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1

The Experiment That Weighed Light

Although Eddington and Dyson collaborated closely in organizing the expeditions of 1919, the two expeditions remained quite separate. Two different English observatories were involved, Dyson being director of one and Eddington of the other. Conscious of the vagaries of the weather, they chose different locations and hoped that the results from each site would confirm each other. Eddington, who was then one of England's most famous astrophysicists, personally led one expedition. He took with him a Northamptonshire clockmaker named Edwin Turner Cottingham to keep their instruments in working order while Eddington himself conducted the experiment. The Royal Obervatory at Greenwich mounted the second expedition. As director of that observatory, Frank Dyson sent two of his assistants, Andrew Claude de la Cherois Crommelin and Charles Rundle Davidson. They would each operate a different instrument, for some further redundancy. Dyson would oversee their data analysis after their return to England. Dyson and Eddington, working together, had hatched the plan and raised the funds, and together they would reveal the results later that year at a packed

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meeting of two of Britain's leading scientific societies. If May 29 is an important date in the history of science, then November 6, 1919, is also famous. The atmosphere that day was like that of a Greek drama, in the words of one participant. As one might expect in a Greek drama, some people greeted the news of the eclipse results with excitement and others with despair. The arguments as to the interpretation of the data still continue.

Just as the expeditions were mounted by two different observatories working closely in concert, two different societies collaborated in sponsoring them. The Royal Society of London, founded in 1660 at Gresham College in London, is England's premier scientific society. For centuries it has brought scientists of all fields together to discuss their work. In the nineteenth century, science diversified, and the number of scientists greatly increased. As different scientific disciplines grew, the scientists formed various professional societies. One of the oldest is the Royal Astronomical Society (usually known as the RAS), which was founded as the Astronomical Society of London in 1820 and took its current name in 1831. Both societies are still very active today, publishing scholarly journals and meeting regularly to hear talks by distinguished scientists.

Throughout their history, these societies have played an important role in sponsoring scientific research, especially where considerable expense is involved. Expeditions for the purpose of scientific discovery are a classic example of where such sponsorship is necessary. The late nineteenth century saw a revolution in astronomy that gave birth to the field of astrophysics. The experimental techniques of physics, including the use of spectroscopy and photography, began to be applied to astronomy, transforming how astronomers did their work. These new techniques increased interest in eclipses of the Sun, and in 1884 the RAS founded the Permanent Eclipse Committee to oversee planning for expeditions to observe solar eclipses.[1]

It was found helpful for the RAS committee to collaborate with a similar eclipse committee organized by the Royal Society to plan an expedition to West Africa in 1893 (Pang 1993). In the wake of that expedition, and so the two societies could collaborate in the future, the Permanent Eclipse Committee became, in 1894, the Joint

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Permanent Eclipse Committee, or JPEC. By 1919 JPEC therefore already had a quarter century of experience in organizing eclipse expeditions. Its chair at that time was Dyson, and it was he who played the leading role in mobilizing resources on behalf of the two expeditions that year. The famous joint meeting of the Royal Society and the RAS was held specifically to hear JPEC's report on the expeditions of 1919.

The astronomers of 1919 thus were blessed to control an institutional framework with the power to mount such expeditions. They would need all the help they could get. They were beset with troubles, most importantly those of war. World War I ended just barely in time (in November 1918) for the expeditions to travel at all. The measurements to be made were much more challenging than those typically attempted during an eclipse. They would attempt to measure the shifts in position of the stars close to the Sun due to the Sun's gravitational pull on the starlight as it passed close by the Sun on its way to Earth. This was what Einstein had predicted. But the amount of the deflection of starlight he had predicted was such that the shift of a star's position, as measured on a photographic plate, would be less than the width of the star's image on the plate. Thus, the effect was quite tiny and would only be measurable with the most sensitive handling of the instruments during the eclipse and the most careful measurements afterward. Even then it would be possible to distinguish the true deflection of starlight from effects caused by changes in optical magnification of the telescope only with long and tedious calculations. These calculations would be performed at Greenwich by *computers*, a word that at that time referred to humans whose job was to crunch numbers using pen and paper only, without the aid of electronic calculating machines.

