The expected measure of precession of their line of nodes was 3" x 10^{-4} yr^{-1} which is equivalent to a displacement of 1.9 m in that time. Monitoring was performed by 50 Earth stations as part of the International Laser Ranging Service. From 10^8 laser ranging observations over the period 1993-2003, the measure of the precession of the line of nodes was given as 4".79 x 10^{-2} yr^{-1} against the relativistic prediction of 4".82 x 10^{-2} yr^{-1}. The result of the observation was 99% ± 5 of the predicted value although the authors allow for 10% uncertainty (Ciufolini and Pavlis, 2004).

A later satellite, Laser Relativity Satellite (LARES), was launched by the Italian Space Agency in 2012. It is a spherical, laser ranged passive satellite with 92 retroreflectors made of a tungsten alloy. Its semimajor axis is 7 820 km, eccentricity 0.000 7 and orbital inclination 69°.5. Measurements are ongoing.

One of the difficulties with accurate positioning is the figure of the Earth. To ascertain deviations from spherical symmetry of the Earth's gravity field, Gravity Recovery and Climate Experiment (GRACE) consists of twin satellites of NASA and the German Aerospace Center launched in 2002 in polar orbit, 500 km above the Earth and 220 km between them. They maintain a microwave ranging link which can measure their separation to 1×10^{-5} m. Optical corner reflectors allow their position to be monitored from Earth against the GPS. Gravity Probe B results reported in 2012 gave the frame dragging effect (Everitt et al., *op. cit.*) as (– 3".72 ± 0.72) x 10^{-4} yr^{-1} compared with the Einstein value of – 3".92 x 10^{-4} yr^{-1}.

LIGHT PROPAGATION IN GRAVITATIONAL FIELDS

Gravitational Optical Light Deflection

The central equation of Einstein which led to his international fame was that the angle of deviation α of starlight in the vicinity of the Sun with mass M and distance from the centre r be given as

$$\alpha = \frac{4GM}{c^2 r} \qquad (11)$$

where half that value was due to time curvature and the other half from space curvature, an intrinsic part of his general relativity (Einstein, 1916 *op. cit.*). This amounted to 1".75 at the limb of the Sun. With the technology at the time, confirmation rested on a photographic comparison of the stars near the Sun at a total solar eclipse and the same stellar field six months before or after the eclipse. The deviation for stars a little away from the limb corresponded to 1/60 mm on the plate (Eddington, 1919). Such a small measurement was difficult to ascertain with the precision instruments available in the early part of the twentieth century.

The 1919 British total solar eclipse expedition to Brazil by Andrew Claude de la Cherois Crommelin and to Principe by Arthur Stanley Eddington and Edwin Turner Cottingham demonstrated that starlight was deflected by the Sun. In 1922, with final results published in 1928, an excursion to Wallal in remote Western Australia by the Lick Observatory led by William Wallace Campbell supported the deflection at the limb of the Sun as 1".75 ± 0.09 (Campbell and Trumpler, 1928). A limitation for this technique depends on the ability of a telescope to resolve small angular separations due to refraction as light passes through the system.

$$\text{Angular resolution in arcsecond} = \frac{2.5 \times 10^5 \text{ x wavelength of light in m}}{\text{diameter of mirror in m}} \qquad (12)$$

For the 33 cm telescope used and visible light, the angular resolution amounted to 0".4. Attempts at repeating the experiment have been performed at a number of total solar eclipses, now nine altogether, and the ones in 1952 and 1973 will be mentioned here.

The National Geographical Society and the Naval Research Laboratory jointly sponsored an expedition to Khartoum in Sudan in 1952 (Biesbroeck, 1953). Disappointingly, wind at the time of the eclipse induced vibrations in the 20 foot (6 m) telescope so that many of the fainter stellar images were not included in the measurement. Nevertheless, one photographic plate exposed for 60 s produced nine measurable stars in the eclipse field and eight in the auxiliary field while a second exposure of 90 s resulted in 11 and eight stars respectively. Two checkplates were secured six months later. The conclusion was 1".70 ± 0.10.

In 1973 the University of Texas mounted a mission to Chinguetti Oasis in Mauritania, Africa (Brune et al., 1976). With a 2.1 m focus, four element astrometric lens, the party prepared for a 6 min 18 s eclipse. Three plates, impregnated with a rectangular scale, were obtained with 60 s eclipse field and 30 s comparison field 10° away in declination. 150 measurable images and 60 comparison field ones were captured. After an elapse of five months, 33 calibration plates were obtained. The result extrapolated to the solar limb of 0".95 ± 0.11 serves to indicate, if general relativity is to be supported, how difficult measurements on photographic plates for the visible region of the spectrum actually is.

Since the launch of the European Space Agency spacecraft Hipparcos (high precision parallax collecting satellite) in 1989, the deflection of light at total solar eclipses has been consigned to a quaint part of history. The 29 cm aperture telescope on board has measured the position of 118 200 stars to a precision of 3" x 10^{-3} for the magnitudes 8 - 9. Any effect on the deflection of starlight by the Sun can now be measured by checking the distance between pairs of stars over time. The advantages inherent in this system were that there was no need for a total solar eclipse, bending by the solar corona could be eliminated, measurements could take place over large angular distances from the Sun and the same instrument was used well calibrated over the entire sky for 37 months. Data were collected on a set of stars chosen within 47 - 133° of the Sun. As an example, the relativistic prediction is that at 90° from the Sun the deflection would be 4".07 x 10^{-3}. As a number of theories incorporate some predictions similar to general relativity, nine so called parameterised post-Newtonian parameters have been introduced. Radiation deflected by the gravitational field of the Sun and entering a telescope on Earth is expressed as an amount equal to

$$1''.749\ \frac{(1+\gamma)}{2} \qquad (13)$$

where γ equals unity in general relativity. The result from Hipparcos was γ = 0.997 ± 0.003 (Froeschlé et al., 1997). An improved astrometric spacecraft from the ESA is Gaia which was launched in December 2013 and took up its residence at the Sun-Earth L_2 Langrangian point in January 2014. The aim of the mission is to record the position of 10^9 objects to a precision of 2".0 x 10^{-5}. A future analysis of results based on a similar method as for the Hipparcos data will improve the accuracy of this experiment.

Gravitational Radio Deflection due to the Sun

Since angular resolution is proportional to the reciprocal of the wavelength of light, the longer wavelength radio region provides an improvement over the visible spectrum. It eventually became possible to measure the position of radio sources so precisely with interferometry, even in the daytime. The blazar 3C279 is a very bright object 12' from the ecliptic and each 08 October it is eclipsed by the Sun. Deflection was measured by two groups in 1969. An Owens Valley Radio Observatory team (Seielstad et al., 1970) in California reported γ = 1.02 ± 0.23 and another Californian band from Goldstone (Muhleman et al., 1970) gave γ = 1.08 ± 0.30. This method was also employed in 1974 with three nearly collinear radio sources, 0116 + 08, 0119 + 11 and 0111 + 02, and a 35 km interferometer baseline (Fomalont and Sramek, 1975). As these radio emitters passed near the Sun, the deflection of their beams was monitored by the National Radio Astronomy Observatory at Green Bank. This comprised three steerable 26 m parabolic antennas with a maximum baseline separation of 2.7 km and a fourth element of 14 m aperture situated 35 km away. The three long baselines are 33.1, 33.8 and 35.3 km. So that the solar coronal refraction may be separated from the contribution from relativity, observations were made simultaneously at two frequencies, 2.695 x 10^9 and 9.085 x 10^9 Hz since electron refraction varies as the square of the wavelength.

The deflection at the solar limb was determined as 1".775 ± 0.019 which was 1.015 ± 0.011 times the Einstein value. This corresponds to the parameter γ = 1.030 ± 0.022. The experiment was repeated 12 months later in 1975. The combination of the 1974 and 1975 measurements (Fomalont and Sramek, 1976) produced a limb deflection of 1".761 ± 0.016 corresponding to 1.007 ± 0.009 times the general relativity prediction and γ = 1.014 ± 0.018.

The source 3C279 mentioned earlier in this area is also known as J1256 – 0547. It and three other radio emitters, J1304 – 0346, J1248 – 0632 and J1246 – 0730, were captured by the Very Long Baseline Array in 1990. This comprises 10 parabolic 25 m telescopes across the United States of America. Previous testing had shown that the system could measure relative positions to 1" x 10^5 (Fomalont et al., 2009a). The system operated at frequencies of 1.5, 2.3 and 4.3 all x 10^{10} Hz so that the effect of the solar corona was minimised. Furthermore, the relativistic bending is independent of the wavelength. The result from the four sources combined was γ = 0.999 8 ± 0.000 3 (standard uncertainty) (Fomalont et al., 2009b).

As the length of the baseline in interferometry increases, the accuracy of the determination of γ improves. A major investigation between 1980 and 1990 was conducted by personnel from the National Oceanic and Atmospheric Administration in Rockville, Maryland (Robertson et al., 1991). 74 radio sources collected by 29 very long baseline observatories produced a set of 342 810 observations. Early data used 3 000 km as the baseline, such as from Westford, Massachusetts to Fort Davis, Texas, but later ones operated between 7 000 – 10 000 km, for example, a 7 832 km stretch from Wettzell, Germany to Hartebeesthoek, South Africa. The expected deflection at the Sun's limb is 1".750, at an angle of 90° away from the Sun 4"x10^{-3} and zero deflection at 180°. The scientists concluded a value for γ of 1.000 2 ± 0.002 (standard uncertainty).

Use was made of data collected during 1979-1999 from 87 very long baseline interferometric sites and 541 radio sources (Shapiro et al., 2004). The information was intended to monitor various motions of the Earth but has been analysed to conclude γ = 0.999 8 ± 0.000 4.

Gravitational radar deflection is progressing to the planets. Measurements were taken in 2002 when Jupiter passed within 4' of the quasar J0842 + 1835, in 2008 for Jupiter 1'.4 from J1925 – 2210 and in 2009 for Saturn 1'.3 from J1127 + 0555. More arrays are devoting time to this new avenue and the results are awaiting analysis (Fomalont et al., *op. cit.* 2009b).

Gravitational Lensing

Gravitational lensing refers to the production of an image of a background object presented to an observer by another object between them. The origin of this thought has been traced to eight pages of a notebook Einstein used in 1912 (Renn et al., 1997). In it he indicated the possibility of a double image of the source due to gravitational light bending and suggested that the intensity of these images would be magnified. In 1936 Einstein returned to this idea and wrote about a background star, when bent in the gravitational field of an intermediate star, would be perceived by an observer in line with both of them not as a point-like star but as a luminous circle around the foreground object. From geometry he obtained an expression for the angular radius (later Einstein radius) of the halo (later Einstein ring) in terms of the deviation angle of light passing the lensing star, the distance of the light from the centre of the foreground object and the distance between observer and lensing star. The derivation is explained in detail by Schneider et al. (1992) as

$$\alpha = \left(\frac{4GM}{c^2} \frac{D_1}{D_2 D_3} \right) \text{ raised to 0.5 power} \qquad (14)$$

where M is the mass of the lens, D_1, D_2 and D_3 are respectively distances between source and lens, lens to observer and source to observer (Schneider et al., 1992). Einstein also noted again that the apparent brightness of the distant star would be enhanced. It is interesting to note that he saw no hope of a direct observation of this spectacle (Einstein, 1936).

An extension from a star as the lensing object was provided in 1937 by Fritz Zwicky (1937). He theorised that the gravitational fields of a number of foreground nebulae may deflect the light from background nebulae and that this might be used to determine nebular masses accurately. He also suggested that a search ought to be conducted among globular nebulae for images of globular clusters. In 1964 a proposal was published in which a supernova could be lensed by a galaxy. This would allow very faint, distant objects to produce an image much closer to the observer so measurements could be extended to much greater distances. The wait was until 1979 when the 2.2 m telescope on Mauna Kea belonging to the University of Hawaii recorded two images which, from their identical properties such as the same redshift z = 1.413, were intimated to be the twin QSO 0957 + 561 (Walsh et al., 1979). The galaxy causing the lensing was soon directly recorded along with a third image (Stockton, 1980).

With the Advanced Camera for Surveys (ACS) aboard the Hubble Space Telescope, the Sloan Lens ACS (SLACS) Survey (Bolton et al., 2008) has provided a 2008 list of 131 strong gravitational lens candidates. There are 70 systems with clear evidence for multiple imaging and another 19 probable ones. Selection was made from the spectroscopic database of an absorption dominated galaxy continuum at one redshift and nebular emission lines at a higher redshift. The lines incorporated the Balmer series and O II at 3.727 x 10^{-12} m and O III at 5.007 x 10^{-12} m.

An interesting gravitational lens system discovered in 1985 (Huchra et al., 1985) shows how it can add support to the theory of general relativity. It has been resolved by the Hubble Space Telescope to be four quasar images with z = 1.695 surrounding a 15 magnitude spiral galaxy 2237 + 0305 with z = 0.039 4. The four images are concentric but have different levels of brightness. From the application of lens models based on the lensing equation derived by Einstein along with the cosmological interpretation of redshifts, all of the data collected can be explained. The first discovery of an Einstein ring occurred in 1988 (Hewitt et al., 1988) with the radio source MG1131 + 0456 being surrounded by an elliptical ring of emission.

Time Dilation

In 1964 Irwin Ira Shapiro (1929-) proposed that with recent advances in radar astronomy, another test for general relativity would be to measure the time delay between emission and detection of radar pulses bounced off Mercury or Venus when they were near superior conjunction (Shapiro, 1964). The Doppler shift cancels on a round trip. The time delay Δt is given by

$$\Delta t = \frac{4GM_S}{c^3} \frac{1+\gamma}{2} \ln \frac{R_E + R_P + R}{R_E + R_P - R} \qquad (15)$$

where G, M_S, c and γ are as defined previously, R_E, R_P and R are respective distances between the Earth and

Sun, planet and Sun and Earth and planet (Reasenberg et al., 1979). This increase in time amounted to 1.6 x 10^{-4} s for Mercury when the beam passes by the Sun at two radii from its centre.

Testing began in 1967 and after three years of 1 700 measurements by the Haystack and Arecibo Observatories, Shapiro reported γ = 1.03 ± 0.04 (Shapiro et al., 1971). The first measurements made of time dilation with spacecraft were at Mars in 1969. NASA sent a dual mission of Mariner 6 and 7 and the echoes were received with the 64 m telescope at Goldstone where the accuracy of the ranging system was rated as 1 x 10^{-7} s. The respective data were total time for round trip: 44.72, 42.87 min; distance of beam from centre of Sun: 3.58, 5.90 solar radii; angle Sun-Earth-spacecraft: 0°.95, 1°.56; approximate time delay: 2.0 x 10^{-4}, 1.8 x 10^{-4} s; γ 1.003 ± 0.04, 1.000 ± 0.012. The combined figure for γ was given as 1.00 ± 0.03 (Anderson et al., 1975). This 3% uncertainty was lowered to 2% for Mariner 9 in orbit of Mars in 1971 (Reasenberg, *op. cit.*).

In 1975 NASA launched Viking 1 and Viking 2 which arrived at Mars in 1976. Each spacecraft consisted of an orbiter and lander with radio links to each other. Receiving stations on Earth were the three of the Deep Space Network. By having two set places on the Martian surface, accuracy was reduced to 0.5% (Michael et al., 1977). Two parameters from the two pulsars in a mutual orbit relate to the shape of the time delay and its range. They are given respectively followed by the Einstein comparison and ratio of observed to predicted values: 0.999 74 [0.999 87, 0.999 87] and 6.21 x 10^{-6} s [6.153 x 10^{-6} s, 1.009] (Kramer, *op. cit.*).

Atomic Clocks

In 1967 time was defined by the International Union of Pure and Applied Chemistry in terms of transitions involving the caesium-133 atom. Calibration was initially against ephemeris time where the motion of the Sun or Moon could be the standard. However, tables of motion of these bodies require many factors to be taken into account. Nevertheless, programs now exist that do give an accurate description of time.

Not long after, in 1971, four clocks containing caesium-133 were calibrated against each other and compared with the reference atomic scale at the United States Naval Observatory. As an experiment to test time changes within general relativity, they were flown on a commercial jet firstly eastward around the world. Their time losses amounted to 5.1, 5.5, 5.7 and 7.4 all x 10^{-8} s to give a mean and standard deviation of – (5.9 ± 1.0) x 10^{-8} s against the relativistic prediction with estimated uncertainty of – (4.0 ± 2.3) x 10^{-8} s. The westward round the world trip resulted in gains of 2.66, 2.66, 2.77 and 2.84 all x 10^{-7} s to result in + (2.73 ± 0.07) x 10^{-7} s against + (2.75 ±0.21) x 10^{-7} s (Hafele and Keating, 1972).

STRONG GRAVITY IMPLICATIONS

Nordtved Effect

A strong equivalence principle is known as the Nordtved effect after Kenneth Leon Nordtvedt (1939). It treats gravity as a geometric property of spacetime. Measurements described at Appache Point Observatory provide support for relativity to a few parts in 10^5 (Murphy, *op. cit.*).

Potential Gravitational Waves

As general relativity has dealt with weak fields within the solar system and stronger ones outside, it may be used to see if it will elucidate the situation with exceptionally strong fields. The conversion of rotational energy into gravitational energy would result in orbital decay in a binary pulsar. While decay has been measured, the search for gravitational waves has begun in earnest. A connection between accelerating masses and gravitational waves is hypothesised. However, compared with electromagnetic radiation from accelerating charges, the energy is extremely small. Thus, in their search for gravitational waves, scientists will firstly need to look at massive energy systems.

Towards the end of their existence, double neutron stars spiral inwards, collide and merge with a predicted enormous release of gravitational radiation. This is suggested to be strong enough to identify at the Earth. Detection is currently being attempted by VIRGO in Italy, GEO600 in Germany, TAMA in Japan and LIGO in the USA (Heuvel, 2003). As an example, (Laser Interferometer Gravitational Wave Observatory (LIGO) is on two sites. Each contains two arms four km long with weights suspended at the end of vacuum tubes. Laser beams measure the distances between the loads. The passage of a gravitational wave is expected to change the distance between the weights which would be detected with an interference pattern between the laser beams.

DISCUSSION

A summary of all the previous material is listed in Table 2. The property includes the title in this paper, the experiment performed relevant to that topic, the year of publication (not the year of the experiment) arranged chronologically for that section and percentage difference from relativity as the difference divided by the general relativity value. If there are two figures listed, the first one uses the central figure of the result against the prediction of general relativity. The second value uses the uncertainty, if it exists in the literature, and takes the larger of the difference from general relativity.

Table 2. Percentage difference from relativity for experiments conducted listed under a section, property and year of publication.

Property	Experiment	Year of Publication	% Difference from relativity
Equivalence of Inertial and Gravitational Mass	Torsion balance	1890	5×10^{-6}
	Torsion balance	1909	1×10^{-6}
	Torsion balance	1935	$2\text{-}5 \times 10^{-7}$
	Torsion balance	1964	1×10^{-9}
	Lunar laser ranging	2005	1×10^{-2}
	Lunar laser ranging	2009	1×10^{-1}
Gravitational Redshift	Gamma rays	1960	5, 15
	Gamma rays	1965	0.1, 0.9
	Hydrogen maser on rocket	1980	0.007
	Voyager 1 at Saturn	1990	0.44, 1
	Galileo spacecraft	1993	1
	Cassini spacecraft	2004	0.002 3
	Psr j0737 – 3039a/b	2006	0.36
Relativistic Perihelion Advance of the Planets	Mercury	1943	0.19, 1.4
	Venus	1956	2.3, 58
	Earth	1956	32, 62
Relativistic Periastron Advance of Binary Pulsars	PSR 1913 + 16 orbital decay	1989	1
	PSR 1913 + 16 periastron advance	1991	0.8, 1
	PSR 1913 + 16 orbital decay	1995	0.3
	PSR 1913 + 16 orbital decay + galactic rotation	1995	0
	PSR 1534 + 12 periastron advance	1998	1
	PSR J0737 – 3039A/B orbital decay	2004	0.3
	PSR 1913 + 16 orbital decay	2005	0.13, 0.4
Geodetic Precession	For Moon	1988	1.9, 2
	For Moon	1994	0.3, 2
	Planetary motions	2005	0.01, 0.03
	Gravity Probe B in Earth orbit	2011	0.28
Lense-Thirring Effect	LAGEOS and LAGEOS II in Earth orbit	2004	0.6, 0.7
	Mars Global Surveyor in orbit	2006	6
	Gravity Probe B in Earth orbit	2012	5, 24
Gravitational Optical Light Deflection	Total solar eclipse	1953	2.9, 4
	Total solar eclipse	1976	46
	Hipparchos	1997	0.3
Gravitational Radio Deflection due to the Sun	3C279 owens valley observatory	1970	2, 25
	3C279 goldstone	1970	8, 38
	3 radio sources and interferometry	1975	3, 6
	3 radio sources and interferometry	1976	1.4, 4
	74 radio sources and interferometry	1991	0.02, 0.3
	541 radio sources and interferometry	2004	0.02, 0.06
	4 radio sources and interferometry	2009	2, 5
Gravitational Lensing	Observations in accord with predictions	-	-

Table 2. Contd.

Time Dilation	Radar ranging to Mercury and Venus	1971	3, 7
	Mariner 6 in Mars flyby	1975	0.3, 0.7
	Mariner 7 in Mars flyby	1975	0, 2
	Viking – 2 orbiters and 2 landers at Mars	1977	0.5
	Mariner 9 in Martian orbit	1979	0, 2
	PSR J0737 – 3039A/B – shape of time delay	2006	0.013
	PSR J0737 – 3039A/B – range of time delay	2006	0.9
Atomic Clocks	Flying eastwards around Earth	1972	48, 73
	Flying westwards around Earth	1972	0.7, 3
Nordtved Effect	Lunar laser ranging	2003	(1) x 10^{-3}

As seen from the table, the equivalence principle has been tested to the 1 x 10^{-9} difference from relativity and the Cassini spacecraft has a measure of difference of 0.002 3% for gravitational redshift. What is significant is that from 10 properties with measurements, so many are at the 10^{-1} and 10^{-2} level.