Fortunately, the science of astrometry, as the measurement of stellar positions is called, had greatly advanced in the decades before 1919. During this era, the distances to a large number of nearby stars were measured for the first time. This was done by very carefully determining tiny shifts in the positions of stars (their *parallax*) between different seasons of the year, due to the Earth's motion. Both Dyson and Eddington had carried out such work when they

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began their careers in astronomy. They had the experience, but they had previously always performed such exacting measurements in optimal conditions. They had used telescopes permanently and appropriately mounted in an observatory, with the equipment needed for data analysis all readily on hand and on-site. Most important, if there was a problem with any of their work, they could simply take a new image on a suitable night and begin again. In 1919, they would have no second opportunities to get things right. They would have no chance to profit by any mistakes they would make—only to regret them.

Some events in astronomy can be missed in the blink of an eye. A transit of Venus occurs only twice in every century or so. But anyone on one whole hemisphere of the globe can observe such a transit, so even if one observer is clouded out or suffers an equipment malfunction, others will witness it. The implacability of scientific advance is enabled by repeatability. Scientists tinker and modify with each new trial, and the expectation is that over time the precision of measurement will relentlessly improve. Take away the ability of scientists to demonstrate their persistence and they become more mortal. They are prone to the vagaries of fate that bedevil most human endeavors. The caprice of weather or of human fallibility may ruin any amount of careful preparation.

Given everything they had to contend with and the limitations imposed by scarce equipment and limited preparation time, the men of 1919 seem to have been very fortunate to get the results they did. Whether they really achieved the measurement precision they claimed has often been doubted. Whether they really overthrew Newton and vindicated Einstein has been questioned. One even sometimes hears the word *fraud* spoken in connection with their work. This is partly because their experiment was repeated many times over the succeeding decades without the level of precision ever noticeably improving. Surely, this suggests something suspicious. Can it be that nothing was learned from one expedition to another? We have to remember that few people were fortunate enough to repeat the experiment. When it comes to eclipse experiments, persistence is frequently rewarded with disappointment. Einstein's closest colleague in astronomy, Erwin Finlay Freundlich, went on at least six expeditions to

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test his mentor's theory and was able to observe totality only once. There is plenty of reason to call Dyson and Eddington lucky, but why should they also be called frauds? The answer is that Eddington was a renowned champion of Einstein's theory. He was quite frank in admitting his expectation, or at least his hope, that the theory would be confirmed. Many people have accused him of bias and have even claimed that he had ulterior motives that went beyond the science of the case. Could it be that this most famous of experiments was decided by someone who had made up his mind beforehand? What does this tell us about the way science is conducted? Are the expense and painstaking care of complex experimentation simply wasted efforts in which scientists merely contrive to confirm their expectations? The expeditions of 1919, it turns out, have something to tell us not only about the history of physics but also about the way science itself works.

Two Astronomers: Eddington and Dyson

Arthur Stanley Eddington was born in 1888 into a Quaker family in a scenic part of the North of England, the Lake District. His father was a school headmaster who died when Eddington was still an infant. His mother moved to the West of England, to Weston-super-Mare, and brought up Eddington and his sister in genteel poverty. Eddington remained very close to his mother and his sister, to whom he was known as Stanley, throughout his life. He was a brilliant student and availed himself of a series of scholarships to attend Owens College (now the University of Manchester) and then Trinity College, Cambridge. In 1904 he became the first student to become Senior Wrangler in only his second year at Cambridge. The title of Senior Wrangler is awarded annually to the student achieving the best mark in the mathematics degree exams, which is typically of three years' duration.

After briefly working at the famous Cavendish laboratory in Cambridge, Eddington went to the Greenwich observatory as chief assistant to the director, who is known as England's Astronomer Royal. His work there resulted in a paper that received Cambridge's Smith's

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FIGURE 1. Frank Watson Dyson and Arthur Stanley Eddington, in a photograph probably taken at an International Astronomical Union meeting in Cambridge, Massachusetts, in 1932. Dyson and Eddington had much in common, including their religious and educational backgrounds, career paths, and passion for astronomy. They cooperated brilliantly in the planning, execution, and subsequent presentation of the eclipse expedition and its results. This photograph appears to have been taken just after a more formal one by the same photographer. Here, Dyson has turned animatedly toward Eddington, who smiles in response.
(Courtesy of the Meggers collection of the Emilio-Segrè Visual Archive.)