CONCLUSION

This paper covers predominantly the period after 1928 to the present. From the three classical astronomical tests of general relativity (anomalous perihelion advance of the perihelion of Mercury, gravitational light bending and gravitational redshift), a plethora of other avenues has developed historically. Even the term relativistic astrophysics did not exist for the first 50 years following Einstein's publication of 1916. Topics covered are weak equivalence principle (equivalence of inertial and gravitational mass and gravitational redshift), orbital precession of a body in gravitational fields (the relativistic perihelion advance of the planets, the relativistic periastron advance of binary pulsars, geodetic precession and Lense-Thirring effect), light propagation in gravitational fields (gravitational optical light deflection, gravitational radio deflection due to the Sun, gravitational lensing, time dilation and atomic clocks) and strong gravity implications (Nordtved effect and potential gravitational waves). Each subject has been plumbed to determine the amount of measurement agreement with general relativity. Three questions were proposed as a guiding principle to this paper.

(i) How much evidence exists to support general relativity?

Einstein originally proposed that his concept could be tested by three astronomical tests. However, there was a significant hiatus between his 1916 publication and further experimentation. There was a need for technology to be developed and experimental techniques both invented and refined before more rigorous delving into the theory could ensue. Torsion balance data existed before 1916 but it continued to improve with better equipment. Lunar laser ranging and radar echoes from the inner planets improved the positioning of these solar system bodies. Allied with computer programs, scientists enhanced ephemerides and many of the perturbations were teased out to ascertain the contribution of each. By extending the reception of data from one station to several with a long base, scientists were able to use interferometry to tighten the uncertainty in their measurements. The introduction of spacecraft in Earth orbit and then venturing to the Moon and all the other planets opened up another methodology for experimentation. Precision was an essential requirement for the operation of these vehicles and so experimentation into relativity advanced. There promises to a burgeoning of data as planned spacecraft are put into service. However, with the myriad sets of results outlined in this article along with many tight constraints on the figures, general relativity has been tested well and not shown to be incorrect.

(ii) Is general relativity a reasonable way of thinking?

General relativity contains a number of simple ideas. From these, several predictions follow and these have been shown to be acceptable to usually better than a 1% level. It does not follow that general relativity is "correct" as other ideas may lead to the same forecasts. A model is judged by the fruitfulness of its operation. Against that criterion, general relativity has been shown to be superb.

A difficulty is that it does not square with notions people have, from their experience, of what reality is. However, experience tells us that the Earth neither spins nor orbits and that a body does not stay in constant motion. Yet, these ideas eventually won the day. People perceive space and time as absolute quantities and are more familiar with the geometry of Euclid than any other. Even though it is the province of scientists to understand the way the Universe operates, it is a task of all in the field to communicate these concepts to the public. Otherwise, the popularity of astrological signs in magazines and the reliance some people put on the ability of these to tell the future act as a signal of minds not thinking scientifically. General relativity is a successful concept and the public needs to have some appreciation of what it says.

(iii) What is the niche that general relativity should occupy?

Significant discussion abounds on the conflict between parts of general relativity and quantum mechanics. As a result, there is a search for a theory of everything. These models ought to be viewed as two of the greatest pieces of inspiration that have flowed from the mind of humans. It is imperative to celebrate such great thought. They are not reality but point to it. General relativity provides a worldview when masses are large and speeds approach that of the speed of light. Instead of seeing the disagreement between the two concepts, one may use whichever idea performs the role of explanation for each situation. This may involve a tension with some but the tension can be manageable. Light is light. On some occasions, its properties are better explained with a particle model and, at others, with a wave formulation. Neither holds a complete explanation; both are necessary to gain a perception of light. Perhaps, unification of general relativity and quantum mechanics may occur. In the meantime, Einstein's worldview may continually be applied to intriguing aspects of the Universe.

Formulated in 1916, general relativity was faced much later with a rapid succession of findings. In 1954 Cygnus A was a strong radio source associated with a distant galaxy that could not be detected optically. X ray sources entered the scene in 1962 followed by quasars in 1963, the 3 K background radiation in 1965, pulsars in 1967 and later further exotic objects of the cosmos. These features have been subsumed under the wing of general relativity and a scientific understanding of these phenomena would not currently exist without such a model.

Conflict of Interest

The author has not declared any conflict of interest.

REFERENCES

Anderson JD, Esposito PE, Martin W, Thornton CL, Muhleman DO (1975). "Experimental test of general relativity using time-delay data from Mariner 6 and 7". Astrophys. J. 200:221-233.

Bertotti B, Iess L, Tortora P (2003). "A test of general relativity using radio links with the Cassini spacecraft". Nature 425:374-376.

Biesbroeck G van (1953). "The relativity shift at the 1952 February 25 eclipse of the Sun". Astronol. J. 58(1207):87-88.

Bolton AS, Burles S, Koopmans LE, Treu T, Gavazzi R, Moustakas LA, Wayth R, Schlegel DJ (2008). "The Sloan lens ACS survey. V. the full ACS strong-lens sample". Astrophys. J. 682(2):964-984.

Brune RA Jr, Cobb CL, DeWitt BS, DeWitt-Morette C, Evans DS, Flloyd JE, Jones BF, Lazenby RV, Marin M, Matzner RA, Mikesell AH, Mitchell RI, Ryan MP, Smith HJ, Sy A, Thompson CD (1976). "Gravitational deflection of light: solar eclipse of 30 June 1973. I. description of procedures and final results". Astronol. J. 81(6):452-454.

Burgay M, D'Amico N, Possenti A, Manchester RN, Lyne AG, Joshi BC, McLaughlin MA, Kramer M, Sarkissian JM, Camilo F, Kalogera V, Kim C, Lorime DR (2003). "An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system". Nature 426:531-533.

Campbell L, Moffatt JW (1983). "Quadrupole moment of the Sun and the planetary orbits". Astrophys. J. 275:L77-79.

Campbell WW, Trumpler R (1928). "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(13):130-160.

Ciufolini I, Pavlis EC (2004). "A confirmation of the general relativistic prediction of the Lense-Thirring effect". Nature 431:958-960.

Clemence GM (1943). "The motion of Mercury 1765-1937". Astronol. J. 1:126-127.

Damour T, Taylor JH (1991). "On the orbital period change of the binary pulsar PSR 1913 + 16". Astrophys. J. 366:501-511.

Dickey JO, Bender PL, Faller JE, Newhall XX, Ricklefs RL, Ries JG, Shelus PJ, Veillet C, Whipple AL, Wiant JR, Williams JG, Yoder CF (1994). "Lunar laser ranging: a continuing legacy of the Apollo program". Science 265(5171):482-490.

Duncombe RL (1956). "The motion of Venus 1750-1949". Astronol. J. 61:266.

Eddington AS (1919). "The total eclipse of 1919 May 29 and the influence of gravitation on light". Observatory 42:119-122.

Einstein A (1905). "On the electrodynamics of moving bodies". Annalen der Physik. 17:891-921.

EinsteinA (1907). "On the relativity principle and the conclusions drawn from it". Jahrbuch der Radioaktivität und Elektronik. 4:411-462.

Einstein A (1916). "The Foundations of the General Theory of Relativity". Annalen der Physik. 49:769-822.

Einstein A (1918)."Über Gravitationswellen" Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften. pp. 154–167.

Einstein A (1936). "Lens-like action of a star by the deviation of light in a gravitational field". Science 89(2188):506-507.

Einstein A, Grossmann M (1913). "Entwurf einer verallgemeinerten Relativitätstheorie und einer Theorie der Gravitation" (Outline of a generalised theory of relativity and of a theory of gravitation). Zeitschrift für Mathematik und Physik. 62:225–261.

Eötvös R v (1890). Mathematische und Naturwissenschaftliche Berichte aus Ungarn [Mathematical and Scientific Reports from Hungary] 8:65.

Eötvös R v (1909). l6th International Geodesic Conference in London.

Eötvös RV, Pekár D, Fekete E (1922). Beiträge zum Gesetz der Proportionalität von Trägheit und Gravität" {Contributing to the law of proportionality of inertia and gravitation}. Ann. Phys. 68:11- 66.

Everitt CW, DeBra DB, Parkinson BW, Turneaure JP, Conklin JW, Heifetz MI, Keiser GM, Silbergleit AS, Holmes T, Kolodziejczak J, Al-Meshare M, Mester JC, Muhlfelder B, Solomonik V, Stahl K, Worden P, Bencze W, Buchman S, Clarke B, Al-Jadaan A, Al-Jibreen H, Li J, Lipa JA, Lockhart JM, Al-Suwaidan B, Taber M, Wang S (2011). "Gravity Probe B: final results of a space experiment to test general relativity". Phys. Rev. Lett. 106(22):1101-1105.

Fomalont EB, Sramek RA (1975). "A confirmation of Einstein's general theory of relativity by measuring the bending of microwave radiation in the gravitational field of the Sun". Astrophys. J. 199:749-755.

Fomalont EB, Sramek RA (1976). "Measurements of the solar gravitational deflection of radio waves in agreement with general relativity". Phys. Rev. Lett. 36(25):1475-1478.

Fomalont E, Kopeikin S, Lanyi G, Benson J (2009a). "Progress in measurements of the gravitational bending of radio waves using the VLBA". Astrophys. J. 699:1395-1402.

Fomalont E, Kopeikin S, Jones D, Honma M, Titov O (2009b). “Recent VLBA/VERA/IVS tests of general relativity” Proceedings IAU Symposium No. 261 Relativity in Fundamental Astronomy. 291-295.
Froeschlé M, Mignard F, Arenou F (1997). “Determination of the PPN parameter γ with the Hipparcos data”. Proceedings of the ESA Symposium at Venice. 402:49.
Gamalath KW (2012). Einstein his life and works. P. 287.
Gefter A (July 2005). “Putting Einstein to the test” Sky and Telescope. pp. 33-40.
Hafele JC, Keating RE (1972). “Around-the-world atomic clocks: observed relativistic time gains”. Science 177:168-170.
Heuvel EPJ van den (2003). “Testing time for gravity”. Nature. 426:504-505.
Hewitt JN, Turner EL, Scneider DP, Burke BF, Langston GI, Lawrence CR (1988). “Unusual radio source MG1131 + 0456: a possible Einstein ring”. Nature 333:537-540.
Hirate CM (2012). “Lecture ix: weak field tests of GR: the gravitational redshift, deflection of light, and Shapiro delay” Caltech.
Huchra J, Gorenstein M, Kent S, Shapiro I, Smith G (1985). “2237 + 0305: a new and unusual gravitational lens”. Astrono. J. 90:691-696.
Hulse RA, Taylor JH (1975). “Discovery of a pulsar in a binary system”. Astrophys. J. 195:L51-53.
Iorio L (2006). “A note on the evidence of the gravitomagnetic field of Mars”. Classical Quantum Gravity 23(17):5451.
Janssen M (2002). “The Einstein-Besso manuscript: A glimpse behind the curtain of the wizard” Introduction to the Arts and Science.
Kramer M, Stairs IH, Manchester RN, McLaughlin MA, Lyne AG, Ferdman RD, Burgay M, Lorimer DR, Possenti A, D’Amico N, Sarkissian JM, Hobbs GB, Reynolds JE, Freire PCC, Camilo F (2006). “Tests of general relativity from timing the double pulsar”. Science 314(5796):97-132.
Krisher TP, Anderson JD, Campbell JK (1990). “Test of the gravitational redshift effect at Saturn”. Phys. Rev. Lett. 64(12):1322-1325.
Krisher TP, Morabito DD, Anderson JD (1993). “The Galileo redshift experiment”. Phys. Rev. Lett. 70(15):2213-2216.
Lyne AG, Burgay M, Kramer M, Possenti A, Manchester RN, Camilo F, McLaughlin MA, Lorimer DR, D’Amico N, Joshi BC, Reynolds J, Freire PCC (2004). “A double-pulsar system: a rare laboratory for relativistic gravity and plasma physics”. Science 303:1153-1157.
McNamara G (2008). Clocks in the Sky: the story of pulsars.112.
Michael, WH Jr, Tolson RH, Brenkle JP, Cain DL, Fjeldbo G, Stelzried CT, Grossi MD, Shapiro II, Tyler GL(1977). “The Viking radio science investigation”. J. Geophys. Res. 82(28):4293-4295.
Morgan HR (1945). “The Earth’s perihelion motion”. Astronol. J. 51:127-129.
Morton DC (1956). “Relativistic advances of perihelions”. J. Royal Astronol. Soc. Canada 1:223.
Muhleman DO, Ekers RD, Fomalont EB(1970). “Radio interferometric test of the general relativistic light bending near the Sun”. Phys. Rev. Lett. 24:1377-1380.
Murphy TW Jr, Adelberger EG, Battat JBR, Carey LN, Hoyle CD, LeBlanc P, Michelsen EL, Nordtvedt K, Orin AE, Strasburg JD, Stubbs CW, Swanson HE, Williams E (2008). “APOLLO: the Apache Point Observatory Lunar Laser-ranging Operation:Instrument Description and First Detections”. Publ. Astron. Soc. Pac. 120:20-37.
Pfister H (2007). “On the history of the so-called Lense-Thirring effect”. Gen. Relativity Gravit. 39(11):1735-1748.
Pijpers FP (1998). “Helioseismic determination of the solar gravitational moment”. Monthly Notices of the Royal Astronomical Society. 297:L76-80.
Pitjeva EV (2005). “Relativistic effects and solar oblateness from radar observations of planets and spacecraft”. Astron. Lett. 31(5):340-349.
Pound RV, Rebka GA Jr (1959). “Gravitational redshift in nuclear resonance”. Phys. Rev. Lett. 3(9):439-441.
Pound RV, Rebka GA Jr (1960a). “Apparent weight of photons”. Phys. Rev. Lett. 4(7):337-341.
Pound RV, Rebka GA Jr (1960b). “Gravitational red-shift in nuclear resonance”. Phys. Rev. Lett. 4(7):439-441.
Pound RV, Snider JL (1965). “Effect of gravity on gamma radiation”. Phys. Rev. 140(3B):788-803.
Prince TA, Anderson SB, Kulkarni SR (1991). “Timing observations of the 8 hour binary pulsar 2127 + 11C in the globular cluster M15”. Astrophys. J. 374:L41-44.
Reasenberg RD, Shapiro II, MacNeil PE, Goldstein RB, Breidenthal JC, Brenkle JP, Cain DL, Kaufman TM, Komarek TA, Zygielbaum AI (1979). “Viking relativity experiment: verification of signal retardation by solar gravity”. Astrophys. J. 234:L219-221.
Renn J, Sauer T, Stachel J (1997). “The origin of gravitational lensing: A postscript to Einstein’s 1936 science paper”. Science. 275:184-186.
Renner J (1935). *Matematikai és Természettudományi Értesítő.* 13:542.
Robertson DS, Carter WE, Dillinger WH (1991). “New measurement of solar gravitational deflection of radio signals using VLBI” Nature. 349(6312):768-770.
Roll PG, Krotkov R, Dicke RH (1964). “The equivalence of inertial and passive gravitational mass”. Ann. Phys. 26:442-517.
Schneider P, Ehlers J, Falco EE (1992). Gravitational Lenses. Springer, Astronomy and Astrophysics. Library XIV
Seidelmann PK ed. (2006). Explanatory Supplement to the Astronomical Almanac. 704.
Seielstad GA, Sramek RA, Weiler KW (1970). “Measurement of the deflection of 9.602-GHz radiation from 3C279 in the solar gravitational field”. Phys. Rev. Lett. 24:1373-1376.
Shapiro II (1964). “Fourth test of general relativity”. Phys. Rev. Lett. 13(26):789-791.
Shapiro II, Ash ME, Ingalls RP, Smith WB, Campbell DB, Dyce RB, Jurgens RF, Pettengill GH (1971). “Fourth test of general relativity: new radar result”. Phys. Rev. Lett. 26(18):1132-1135.
Shapiro II, Reasenberg RD, Chandler JF, Babcock RW (1988). “Measurement of the de Sitter precession of the Moon: a relativistic three-body effect”. Phys. Rev. Lett. 41(23):2643-2646.
Shapiro SS, Davis JL, Lebach DE, Gregory JS (2004). “Measurement of the solar-gravitational deflection of radio waves using geodetic very-long-basline interferometry data, 1979-1999”. Phys. Rev. Lett. 92(12):1101-1104.
Sitter W de (1916). “On Einstein’s theory of gravitation, and its astronomical consequences, second paper”. Monthly Notices Royal Astron. Soc. 77:155-184.
Sitter W de (1917). “Planetary motion and the motion of the Moon according to Einstein’s theory”. Proceedings of the Royal Netherlands Academy of Arts Sci. 19(1):367-381.
Stairs IH, Arzoumanian Z, Camilo F, Lyne AG, Nice DJ, Taylor JH, Thorsett SE, Wolszczan A (1998). “Measurement of relativistic orbital decay in the PSR B1534 + 12 binary system”. Astrophys. J. 505:352-357.
Staveley-Smith L, Wilson WE, Bird TS, Disney MJ, Ekers RD, Freeman KC, Haynes RF, Sinclair MW, Vaile RA, Webster RL, Wright AE(1966). “The Parkes 21 cm multibeam receiver”. Publ. Astron. Soc. Australia.13:243-248.
Stockton A (1980). “The lens galaxy of the twin QSO 0957 + 561”. Astrono. J. 242:L141-142.
Taylor JH (1992). “Pulsar timing and relativistic gravity”. Philosophical Trans. Royal Soc. 341:116-134.
Taylor JH, Weisberg JM (1989). “Further experimental tests of relativistic gravity using the binary pulsar 1913 + 16”. Astrophys. J. 345(1):434-450.
Treschman KJ (2014a). “Early astronomical tests of general relativity: the gravitational deflection of light”. Asian J. Phys. 23(1-2):145-170.
Treschman KJ (2014b). “Early astronomical tests of general relativity: the anomalous advance in the perihelion of Mercury and gravitational redshift”. Asian J. Phys. 23(1-2):171-188.
Valença J de (2008). “Gravitational Waves” bachelor project online.
Vankov AA (1915). “Einstein’s Paper: Explanation of the perihelion motion of Mercury from General Relativity Theory” online, translated from German to English by Rydin RA.
Vessot RFC, Levine MW, Mattison EM, Blomberg EL, Hoffman TE, Nystrom GU, Farrel BF, Decher R, Eby PB, Baugher CR, Watts JW, Teuber DL, Wills FD (1980). “Test of relativistic gravitation with a space-borne hydrogen maser”. Phys. Rev. Lett. 49(26):2081-2085.
Walsh D, Carswell RF, Weymann RJ (1979). “0957 + 561 A, B – twin quasi-stellar objects or gravitational lens?”. Nature 279:381-384.
Weisberg JM, Taylor JH (2005). “The relativistic binary pulsar B1913 + 16: thirty years of observations and analysis”. Binary Radio Pulsars

ASP Conference Series. 328:25-31.
Will CM (2006). “The confrontation between general relativity and experiment”. Living Rev. Relativity 9(3):1-100.
Will M (1995). “Stable clocks and general relativity” in Dark Matter in Cosmology, Clocks and Tests of Fundamental Laws, Proceedings of the 30th Recontres de Moriond, Moriond Workshop ed. Guiderdoni B et al, pp. 417-427.
Williams JG, Turyshev SG, Boggs DH (2004). “Progress in lunar laser ranging tests of relativistic gravity”. Phys. Rev. Lett. 93(26):1101-1104.
Williams JG, Turyshev SG, Boggs DH (2009). “Lunar laser ranging tests of the equivalence principle with the Earth and Moon”. Int. J. Modern Phys. 518:1129-1175.
Wolszczan A (1991). “A nearby 37.9-ms radio pulsar in a relativistic binary system”. Nature 350(6320):688-690.
Zhao SS, Xie Y (2013). “Parametrized post-Newtonian secular transit timing variations for exoplanets”. Res. Astronol. Astrophys. 13(10):1231-1239.
Zwicky F (1937). “On the masses of nebulae and of clusters of nebulae”. Astrophys. J. 86(3):217-246.

academicJournals

Vol. 10(15), pp. 456-465, 16 August, 2015
DOI: 10.5897/IJPS2015.4382
Article Number: EA05AE854540
ISSN 1992 - 1950

http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

General Relativity support from the double pulsar

Keith John Treschman

51 Granville Street Wilston 4051 Australia.

Received 25 June, 2015; Accepted 27 July, 2015

After the final publication of the Theory of General Relativity by Albert Einstein in 1916, experimental confirmation rested on three astronomical tests. These were the amount of bending of starlight at the edge of the Sun, the change in frequency of light emanating from the gravitational field of the Sun and an explanation in terms of the theory of a remnant quantity in the perihelion advance of Mercury which had been calculated previously. The field of activity then was sparse and Quantum Mechanics attracted many scientists to its realm. However, a proliferation of renewed interest emerged 50 years on from 1916 with new thinking, improved instrumentation, the advent of spacecraft and the discovery of a number of exotic objects. The previous tests had been within the solar system. Now, there could be a transition from a weak to strong gravitational field testing. Neutron stars and pulsars were proposed based on ideas inherent within Einstein's conjecture as explanations for otherwise mysterious radio signals. In 2003, the advent of a two pulsars in mutual orbit allowed astrophysicists to delve into more precise tests of Einstein's theory. One of the parameters measured with this double pulsar has agreed with General Relativity to the 0.05% level. Three others are different from predictions by 1.4, 0.68 and 5.5%. Testing of these other parameters over a longer period of time promises to distinguish the accuracy between Einstein's ideas and concepts from other scientists.

Key words: General Relativity, neutron star, pulsar, double pulsar.

INTRODUCTION

In a review paper on relativity in 1907 Albert Einstein (1879-1955) presented an equivalence of acceleration and gravity (Einstein, 1907). From this connection, he deduced that gravitation could influence light. In particular, he submitted that light could be bent and also its frequency altered in a gravitational field. However, it was 1911 before he thought these two effects could be detected experimentally near the Sun (Einstein, 1911). Subsequently, during the development of his general theory, he determined, from his equations in 1915, a figure for the anomalous advance of the perihelion of Mercury (Einstein, 1915). In the following year he doubled his value for the amount of movement of light at the limb of the Sun (Einstein, 1916).

These three outcomes of General Relativity – gravitational deflection, the amount of Mercury perihelion increase and gravitational redshift - became the early classical tests for a new paradigm. The histories of these have been covered by the writer in two previous papers up to the year 1928 (Treschman, 2014a, b). Development after this date depended on improved instrumentation, the arrival of spaceflight and new applications from

E-mail: treschmankm@bigpond.com, Tel: 61-7-38562262.

different modes of thinking. The period 1928 to the present has been treated by Treschman (2015) under the topics:

(a) Weak equivalence principle (equivalence of inertial and gravitational mass and gravitational redshift),
(b) Orbital precession of a body in gravitational fields (the relativistic perihelion advance of the planets, the relativistic periastron advance of binary pulsars, geodetic precession and the Lense-Thirring effect),
(c) Light propagation in gravitational fields (gravitational optical light deflection, gravitational radio deflection due to the Sun, gravitational lensing, time delay and atomic clocks) and
(d) Strong gravity implications (Nordtved effect and potential gravitational waves).