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prize in 1907, and this led to him being elected a fellow of his old Cambridge college, Trinity. In 1913 he succeeded Charles Darwin's son George as the Plumian Professor of Astronomy and the next year was made director of the Cambridge Observatory. His rapid ascent to the heights of British science is very reminiscent of the path followed more than a decade previously by his colleague Dyson.

Frank Dyson's background and career were very similar to Eddington's. It is not hard to see why the two men should have gotten along well. Like Eddington, Dyson was religiously nonconformist. His father was a Baptist minister. Although born in Leicestershire in 1868, he mostly grew up in Yorkshire, from where the Dysons had originally hailed. Like Eddington, he was a Trinity student at Cambridge. He was Second Wrangler in 1889, compared to Eddington's achievement of Senior Wrangler fifteen years later. Both men won the Smith's prize (Barrow-Green 1999) and were awarded fellowships at Trinity as a result. Both began their astronomy careers in the important position of chief assistant at the Royal Observatory at Greenwich. In fact, Eddington succeeded Dyson in this position when the latter went off to Edinburgh as Astronomer Royal for Scotland. Of course, the odd similarity of his résumé with Eddington's mostly reflects the well-trodden path of the best and brightest coming up through the Cambridge system. Here were two talented and highly intelligent men who went to the forefront of their profession at each step on the ladder.

Because of the difficulties posed by wartime conditions, there is a mildly improvised air about the 1919 eclipse expeditions. Compromises were made in equipment and personnel since many instruments and people were simply not available because of the war. But in its two leaders, the expedition was blessed with men who were superbly qualified for the task at hand. If they were self-selected, it was because they were among the few who clearly saw the need for such a test at the time. As we shall see, it would have been hard to find two people with more experience of differential astrometry to undertake the experiment, especially since this was a very new field in which Dyson and Eddington were pioneers.

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Although their backgrounds were similar, their careers diverged in one sense. Dyson reached the heights of astronomy as England's Astronomer Royal and immersed himself in observational work and in the organizational tasks of the leader of England's astronomical community. Eddington, though also an observatory director, was a Cambridge professor continuing the Cambridge tradition of theoretical physics. Even if he applied that physics training primarily to astronomical problems, he remained at the forefront of European theoretical physics, so he brought a unique double perspective to bear on the problem of testing Einstein's theory of general relativity. On the one hand, he understood the theory as well as anyone did; on the other hand, he had the observational skills to go out and test it, since this could only be done through high-precision astronomy.

Eddington's fame was based upon the study of light and gravity. It was he who showed that the radiation pressure of sunlight trying to escape the interior of the Sun is what keeps the Sun from collapsing under its own gravitational force. This remarkable insight defies ordinary intuition, since the most incredible weight in the solar system, that of the Sun, is held up by literally the "lightest" support imaginable, light itself. So intense is the power of sunlight emerging from the core of the Sun that it can accomplish this Herculean task of supporting the weight of the Sun on its shoulders. This aspect of Eddington's work certainly prepared him for the eclipse experiment of 1919. Einstein had argued that if gravity was a universal force, it ought to affect light. Eddington was well prepared to think of light as a thing having weight and heft. Indeed, it was he himself who presented the eclipse test as an attempt to weigh light. Physicists of the nineteenth century had naively presumed that light was weightless. Now Eddington and Dyson would prove them wrong.