The only double pulsar (two pulsars in mutual orbit) discovered to date has provided a series of unique tests for General Relativity and represents, within the uncertainties, the smallest departure from predictions of the Einstein theory. This paper will concentrate on an analysis of data for this topic. This paper traverses the proposal from the neutron in the atom onwards to a forecast that stars could exist that would be composed entirely of neutrons. Pulsars are then investigated. An understanding of them is revealed as a result of classifying them into three groups. While binary pulsars (a pulsar in mutual orbit with an object not a pulsar) are treated, the emphasis is on the only double pulsar yet discovered, PSR J0737-3039 A and B. Observational data on this pair with the Parkes Radio Telescope in Australia in 2003 provide a highly precise test of the General Theory of Relativity. This paper uses published data to investigate what precision can be reached and how well the General Theory is supported by these observations.

NEUTRON STARS

James Chadwick (1891-1974) is credited with interpreting his experiments on firing protons and alpha particles at different elements in 1932 as evidence for a particle of mass 1 and charge 0, that is, a neutron (Chadwick, 1932). However, his former supervisor, Ernest Rutherford (1871-1937), had proposed the existence of the neutron 12 years earlier. In a lecture Rutherford outlined his radiation experiments to infer the presence in the atom of a very small nucleus surrounded by electrons. He also conjectured there were electrons within the nucleus performing a different role from those outside the nucleus. He suggested that an atom of helium consisted of four hydrogen atoms and two electrons inside giving a charge of +2 and a mass of 4, with two electrons outside. '…it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet.' (Rutherford, 1920).

Surprisingly, within two years of Chadwick's pronouncement, (Wilhelm Heinrick) Walter Baade (1893-1960) and Fritz Zwicky (1898-1974) hypothesised that '*a super-nova* [sic] *represents a transition of an ordinary star into a body of considerably smaller mass*' (Baade and Zwicky, 1934a) and '*a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density*'. (Baade and Zwicky, 1934b)

Recent work has attempted to elicit an equation of state for neutron stars. Theoretical models have been proposed for their nature with a view to establishing limits on their masses as well as a link between the mass and radius. A typical 1.4 $M_{\odot}$ (mass of Sun) object would have a radius of approximately 11.5 km (Lattimer, 2012).

PULSARS

Angular momentum L is defined as

$$L = I\omega \quad (1)$$

where I is the moment of inertia and ω is the angular velocity. For a sphere

$$I = 2/5\, MR^2 \quad (2)$$

For mass M and radius R. Thus,

$$L = 2/5\, MR^2\omega. \quad (3)$$

Since angular momentum is conserved, as the radius of an object, in this case a neutron star, decreases, the angular velocity must increase. Hence, any neutron star with an initial spin was predicted to have a rapid rotation before any such object was even observed.

In addition, since the entity is expected to have a conducting fluid, a magnetic flux ought to exist. At the surface, the flux would be a product of the magnetic field strength B and the area of the surface. Again, as the neutron star shrinks resulting in a smaller surface area, B would be expected to increase.

The forecasts of a rapidly spinning, compact object with a high magnetic field became a reality in 1967 with the discovery of the first pulsar (pulsating source of radio) by (Susan) Jocelyn Bell (1943) (Hewish et al., 1968). In 1968, pulsars were connected with the Vela supernova remnant (Large et al., 1968) and the Crab Nebula relic (Staelin et al., 1968). The cause of the regular and rapid pulses had three possibilities: binary stars, pulsating stars or rotating stars. In 1969, Thomas Gold (1920-2004) dispensed with binary stars on the basis that the periods would decrease as energy was lost, contrary to the observed increase; he eliminated pulsating stars on the

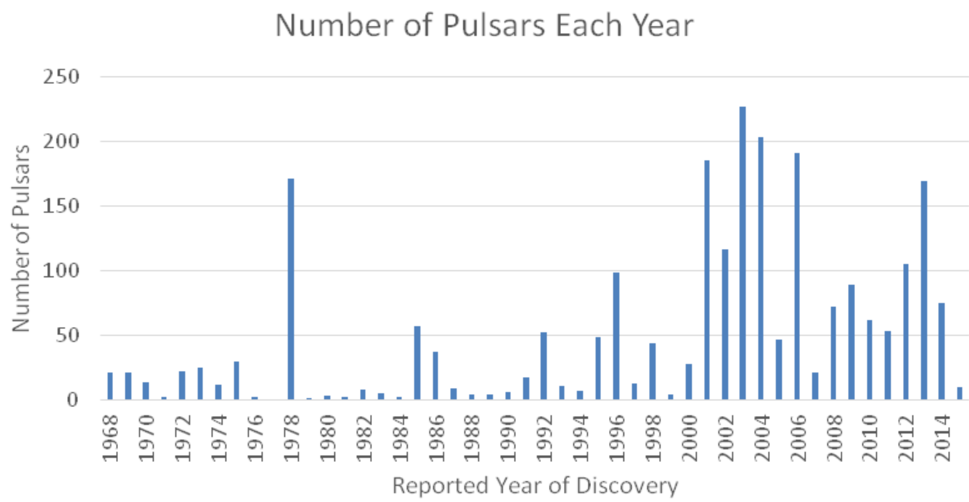


Figure 1. Number of pulsars per year of publication with later peaks due to Parkes.

foundation of the length of the period; finally, the rotation rate did not fit a white dwarf as it would fly apart at these speeds, which left, he argued, a rotating neutron star (Gold, 1969).

PULSAR SURVEYS

Large scale surveys using radio telescopes which led to the discovery of many pulsars have been conducted principally with the 100 m Green Bank Telescope in West Virginia, USA the 305 m Arecibo Observatory in Puerto Rico, the 76 m Jodrell Bank Observatory in England, the two 778 m x 12 m cylindrical paraboloids of the Molonglo Observatory Synthesis Telescope in Australia but more than half of the currently known pulsars have been identified at the 64 m CSIRO (Commonwealth Scientific and Industrial Research Organisation) Parkes Observatory in Australia (Manchester et al., 2005). The proliferation of the number of pulsars detected at Parkes is due, firstly, to the installation in 1997 of a 13 beam receiver. This multibeam pulsar survey commenced in August 1997 with each pointing of the telescope occupying 35 min duration (Manchester, 2001). In the first year of surveillance, each hour of observing time resulted in a new pulsar (Manchester et al., 2001). Secondly, the centre of the Milky Way Galaxy where pulsars are concentrated goes overhead in the Southern Hemisphere. As of May 2015, the Australia Telescope National Facility, that maintains a catalogue for the discoveries from all observatories, had listed 2405 pulsars (ATNF). These are distributed in Figure 1 by the number per year in which they were published. The peak in 1978 is due mainly to a Molonglo survey (Manchester et al., 1978) and the larger numbers in 2001, 2003, 2004, 2006 and 2013 represent surveys published principally from Parkes.

BINARY PULSARS

While theories were being advanced associating the origin of pulsars with supernovae, another development in the pulsar story was made in 1974 by Russell Alan Hulse (1950) and Joseph Hooton Taylor, Jr (1941). As they conducted a survey at the Arecibo Observatory, they detected the first binary pulsar where a pulsar and another neutron star were in mutual orbit (Hulse and Taylor, 1975). Since then, the total has reached 242 binaries where the companion may be a main sequence star, a neutron star, a white dwarf, a low mass star or another pulsar. These objects orbit each other where the range in period in the ATNF Pulsar Catalogue is from 1.6 h to 23 y.

One of the valuable outcomes from binary pulsars is that the masses of neutron stars may be determined. In a review paper by Lattimer, 33 calculated masses were shown from X-ray – optical, neutron star – neutron star and neutron star – white dwarf binaries. In this selection, the span of masses encompassed 1.00 – 1.700 $M_{\odot}$ (Lattimer, 2012).

CLASSIFICATION OF PULSARS

In 1982 a very fast rotator was timed at 1.558 ms for one spin (Backer et al., 1982). The term 'millisecond pulsar' was applied and encompassed any pulsar with a period shorter than 10 ms (Bhattacharya and van den Heuvel, 1991). At the other end of the spinning scale, a seemingly different type of object with pulses of 5.54 s was uncovered with the Parkes radio telescope in 2006 (Camilo et al., 2006). It was actually connected with a burst of X-rays previously detected by spacecraft in 2003. This class contains the so called magnetars and comprises anomalous X-ray pulsars and gamma ray bursters.

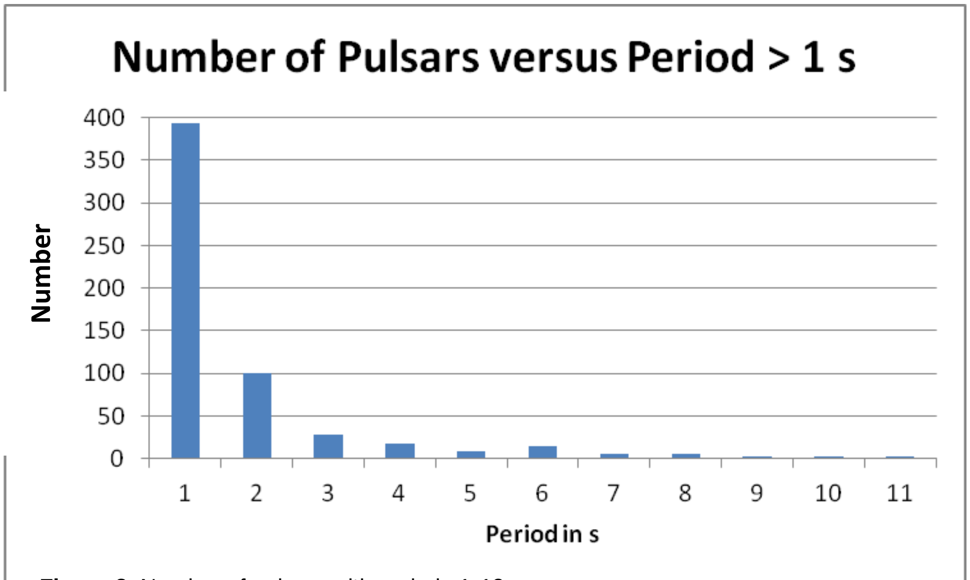


Figure 2. Number of pulsars with periods 1-12 s.

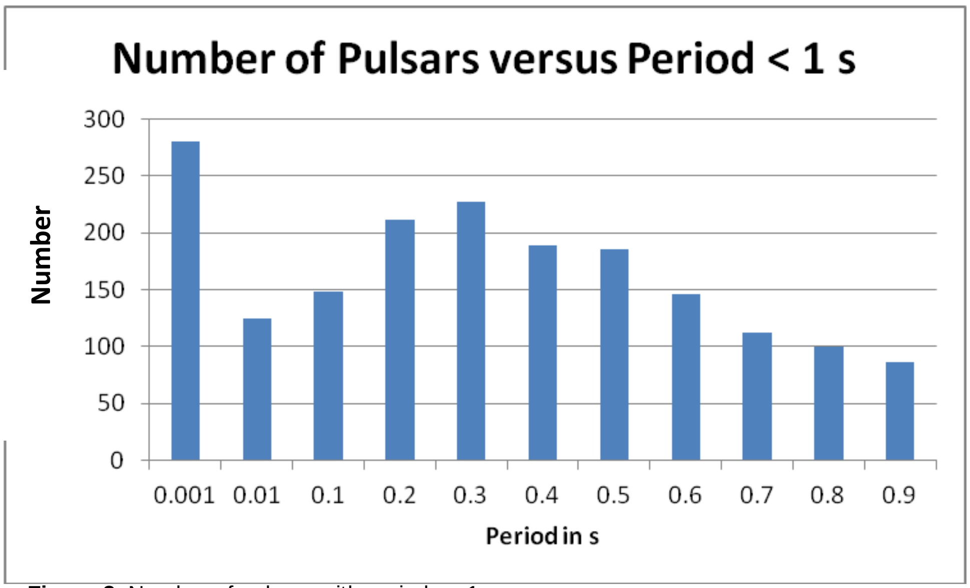


Figure 3. Number of pulsars with periods < 1 s.

From the ATNF catalogue of all known pulsars, the one with the slowest spin has a period *P* of 11.8 s and the fastest 1.4 ms, that is, over 700 times per second. Of the 2405 pulsars that have been logged, 2392 have their measured period displayed. The 581 with a period > 1 s are exhibited in Figure 2 where 1 s refers to the duration > 1 s but < 2 s and so on. For the 1811 pulsars with periods < 1 s, 1406 have a spin > 0.1 s. From an analysis of 815 pulsars, it has been estimated that perhaps 40% are born in the range 0.1 to 0.5 s (Vranesevic et al., 2004). Thus, the region 0.1 to 1.0 s has been further subdivided into 0.1 s lots as in Figure 3.

"*The pulse period is very predictable, but it is not constant. … Pulsars are powered by the kinetic energy of rotation. They steadily lose energy, mainly in the form of a high-energy wind of charged particles and magnetic-dipole radiation, that is, electromagnetic waves at the neutron star's rotation frequency* (Manchester, 2001)". The measure of this loss of energy may be gauged in the slowdown rate of the period, $\dot{P}$ in s s^{-1}. An interesting pattern emerges if the logarithm of $\dot{P}$ is graphed against the logarithm of *P*. The plots in Figure 4 are produced from within the ATNF catalogue but here have been teased apart into the majority of pulsars, the high energy ones and the binaries respectively from left to right. The product of *P* and $\dot{P}$ leads to a measure of the magnetic field at the surface B_S as in the formula:

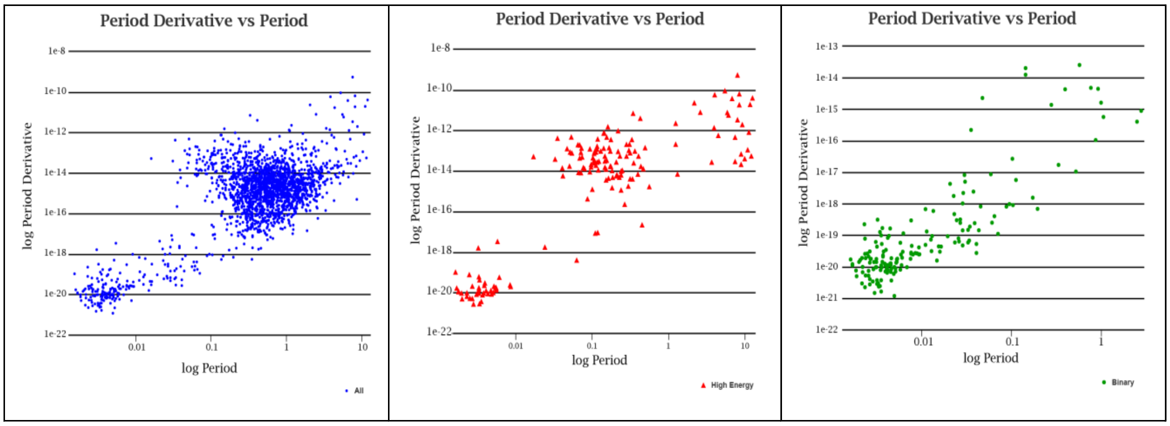


Figure 4. Log of change of period per s versus log of period for, from left, most pulsars, high energy pulsars, binaries. Note that the vertical axes are identical but the horizontal scale for the binaries is different from that of the other two.

$$B_S = (3c^2 I/8\pi^2 R^6 P\dot{P})^{0.5} \text{ in G (gauss)} \quad (4)$$

$\approx 3.2 \times 10^{19} (P\dot{P})^{0.5}$ G for $I \approx 10^{38}$ kg m^2 and $R \approx 10^4$ m (Bhattacharya and van den Heuvel, 1991). For a typical high energy pulsar in the centre panel of Figure 4, $10^{19} \times (10^{-1}$ s x 10^{-13} s s$^{-1})^{0.5} \approx 10^{12}$ G. From the surface magnetic field data in the ATNF catalogue, the highest is given as 2.22 x 10^{14} G. This region embodies the magnetars which have large magnetic fields, slower rotations but faster rates of loss of energy. Also, the loss is not always uniform and is often in the form of bursts of X-rays or gamma rays. The decay of *B* powers the emission of radiation predominately in the high energy end of the spectrum. The bursts are believed to be connected with two different situations: the collapse of a star and the merger of neutron stars. From the left panel of Figure 4, a central pulsar at 10^{-1} s and change at 10^{-15} s s^{-1} has $B_S \approx 10^{11}$ G from Equation (4). They are faster rotators, have medium magnetic fields but lose their energy more slowly than the magnetars. In contrast, the binaries in the right panel of Figure 4 would have a typical result of 10^{-2} s, loss at 10^{-20} s s^{-1} for $B_S \approx 10^8$ G. The lowest value in the catalogue is 3.21 x 10^7 G. These binary pulsars are fast rotators, most reside in the millisecond class, have lower magnetic fields by comparison and lose their energy much more slowly. More than half of them have been detected in globular clusters (D'Amico et al., 2003). Their scenario is that they were older, slow rotators and even though they probably also formed from supernovae, each possessed a companion which was not ejected by this mammoth event. As the companion evolved, some of its matter accreted to the other member. The rise in angular momentum led to an increase in rotation rate of what effectively became a recycled pulsar (Possenti et al., 2004).

DOUBLE PULSAR

Where the term binary pulsar is applied to a pulsar and a companion other than another pulsar, the term double pulsar is used for two pulsars in mutual orbit. The only double pulsar system discovered to date is PSR J0737-3039A and PSR J037-3039B in the constellation Puppis, referred hereafter as A and B. The data for A were collected by Marta Burgay (1976) in April 2003 at Parkes and processed at Jodrell Bank (Burgay et al., 2003). In October of the same year, Duncan Ross Lorimer (1969) was testing code at Parkes on the data of Burgay and identified a second pulsar which was not detectable in the original records as B was only strong for two short intervals each orbit (Possenti et al., 2004). The saga is articulately presented in chapter 14 of McNamara's book on pulsars (McNamara, 2008). It was decided by the parties involved (Sarkissian, 2014) that as Burgay had already submitted for publication, it would be followed later by Andrew Lyne as principal author who was supervising Burgay (Lyne et al., 2004). Some of the physical parameters of the double pulsar are displayed in Table 1. The digit/s in parentheses following the measurement refer/s to the uncertainty in the last digit/s.

There are five orbital parameters, known as Keplerian parameters, which are required to reference the time of arrival of pulses to the barycentre of the binary system (Kramer, 2004). They are based on Newton's laws of motion and his law of universal gravitation and are calculated as an isolated two-body situation. These are shown in Table 2.

However, changes do arise due, in some situations, to the presence of other masses and, in the case of the double pulsar, to the effects of relativity. Departures from the Keplerian descriptions are referred to as post-Keplerian parameters (PKPs). Stairs explains: "*The tests of GR [General Relativity] that are possible through pulsar timing fall into two broad categories: setting limits*

Table 1. Some physical parameters of the double pulsar (Kramer, 2006a).

Physical parameter	Values
right ascension	$07^h37^m51^s.249\ 27(3)$
declination	-30°39'40".719 5(5)
spin frequency A	44.054 069 392 744(2) s^{-1}
spin frequency B	0.360 560 355 06(1) s^{-1}
inclination *i*	88°.69(-76, +50)

Table 2. Keplerian parameters of the double pulsar (Kramer et al., 2006a).

Parameter	Pulsar A	Pulsar B
orbital period P_b	0.102 251 562 48(5) d	
eccentricity *e*	0.087 777 5(9)	-
projected semi-major axis $x = a/c \sin i$ for *a*, semi-major axis	1.415 032(1) s	1.516 1(16) s
longitude of periastron from the ascending node ω	87°.033 1(8)	87°.033 1 + 180°.0
the epoch of periastron passage (MJD)	53 156.0	

on the magnitudes of the parameters that describe violations of equivalence principles, often using an ensemble of pulsars, and verifying that the measured post-Keplerian timing parameters of a given binary system match the predictions of strong-field GR better than those of other theories (Stairs, 2003)''.

Measurements are performed on the time of arrival of the pulse energy. As this signal travels through interstellar space, the presence of electrons along the path interferes differently with the frequencies so that the higher the frequency the earlier the arrival. The pulse dispersion is thus an approximate measure of distance. '*The observational parameters … are obtained from a least-squares solution of the arrival-time data …*' (Will, 2006).

ANALYSES OF DOUBLE PULSAR PARAMETERS

Stairs lists the following five equations of PKP in terms of the stellar masses (Stairs, 2003).

$$\dot{\omega} = 3\,(P_b/2\pi)^{-5/3}\,(T_\odot M)^{2/3}\,(1 - e^2)^{-1} \quad (5)$$

$$\Upsilon = e(P_b/2\pi)^{1/3} T_\odot^{2/3} M^{-4/3} M_B(M_A + 2M_B) \quad (6)$$

$$\dot{P}_b = -192\pi/5\,(P_b/2\pi)^{-5/3}\,(1 + 73/24\,e^2 + 37/96\,e^4)(1 - e^2)^{-7/2}\,T_\odot^{5/3}\,M_A M_B\,M^{-1/3} \quad (7)$$

$$r = T_\odot M_B \quad (8)$$

$$s = x(P_b/2\pi)^{-2/3} T_\odot^{-1/3} M^{2/3} M_B^{-1} \quad (9)$$

The symbol $T_\odot$ stands for the time for light to cross the radius of the Sun and is a term that allows the resultant pulsar masses to be given in terms of $M_\odot$. $T_\odot = GM_\odot/c^3 = 6.673 \times 10^{-11}$ N m^2 kg^{-2} x 1.989 1 x 10^{30} kg/(2.997 924 58 x 10^8 m $s^{-1})^3$ = 4.926 x 10^{-6} s. This compares closely with the literature value of 4.925 490 947 x 10^{-6} s. *x* is the projected semi-major axis of the binary orbit.