Eddington's ideas about the interior structure of the Sun ultimately led to the modern study of gravitational collapse and the discovery of collapsed stars like neutron stars and black holes. Ironically, Eddington rejected the idea that such ultradense objects could exist, disappointing a young student, Subramanian Chandrasekhar, known as Chandra, who imagined that he was building upon his

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mentor's groundbreaking work. In a similar way, the inventors of quantum mechanics were shocked that Einstein rejected their ideas. Instead, both men engaged in the quest for a unified field theory (nowadays, sometimes called a "theory of everything") in their later years. Neither received any kudos for this later work. It was viewed as eccentric and outside the mainstream of physics. Eddington was obsessed with numbers and tried to calculate how many fundamental particles are in the universe based on what most physicists regarded as a kind of numerology. Later, the philosopher Bertrand Russell recalled "enjoy[ing] asking him questions to which nobody else would have given a definite answer," such as "How many electrons are there in the Universe? . . . He would give me an answer, not in round numbers, but exact to the last digit." Russell also recalled Eddington's satisfied response to the discovery of the expansion of the universe: "He told me once, with evident pleasure, that the expanding universe would shortly become too large for a dictator, since messages sent with the velocity of light would never reach its more distant portions."[2]

Two Observatories: Greenwich and Cambridge

The eclipse expeditions of 1919 were organized on behalf of two learned societies by the Joint Permanent Eclipse Committee, but they were carried out by personnel from two different English observatories. Typically, this was how such expeditions were mounted at the time. The English system of coordination through the learned societies was used primarily to facilitate government funding and arrange for the sharing of equipment between observatories. Crucially, the data analysis was carried out separately at the two observatories, and the expeditions took their own data quite independently of each other at two different sites. This is important to keep in mind because Eddington's subsequent fame has overshadowed everyone else who participated, and some modern commentators talk almost as if Eddington was solely responsible for every decision taken. At the time, no one in England would have made this mistake. Dyson was a well-respected and widely known public figure. As Eddington

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himself took pains to point out, it was Dyson's expertise and influence that made the whole enterprise possible.

The Principe team was led by Eddington, in his capacity as director of the Cambridge Observatory. Eddington's role was largely personal. He understood the theory being tested and was experienced in the type of astrometry required to measure the predicted effect. But his observatory was not known for its expertise in eclipses, and the equipment he used was largely borrowed from the Oxford Observatory. He was accompanied not by one of his own staff but by Cottingham, who was familiar with the equipment to be used, as he counted both the Oxford and Cambridge Observatories among his clients. Cottingham's role was largely to maintain the equipment in working order at the site. It is probable that Eddington alone handled the data analysis of the Principe expedition. We cannot determine how this was done because none of the data analysis sheets or photographic plates have survived. We do know that Eddington began the data analysis on Principe by himself, so it is almost certain that he continued on his own when back in England.

The expedition to Sobral in Brazil was under the direction of Dyson, the Astronomer Royal. He sent two members of his own staff, and some of the equipment was from his own observatory. Although he did not go himself, he directed the data analysis after the expedition returned to England. Key points in the data analysis sheets are in his handwriting, and he cowrote the report on the expeditions with Eddington. He took the lead in publicizing the results among the astronomy community and was coequal with Eddington in communicating them to the general public. They were both important public scientific figures who had a gift for popularization.[3]

The Royal Observatory at Greenwich opened in 1676, having been commissioned by King Charles II the previous year. He created the position of Astronomer Royal at the same time. Until recently, the Astronomer Royal also served as the director of the observatory. In the eighteenth century, the observatory played a leading role in solving the problem of longitude. As a result, the prime meridian, the reference longitude for most of the world, runs through the old observatory at Greenwich to this day. Since the best-known method

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FIGURE 2. A view of the Royal Observatory at Greenwich in the 1920s. The dome in the foreground at right is where the astrographic telescope was housed. Frank Dyson and Charles Davidson spent many years working on this instrument, and its lens accompanied Davidson to Sobral in 1919. In 1894 high winds blew the shutter off the dome, and the headpiece fell into the room below, narrowly missing Davidson as he and Dyson were at work. The Royal Observatory is now a museum. (Image courtesy of Graham Dolan.)

of finding longitude at sea involved the use of precision timekeeping, the observatory was placed in charge of timekeeping for the British navy. This involved, among other things, dropping a ball down a spire at the top of the observatory at 1:00 p.m. each day by which ships in the Thames below could set their timepieces. By the early twentieth century, timekeeping had become important in civilian life, following the growth of the railways. Previously, towns had kept their own local time, but now it became desirable for everyone in England to follow Greenwich time. In order to facilitate this, Dyson developed the pips system with the BBC (British Broadcasting Corporation). This involved sending out a radio signal broadcasting the sound of six pips marking the seconds leading up to each hour. This permitted everyone with a radio set capable of receiving the BBC to set their clocks against master clocks at Greenwich, which controlled the time signal.