In Equation (5), $\dot{\omega}$ is the time rate of change of the longitude of periastron from the ascending node. It is the relativistic advance of periastron and is analogous to the relativistic perihelion advance of Mercury (or any other planet) in the solar system. This equation may be rearranged to provide a solution for *M*, the mass of the system which equals the sum of the individual masses M_A + M_B.

$$M = [\dot{\omega}/3\,(P_b/2\pi)^{5/3}\,T_\odot^{-2/3}\,(1 - e^2)]^{3/2} \quad (10)$$

Since $\dot{\omega}$ = 16.899 47° yr^{-1}, it needs to be changed into radian s^{-1}, and P_b to s. This resultant value and subsequent ones are taken from Kramer et al. (2006a). M = 2.587 08(16) $M_\odot$. Thus,

$$M_A + M_B = 2.587\ 08 \text{ or } M_B = -M_A + 2.587\ 08. \quad (11)$$

A graph of M_B versus M_A may then be drawn. As further PKPs are derived in terms of masses, these are added as graphs on the original plot. The intersection gives specific values for the masses of A and B. General Relativity may then be judged as to how constrained the quantities of the masses are. This method has an appeal

Table 3. Post-Keplerian parameters and other results of the double pulsar (Kramer, 2006a).

Parameter	Value	Equation
advance of periastron $\dot{\omega}$	16.899 47(68) ° yr^{-1}	5
gravitational redshift Υ	0.385 6(26) x 10^{-3} s	6
orbital period derivative $\dot{P}_b$	-1.252(17) x 10^{-12} s s^{-1}	7
Shapiro delay *r*	6.21(33) x 10^{-6} s	8
Shapiro delay *s*	0.999 74(-39,+16)	9
mass of system	2.587 08(16) $M_{\odot}$	
mass of A	1.338 1(7) $M_{\odot}$	
mass of B	1.248 9 $M_{\odot}$	
mass ratio	1.071 4(11)	
distance based on dispersion measure	≈ 500 pc (10^{20} m)	

visually. Alternatively, two equations give two unknowns of the masses which may be solved mathematically. Then, further parameters are derived from the masses and the difference between the new parameter and its observational value provides a percentage variation for the theory of General Relativity.

Equation (6) contains the gravitational redshift parameter Υ and is a combination of time delay and gravitational redshift. The frequency change is predicted by Einstein in that time runs differently in the region of a mass and a volume somewhat removed. It corresponds to the average amplitude of delays in arrival time due to changes in speed of the pulsars and the distance between them as they traverse their elliptical orbit. For the measured Υ = 0.385 6(26) x 10^{-3} s, Equations (5) and (6) yield

M_A = 1.338 1(7) $M_{\odot}$ and M_B = 1.248 9 $M_{\odot}$.

The time derivative of the orbital period change $\dot{P}_b$ is caused by gravitational wave damping. Equation (7) produces a result of -1.252(17) x 10^{-12} s s^{-1}. Due to the fortuitous circumstance of the double system being almost edge on to the line of sight, the two parameters representing the Shapiro delay may also be determined (Kramer et al., 2006b). From Equation (8) the Shapiro delay *r* due to the medium of transmission is calculated as 6.21(33) x 10^{-6} s. In reverse, it is the range of the Shapiro delay that provides an estimate of the companion mass as the signal from A passes through the spacetime of B (van Straten et al., 2001).

To conclude the calculations of the PKPs, Equation (9) derives the shape of the Shapiro delay $s \equiv \sin i$ (Burgay et al., 2005) as 0.999 74(-39, +16). A further parameter which is possible with the double pulsar is to obtain a mass ratio *R* of the components by measuring the semi-major axes *a* of the elliptical orbits from the equality in the following subsequent equation.

$$R = M_A/M_B = a_B/a_A \quad (12)$$

This gives 1.071 4(11). The measurements of the PKPs from Equations (5) to (9) and data on masses and distance are summarised in Table 3. The advance of the periastron $\dot{\omega}$ has been measured to a precision approaching 10^{-5}. If this and *R* are used to solve for M_A and M_B, the values of the other four PKPs mentioned here may be calculated. This then gives tests of General Relativity as shown in Table 4 (Kramer et al., 2006a).

Departures from General Relativity are calculated here as the uncertainty in the ratio of 1.0 as a percentage. For example, for *s* the uncertainty is 0.000 50 which is 0.05%. Hence, differences from GR are 1.4% for $\dot{P}_b$, 0.68% for Υ, 5.5% for *r* and 0.05% for *s*. This result for *s* is the most precise test ever of any technique used for comparison with Einstein's theory. The parameters $\dot{\omega}$, Υ, *r* and *s* were obtained within seven months of observation. This level of precision of $\dot{P}_b$ followed 2.5 years of timing.

FURTHER DATA

The distance datum based on the dispersion measure is claimed to be in error by a factor of two. With measurements between 2006-2008 of the annual geometric parallax with the Australian Long Baseline Array, the figure has been given as 1 150 (+220,-160) pc (Deller et al., 2009). From the separation between the pulsars of 8 x 10^{8} m, the precision of $\dot{P}_b$ is such as to be able to deduce a decreasing separation between the pulsars of 7 mm d^{-1} (Kramer et al., 2006a). After 10 more years of timing, this parameter may reach the 0.01% level.

Table 4. PKP comparisons of observed and GR predictions for the double pulsar.

PKP	observed value	GR value	ratio observed/GR
$\dot{P}_b$ s s^{-1}	1.252(17)	1.247 87(13)	1.003(14)
Υ x 10^{-3} s	0.385 6(26)	0.384 18(22)	1.003 6(68)
r x 10^{-6} s	6.21(33)	6.153(26)	1.009(55)
s	0.999 74(-39,+16)	0.999 87(-48,+13)	0.999 87(50)

The supernova which caused the two pulsars did not throw the binary system apart but would be expected to result in a misalignment between the pulsar spin axes and their orbital axis. Geodetic precession would lead to relativistic spin-orbit coupling so that the pulsar spin axes would precess about the total angular momentum axis (Kramer, 2004; Manchester, 2010). The angular frequency period Ω_p for this is embedded in the relationship

$$\Omega_p = ½ (P_b/2\pi)^{-5/3} T_\odot^{2/3} M_B(4M_A + 3M_B)/(1 - e^2)M^{4/3}. \quad (13)$$

The calculated period for pulsar B around the total orbital angular momentum axis is 70.95 year (Manchester, 2015a). 360°/70.95 yr = 5°.074 yr^{-1}. Within an uncertainty of 13%, the precessional rate obtained of 4°.77 (+0.66,-0.65) yr^{-1} is consistent with a General Relativity prediction of 5°.073 4 ± 0°.000 7 yr^{-1} (Breton et al., 2008). From a study of eclipses of pulsar A by the magnetosphere of pulsar B, it has been inferred that the inclination of the rotation axis of pulsar B to the normal of the orbital plane is ≈ 60° and its angle to the magnetic axis 75° (Lyutikov and Thompson, 2005). Pulse profile analysis points to ≈ 90° for the difference between the spin and magnetic axes of pulsar A but only 3°.2 difference between its spin and orbital angular momentum axes (Ferdman et al., 2013). As a result, no secular change has been pursued for a measurement of the precessional period of pulsar A. Some further data given in Table 5 (Lyne et al., 2004), on the rotational periods P of pulsars A and B together with their time rates of change $\dot{P}$ may be used to calculate their surface magnetic fields and time rate of energy loss $\dot{E}$.

Table 5. Parameters for spin periods and their time rates of change.

Parameter	Observed value
P_A	0.022 699 378 556 15(6) s
$\dot{P}_A$	1.74(5) x 10^{-18} s s^{-1}
P_B	2.773 460 747 4(4) s
$\dot{P}_B$	0.88(13) x 10^{-15} s s^{-1}

From Equation (4), $B_A = 6.3 \times 10^9$ G and $B_B = 1.2 \times 10^{12}$ G (Yuen et al., 2012). Also,

$$\dot{E} = -4\pi^2 I \dot{P} / P^3. \quad \text{(Manchester, 2001)} \quad (14)$$

$\dot{E}_A = 5.9 \times 10^{26}$ W and $\dot{E}_B = 1.6 \times 10^{23}$ W where 1 W ≡ 10^7 erg s^{-1} (Yuen et al., 2012). Some concept of the dense nature of a pulsar may be gauged by comparison with the atomic nucleus. With the masses of pulsar A and a neutron being respectively 1.338 1 $M_\odot$ and 1.674 928 6 x 10^{-27} kg, on the assumption that pulsar A were comprised totally of neutrons, there would be of the order of 10^{57} neutrons present. The density of pulsar A, taking the radius as 1.15 x 10^4 m, would be 4.2 x 10^{17} kg m^{-3} compared with that of an atomic nucleus of 2.3 x 10^{17} kg m^{-3}. The designation neutron star is truly appropriate.

FUTURE

As a result of the dynamic changes in the double pulsar system PSR J0737-3039A/B, the beam of pulsar B ceased sweeping across Earth in 2008. However, it is expected to again intersect Earth in the near future (Manchester, 2015b). The longer the time span of observations, the more precise the measurements of this system become. This places tighter constraints on the parameters and provides a more stringent test of General Relativity or competing theories.

Radio receivers are the instruments which provide accurate measurement of timing for pulsars. Nevertheless, other realms of the electromagnetic spectrum may elucidate data that give a more detailed picture of the operation of the double pulsar. In 2006, the Chandra X-ray Observatory collected data on the system at this high energy end and the interpretation was that it showed that the emission was due to the shock from pulsar A interacting with the interstellar medium (Granot and Mészáros, 2004). Later, in 2012, the Hubble Space Telescope acquired images in the far ultraviolet region (Durant et al., 2014).

A 500 m radio telescope is slated for first light in China in 2016. A stated objective of this project is an emphasis on collecting information on more distant pulsars (Nan et al., 2011). When the Square Kilometre Array begins its operation, it also has targeted pulsar surveys with an emphasis on the millisecond variety (Carilli and Rawlings, 2004) with improved timing precision (Shao et al., 2014).

As a larger collection of pulsar, binary pulsar and double pulsar samples increases, measurements of moments of inertia will allow a deeper insight into the nature of superdense matter (Kramer et al., 2006a).

One of the pursuits in pulsar investigation is the detection of gravitational waves which are predicted by General Relativity. The amount of release of energy is consistent with the theory but the instrumentation available today is not sensitive enough to detect and measure it. When a figure was forthcoming for the merger rate of the double pulsar of 85 x 10^6 yr (Burgay, 2011), the expected rate of binary pulsar collisions increased dramatically. This gave greater impetus to the likelihood of detecting this far greater amount of energy. The Laser Interferometric Gravitational-Wave Observatory (LIGO) in the United States of America, the Japanese TAMA project, German-British GEO detector in Germany and the European Gravitational Observatory in Italy have embarked on the quest to discovery such a phenomenon (Abbott et al., 2009).

This prominence given to increasing the precision of measurements is not just about discriminating between rival theories for understanding the Universe. General Relativity has passed with flying colours any test thrown at it. However, it started in 1915 as a theoretical construct without any experimental support. Scientists ''*did not dream that transition to a relativistic system would have observational consequences* (Kuhn, 1962, 2012)''. The situation morphed when it was realised that there were three 'classical' predictions upon which its mettle could be judged. Even then, the field was quite dormant. Interest was piqued 50 years after the formulation of the theory as new thinking was applied, instrumentation progressed, the space era had begun and more exotic objects started presenting themselves in the cosmos. Up to this point, it could be seen that Newton's laws could still be applied with Einstein filling in when speeds increased into the regime of the speed of light or masses became somewhat larger than that of the Sun. However, the application of General Relativity in the confines of the solar system, known as the weak field situation, completely trumps Newtonian theory in the strong fields of, for example, pulsars. A paradigm shift ensued. Where might General Relativity lead us? Just as the extent of its applicability was not predictable, the theory needs to be mined for what else it may elucidate. As one sign of the dramatic change, one may look at a criterion for a paradigm shift in conferences held specifically in a field. The first international convocation completely devoted to General Relativity was in 1955, a few months subsequent to Einstein's death. These are now held each three years, with 21 having occurred. Now, at the 100 year anniversary of General Relativity, the field is still providing promise for many scientists.

CONCLUSION

The prediction of superdense forms of matter predated the recognition of neutron stars. With the arrival on the scene of pulsars in 1967, an entire new field emerged and General Relativity was the guiding post to scientific understanding. Entering the scene in 1974, binary pulsars extended the possibilities and precision of measurement. In 2003, the discovery of a double pulsar has provided scientists with a unique gamut of prospects in the strong field arena. Astronomical tests of General Relativity have included inertial and gravitational equivalence, gravitational redshift, relativistic perihelion and periastron advance, geodetic precession, light propagation in gravitational fields and implications in strong gravity regimes. Of all of these, the most accurate figure to date of 0.05% for the departure between observation and General Relativity comes from a parameter of the double pulsar PSR J037-3039A/B.

Conflict of Interest

The authors have not declared any conflict of interest.

ACKNOWLEDGEMENTS

Two members of the team involved in the discovery of the double pulsar have been most helpful. Dr John Sarkissian, Operations Scientist at the Parkes Radio Telescope, gave me, per telephone, background to the discovery of the double pulsar and the decisions made by a number of members of the group. Dr Dick Manchester, a CSIRO Fellow provided time for me in my visit to the Sydney arm of the Parkes radio telescope where he answered my questions on the techniques involved in pulsar measurement. Subsequently, he has responded to a number of queries I had in my understanding of facets of the double pulsar measurements.

This paper forms part of my PhD dissertation at the University of Southern Queensland. My supervisors, Dr Brad Carter and Dr Nick Lomb, have provided feedback on my written work, including recommendations for improved communication of some ideas.

REFERENCES

Abbott BP et al (2009). "LIGO: The Laser Interferometer Gravitational-Wave Observatory" Reports on Progress in Physics arXiv:0711.3041:1-50.

Australia Telescope National Facility Pulsar Catalogue http://www.atnf.csiro.au.

Baade W, Zwicky F (1934a). On super-novae. Proceedings National Academy Sci. 20(5):254-259.
Baade W, Zwicky F (1934b). Cosmic rays from super-novae. Proceedings National Academy Sci. 20(5):259-263.
Backer DC, Kulkarni SR, Heiles C, Davis MM, Goss WM (1982). “A millisecond pulsar”. Nature 300:615-618.
Bhattacharya D, van den Heuvel EPJ (1991). Formation and evolution of binary and millisecond pulsars. Phys. Lett. 203(1- 2):1-124.
Breton RP, Kaspi VM, Kramer M, McLaughlin MA, Lyutikov M, Ransom SM, Stairs IH, Ferdman RD, Camilo F, Possenti A (2008). Relativistic spin precession in the double pulsar. Science 321:104-107.
Burgay M, D’Amico N, Possenti A, Manchester RN, Lyne AG, Joshi BC, McLaughlin MA, Kramer M, Sarkissian JM, Camilo F, Kalogera V, Kim C, Lorimer DR (2003). An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system. Nature 426:531-533.
Burgay M, D’Amico N, Possenti A, Manchester RN, Lyne AG, Joshi BC, McLaughlin MA, Kramer M, Sarkissian JM, Camilo F, Kalogera V, Kim C, Lorimer DR (2005). The highly relativistic binary pulsar PSR J0737−3039A: discovery and implications. ASP Conf. Series 328:53-58.
Burgay M (2011). The double pulsar system in its 8th anniversary. Science with Parkes @ 50 Years Young.
Camilo F, Ransom SM, Halpern JP, Reynolds J, Helfand DJ, Zimmerman N, Sarkissian J (2006). Transient pulsed radio emission from a magnetar. Nature 442:892-895.
Carilli CL, Rawlings S (2004). Science with the square kilometer array: motivation, key science projects, standards and assumptions. arXiv: astro-ph/0409274.
Chadwick J (1932). Possible existence of a neutron. Nature 129:312.
D’Amico N, Possenti A, Manchester RN, Lyne AG, Camilo F, Sarkissian J (2003). Searching for millisecond pulsars in globular clusters at Parkes. Astron. Soc. Pacific Conf. Series 302:375-379.
Deller AT, Bailes M, Tingay SJ (2009). Implications of a VLBI distance to the double pulsar J0737-3039A/B. Science arXiv:0902.0996.
Durant M, Kargaltsev O, Pavlov GG (2014). Hubble Space Telescope detection of the double pulsar system J0737−3039 in the far-ultraviolet. Astrophys. J. 783(1):L22-L26.
Einstein A (1907). On the relativity principle and the conclusions drawn from it. Jahrbuch der Radioaktivität und Elektronik. 4:411-462.
Einstein A (1911). On the influence of gravitation on the propagation of light. Annalen der Physik 35:898-908.
Einstein A (1915). Explanation of the perihelion motion of mercury from the general theory of relativity. Preußische Akademie der Wissenschaften (Prussian Academy of Sciences). 6(21):831-839.
Einstein A (1916). The foundations of the general theory of relativity. Annalen der Physik. 49:769-822.
Ferdman RD, Stairs IH, Kramer M, Breton RP, McLaughlin MA, Freire PCC, Possenti A, Stappers BW, Kaspi VM, Manchester RN, Lyne AG (2013). The double pulsar: evidence for neutron star formation without an iron core-collapse supernova. Astrophys. J. 767 (85):1-11.
Gold T (1969). Rotating neutron stars and the nature of pulsars. Nature 222(5175):25-27.
Granot J, Mészáros P (2004). High energy emission from the double pulsar system J0737-3039. Astrophys. J. 609:L17-L20.
Hewish A, Bell SJ, Pilkington JDH, Scott PF, Collins RA (1968). Observation of a rapidly pulsating radio source. Nature 217:709-713.
Hulse RA, Taylor JH (1975). Discovery of a pulsar in a binary system. Astrophys. J. 195:L51-53.
Kramer M (2004). General relativity with double pulsars. SLAC Summer Institute on Particle Phys. (SSI04):1-14.
Kramer M, Stairs IH, Manchester RN, McLaughlin MA, Lyne AG, Ferdman RD, Burgay M, Lorimer DR, Possenti A, D’Amico N, Sarkissian JM, Hobbs GB, Reynolds JE, Freire PCC, Camilo F (2006a). Tests of general relativity from timing the double pulsar. Science 314(97):97-102.
Kramer M, Stairs IH, Manchester RN, McLaughlin MA, Lyne AG, Ferdman RD, Burgay M, Lorimer DR, Possenti A, D’Amico N, Sarkissian J, Joshi BC, Freire PCC, Camilo F (2006b). Strong-field tests of gravity with the double pulsar. Annalen der Physik. 15(1-2):34-42.
Kuhn TS (1962, 2012 edition). The structure of scientific revolutions. University of Chicago Press.
Large MI, Vaughan AE, Mills BY (1968). A pulsar supernova association?. Nature 20(5165):340.
Lattimer JM (2012). The nuclear equation of state and neutron masses. Ann. Rev. Nuclear Particle Sci. 62:485-515.
Lyne AG, Burgay M, Kramer M, Possenti A, Manchester RN, Camilo F, McLaughlin MA, Lorimer DR, D'Amico N, Joshi BC, Reynolds JE, Freire PCC (2004). A double-pulsar system: a rare laboratory for relativistic gravity and plasma physics. Science 303:1153-1157.
Lyutikov M, Thompson C (2005). Magnetospheric eclipses in the double pulsar system PSR J0737-3039. Astrophys. J. 634:1223-1241.
McNamara G (2008). Clocks in the sky – the story of pulsars, Springer.
Manchester RN, Lyne AG, Taylor JH, Durdin JM, Large MI, Little AG (1978). The second Molonglo pulsar survey – discovery of 155 pulsars. Monthly Notices Royal Astron. Soc. 185:409-421.
Manchester RN (2001). “Finding pulsars at Parkes”. Publ. Astron. Soc. Australia. 18:1-11.
Manchester RN, Lyne AG, Camilo F, Bell JF, Kaspi VM, D’Amico N, McKay NPF, Crawford F, Stairs IH, Possenti A, Kramer M, Sheppard DC (2001). The Parkes multi-beam survey – I. observing and data analysis systems, discovery and timing of 100 pulsars. Monthly Notices Royal Astron. Soc. 328:17-35.
Manchester RN, Hobbs GB, Teoh A, Hobbs M (2005). The Australia Telescope National Facility Pulsar Catalogue. Astronol. J. 129:1993-2006.
Manchester RN, Kramer M, Stairs IH, Burgay M, Camilo F, Hobbs GB, Lorimer DR, Lyne AG, McLaughlin MA, McPhee CA, Possenti A, Reynolds JE, van Straten W (2010). Observations and modeling of relativistic spin precession in PSR J1141-6545. Astrophys. J. 710:1694-1709.
Manchester RN (2015a). Pulsars and gravity. Int. J. Modern Phys. D. 24. arXiv:1502.05474.
Manchester RN (2015b). Personal conversation in Sydney.
Nan R, Li D, Jin C, Wang Q, Zhu L, Zhu W, Zhang H, Yue Y, Qian L (2011). The five-hundred-meter aperture spherical radio telescope (FAST) project. Int. J. Phys. D:1-36.
Possenti A, Burgay M, D’Amico N, Lyne AG, Kramer M, Manchester RN, Camilo F, McLaughlin MA, Lorimer D, Joshi BC, Sarkissian JM, Freire PCC (2004). The double-pulsar PSR J0737-3039A/B. Memorie della Società Astronomica Italiana. Supplementi. 5:142-147.
Rutherford E (1920). Nuclear constitution of atoms. Bakesian Lecture, Proc. Roy. Soc. London. 97(686):374-400.
Sarkissian J (2014). Telephone conversation.
Shao L, Stairs IH, Antoniadis J, Deller AT, Freire PCC, Hessels JWT, Janssen GH, Kramer M, Kunz J, Lämmerzahl C, Perlick V, Possenti A, Ransom S, Stappers BW, van Straten W (2014). Testing gravity with pulsars in the SKA era. Proceed. Sci. arXiv:1501.00058:1-20.
Staelin DH, Reifenstein III, Edward C (1968). Pulsating radio sources near the Crab Nebula. Science 162(3861):1481–1483.
Stairs IH (2003). Testing general relativity with pulsar timing. Living Rev. Relativ. 6:5-49.
Treschman KJ (2014a). Early astronomical tests of general relativity: the gravitational deflection of light. Asian J. Phys. 23(1- 2):145-170.
Treschman KJ (2014b). Early astronomical tests of general relativity: the anomalous advance in the perihelion of mercury and gravitational redshift. Asian J. Phys. 23(1- 2):171-188.
Treschman KJ (2015). Recent astronomical tests of general relativity. IJPS 10(2):90-105.
van Straten W, Bailes M, Britton MC, Kulkarni SR, Anderson SB, Manchester RN, Sarkissian J (2001). A test of general relativity from the three-dimensional orbital geometry of a binary pulsar. Nature 412:158-160.
Vranesevic N, Manchester RN, Lorimer DR, Hobbs GB, Lyne AG, Kramer M, Camilo F, Stairs IH, Kaspi VM, D’Amico N, Possenti A, Crawford F, Faulkner AJ, McLaughlin MA (2004). Pulsar birthrates from the Parkes multibeam survey. Astrophys. J. 617:L139-L142.
Will CW (2006). The confrontation between general relativity and experiment. Living Rev. Relativ. 9:1-100.
Yuen R, Manchester RN, Burgay M, Camilo F, Kramer M, Melrose DB, Stairs IH (2012). Changes in polarization position angle across the eclipse in the double pulsar system. Astrophys. J. 752:L32-L36.

CSIRO PUBLISHING

Historical Records of Australian Science, 2015, **26**, 150–163
http://dx.doi.org/10.1071/HR15002

General Relativity in Australian Newspapers: The 1919 and 1922 Solar Eclipse Expeditions

Keith John Treschman

51 Granville Street, Wilston, Qld 4051, Australia. Email: treschmankm@bigpond.com

In 1922 there was a total solar eclipse with the central track traversing the Australian continent from Western Australia, through South Australia and across Queensland. Local and overseas astronomers mounted major observing campaigns to verify the amount of gravitational light bending predicted by the Theory of General Relativity. This paper looks at how the media reported the results from previous expeditions in 1919, which were conducted by the British, and the necessity for the 1922 measurements in Australia. It was this latter local eclipse that was the impetus for Australian correspondents to report on General Relativity. In general, the Australian newspapers chronicled informatively and accurately, they provided a good coverage of the eclipse parties and stressed the significance of the 1922 investigations.

Additional keywords: 1919 eclipse, 1922 eclipse, Australian newspapers, Australian public, General Relativity, gravitational deflection, gravitational redshift, Mercury anomaly.

Introduction

The General Theory of Relativity of 1916 provided an advance in Physics by Albert Einstein (1879–1955)[1] on the Universal Law of Gravitation by Isaac Newton (1642–1727). While the application of Newton's laws had connected the motion of the planets with that of objects on the Earth and provided great predictive power from his mathematics, it suffered from not providing a structure for the concept of force at a distance. Einstein now provided a mechanism whereby gravity could be understood as a property of space itself.

However, the theory needed evidence for its support. Early on, there arose three astronomical tests against which General Relativity could be tested. First, in 1907, Einstein was of the opinion that light could be bent in a gravitational field,[2] but it was 1911 before he realized that the amount of displacement was sufficient to be detected in the presence of the Sun.[3] He revised his figure upwards in a 1916 paper and proposed that the transposition would be 1".7 at the limb of the Sun and that this would decrease in proportion to the square of the distance from the centre of the Sun.[4]

Second, in 1915, Einstein deduced another possible supporting concept. For a two body problem in Newtonian physics, such as a single planet and the Sun, the planet would be expected to trace an elliptical orbit with its perihelion returning to the same point in space. However, in the presence of other planets, the point of perihelion would move in the direction of the motion, that is, advance in space. Yet, the mathematics that incorporated all the forces that were thought to be involved resulted in a small, unexplained difference. For the planet closest to the Sun, this became known as an anomalous advance of the perihelion of Mercury. The experimental figure had stood at 43" century^{-1} since 1882.[5] Einstein derived from his field equations a figure of 45" $\pm$ 5" century^{-1} for this residual amount.[6]

For the third astronomical test, Einstein proposed in the same 1907 paper[7] that atoms on the surface of the Sun would be affected by the gravitational field surrounding it. He reasoned that as light left the Sun, it would expend energy working against gravity. Since the energy of a photon is proportional to its frequency, a lower frequency would be expected. The speed of light is constant in the work of Einstein. As the speed of light is the product of frequency and wavelength, a lower frequency would necessitate a longer wavelength. In the optical region of the spectrum, red light has a longer wavelength than blue. This phenomenon was called gravitational redshift. Einstein postulated that this change expressed as a ratio of the difference between the observed wavelength and the wavelength of the source divided by the source wavelength would amount to 2.12×10^{-6}.

The scientific literature of the time produced argument and counterargument with regards to these three tests of General Relativity. A significant public attempt to measure light deflection, the first of the tests mentioned above, took place with two British expeditions at the total solar eclipse of 29 May 1919. This required photographing stars near the Sun during the eclipse and comparing their positions with photographs of the same region of the sky without the presence of the Sun. For the latter to occur at night, the time period needed to be six months either before or after the eclipse. Debate ensued whether this eclipse was sufficient to support General Relativity. Thus, it was considered by many scientists that further experimentation was necessary. Hence, the next measurement was effected in Australia at the total solar eclipse on 21 September 1922.

During the time that General Relativity was attempting to obtain a foothold among scientists, the main method of communication to the general population was via newspapers. Lectures were also delivered to the public and the content of these were often reported in the news media. Journalists were also in attendance at the public welcome given for overseas astronomers in 1922 as they traversed the continent. Speeches from those being feted were part of the occasion. So, the reporters heard first-hand from those involved in the measurements what was anticipated and also some of the preliminary accomplishments.

This article analyzes Australian newsprint to show how the Australian public, through the media, were informed of one of the key predictions of Einstein's theory, that is, the gravitational bending of light. It also ascertains how the attempted verification in 1919 was regarded and why the observations at the September 1922 Australian eclipse were needed. The second and third tests, that is, the Mercury anomaly and gravitational redshift, were not the subject of the eclipse expeditions. Nevertheless, any mention of these topics was noted in the inspection of the newspapers throughout this period.

Methodology

An online search was made of Australian newspapers via the website Trove, which is provided by the National Library of Australia. The input was 'Einstein' AND 'relativity'. The articles were then arranged chronologically from the earliest to more recent. Each article was classified into the year of publication, analyzed for its main theme, the eclipse party to which it referred, differentiated into the three classical tests of relativity, if mentioned, and the words of support or otherwise for the proposed theory.

The earliest record was January 1911 and the span was to 31 December 1928. The reason for this finishing date will be explained later. Several of the newspapers were syndicated and so sometimes the same article appeared in several of them or a story would be picked up by one and copied by another. Where an article was the same or substantially so, only the first record was included in the tally. The study period spanned 18 years and included 266 separate newspaper articles on General Relativity.

The Major Interest Regarding General Relativity

Of the 266 newspaper articles, the number referring to General Relativity in each year is shown in Table 1.

The year 1922, when the eclipse was observed in Australia, encompassed 52% of the 266 distinct newspaper pieces. The preceding year was devoted to many of the preparations for the total solar eclipse and the year following included several results of the 1922 parties. These three years (1921–3) accounted for 81% (82% from the table is due to rounding) of the featured articles over the time period 1911–28.

Within the eclipse year of 1922, the 137 stories are subdivided into the month of publication in Table 2.

For the month in which the eclipse occurred, September, the proportion for the year was the largest at 37%. Thus, the eclipse in Australia was a major focus of newspaper space devoted to General Relativity. This is shown further if the articles are analyzed by their major subject material. Sometimes more than one topic was covered in some pieces. If so, the crux of the message was distilled either by referring to the number of words devoted to a subject or by selecting the

Table 1. Number of newspaper articles per year 1911–28

Year	1911	1912	1913	1914	1915	1916	1917	1918	1919
Number	1	0	2	1	0	0	4	0	11
%	0.4	0	0.8	0.4	0	0	1.5	0	4
Year	1920	1921	1922	1923	1924	1925	1926	1927	1928
Number	24	36	137	43	6	2	4	0	3
%	9	14	52	16	2	0.8	1.5	0	1

Table 2. Number of newspaper articles per month in 1922

Month	January	February	March	April	May	June
Number	13	5	8	3	6	10
%	9	4	6	2	4	7
Month	July	August	September	October	November	December
Number	10	14	51	12	3	4
%	7	10	37	9	2	3

Table 3. Number and % of newspaper articles by main theme

Main theme	Number	%	Main theme	Number	%
1922 total solar eclipse	134	50	Gravitational redshift	5	2
Relativity	72	27	Ether	4	2
Einstein	23	9	Perihelion advance of Mercury	3	1
1919 total solar eclipse	14	5	Energy-mass	2	1
Gravitation	9	3	**Total**	**266**	**100**

central idea that was portrayed. The main theme is recorded in Table 3.

One half of the articles concentrate on the 1922 total solar eclipse as this was perceived as being the major interest of the Australian public. With the next highest percentage of 27% for relativity, it could be inferred that the education of the audience was also a priority.

The Three Astronomical Tests

As it was the property of gravitational light deflection that was being measured at this eclipse, it is not surprising then that this would be the most pronounced of the three astronomical tests. However, some space was devoted to the other two tests as some interest was being generated about this new theory of Einstein. The proportion of each astronomical point of evidence in the newspaper presentations is shown in Table 4.

The 1919 and 1922 Total Solar Eclipses

The paths of the 1919 and 1922 eclipses are shown in Fig. 1.

The British sent two parties to the 1919 total solar eclipse. Charles Rundle Davidson (1875–1970) of the Royal Greenwich Observatory was the leader to Sobral in Brazil. With two telescopes, the resulting deflections at the limb of the Sun were 0".93 and 1".98 $\pm$ 0.12 compared with the then current calculation from relativity of 1".75. Opting for Príncipe, an island off the west coast of Africa, Arthur Stanley Eddington (1882–1944), Director of Cambridge Observatory, obtained a figure of 1".61 $\pm$ 0.30. Presenting the outcome, the Astronomer Royal Frank Watson Dyson (1868–1939) eliminated the lower value from Brazil and concluded that the remaining two encompassed Einstein's quantity.[8] The experimental uncertainties made measurements at these eclipses quite difficult.

Table 4. Number and % of newspaper articles for the three astronomical tests

Property	Number	Percentage
Gravitational light deflection	52	50
Perihelion advance of Mercury	33	32
Gravitational redshift	19	18

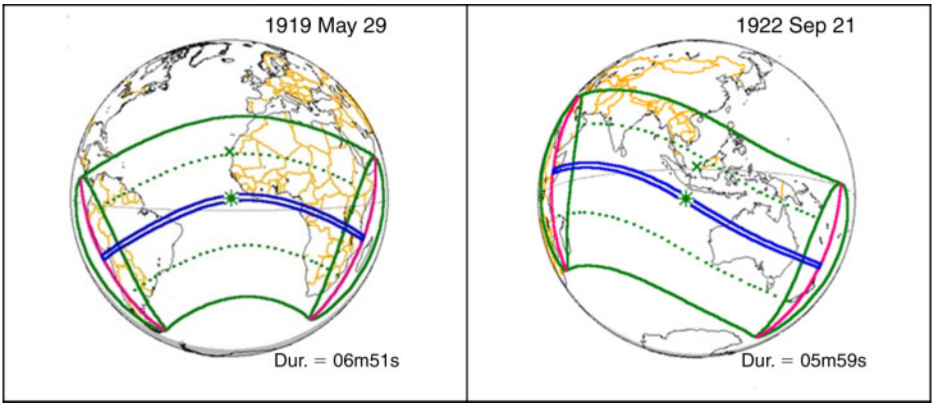


Figure 1. Paths of 1919 (left) and 1922 total solar eclipses. (Eclipse Predictions by Fred Espenak, NASA/GSFC).

Differing interpretations of the 1919 results required further attempts and this is what led some groups to Australia for the 1922 eclipse.

The path of the 1922 total solar eclipse from west to east in the Australian region cut across Christmas Island (transferred as territory from the UK to Australia in 1957), passed over Wallal on the coast of Western Australia near Broome, sliced into the north-eastern part of South Australia, and crossed into Queensland through Goondiwindi and Stanthorpe, 160 km to its east (Fig. 2).

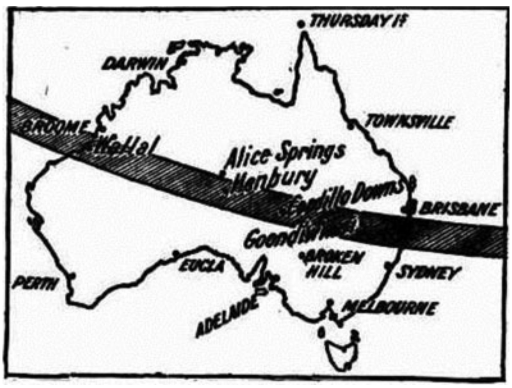


Figure 2. Path of 1922 eclipse across Australia[9]. (*Argus* (Melbourne), 14 January 1922, p. 7).

There were eight parties that attempted a measurement of the amount of light deflection in 1922. These are listed with the name of the leader, his lifespan, the affiliation of that person and the place of observation:

1. William Wallace Campbell (1862–1938), Lick Observatory, California, USA to Wallal, Western Australia
2. Harold Spencer Jones (1890–1960), Royal Observatory, Greenwich, England to Christmas Island
3. Erwin Finlay-Freundlich (1885–1964), Berlin Observatory, Germany, joint German-Dutch party to Christmas Island
4. John Evershed (1864–1956), Kodaikanal Observatory, India to Wallal
5. Clarence Augustus Chant (1865–1956), University of Toronto, Canada to Wallal

6. George Frederick Dodwell (1879–1963), Adelaide Observatory to Cordillo Downs, South Australia
7. William Ernest Cooke (1863–1947), Sydney Observatory to Goondiwindi, Queensland
8. Joseph Mason Baldwin (1878–1945), Melbourne Observatory to Goondiwindi

   Another five groups carried out investigations that did not include light displacement in their operation:

9. J. Hargreaves, England to Wallal
10. Alexander David Ross (1883–1966), Perth Observatory to Wallal
11. Oscar Ulrich Vonwiller (1882–1972), University of Sydney to Goondiwindi
12. Donald G Coleman, Carnegie Institution of Washington to Coongoola, Queensland
13. Walter Francis Gale (1865–1945), New South Wales Branch of the British Astronomical Association to Stanthorpe, Queensland

A more comprehensive description of the British odysseys and the 13 groups above is given in another paper by the author.[10] For these 13 excursions, the number of articles in which the leader or group is mentioned is displayed in Table 5. Here, the top set of rows displays the eight parties involved in attempts to measure light deflection. The second set contains the five gatherings that did not attempt to measure any possible displacement of light.

There were 232 articles out of a total of 266 (87%) where a leader or group is mentioned. It could be interpreted that the newspaper presented the events as human interest stories. The 8 of the 13 groups that were devoted to a light displacement attempt comprised 78% (180) of the references. Campbell with his party from the Lick Observatory is at the top of the list with 23%. The Lick Observatory was a well-financed institution. Its personnel had experience in 11 eclipses before the 1922 occasion and Campbell had been the leader of six of these. He had already established himself as a noted astronomer in world circles. On his train trip from Sydney to Perth he was feted at many localities where he responded in speeches to welcomes extended to the astronomers. On some of these occasions he outlined the work that was being attempted and the importance to Einstein's theory of obtaining measurements. There were journalists present on each of these occasions.

To emphasize that Campbell was seen as the hub of activity in 1922, statistics for the six localities where eclipse groups gathered were collected. The place Wallal was the site for five groups including Campbell's, Goondiwindi for three, Christmas Island for two and one each at Cordillo Downs, Stanthorpe and Coongoola. The number of articles where these are referred to at least once is shown in Table 6.

The locality is mentioned in 113 of 266 articles, a proportion of 42%. Wallal figures as the most prominent place comprising 40% of articles that make mention of an eclipse site in 1922. The other four groups at Wallal viewed Campbell as the central person. There was high expectation that if any worthwhile result were to be obtained, it would be delivered by Campbell and the Lick Observatory.

Simplification of General Relativity to the Australian Public

There is no doubt that a complete understanding of General Relativity requires a thorough grounding in specialized mathematics. Australian newspapers made no attempt at this but rather stressed the level of difficulty in comprehending Einstein's ideas. Einstein was quoted as saying that 'only he and 12 other scientists can understand' the theory.[11] The reason for not providing a detailed explanation was well summarized as '… for it embraces problems which the greatest intellects of the universe have not yet solved, and, as a fact, one has to be thoroughly grounded in such sciences as mathematical physics and astronomy to have an appreciable conception of what it is all about. Indeed, an explanation worthy of being termed one has yet to be forthcoming.'[12]

Nevertheless, consequences of the theory were presented. In some instances, the technical words used suggest that the writer of the newspaper piece would have received details from an astronomer or other scientist. One attempt described matter as having 'length, breadth, height and time', 'size and mass' were dependent 'on the velocity of movement' and 'mass increased at very high velocities'.[13] Another scribe took this further by presenting all motions

Table 5. Number of newspaper articles recorded for each of 13 expeditions in 1922

Leader	Campbell	Spencer Jones	Finlay-Freundlich	Evershed	Chant	Dodwell	Cooke	Baldwin
Number	53	14	4	7	28	30	26	18
%	23	6	2	3	12	13	11	8
Leader	Hargreaves	Ross	Vonwiller	Coleman	Gale		Total	
Number	9	19	12	3	9		232	
%	4	8	5	1	4			

Table 6. Number of newspaper articles per locality in 1922

Location	Wallal	Goondiwindi	Christmas Island	Cordillo Downs	Stanthorpe	Coongoola	Total
Number	45	24	20	12	8	4	113
%	40	21	18	11	7	4	

as relative to others and that everything was moving. Time was described as being different on two moving bodies and that 'space and time do not exist as distinct things'. Without a connection to any understanding, it was stated that 'a body shortens a fraction of its length when in motion in the direction of its motion', that the 'shape or mass of bodies changes according to their velocity', that 'light rays deflected', space was curved and 'light returns to the same point'.[14]

The three astronomical consequences in the early years of General Relativity were presented as outlined previously in Table 4.

For gravitational light deflection, some pertinent writing pieces were 'gravitation is also incorporated in the union of space and time, a gravitational field being regarded as in a way equivalent to a curvature in the four dimensional space time system'[15]; 'The fundamental part played by gravitation in the generalised theory of relativity is due to the impossibility of discriminating between a gravitational field and an acceleration of the framework of reference'[16] and a 'ray of light has a curved path in an intense gravitational field'.[17]

With regard to the anomalous advance of the perihelion of Mercury, the coverage that gives a detailed history of this puzzle follows:

> For a long time astronomers have been puzzled by an unexplained discordance in the motion of Mercury in its revolution round the sun. Leverrier, in 1859, from a discussion of all the observed transits of Mercury, found that its perihelion has a movement of nearly 38 seconds of arc per century over and above what can be accounted for by the action of the known planets.

The journalist goes on to give a history of the search for a planet or ring of planets closer to the Sun than Mercury but states that this pursuit had drawn a blank at both total solar eclipses and transits. Even suggestions of a slight change to the inverse square law of Newton were described.[18]

Receiving the smallest number of references of the three earliest astronomical tests, gravitational redshift was nowhere presented as due to the way the gravitational field of the Sun was connected to an alteration of the frequency of light. There is mention that the 'rates of clocks depend on their gravitational fields'.[19] A very brief number of words refers to the 'displacement of lines in the solar spectrum'[20] and just as fleeting a reference is 'displacement of dark lines to red end of solar spectrum'.[21]

Correct and Misleading Information

General Relativity was still in its infancy. Many scientists had not been exposed to its concepts or did not possess a firm grasp of the theory. Yet, the journalists wrote several articles that were surprisingly accurate.

One mistake that did the rounds was an attempt at an explanation that time was relative. The example given was 'that a day on Earth is not the same as that of Mercury or Neptune' where the former is one quarter as long and the latter

164 times.[22] Another strange comment was that 'he [Einstein] contends there is no difference between a year and a century'.[23]

There were some words used where a pedant might take the writer to task. Any mass curves space in its vicinity and it is this that results in the straight line path of light appearing to curve in this region. One could argue about the statement that 'rays of light are attracted towards a heavy gravitating body'.[24] However, 'attraction between two bodies is modified when the speed approaches the speed of light' does not have much support scientifically.[25]

Results of the British Eclipse Expeditions of 1919

There was a series of articles that described support for the British expeditions of 1919. At a joint meeting of the Royal Society and Royal Astronomical Society on 6 November 1919 in London, Dyson declared that the 'photographs demonstrated the accuracy of the physicist Einstein's theory'.[26] He 'expressed the conviction, that the results of the recent experiments were definite and conclusive'.[27] In a cable message from London after the announcement, Dodwell, who was the Government Astronomer of South Australia and the leader of one of the 1922 eclipse parties, indicated that the results were a 'direct test of the truth of a remarkable … theory of relativity … [of] Professor Einstein'.[28]

This thread of confirmation was evident through many Australian newspaper reports, some of which referred to the bending of light. Eddington and Dyson were at the forefront of supporters.[29] Other articles backing the 1919 results couched their espousal in words such as verification, vindication, agreement, concordance, triumph or favourable.[30] However, as the 1922 eclipse approached, voices were raised questioning the adoption of the 1919 conclusions. There was some disquiet with the patronage that had been displayed. Objections were raised because of the technique of using a mirror to reflect the sky into the telescope as well as the distortion caused by the mirror at one of the two sites. It was even suggested that physicists were in favour but astronomers were divided. A distinction was made between countries, with England for and America split in their opinions.[31]

There were 107 newspaper references in this time period to whether measurements of light bending had supported, not supported or required more evidence in regard to Einstein's theory. The numbers are differentiated in Table 7.

The scientific community was still debating the merits of General Relativity. Most revolutions in Science follow a similar pattern. From the newspapers, 47% reflect the stance of those referred to as early adopters of a paradigm shift. 20% display the opinions of a group who are unconvinced that the result of the 1919 eclipse was sufficient to marshal support. New ideas often follow a slow process where more and more data are necessary before a group of scientists are prepared to move from their tentative stance to one of reasonable acceptance and this is shown in the 33% of articles devoted to more evidence required.

Purpose of 1922 Measurements

Some examples of the gamut of reasons given for the importance of measurements at the 1922 total solar eclipse were that better equipment now existed, more experience in what had been gained, additional evidence was necessary and there was even a suggestion that while the best photographs of 1919 confirmed Einstein's prediction, the poorer ones did not. Also, the unfavourable sky in Africa at the previous attempt was mentioned.[32] Tellingly, Dyson now questioned the technique of the use of a coelostat in 1919 so that in 1922 an equatorial mount would replace the necessity of employing a mirror. He acknowledged there had been a partial failure of the astrographic telescope at Sobral and the results were not entirely satisfactory.[33] He went further by commenting that the sought after measurement was as low as 1/10 the diameter of a dot and that further verification was desirable.[34] Ross summarized the situation that the '1919 eclipse on the whole confirmed Einstein's theory but certain measurements did not conform to it. … from instruments not performing satisfactorily.'[35]

Results of 1922 Eclipse Measurements

The first proclamation of results from the 1922 eclipse was publicised in the press in 1923.