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The early twentieth century was a golden age for astronomy. The subject had great prestige after the dramatic discoveries of the previous 150 years, including the addition of two new planets to the solar system. As new universities were founded in the late nineteenth century, many of them built observatories. Even the observatories of the older universities are not as old as one might think. Eddington's observatory in Cambridge was built in 1823, for instance. In the nineteenth century, British eclipse expeditions were dominated by London observatories—not only Greenwich but also newer facilities like Kew Observatory and the Solar Physics Observatory at the Royal College of Science in Kensington (now part of Imperial College, London). The Kew Observatory had been built for King George III in the eighteenth century (it is often known as the King's Observatory) to allow him to observe the transit of Venus in 1769. In the nineteenth century, the British Association for the Advancement of Science took over the building. Its director in the mid-nineteenth century, Warren de la Rue, was a pioneer of the use of photography in astronomy and focused particularly on solar physics. Because of his interest in astronomical photography, he donated the astrographic telescope to the Oxford Observatory for use in the *Carte du Ciel* project.[4] The lens from this telescope would be taken by Eddington to Principe. The Solar Physics Observatory in Kensington was built for Sir Norman Lockyer, a key member of JPEC for decades and the founder of the journal *Nature*.

By 1919 the Kew Observatory had become the home of the Met Office, Britain's national weather forecasting service, and Lockyer's Kensington observatory had been closed down. Lockyer had moved to Sidmouth in southwestern England, where he had a new observatory called the Hill Observatory (now known as the Norman Lockyer Observatory). Most of the equipment from his London observatory went to Cambridge to the new Solar Physics Observatory, a near neighbor to Eddington at the Cambridge Observatory. As an illustration of how common and influential amateur observatories were at this time, Sidmouth played host to not one but two observatories in 1917. The other was the personal observatory of a wealthy

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German engineer, Adolph Friedrich Lindemann. Lindemann had been involved in the laying of one of the first successful transatlantic cables for telegraphic communication between Europe and America. He and his son, a promising young physicist named Frederick Alexander Lindemann, were interested in astronomy and in Einstein's theory. Since they both spoke German and spent time in Germany, they were more familiar with his work than most astronomers in Britain and were interested in joining the effort to test the theory. Not being eclipse specialists, they wondered if the light deflection experiment might be accomplished during the daytime, using filters to try to pick out the light of particularly bright stars against the glare of the sky. After some experiments carried out at Sidmouth, they wrote a paper proposing that a bigger observatory should try the observation at the conjunction of the Sun with Regulus on August 21, 1917. Regulus, also known as Alpha Leonis, since it is the brightest star in the constellation Leo, is the brightest star close to the ecliptic and thus the brightest star that the Sun comes close to in the sky. John Evershed, at the Kodaikanal observatory in India, a solar astronomer already used to testing Einstein's theory, took up the challenge and tried the observation on that date. We can argue that this was the first attempt to test Einstein's full theory of general relativity (before 1915 he had a different prediction for light deflection, as we shall see). As such it had a very fitting centenary because on August 21, 2017, Regulus was once again close to the Sun, but on this occasion the Sun was in total eclipse across a swath of land through the middle of the United States. This made the 2017 eclipse easily accessible by professional and amateur astronomers who cared to attempt the Einstein test.

But back in 1917, the attempt failed. Regulus could not be imaged in full daylight near the Sun. So it seemed that if the measurement was to be accomplished at all, it would have to be at an eclipse. In the wake of World War I, with astronomers of many countries still on war duty or struggling to survive amid revolution and upheaval, the field was wide open for Cambridge and Greenwich to make the running in 1919.

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