> C. A. Chant, professor of astronomy at University of Toronto, … announced [the]correctness

Table 7. Decision on General Relativity from 1919 eclipse

Decision	Support	More evidence	Not support	Total
Number	50	35	22	107
Percentage	47	33	20	100

> of Einstein's theory of relativity. More than 30 stars on photographic plate but 23 submitted for measurement, eight later rejected. … [deflection] approximately that required.[36]

To this, both Gale and Cooke cautioned judgement and said that it was necessary to await Campbell's declaration as he had photographed more stars and possessed superior equipment.[37] Even though the Lick Observatory measurements were not completely finished by 1923, Campbell summarized his

> results of photographs are in exact accord with the requirements of the Einstein theory. One and seventy-five hundredths seconds of arc is as close as the most ardent proponent of the Einstein theory could hope for. It is so close that the Lick Observatory will not repeat the test at the solar eclipse in Mexico in September.[38]

He indicated that he and Trumpler who were carrying out duplicate analyses were in agreement '…the extremely exact measurements made by these two scientists of photographic plates, is absolutely phenomenal. 84 stars average 1".74'.[39]

Results of the Canadian party and Lick Observatory continued to appear in the newspapers and to these were added figures from the South Australian expedition.[40] Finally, in 1928,

> Professor AD Ross received from the Lick Observatory [the news] that measurement from Wallal 1922 now completed. Results are in complete harmony with the predictions of the theory. April 1923 figure was given for 15 foot (4.6 m) plates. Six plates from five foot (1.5 m) more laborious as [there were] smaller displacements. Stars far out … [had] no deviation so comparison could be made. 1".75 at edge ± 0".09, Newton 0".87, Einstein 1".74, Lick Observatory 1".66–1".84. Result appeared conclusive.[41]

There was a tendency in several commentaries to view the eclipse measurements as a showdown between proof and disproof or truth versus otherwise of General Relativity.[42] One example was 'The test for the truth or otherwise of this theory was the principal object of the research at the recent eclipse.'[43] Gleaned from the reading, 22 formulations of this type emerged, an 8% subset of the 226 accounts.

Mercury Anomaly

While Australian newspaper articles were predominantly devoted to the gravitational deflection that was being measured at the eclipse, there were some snippets linking General Relativity with the anomalous advance in the perihelion of Mercury. Some accounts indicated that Mercury was the first success for the theory[44] whereas another opined that the result was not satisfactory.[45] Further, it was deemed necessary to search for alternative explanations. Two of the positive contributions were that 'Mercury's orbit [of] 43 s per century [was] accounted for by general theory of relativity.'[46] and Einstein 'was also the first to give a rational solution to the long-standing puzzle of the rotation of Mercury's orbit.'[47]

Gravitational Redshift

It was necessary to take photographs of the spectrum of the Sun or other stars to examine the third of the early astronomical tests. In addition to Evershed and Eddington, the other major contributors were Charles Edward St John (1857–1935) and Walter Sydney Adams (1876–1956) both at the Mount Wilson Observatory. Up to 1922, newspapers reported that the results were uncertain, no success occurred, not yet verified, not yet detectable or indeterminate.[48] A shift in opinion was evident in 1923. In a letter from Evershed to Ross he remarks that 'line shifts [are] favourable to Einstein interpretation.'[49] The mood is summed up in '…and the spectroscopic enquiries, although not yet brought to a decisive issue, grow steadily more favourable.'[50]

By 1924, Dyson was convinced that Evershed and St John had placed the matter 'beyond doubt' for Einstein.[51] 'Dr Charles St John … experimentally confirmed Einstein's third prediction, the gravitational displacement of the solar spectrum

… [to] the exact degree predicted by Einstein.'[52] Once Eddington's measurements on Sirius B were compiled in 1925 the larger displacements due to a much larger mass strengthened the case for General Relativity.[53]

Many contributing factors involved in solar frequency displacements had been ironed out by 1928 and the contributions of Evershed and St John were now convergent.

'By the use of the most powerful spectrographs available, St John has measured the wavelengths of 1,500 colors in solar light with an error … estimated at less than one part in five million. … prediction of theory is verified not only to the existence of the effect, but also to its precise amount.'[54]

Discussion of Results

In the coverage of Australian newspapers 1911–28 examined in this article there were 266 distinct articles where Einstein and relativity were mentioned. However, the interest shown in the General Theory of Relativity in the years 1915–16 of the publications of Einstein was nil (Table 1). Einstein wrote in German from Berlin and there was little scientific communication from Germany to the English speaking world during the years of the 1914–8 world war. At this time the Netherlands remained neutral and Willem de Sitter (1872–1934) of the Leiden Observatory communicated with Einstein. He was the conduit in 1916 of linking with Britain via Eddington who was then secretary of the Royal Astronomical Society.[55] In the four articles in 1917 (2% of total), the three astronomical consequences are firstly discussed. The outcome of the two British eclipse expeditions in May 1919 to attempt to measure the gravitational deflection of light was announced in November of the same year. Yet publications in 1919 amounted to a mere 4% attention of all the articles covered. While these results were important for Science, they had limited interest to Australian readers. Most publications (52% of the entirety) were recorded in 1922, the year of the total solar eclipse across Australia. If the previous and subsequent years are added, as the topics dealt with were predominantly the lead up to and results from this eclipse, these three years account for 81% of publications. In the calendar year of 1922, the highest proportion of written pieces (37% of the 137) came out in the eclipse month of September (Table 2). Each of the 226 articles was classified according to one of nine major themes (Table 3). The 1922 event occupied 50% coverage with the topic of relativity next at 27%, followed by Einstein the man at 9% and the 1919 occurrence with 5%. The conclusion reached from the foregoing analyses is that it was the occurrence of the 1922 eclipse that brought General Relativity to the attention of the Australian public.

Only a small number of efforts was made to explain General Relativity theory in Australian newspapers and journalists obviously decided it was simpler for the public to be treated to its astronomical consequences. They seemed to have assumed that the concept of the displacement of light was easier to comprehend than an unaccounted for amount of the perihelion advance of Mercury or a change in frequency of light in the region of a massive body. This is borne out in the statistics (Table 4) where gravitational deflection commands 50% of these three outcomes and Mercury and gravitational redshift 32% and 18% respectively. Apart from the relative simplicity of the idea of the bending of light, this was the only criterion of the three that was measured at the 1922 eclipse.

From a total of 232 times the 13 groups on eclipse duties in Australia and Christmas Island are mentioned at least once in a newspaper account, the eight that were devoted to gravitational deflection (top line in Table 5) had 78% coverage. Individually, Campbell tops the citation at 23%, followed by Dodwell with 13% and Chant at 12%. Campbell was seen as the prominent person and the one most likely to obtain a useful measurement.

There would be expected to be interest in the Australian contingents as newspapers rely on local interest angles to attract readers and these six entities (Dodwell, Cooke, Baldwin, Ross, Vonwiller, Gale) comprised 49% exposure. Of these, the first three were part of the group of eight with a focus on light deflection.

As Campbell occupied the epicentre of activity, his sphere of operation was given importance. There were 5 of the 13 parties conducting investigations at this site in Western Australia (Table 6). Of the 226 printed articles, Wallal is referenced in 20% of them. This could increase to 21% if two entries for Ninety Mile Beach, which describes the same locality, were included. Goondiwindi, with three groups all Australian, achieved 9%. If this total of 113 for place names is used, Wallal comprised 40%.

From the section titled 'Simplification of General Relativity to the Australian Public', it may be summarized that the public were told that General Relativity was too complicated for other than mathematical scientists. However, some of the consequences were specified with particular emphasis on light bending. The Mercury situation was given some detail but, while gravitational redshift was referenced, no connection to General Relativity was established. For all the stress on how complicated General Relativity was, the deduction from the segment 'Correct and Misleading Information' is that the newspaper accounts were remarkably accurate with only one major discrepancy, that is, giving an example of the relativity of time as a difference in daylength on Earth, Mercury and Neptune as previously mentioned.

The newspapers of this period carried comments on the interpretation of the results from the British eclipse sojourns in 1919. One hundred and seven accounts were divided into those that supported the conclusions, ones that described that more evidence was required and those that indicated that the results were insufficient to declare for the predicted amount of light bending (Table 7). Respectively, the proportions were 47%, 33% and 20%. For a two-way division of for: not for, the shares were thus 47%: 53%.

These figures were indicative of the divisions within the scientific community at the time. In 1919, Dyson, in commenting on the British success, became the major driver of the view that the measurements were a success. It is possible that a psychological effect may have been in play.[56] Since the British had couched their hypothesis in wanting to distinguish between a deviation of zero, 0".87 derived from Newton or 1".75 of Einstein,[57] they knew their target before they started. Without deliberately manipulating the data, they may have displayed a psychological functional fixedness[58] and eliminated one of the three sets of data so that the average of the other two would favour Einstein.

There were three strands taken in the way the newspapers reported the purpose of such interest in the 1922 total solar eclipse as shown in the division 'Purpose of the 1922 Measurements'. As a standard part of the scientific method, any experiment must be repeated before agreement is reached so 1922 would reinforce the case established in 1919. On another tack, the presentation was that the 1919 results were not satisfactory. Finally, the situation expounded was that there was a serious enterprise with many institutions present and they carried superior equipment and some experienced personnel. In this diverse range of text, it may be seen that the situation is a mirror of the differing views of the 1919 results as discussed above.

For the 1922 explorations in the sector 'Results of the 1922 Eclipse Measurements', the final calculations from Campbell were not published until 1928. This is one reason that this investigation screens the newspapers until that year. It is argued in the author's paper previously mentioned[59] that General Relativity was prematurely accepted in 1919. Further, it is contended that 1928 would have been a more appropriate date for accepting the gravitational displacement measurement as being in line with Einstein's prediction.

In the same section, which discusses the popular and scientific acceptance of a theory, there is some tendency to display Science in black and white tones. Philosophical notions of how Science operates by Karl Popper propose that experiments need to rest on falsification.[60] An idea needs to be expressed such that it may be discredited. If, however, it stands that test, then it is held in a tentative state. Should it withstand a barrage of trials, it becomes more and more acceptable to a larger number of scientists. The newspapers led the public along a two-choice selection procedure. In Science, 'Rather than a single group conversion, what occurs is an increasing shift in the distribution of professional allegiances.'[61]

The eight per cent of print articles mentioning proof or truth clearly show a popular notion of a theory. Yet, the musings of much of the print at the time was about producing a definitive answer to gravitational displacement. Some of the scientists were also quoted along these lines. Science is not often displayed in its manner of operation. This point is lacking.

> Few philosophers of science still seek absolute criteria for the verification of scientific theories. Noting that no theory can be exposed to all possible relevant tests, they ask not whether

> a theory has been verified but rather about its probability in the light of the evidence that actually exists … compare the ability of different theories to explain the evidence at hand.[62]

Rather than concentrating on how the newspapers may have given a differentiated view between the popular and scientific acceptance of a theory, one could analyse how effectively scientists themselves correctly use the language of their discipline and how well they communicate their modus operandi to the public.

When space was devoted to the three classical astronomical tests of General Relativity, it has been shown that 50% covered gravitational light deflection. However, 32% made mention of the Mercury anomaly in the component of this name. Some unrest existed concerning the acceptance of spacetime being an explanation for the behaviour of Mercury but the articles are generally supportive of acceptance even as early as 1917. In Science, there was a difficulty that not a single experiment could be performed to test this idea with Mercury. It was 1956 before the anomalous advances of Venus and Earth were published and modern computer programs were required before the long-term variations in planetary orbits had a better foundation.[63]

With only 18% of the three astronomical tests allocated to the effect of mass on the frequency of light (section on 'Gravitational Redshift'), it, nonetheless, became an interesting story in its association with very dense stars. The reports were mainly in the latter phase of these experiments. There was still no piece which attempted to connect the influence of spacetime with a wavelength change but there was mention made of how this was easier to measure with the spectrum of more dense stars than with that of the Sun. The conclusive statement (and the last article referenced) was in 1928. This is another reason why this year has been selected as completing the time span of scanning the newspapers.

Conclusion

The Australian newspapers made a valiant attempt to describe to their readers what has since become a revolution in physics. As for previous upheavals 'Copernicanism made few converts for almost a century after Copernicus' death. Newton's work was not generally accepted, particularly on the Continent, for more than half a century after the *Principia* appeared'.[64] The transformation continues today. Many more tests of General Relativity have surfaced and the theory continues to be tested with improved equipment and increasing accuracy.[65] Not many people today could describe what Einstein proposed. Thus, the media of the earlier time period had a difficult task in hand.

However, the newspapers performed an admirable task of informing the Australian public in areas that were considered understandable. The focus of the 1922 total solar eclipse was to measure the deflection of light. Thus, this consequence of General Relativity was where the media concentrated even if, at times, gravitational deflection was taken as being almost synonymous with General Relativity.

The attempted verification in 1919 resulted in adherents and sceptics within the scientific community. The newspapers displayed this conflict and, on balance, promoted that the results were inconclusive. There was certainly much interest in the 1922 total solar eclipse among Australians as most expeditions set up in this country. The newspapers played to this attentiveness by emphasizing the importance of measurements on this occasion as crucial to making a judgement on Einstein's theory of General Relativity. Hence, the Australian public, through the media, were fully informed that one of the key predictions of Einstein's theory was the gravitational bending of light, that the attempted verification in 1919 was inconclusive and that as a result observations at the September 1922 Australian eclipse were crucial. Less emphasis was given to the Mercury anomaly and gravitational redshift.

This article has looked at how the newspapers informed the Australian public on the development of General Relativity up to 1928. Future analysis in the post-1928 period could reveal whether tests other than the three of light defection, anomalous planetary advance or gravitational redshift covered here were presented in the newspapers or was it the 1922 local occurrence of the total solar eclipse that gripped the interest of people of this continent?

Acknowledgements

This paper forms part of my PhD dissertation at the University of Southern Queensland. My supervisors, Dr Brad Carter and Dr Nick Lomb, have provided feedback on my written work, including recommendations for improved communication of some ideas. Dr Lomb suggested the idea of a gleaning of Australian newspapers for articles about General Relativity.

Endnotes

1. A. Einstein, 'The Foundations of the General Theory of Relativity', *Annalen der Physik*, 49 (1916), 769–822.
2. A. Einstein, 'On the Relativity Principle and the Conclusions Drawn From It', *Jahrbuch der Radioaktivität und Elektronik*, 4 (1907), 411–462.
3. A. Einstein, 'On the Influence of Gravitation on the Propagation of Light', Annalen der Physik, 35 (1911), 898–908.
4. Einstein, already cited (n. 1).
5. S. Newcomb, 'Discussions and Results of Observations on Transits of Mercury from 1677 to 1881', *Astronomical Papers of the American Ephemeris and National Almanac*, I, 367–487 (1882), 473.
6. A. Einstein, 'On the General Theory of Relativity', Preußische Akademie der Wissenschaften (Prussian Academy of Sciences), 6, (1915), document 21, 778.
7. Einstein, already cited (n. 2).
8. F. W. Dyson, A. S. Eddington, and C. Davidson, '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*, 220 (1920), 291–333.
9. *Argus* (Melbourne), 14 January 1922, p. 7.
10. K. J. Treschman, 'Early Astronomical Tests of General Relativity: The Gravitational Deflection of Light', *Asian Journal of Physics*, 23(1–2) (2014a), 145–170.
11. *Argus* (Melbourne), 16 September 1922, p. 10.
12. *Queensland Times* (Ipswich), 18 September 1922, p. 3.
13. *Advertiser* (Adelaide), 13 August 1921, p. 9.
14. *Kalgoorlie Miner* (Western Australia), 24 September 1920, p. 1.
15. *Australasian* (Melbourne), 31 March 1917, pp. 42–43.
16. *Australasian* (Melbourne), 1 September 1917, p. 48.
17. *Australasian* (Melbourne), 30 June 1917, p. 43.
18. *Daily Herald* (Adelaide), 5 April 1917, p. 3.
19. *Brisbane Courier* (Brisbane), 12 April 1920, p. 7.
20. *Kalgoorlie Miner* (Western Australia), 20 May 1922, p. 15.
21. *Kalgoorlie Miner* (Western Australia), 7 June 1922, p. 11.
22. *West Australian* (Perth), 26 June 1922, p. 7.
23. *Queenslander* (Brisbane), 23 September 1922, p. 32.
24. *Richmond River Express and Casino Kyogle Advertiser* (New South Wales), 17 March 1922, p. 3.
25. *Australasian* (Melbourne), already cited (n. 17).
26. *Register* (Adelaide), 11 November 1919, p. 7.
27. *Daily Herald* (Adelaide), 12 November 1919, p. 5.
28. *West Australian* (Perth), 11 November 1919, p. 8.
29. *Queenslander* (Brisbane), 10 January 1920, p. 13; *Brisbane Courier* (Brisbane), 12 April 1920, p. 7; *West Australian* (Perth), 17 June 1920, p. 9; *Advertiser* (Adelaide), already cited (n. 13); *Hebrew Standard of Australasia* (Sydney), 14 January 1921, p. 12; *Argus* (Melbourne), 8 December 1921, p. 9; *Evening News* (Sydney), 16 December 1921, p. 6; *West Australian* (Perth), 7 August 1922, p. 9; *Western Mail* (Perth), 9 March 1922, p. 7; *Scone Advocate* (New South Wales), 19 September 1922, p. 2.
30. *Argus* (Melbourne), 11 November 1919, p. 7; *Queensland Times* (Ipswich), 12 November 1919, p. 5; *World's News* (Sydney), 17 January 1920, p. 8; *Australasian* (Melbourne), 7 February 1920, p. 47; *West Australian* (Perth), 19 March 1921, p. 16; *Register* (Adelaide), 23 November 1921, p. 8; *Argus* (Melbourne), already cited (n. 11); *West Australian* (Perth), 21 March 1922, p. 10; *Barrier Miner* (Broken Hill, New South Wales), 13 May 1922, p. 3; *Daily News* (Perth), 5 June 1922, p. 7; *West Australian* (Perth), 7 June 1922, p. 11; *Sydney Morning Herald* (Sydney), 16 September 1922, p. 12; *Queenslander* (Brisbane), already cited (n. 23); *Register* (Adelaide), 26 October 1922, p. 10; *Argus* (Melbourne), 2 December 1922, p. 8.
31. *Sydney Morning Herald* (Sydney), 11 November 1919, p. 7; *Daily News* (Perth), 6 December 1921, p. 2; *Daily News* (Perth), 23 January 1922, p. 5; *West Australian* (Perth), already cited (n. 22); *Richmond River Express and Casino Kyogle Advertiser* (New South Wales), 25 August 1922, p. 7; *Argus* (Melbourne), 21 March
1923, p. 17.
32. *Australasian* (Melbourne), already cited (n. 30); *Register* (Adelaide), 1 January 1921, p. 6; *West Australian* (Perth), 19 March 1921, already cited (n. 30); *Newcastle Morning Herald and Miners' Advocate*, (New South Wales), 20 August 1921, p. 15; *Sydney Morning Herald* (Sydney), 2 November 1921, p. 10; *Daily Herald* (Adelaide), 29 November 1921, p. 3; *Chronicle* (Adelaide),

10 December 1921, pp. 32–33; *Evening News* (Sydney), already cited (n. 29); *Daily Herald* (Adelaide), 14 January 1922, p. 4; *Argus* (Melbourne), already cited (n. 9); *Zeehan and Dundas Herald* (Tasmania), 20 January 1922, p. 3; *Daily News* (Perth), 23 January 1922, as above (n. 32); *Wellington Times* (New South Wales), 26 January 1922, p. 8; *Australasian* (Melbourne), 4 March 1922, p. 54; *Evening News* (Sydney), 15 April 1922, p. 4; *West Australian* (Perth), already cited (n. 22); *Newcastle Morning Herald and Miners' Advocate* (New South Wales), 26 June 1922, p. 5; *Argus* (Melbourne), 30 June 1922, p. 14; *Sydney Morning Herald* (Sydney), 7 August 1922, p. 9; *Register* (Adelaide), 14 August 1922, p. 9; *Worker* (Brisbane), 14 September 1922, p. 16; *Sydney Morning Herald* (Sydney), 19 September 1922, p. 8; *West Australian* (Perth), 20 September 1922, p. 11. *West Australian* (Perth), 21 September 1922, p. 9; *Barrier Miner* (Broken Hill, New South Wales), 21 September 1922, p. 2; *Argus* (Melbourne), 21 September 1922, p. 8; *West Australian* (Perth), 21 September 1922, p. 8; *Daily Advertiser* (Wagga Wagga, New South Wales), 21 September 1922, p. 2; *Riverine Herald* (Echuca, Victoria), 22 September 1922, p. 2; *West Australian* (Perth), 22 September 1922, p. 9; *Sydney Morning Herald* (Sydney), 22 September 1922, p. 8; *Advocate* (Burnie, Tasmania), 23 September 1922, p. 2; *Sydney Morning Herald* (Sydney), 2 Mar 1923, p. 12; *Gippsland Times* (Victoria), 5 April 1923, p. 3.

33. *Argus* (Melbourne), 8 December 1921, p. 9.
34. *Brisbane Courier* (Brisbane), 18 June 1923, p. 13.
35. *Daily News* (Perth), 4 August 1922, p. 6.
36. *West Australian* (Perth), 7 April 1923, p. 13.
37. *Sydney Morning Herald* (Sydney), 9 April 1923, p. 8.
38. *Barrier Miner* (Broken Hill, New South Wales), 13 April 1923, p. 1.
39. *Register* (Adelaide), 13 April 1923, p. 9.
40. *West Australian* (Perth), 16 April 1923, p. 6; *Western Mail* (Perth), 19 April 1923, pp. 14–15; *Morning Bulletin* (Rockhampton, Queensland), 24 May 1923, p. 8; *Brisbane Courier* (Brisbane), already cited (n. 34); *West Australian* (Perth), 13 July 1923, p. 9; *News* (Adelaide), 25 July 1923, p. 10; *Australasian* (Melbourne), 4 August 1923, p. 50; *Maitland Daily Mercury* (New South Wales), 18 August 1923, p. 2; *Queenslander* (Brisbane), 15 September 1923, p. 41; *West Australian* (Perth), 14 November 1923, p. 9; *West Australian* (Perth), 4 March 1924, p. 14; *West Australian* (Perth), 15 March 1924, p. 20.
41. *West Australian* (Perth), 7 April 1928, p. 13.
42. *Recorder* (Port Pirie, South Australia), 28 January 1921, p. 4; *Register* (Adelaide), 14 April 1922, p. 7; *Bathurst Times* (New South Wales), 5 July 1922, p. 1; *West Australian* (Perth), 7 July 1922, p. 12; *Sydney Morning Herald* (Sydney), 20 July 1922, p. 8; *Western Argus* (Kalgoorlie, Western Australia), 25 July 1922, p. 17; *Western Mail* (Perth), 10 August 1922, p. 20; *Sydney Morning Herald* (Sydney), 12 September 1922, p. 8; *Northern Times* (Carnarvon, Western Australia), 16 September 1922, p. 2; *Dubbo Liberal and Macquarie Advocate* (New South Wales), 19 September 1922, p. 2; *Albany Advertiser* (Western Australia), 20 September 1922, p. 3; *Kadina and Wallaroo Times* (South Australia), 27 September 1922, p. 2; *Sunday Times* (Sydney), 6 August 1922, p. 2; *Richmond River Herald and Northern Districts Advertiser* (New South Wales), 25 August 1922, p. 7; *Queenslander* (Brisbane), 9 September 1922, p. 19; *Daily Herald* (Adelaide), 21 September 1922, p. 2; *Windsor and Richmond Gazette* (New South Wales), 22 September 1922, p. 2; *Daily News* (Perth), 3 October 1922, p. 4; *Maitland Daily Mercury* (New South Wales), 2 February 1923, p. 2; *Sydney Morning Herald* (Sydney), 22 March 1923, p. 9; *Gippsland Times* (Victoria), already cited (n. 32).
43. *Sydney Morning Herald* (Sydney), 2 March 1923, p. 12.
44. *Australasian* (Melbourne), already cited (n. 15); *Daily Herald* (Adelaide), already cited (n. 18); *Argus* (Melbourne), 3 January 1920, p. 6; *Daily News* (Perth), already cited (n. 30); *Brisbane Courier*
(Brisbane), 15 September 1922, p. 5; *Recorder* (Port Pirie, South Australia), 20 September 1922, p. 2; *Queenslander* (Brisbane), already cited (n. 23); *Richmond River Herald and Northern Districts Advertiser* (New South Wales), 29 September 1922, p. 2; *West Australian* (Perth), 11 October 1922, p. 8; *Daily Herald* (Adelaide), 26 October 1922, p. 2.
45. *West Australian* (Perth), already cited (n. 20).
46. *Western Mail* (Perth), already cited (n. 29).
47. *Albany Advertiser* (Western Australia), 20 September 1922, already cited (n. 42).
48. *Argus* (Melbourne), already cited (n. 44); *Albury Banner and Wodonga Express* (New South Wales), 9 January 1920, p. 44; *Queenslander* (Brisbane), already cited (n. 29); *West Australian* (Perth), 19 March 1921, already cited (n. 30); *West Australian* (Perth), already cited (n. 22); *West Australian* (Perth), 27 May 1922, p. 15; *Brisbane Courier* (Brisbane), already cited (n. 44); *Queenslander* (Brisbane), already cited (n. 23); *Daily Herald* (Adelaide), 26 October 1922, already cited (n. 44); *Register* (Adelaide), 7 April 1923, p. 9.

49. *West Australian* (Perth), 9 April 1923, p. 4.
50. *West Australian* (Perth), 16 April 1923, already cited (n. 40).
51. *West Australian* (Perth), 4 March 1924, already cited (n. 40).
52. *Maitland Daily Mercury* (New South Wales), 26 April 1924, p. 2.
53. *Chronicle* (Adelaide), 19 September 1925, p. 61; *Register* (Adelaide), 6 October 1925, p. 5.
54. *Kadina and Wallaroo Times* (South Australia), 22 August 1928, p. 1.
55. J. Crelinsten, *Einstein's Jury: The Race to Test Relativity*, Princeton University Press (2006).
56. A. S. Luchins, 'Mechanization in Problem Solving', *Psychological Monographs*, 54, no. 248 (1942).
57. Dyson, already cited (n. 8).
58. K. Duncker, 'On Problem Solving', *Psychological Monographs*, 58 (270) (1945), 5.
59. Treschman, already cited (n. 10).
60. K. Popper, *The Logic of Scientific Discovery*, (London, 2005), 1935 first publication.
61. T. S. Kuhn, *The Structure of Scientific Revolutions*, University of Chicago Press (1962).
62. Kuhn, as above.
63. K. J. Treschman, 'Early Astronomical Tests of General Relativity: The Anomalous Advance in the Perihelion of Mercury and Gravitational Redshift', *Asian Journal of Physics*, 23(1–2) (2014b), 171–188.
64. Kuhn, already cited (n. 60).
65. K. J. Treschman, 'Recent Astronomical Tests of General Relativity', *International Journal of Physical Sciences*, 10(2) (2015), 90–105.

Discussion

The hypotheses are:

1. Australia played a key role in the acceptance and verification of General Relativity from the 1922 total solar eclipse across the continent as well as the discovery in 2003 at Parkes Radio Telescope of the first, and to this date only, pair of pulsars in mutual orbit.

2. The Theory of General Relativity was accepted prematurely.

Paper 1: Early astronomical tests of General Relativity: the gravitational deflection of light

There were three classical astronomical tests of General Relativity [Introduction 1-2]. One of the three was the bending of light as it passed a massive object. From Einstein's first mention of this in 1907, he realised in 1911 that this could be implemented by measuring any change in the position of stars during a total solar eclipse. His calculation in 1911 for the amount of shift at the edge of the Sun was increased in 1916 to 1".75 and he established that there would be a proportional decrease in the deflection as the distance from the Sun's centre increased [146].

In 1919 the British undertook expeditions to Brazil [147-8] and the west coast of Africa [148] to photograph the positions of stars near the Sun and compare them with the same part of the night sky several months apart. While the results were commendable in being a first attempt at a measurement of gravitational deflection and paved the way for future endeavours, the interpretation of the data of those involved is criticised. Firstly, it is suggested that their hypothesis ought not to have been couched in trying to determine which of three possibilities of zero deflection, 0".87 which could be derived from Newton's laws [145-6] or 1".75 of Einstein would eventuate [147]. The investigation would have been better served if the aim were to find a measure of deflection, if any, on this occasion. An argument is mounted that, from the outset, this proposal may have held a psychological bias which may have influenced what the scientists were measuring. The deflection predicted by Einstein is such a small amount for the instrumentation that existed in 1919. With some of the photographic equipment, the Einstein displacement amounted to 1/60 mm on some plates and this figure would be even smaller for stars further from the Sun. Also, plates of the sky with and without the Sun were not compared directly but made via an intermediary scale plate [148]. The Astronomer Royal Frank Dyson made some dubious decisions to eliminate certain data [149]. In Brazil the superior telescope took short exposures to counter some oscillation in the drive chain of the movable mirror which reflected light into the fixed telescope. From the 19 photographs obtained with this telescope, 12 stars gave an average displacement at the limb of 0".93. For the other telescope at Brazil, seven of the eight exposures were useable and seven stars were calibrated to yield a value of 1".98 ± 0.12. The device used in west Africa was similar to the superior one at Brazil. Of the 16 plates from Africa, 10 were eliminated because of cloud cover. For the remaining six photographs, 11 stars provided a measurement. The quality of images was poor and a weighting was applied to each star to account for the diffuseness of some of the images. Eventually, only two plates were considered good enough to use and five stars were recorded. These were placed against two comparison plates with a range of 1".94 to 1".44 for one plate and 1".55 to 1".67 for the other. These were averaged to 1".65 at the time but with later comparison plates to 1".61 ± 0.32. So, for the three telescopes the central readings were 0".93, 1".98 and 1".61. The lowest value was eliminated with the questionable argument that there were systematic errors even though shorter exposures were used to lessen these effects. Dyson stated that the images at Brazil were far superior to those with a similar instrument in west Africa. There were 12 stars in the former against five in the latter and Brazil was almost cloud free during the eclipse whereas west Africa was troubled by the weather. In spite of these factors, Dyson still favoured the two figures which surrounded the Einstein value of 1".75. A more telling result is that the seven stars with the lower grade telescope at Brazil yielded an inverse relationship between displacement and distance from the centre of the Sun with a correlation coefficient of 0.93. Given all the foregoing discussion, the conclusions ought to have been more tentatively presented than the definitive statement that ensued in 1919.

The experiment was repeated at the 1922 total solar eclipse in Australia. There were 13 parties that congregated in the Australian region for the eclipse, eight of which were intending to determine a measure of light deflection. For these eight, representatives from Royal Greenwich Observatory [155] and a German-Dutch party [156] set up stations on Christmas Island in the Indian Ocean between Western Australia and Indonesia. At a remote station called Wallal near Broome in Western Australia there was a group from Kodaikanal Observatory in southern India [156-7], a Canadian troupe from the University of Toronto and Dominion Astrophysical Observatory [157] and members of Lick Observatory from the USA [152-5]. In a remote part of South Australia, an assembly from Adelaide Observatory trained their telescope [158-61]. Further east at Goondiwindi in Queensland, personnel under the banners of Sydney Observatory [162-3] and Melbourne Observatory [163] each set up a station. Another five groups were involved in matters other than light deflection. These were an English party [157-8] and Perth Observatory [158] both at Wallal, the University of Sydney camped at Goondiwindi [161-2], the Carnegie Institution of Washington at Coongoola in the far south west of Queensland [163] and the New South Wales Branch of the British Astronomical Association at Stanthorpe in southern Queensland [163-4].

The adventures of the eight parties devoted to measurements of light deflection show the difficulties inherent in the procedure. The two companies on Christmas Island were clouded out during the eclipse and no results were obtained [155-6]. The Indian contingent obtained five sets of images but the attempt was beset by glitches in the equipment, fog on some plates, movement of the stellar images and poor definition. No useful measurement ensued [156-7]. By 1923 the Canadians had whittled their results to two plates with 15 star images. The outcome was that the displacement did indeed decrease with distance. By comparison with a graph based on Einstein's values, the 16 stars were within 0".1 to 0".6 of the prediction of General Relativity. At the limb, the quantities were 1".30 and 2".17 for the two plates, giving an average of 1".73. This was claimed to vindicate the Einstein value of 1".75. However, there is a significant variation between 1".30 and 2".17 [157].

Enter Wallace Campbell of Lick Observatory. His institution had been involved with 11 total solar eclipse expeditions before the 1922 one and, of these excursions, Campbell had been in charge six times. He was a meticulous planner and his previous experience, superior equipment and strong financial support allowed a greater number of stellar displacements to be ascertained. In 1923 his colleague Robert Trumpler had measured between 69-85 stars on four plates from a pair of longer focal length cameras and obtained measurements that ranged from 1".62 ± 0.22 to 1".91 ± 0.19, giving an average of 1".78 ± 0.11 for the limb displacement. By the same time Campbell had obtained measurements from three of the four plates. He used 62-80 stars, had a range of 1".35 ± 0.22 to 1".78 ± 0.22, with a mean of 1".60 ± 0.14. With a slightly lower weight placed on one plate relative to the other three, their combined results were 1".72 ± 0.11 against the Einstein figure of 1".75. They also agreed with the inverse relationship away from the Sun [164-5]. However, it was 1928 before the final results were published. This time, Trumpler alone measured 145 stars on six plates from the shorter focal length cameras. In addition, this time he made a direct comparison of plates, that is, without an intermediary plate so that accuracy was improved. When all the results were combined, the announcement in 1928 was that the 1923 figure of 1".72 ± 0.11 was given a weighting of two and it was decided to weight the pair of shorter focal length cameras which produced 1".82 ± 0.15 as one. Support was given to the inverse relationship and the final value was 1".75 ± 0.09 against General Relativity of 1".75 [164-5]. There was now strong support for Einstein based on this classical astronomical test.

The four plates taken on borrowed equipment for the South Australian expedition were sent to Greenwich for analysis. Two plates only were measured with 11-14 stars compared against 16. The results pronounced in 1924 were spread at 2".36 and 1".18. While the average of 1".77 was close to the Einstein value, the wide distribution did not make a strong case for General Relativity [160-1].

At Goondiwindi, atmospheric conditions were not conducive to good outcomes. The fates of the Sydney Observatory [162-3] and the Melbourne University parties [163] were sealed with poor performance of equipment for both contingents.

In this vein, the 1919 results are herein contested. It is claimed that there was too early an acceptance by scientists of General Relativity. It is suggested that the 1919 British results were tentative, at the least, and that decisions about which results to include were contentious. It is concluded that the 1922 total solar eclipse across Australia was a necessary follow up to the 1919 measurements. Yet, this does not appear in popular accounts of the narration of General Relativity.

This presentation has attempted to attach much more significance to the 1922 endeavours. There is a need to address the currently held historical record. Of local interest, the crucial role played within Australia of the development of this theory is not part of the national awareness and yet these events were a crucial contribution to the unfolding of a new view of the Universe. The input of Walter Campbell of the Lick Observatory has been stressed in these pages. His 1922 trip to Wallal in Western Australia secured measurements during a total solar eclipse but his final publication was not until 1928. The theme in this thesis is of an ongoing development of a scientific theory. The conclusion proposed is that the results of Campbell, as opposed to those of the 1919 excursion, were more decisive. So, based on evidence from gravitational light bending, 1928 and not 1919, was the year that General Relativity should have become acceptable.

Conclusions from history of gravitational deflection of light

- The results from the 1922 total solar eclipse in Australia finally published in 1928, rather than those from the 1919 eclipse, was the year in which sufficient evidence existed to proclaim that General Relativity was supported by the classical astronomical test of gravitational light deflection. Against the criterion of gravitational light deflection, General Relativity was prematurely accepted.
- Australia played a key role in the acceptance and verification of General Relativity from the 1922 total solar eclipse across the continent.

Paper 2: Early astronomical tests of General Relativity: the anomalous advance in the perihelion of Mercury and gravitational redshift

From the first predicted transit of Mercury by Kepler for the year 1631 [172], a total of 52 have been observed [173]. The simplicity of an elliptical orbit of the planet rested on only a Sun-Mercury interaction. Perturbations due to the other planets would swing the perihelion point in space. The contributions from each other planet had to be applied to obtain an orbit of Mercury that was consistent with observations. To this end, the masses of Mercury and the other planets needed to be ascertained. The timing of first, second, third and fourth contacts during a transit of Mercury and the meridian passages of this innermost planet continued to be recorded. In the 1859 publication of Urbain Le Verrier, he obtained a remaining discrepancy which became known as the anomalous advance in the perihelion of Mercury [174]. There were a number of explanations proposed to account for this and the one that caught the public's attention was the search for a planet even closer to the Sun. Monumental work on 62 000 meridian passages for Mercury, Venus and Earth was compiled by Simon Newcomb by 1895 [174]. So, by the time of Einstein, there was an unaccounted value of 42".95 per century.

In 1915, Einstein produced a value of 45" ± 5 per century from his equations [175]. Even though Einstein was excited that he could account for the Mercury anomaly, other interpretations needed to be explored.

This is a convenient point to comment on the philosophy of scientific knowledge. Hypotheses are proposed in the language that 'If A exists, then B follows.' It is necessary to be presented in a form where A could exist and B would be shown to be false. Thus, according to Karl Popper, the possibility of the falsification of an idea is important in the manner in which the hypothesis is couched.[1] However, in going from B to A, the situation is not clear cut. There may another factor or other factors which might be proposed to predict the existence of B. So, in spite of the ecstasy of Einstein[2], correlation does not necessarily indicate causation. Other avenues needed to be explored. If competing proposals could be falsified, the argument for General Relativity proposal would become more favoured.

It was 1956 before the experimental discrepancies in the perihelion advance for Venus and Earth could be matched against the theory [176]. So, now there were more cases than Mercury where the results at least did not negate the predictions of General Relativity. It was into the 1980s before long term orbital predictions requiring numerical integration were calculated and these depended on refined values for say the shape, mass and composition of Mercury. Furthermore, the variations are not smooth [177-8]. Many influences needed to be teased out before definitive statements could be made about this particular classical test.

Similar to the unfolding of the first classical test of gravitational deflection, this paper refutes the immediate acceptance of another classical test, the Mercury anomaly, calculated by Einstein from his equations in 1915. The mechanics of planetary motion relies on many factors. A reasonable description of the orbital behaviour of Mercury required later developments in ascertaining, for example, better values of the mass of Mercury as well as the use of integral mathematics with computer algorithms. Since, the latter did not occur until the 1980s, it was this time period when acceptance resting on this particular test should have secured its first significant foothold.

Conclusion from history of the anomalous advance in the perihelion of Mercury

- 1915 was too early an acceptance of General Relativity based on the classical astronomical test of the perihelion advance of Mercury. A more appropriate time was the 1980s.

Within this same second paper the historical observations of gravitational redshift are outlined. Before the 1919 total solar eclipse, the contributors to measurements of the wavelengths of the solar spectral lines were Henry Rowland, Lewis Jewell and William Humphrey of Johns Hopkins University, John Mohler of Dickinson College, J Halm, Maurice Fabry of the University of Marseille, another French scientist Henri Buisson, R Rossi, Walter Adams and Charles St. John both from Mount Wilson Observatory, Karl Schwarzchild of Astrophysical Observatory in Potsdam and John Evershed and Thomas Royds both from Kodaikanal Observatory in India [179-80]. At this time, no clear opinion was noted as some results seemed to contradict others and the discrepancies between experiment and theory were too wide for a positive pronouncement for General Relativity [180-1].

It is interesting that after the 1919 eclipse results, believed by some to confirm General Relativity based on gravitational light deflection, some spurious work found evidence for gravitational redshift that supported Einstein [181]. Nevertheless, the 1919 result did provide an impetus for a concentrated effort for solar wavelength measurements principally by Evershed and St. John [181-2]. In 1924, Arthur Eddington of Royal Greenwich Observatory presented both theory and measurements for the existence of white dwarf stars. With these very dense objects, he applied the theory of Einstein to predict a much larger frequency shift of spectral lines than were calculated for the Sun [182]. Here, now were larger displacements which could more easily be measured and Adams obliged with a very large telescope [182-3]. Experimentalists could now return to the Sun with somewhat more confidence. In a 1928 monumental work, St. John provided a wealth of data and interpretations of factors involved in previous solar measurements [183]. He was able to deliver a convincing argument that the solar research did indeed lend great support to the Einstein prediction of gravitational redshift. Thus, the year 1928 marked a watershed for General Relativity as it is argued in these first two papers that both gravitational light deflection and gravitational redshift reached a position which was consistent with theoretical predictions.

Conclusion from history of gravitational redshift

- The year 1928, not 1923, was when sufficient experimental evidence emerged to support General Relativity with the classical astronomical test of gravitational redshift.

Paper 3: Recent astronomical tests of General Relativity

This paper traces more astronomical tests from 1928 to the present. An explanation of each development is presented and the published departure between the experimental values and predictions from General Relativity are displayed as a % departure from the Einstein value. There are 13 sets of investigation.

(1) In 1907, Einstein declared that acceleration and gravitation were identical [90] and experiments were conducted to test the equivalence of inertial and gravitational mass. The torsion balance research of the Hungarian Loránd Eőtvős predated the announcement of this equivalence principle. With improvements to equipment, investigations by Eőtvős and his co-worker János Pekár as well as by 1964 Robert Dicke, Peter Roll and R Krotkov increased the accuracy from 10^{-6}% to 10^{-9}%

[91]. Consequent on the age of spacecraft, reflectors placed on the Moon beginning in 1969 allowed measurements via laser pulses sent from and received on the Earth to measure the Earth-Moon distance [91-2]. Both of these bodies accelerate in the gravitational field of the Sun and the measurements could establish if these were different. Accuracy with these lunar ranging data also increased over time with larger light gathering telescopes, a higher altitude station to lessen Earth atmospheric effects, upgraded equipment to capture more photons, an improved timing mechanism and development in laser technology to the extent that the difference from the predictions of General Relativity by 2009 was quantified at 0.1%.

(2) The topic of gravitational redshift has been covered in the second paper up to 1928 from measurements of the wavelengths of solar and white dwarf spectral lines. Another tack was taken by Robert Pound, Glen Rebka, Jr and Joseph Snider by computing any changes to the frequency of gamma rays, rather than optical ones, with and against gravity in an experiment at Harvard University [92]. By 1965, they claimed 0.1% deviation from Einstein. The first spacecraft employed for this factor was in 1976 when the frequency of a hydrogen maser on board was compared to that of one on Earth and the result published in 1989 was with an agreement of 0.007%.

In this new age of spacecraft, other possibilities were envisaged. One or several specific frequencies could have any change detected and a Voyager 1 frequency shift at Saturn in 1990 resulted in an accord of 0.44%, Galileo, on its way to Jupiter, near Venus in 1990 of 1% and Cassini sent to Saturn which in 2004 provided an unprecedented value of 0.0023% for solar redshift.

After the discovery of a double pulsar in 2003, the modification of frequency of one pulsar in the gravitational field of another could be attained. This amounted to a relativistic difference in a 2006 publication of 0.23% [93].

(3) The topic of relativistic perihelion advance of Mercury was covered in the second paper. With more meridian observations and transits of Mercury, Gerald Clemence established in 1943 a 0.19% deviation from General Relativity [93-4]. By 1956 Raynor Duncombe had gathered data for over 20 000 meridian passages of Venus and his conclusion was 2.3% for the relativistic perihelion advance of Venus [94]. From studies of the Sun, H Morgan along with the previous two researchers produced a large discrepancy of 32% in 1956 for the relativistic advance of the perihelion of Earth [94]. On its own, this calculation for Earth is quite discordant but the values for the other two planets provide confidence to gather more data on solar phenomena to refine the situation for the Earth.

(4) Extending the principle involved in the perihelion advance of the planets, one may apply the same Physics to the periastron advance of a pulsar in a binary system. As the change per year is over 1000 times that for Mercury, greater precision is possible. In 1991 one binary system agreed with Einstein to 0.8% and in 1998 another to 1% [95].

The first binary pulsar was discovered in 1974 by Russell Hulse and Joseph Taylor, Jr and designated PSR 1913 + 16. In 1918 Einstein had proposed that any binary system would radiate gravitational wave energy and he provided a calculation for the orbital decay that would ensue. From a monitoring of the radio frequency of a pulsar in a double system over time, the change may be detected. For this system, the proximity to General Relativity has narrowed from 1% in 1989, through 0.3% in 1995 to 0.13% in 2005. With a galactic rotation correction in 1995, the difference was 0% [94-5]. In 2003 PSR J0737 – 3039A/B was the first system detected where both binary objects were pulsars. Its orbital decay is within 0.3% of the predicted value [95-6].

(5) Einstein completed his Theory of General Relativity in 1916 and his revolutionary ideas had depended on astronomical support from gravitational light deflection, the anomalous perihelion advance of the perihelion of Mercury and gravitational redshift. However, his theory was subsequently mined by others whose insight provided potential experimental applications. In 1916 Willem de Sitter recognised the Earth-Moon system as freely falling in the gravitational field of the Sun. Therefore, he reasoned that the Moon ought to undergo a relativistic orbital precession which became known as geodetic precession. Analysing the lunar ranging data from 1970-86, Irwin Shapiro provided a difference of 1.9% in 1998 [96]. By extending the data set to 1993, J Dickey tapered the discrepancy to 0.3% [96].

From 1961-2003 a quarter of a million high precision radar measurements have been executed for the inner planets and spacecraft by the USA and Russia. Perturbations due to 301 larger asteroids and some smaller ones were extracted so that in 2005 the geodetic precession of the Moon agreed to 0.01% [96]. There were now satellites operating in Earth's orbit and the precessional rate change of Gravity Probe B concurred with General Relativity in 2011 to 0.28% [96].

(6) In the footsteps of de Sitter, in 1918 Josef Lense and Hans Thirring perceived that a massive rotating body would be expected to drag its spacetime around with it. This secular precession of an orbiting body known as frame dragging was a much smaller effect than geodetic precession. However, measurements on planetary orbiting spacecraft yielded agreements with General Relativity of 0.6% for LAGEOS and LAGEOS II in Earth orbit in 2004, 6% for Mars Global Surveyor in 2006 and 5% for Gravity Probe B in 2011.

(7) The classical astronomical test of gravitational deflection in the optical realm was the subject of the first paper. The inherent difficulties of photographing and measuring such a small deflection during a total solar eclipse as was accomplished in 1919 and 1922 were highlighted when further attempts were made. These were more for historical reasons as other techniques were delivering more accurate results. In 1953 a team returned 2.9% [97] and in 1976 another group produced a highly discordant difference of 46% [97-8]. Nevertheless, by 1997 Hipparcos had measured the position of over 10^5 stars to a precision of the order of 10^{-3} arcsecond. With such data, measurements of solar deflection could be effected outside an eclipse and taken over a larger part of the sky so that solar coronal effects could be eliminated. Consonance with Einstein reached 0.3% [98].

(8) While the earlier attempts at light propagation were concerned with the optical region, the later extension to the radio spectrum and interferometric techniques allowed an improvement in angular resolution. Thus, more precise measurements with radio emitters and daylight observation were possible. The position of radio sources in the sky could be gauged as the Sun passed by them. From a single radio emitter published in 1970, departures of 2% and 8% were recorded by two different stations [98]. With a baseline of 35 km and three radio objects, 3% was the outcome in 1975 and 1.4% in 1976 [98]. As the baseline increases, accuracy is enhanced. With 74 radio sources, 29 collection antennae, large baselines with the largest reaching 10 000 km and over 300 000 observations, 0.02% discrepancy was published in 1991 [98-9]. Still further, in 2004 an analysis of 20 years of data on 541 radio sources by 87 collectors with long baselines generated 0.02% [99]. By 2009, the precision of these experiments had proceeded to such an extent that by 2009, Jupiter and Saturn could be used as intervening masses for three quasars and this netted a difference of 2% [99].

(9) From a 1912 notebook of Einstein, he calculated how much a background star would be deflected by an intermediate one but did not hold hope, even in 1936, of this being observed. Instances of input from others have been shown previously. In this case, an augmentation was made, this time by Fritz Zwicky in 1937, that if stars were replaced by nebulae, there might be more chance of witnessing this gravitational lensing effect. In 1979, twin quasars were lensed by a galaxy. By 2008, 70 different systems with multiple images were collected by a camera on board the Hubble Space Telescope. While the property is in accord with Einstein, measurements are yet to be effected [99].

(10) Yet another application was tabled in 1964 by Irwin Shapiro who hypothesised that there would be a time delay in radar signals echoed from the planets due to relativity. Following three years of measurements, Shapiro obtained in 1971 a difference of 3% [99, 101]. As has been the case with General Relativity throughout its 100 years, new ideas have been applied at certain junctures to continue research. Spacecraft became targets from the 1970s. In 1975 Mariner 6 flew by Mars and this resulted in 0.3% and in the same year with a Mariner 7 Mars flyby the outcome was 0%. In 1977 a Viking program with two orbiters and two landers on Mars produced 0.5% and the result for Mariner 9 in Martian orbit in 1979 was 0.2% [101]. The double pulsar previously mentioned has given a wealth of precise data as the pulse frequency of each is influenced by the mass of the other. The pulse profile has a characteristic shape and range and when observed in the context of time delay yielded, in 2006, deviations from Einstein to the values of 0.013% and 0.9% respectively [101].

(11) Atomic clocks provide extremely precise measures of time. In order to test Einstein's conjecture that time would alter with the speed of an observer relative to a stationary one, four devices based on caesium 133 were flown eastwards and westwards around the Earth in 1971 and the respective deviations were 48% and 0.7% [101]. The large discrepancy in the former result had one clock about 40% different from the other three.

(12) In 1939 Kenneth Nordtvedt, in treating gravity as a geometric property, saw that since the Earth and Moon were both under the influence of the gravitational field of the Sun, there ought not to be any difference between their accelerations as relativity suggested that these were independent of their masses. This strong equivalence principle was gauged to 0.001% in 2003 from lunar ranging data.

(13) Within the solar system, weak gravitational fields exist compared with the potential of stronger fields elsewhere such as the much larger masses of neutron stars. At the end of the lifetime of a double neutron star system, the release of predicted gravitational waves on their collision is expected to be prodigious in energy at the source but very faint by the time they reach Earth. Observatories have been built and more are in the pipeline to attempt to capture such energy [101].

In general, with but a few exceptions, the results in the third paper (which dealt with astronomical tests after 1928) display small departures from figures predicted by Einstein's Theory of General Relativity. In some of the areas of investigation, a convergence between the experimental and theoretical figures ensues as explorations occur over quite a period of time. This theory may have commenced in the early part of the 20th century but research into it is still ongoing. Scientists are always interested in delving even deeper into the wonders of a scientific paradigm. General Relativity has not been shown to be incorrect over the last 100 years. However, because of the nature of the logic of Science where speculation is better served by falsifiability than verifiability as proposed by Karl Popper, the word 'proof' should not be used. There may be other reasons for the values obtained for the physical Universe. Refinements of earlier experiments may be performed as the quality and precision of equipment improves. Novel thinking presented avenues that were not originally part of the theory. In addition, more exotic objects with large gravitational fields were discovered and the gathering of data over much longer periods provided a larger amount of data. Also, spacecraft are now routinely employed in measurements. A greater sharing of the output of observatories as in a larger baseline in interferometry allowed more precise observations and the progression of technology permitted a larger scope for experimentation. As the separation between experimental results and theoretical predictions narrowed, some competing explanations to General Relativity were dismissed and Einstein's concept received increasing support. Even though a critical mass of scientists now believes there is enough evidence to favour General Relativity as the best explanation of the data, the scientific establishment continues in its quest for closer approximations. This is how Science operates. Disproof of any idea may ensue but proof is not a pronouncement that ought ever made by the scientific community.

Results from recent astronomical tests of General Relativity

- In addition to the three classical tests of General Relativity, another 13 areas of research continue to explore the differences between predicted values and observational data.
- The smallest percentage departure between predicted values and observational data for the 13 areas of research are listed.

(1) equivalence of inertial and gravitational mass …………………..	1×10^{-9}
(2) gravitational redshift ………………………………………………………	0.0023
(3) relativistic perihelion advance of the planets ……………………	0.19
(4) relativistic periastron advance of binary pulsars ……………….	0.13
(5) geodetic precession ……………………………………………………….	0.01
(6) Lense-Thirring effect ……………………………………………………….	0.6
(7) gravitational optical light deflection ……………………………….	0.3
(8) gravitational radio deflection due to the Sun ……………………	0.02
(9) gravitational lensing ………………………………………………………	accords with predictions
(10) time dilation …………………………………………………………………	0.013
(11) atomic clocks ………………………………………………………………..	0.7
(12) Nordtved effect …………………………………………………………….	1×10^{-3}
(13) potential gravitational waves ……………………………………….	not yet observed

<u>Paper 4: General Relativity support from the double pulsar</u>

This paper is devoted entirely to the double pulsar PSR J0737 – 3039A/B and its discovery in 2003 at Parkes Radio Telescope as it represents the possibility of unprecedented accuracy.

Pulsar A has a spin frequency of 44 s^{-1} and B 0.4 s^{-1}. There are five orbital parameters (Keplerian) which are used to define the orbit of any object, namely, orbital period, eccentricity, projected semi-major axis, longitude of periastron from the ascending node and the epoch of periastron passage. The orbital period is 0.1 d and the eccentricity of the pair in orbit is 0.09 [461]. However, departures from the Keplerian description are postulated due to relativistic effects as the frequency of the pulse of one of the pair is influenced by the gravitational field of the other.

Observational measurements are made on the time of arrival of the data. Differences are referred to as post-Keplerian parameters.

Ingrid Stairs, Professor of Astronomy and Physics at the University of British Columbia, has presented five equations of these post-Keplerian parameters based on General Relativity [461]. Each equation incorporates either the mass of the binary system or the individual pulsar masses. Each equation is independent from the others. A derived solution of two of these equations yields the masses of the pulsars. Further solutions with the other equations also produce masses of the pulsars. The results from each equation are compared for consistency. The masses of A and B respectively are given as 1.4 and 1.3 times the mass of the Sun. The five post-Keplerian parameters are approximately advance of periastron 17° yr^{-1}, gravitational redshift 0.4 s, the derivative, that is, change of the orbital period -1.3 s s^{-1}, the range of delay due to the medium of transmission 6.2 s and the shape of this delay 1.0 [462].

After two and a half years of the measurement of the orbital period, the precision of the measurements are such that the 8×10^8 m distance between the pulsars is stated to be decreasing by 7 mm d^{-1}. If the equation for the advance of periastron is the first one used to commence solutions to the other four, then the observed value of these post-Keplerian parameters may be divided by their calculated values and the closer the ratios are to unity, then the closer they approximate the Einsteinian framework. Any uncertainty in these ratios may be expressed as a % departure from General Relativity.

Results from the double pulsar

- Percentage departures of parameters for double pulsar from Einstein prediction are listed [462].

orbital period	1.4
gravitational redshift	0.68
range of the time delay	5.5
shape of the time delay	0.05

Even though these results are impressive, scientists continue to seek more precise results which may ensue from longer periods of observation. An antenna of effective 500 m diameter is slated to search for more double pulsars to extend this very valuable tool to probe General Relativity further [463-4].

The double pulsar provides a unique test of General Relativity in the strong field regime. With both signals received at Earth from these two pulsars in mutual orbit, this unprecedented condition allowed for much greater precision of measurements. The value for the shape of the time delay is the most precise test that has been applied to forecasts of the theory.

Conclusion from the double pulsar

- The case for the support of General Relativity was significantly enhanced by investigations of the double pulsar system. Australia played a key role in the acceptance and verification of General Relativity from the discovery in 2003 at Parkes Radio Telescope of the first, and to this date only, pair of pulsars in mutual orbit.

Paper 5: General Relativity in Australian Newspapers: The 1919 and 1922 Solar Eclipse Expeditions

From an online search of Australian newspapers that were found with an input of “Einstein” AND “relativity”, the earliest was January 1911. The span was closed at 31 December 1928 to fit the statements that 1928 ought to have been a defining year for acceptance of Einstein based on gravitational light deflection (first paper) and gravitational redshift (second paper). In this 18 year time span, there were 266 distinct newspaper articles [151].

For the year 1922 in which the total solar eclipse occurred across Australia, there appeared 137 of the 266 articles (52%) [152]. The three years 1921-23 also contained preparations for and results from the eclipse and these years covered 216 (81%) of the 266 pieces [152]. Of the 137 stories in 1922, 51 (37%) were printed in the month of September, the time of the eclipse [152]. Newspapers aim to appeal to their readers by emphasising community news so that the local interest in the eclipse in Australia is reflected in these figures. When each of the articles was analysed for its main emphasis, nine themes emerged. 134 (50%) were devoted to the 1922 total solar eclipse, followed by 72 (27%) about relativity and 23 (9%) with its focus on Einstein [152]. There were 104 commentaries which encompassed at least one of the three classical astronomical tests for General Relativity. Of these 52 (50%) were devoted to the test of gravitational light deflection. This was the only test being conducted at the eclipse sites in 1922 and so this was to be expected. Indeed, at times the phrase ‘gravitational light deflection’ was taken to be equivalent to General Relativity. The other tests discussed were 33 (32%) for the perihelion advance of Mercury and 19 (18%) about gravitational redshift [153].

Of the total of 226 separate coverages, 232 (87%) made mention of a leader or group involved in the 1922 total solar eclipse in Australia or Christmas Island [155]. In the first paper are the stories of the 13 groups that intended to attempt some measurements during the eclipse. Of these, eight were specifically seeking a result for gravitational light deflection and these comprised 180 (78%) of the stories [155]. Walter Campbell of the Lick Observatory topped the list with 53 (23%) of the mentions. He was the most noted of the astronomers in Australia and he and his institution had extensive experience in eclipse expeditions. In addition, he lectured or gave after dinner speeches at many of the localities on his way between Sydney and Perth where journalists were in attendance. Next in order to Campbell were George Dodwell of Adelaide Observatory 30 (13%), Clarence Chant 28 (12%) leading a Canadian party and William Cooke of Sydney Observatory 26 (11%). These four leaders were all involved in taking light deflection photographs [155]. The six groups that comprised the Australian contingent were written about in 104 (45%) of the pieces [155]. In terms of localities, there were five groups at Wallal and of the 113 pieces which referred to a place, it occupied 45 (40%) of the total. This was the site chosen by Campbell [155].

In the first paper criticism is directed towards the ready acceptance in some quarters of General Relativity following the British total solar eclipse expeditions of 1919. The Australian newspapers in the fifth paper performed a commendable public service by informing readers about this difficult to understand area. In spite of the level of complexity, the newspaper writers were generally accurate in their presentation of the theory. In particular, they gave a flavour of the disagreement in Science between those scientists that said that the 1919 results were sufficient on their own to support Einstein and those scientists who believed they were insufficient. They outlined the necessity of the 1922 investigations as the 1919 results were regarded as inconclusive by important members of the scientific community. From an analysis of the 107 newspaper articles which gave an opinion with regard to any conclusion from the 1919 event, 50 (47%) supported

General Relativity, 35 (33%) believed more evidence was required and 22 (20%) were in the non-supporting camp [157].

The tentative nature of accepting a theory was borne out by the newspapers in mentioning proof or truth in only 8% of what was written [157]. While there were some articles among the 8% which purported to be a showdown between proof and disproof, the newspapers generally presented a balanced commentary.

Results from the Australian newspapers

- A majority of the 266 articles in Australian newspapers referring to General Relativity between 1911 and 1928 were in 1922, the year of the total solar eclipse in Australia and most were covered the years 1921-23.
- Of the articles in Australian newspapers referring to General Relativity in 1922, the peak was in September, the month of the total solar eclipse in Australia.
- One half of the articles in Australian newspapers referring to General Relativity between 1911 and 1928 had the 1922 total solar eclipse as their main theme.
- Of the articles in Australian newspapers referring to any of the three classical astronomical tests of General Relativity between 1911 and 1928, the order of importance was gravitational light detection, the perihelion advance of Mercury and gravitational redshift.
- Of the articles in Australian newspapers between 1911 and 1928 which referred to any of the thirteen expeditions in 1922, the maximum number concerned Walter Campbell of Lick Observatory. A larger component was on the eight of the thirteen groups attempting a light displacement measurement. There was also local interest for the six groups of the Australian contingent where three attempted a gravitational light displacement measurement and three did not.
- Where a site is mentioned between 1911 and 1928, Wallal had five groups and carried the major coverage.
- Between 1911 and 1928 the Australian newspapers performed admirably in their accurate presentation of the issues in General Relativity, their use of language was scientifically precise and they reflected the different stances among scientists to the public.
- Of the articles in the Australian newspapers between 1919 and 1928 which interpreted the results from the 1919 total solar eclipse, a larger proportion favoured the combination of more evidence required and not supported over support. Thus, this showed why the 1922 results were important and necessary.

Remarks

The astronomical tests of General Relativity followed a circuitous path from 1907 to the present. This historical development is an indication of the manner in which Science operates. The fantasy of one defining moment popularised in some accounts of scientific ideas is far from reality. A new paradigm results from a steady accumulation of experimental results which are best interpreted with an idea that is eventually adopted by scientists. The theory so far has not been shown to be wrong. It is the best that is available to answer the evidence. Nonetheless, experiments continue to be performed to plumb its depths. Investigations have not come to a stop in 2015. The theory has stood the test of both weak and strong gravity regimes. It has yet to be examined in exceptionally strong fields which may surround an object approaching the dimensions predicted for a black hole.

There still remains an incompatibility between Quantum Mechanics and General Relativity. One writer contemplating quantum gravity opined that “The consistent implementation of the gravitational interaction into the quantum framework is considered to be the outstanding problem in fundamental physics.”[3] It will be interesting to follow this path to see if some unification is possible or if one becomes subsumed under the other or if General Relativity breaks down at some point. The future still looks a fascinating one for the Theory of General Relativity.

However, even though Einstein’s pronouncements were 100 years ago and a number of technological developments such as the global positioning system are dependent on General Relativity, it could be argued that this view of the Universe has still not become part of the fabric of public thinking. What is fair to say is that scientists and educators still have a mammoth task in bringing the public with them on both an understanding of this paradigm and, just as importantly, an appreciation of the scientific method. From the point of view of the public today, no longer is the view of scientists accepted in their field of expertise as witnessed in some current debates concerning climate change. The education of the public has not progressed sufficiently to understand how Science operates. If the consequences are inconvenient politically, economically or socially, a more educated populace in general terms and one now receptive to information from so many other forms of communication may refuse to accept the Science. Sometimes, unfortunately, the public equates the tentativeness of acceptance of a theory with a lack of surety that they demand. It is not the Science that is at issue but a public misunderstanding of how Science operates. It behoves scientists to be more skilful at representing the Nature of Science.

Conclusion Concerning Hypotheses

This excursion through history for General Relativity supports the hypotheses:

1. Australia played a key role in the acceptance and verification of General Relativity from the 1922 total solar eclipse across the continent as well as the discovery in 2003 at Parkes Radio Telescope of the first, and to this date only, pair of pulsars in mutual orbit.
2. The Theory of General Relativity was accepted prematurely.

It also points to its future application to provide an insight into how other scientific revolutions generally occur. A number of major scientific revolutions have strong similarities with the story told within these pages. This presentation may be used as a template for following the acceptance of Heliocentrism, Evolution, Atomic Theory, Plate Tectonics and Dark Matter/Energy. These have also taken vast stretches of time and, in some cases, continue to unfold. Thus, this coverage of General Relativity has the potential to act as an example.

Findings

This thesis has contributed to knowledge in the history of General Relativity in a number of ways. The 1922 total solar eclipse across Australia was a significant event in this nation’s history. Yet, little is known of its significance. The 1919 eclipse expeditions continue to receive the kudos for “proving” Einstein’s work. This work has sought to address this situation. Based on the classical astronomical test of gravitational light deflection, it is concluded that General Relativity was prematurely accepted. Insufficient evidence existed in 1919 to support this theory and the result was tentative.

One of these papers brings together for the very first time the history of the 13 parties that gathered in 1922 across Australia and Christmas Island to perform scientific work. The results and contributions of each are presented to perceive the value from each of them, particularly of the eight groups that attempted a measurement of light deflection. The story of Walter Campbell of Lick Observatory is instructive. Even though photographs were obtained in 1922, it was 1928 before the results were finally published. It is thus Campbell in this latter year who should receive accolades for his experimental work which supported General Relativity. This thesis demonstrates how Australia played a key role in the acceptance and verification of General Relativity from the 1922 total solar eclipse across the continent.

Similarly, it is highlighted in these papers how another classical astronomical test, the advance in the perihelion of Mercury, had not run the gauntlet of scientific scrutiny sufficiently by 1915. It has been shown that a pronouncement on this criterion should have waited until the 1980s. Also, for the third classical astronomical test, gravitational redshift, it is argued here that 1923 was too early a proclamation. The factors involved with an analysis of spectral line frequency shifts from the Sun were not completely understood until the year 1928. So, for the three classical astronomical tests, the theory of General Relativity was accepted prematurely.

Again, in many books and articles, only these three astronomical tests are presented. The 13 strands of further tests for General Relativity presented here are not new. However, they have been gathered in this thesis to provide a sweep of history to see that this scientific revolution continues. Each of these tests is placed against a background, not of proof but against the question of how much evidence exists to support General Relativity. It has been shown that General Relativity has been the guiding light through discoveries in 1954 of Cygnus A, a strong radio source associated with a distant galaxy not detected optically, in 1962 of X-ray sources, in 1963 of quasars, in 1965 of the 3 K background radiation, in 1967 of pulsars, in 1974 of a binary pulsar, of subsequent discoveries of exotic objects and, in particular, in 2003 with the first double pulsar discovered with Parkes Radio Telescope where Australia played a key role in the acceptance and verification of General Relativity from the discovery in 2003 at Parkes Radio Telescope of the first, and to this date only, pair of pulsars in mutual orbit.

In these papers is the first analysis of Australian newspapers of General Relativity in the early years of its development up to 1928. They were instructive in providing a flavour of the time, particularly with regard to how scientists differed in whether there was sufficient evidence following the 1919 total solar eclipse. The papers provided the public with an understanding of why the 1922 measurements were considered necessary. They are a valuable tool in viewing what was occurring in Science, how Science operates and how the public received information about an area in which many did not have the necessary mathematical skills for a complete understanding.

References

1. K. Popper, *The Logic of Scientific Discovery*, (London 2005, 1935 first publication).
2. Referenced in A. Pais, *'Subtle is the Lord': The Science and the Life of Albert Einstein* (1982), Oxford University Press, 253.
3. C. Kiefer, Quantum Gravity: General Introduction and Recent Developments, *Annalen der Physik*, arXiv: gr-qc/0508120 (2005) 15: 129-48.