

Einstein, Eddington and the 1919 Eclipse

Peter Coles

School of Physics & Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD.

Abstract. The modern era of cosmology began with the publication of Einstein's general theory of relativity in 1915. The first experimental test of this theory was Eddington's famous expedition to measure the bending of light at a total solar eclipse in 1919. So famous is this experiment, and so dramatic was the impact on Einstein himself, that history tends not to recognize the controversy that surrounded the results at the time. In this paper I discuss the experiment in its historical and sociological context and show that it provides valuable lessons for modern astronomy and cosmology.

1. Introduction

Science has developed at an astonishing rate over the past hundred years and in the physical sciences developments have been particularly remarkable. Physicists have unravelled the structure of matter on the tiniest accessible scales, breaking up atomic nuclei into elementary particles and studying the forces that cause these particles to interact. Astronomers discovered in this century that the Universe is expanding, and cosmologists are now trying to understand the very instant of creation at the Big Bang that started this expansion off. These daring adventures of the mind are based on foundations of experiment, observation and theory.

The modern era of scientific thought began with Galileo and Newton. But the early years of the twentieth century saw a dramatic acceleration in this progress. In 1919 an experiment was performed that was intended to test Einstein's general theory of relativity. The results caused a media sensation and made Albert Einstein into a household name. As well as providing an illustration of Einstein's theory, the story of this experiment and its aftermath also reveals interesting insights into the relationship between science and wider society. But let's start with the background to the experiment and its scientific importance.

2. Universal Gravitation

2.1. Newton's Laws

Gravity is one of the fundamental forces of nature. It represents the universal tendency of all matter to attract all other matter. This universality sets it apart from, for example, the forces between electrically-charged bodies, because

electrical charges can be of two different kinds, positive or negative. While electrical forces can lead either to attraction (between unlike charges) or repulsion (between like charges), gravity is always attractive.

In many ways, the force of gravity is extremely weak. Most material bodies are held together by electrical forces between atoms which are many orders of magnitude stronger than the gravitational forces between them. But, despite its weakness, gravity is the driving force in astronomical situations because astronomical bodies, with very few exceptions, always contain exactly the same amount of positive and negative charge and therefore never exert forces of an electrical nature on each other.

One of the first great achievements of theoretical physics was Isaac Newton's theory of universal gravitation, which unified what had seemed to be many disparate physical phenomena. Newton's theory of mechanics is encoded in three simple laws:

1. Every body continues in a state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed upon it.
2. Rate of change of momentum is proportional to the impressed force, and is in the direction in which this force acts.
3. To every action, there is always opposed an equal reaction.

These three laws of motion are general, applying just as accurately to the behaviour of balls on a billiard table as to the motion of the heavenly bodies. All that Newton needed to do was to figure out how to describe the force of gravity. Newton realised that a body orbiting in a circle, like the Moon going around the Earth, is experiencing a force in the direction of the centre of motion (just as a weight tied to the end of a piece of string does when it is twirled around one's head). Gravity could cause this motion in the same way as it could cause apples to fall to Earth from trees. In both these situations, the force has to be towards the centre of the Earth. Newton realised that the right form of mathematical equation was an inverse-square law:

$$F = G \frac{M_A M_B}{r^2}. \quad (1)$$

In other words the attractive force F between any two bodies of masses M_A and M_B depends on the product of the masses of the bodies and upon the square of the distance r between them. The quantity G is a fundamental constant, called Newton's constant. Combined with Newton's Second Law,

$$F = M \frac{dv}{dt}, \quad (2)$$

this allows one to calculate the changes in motion and position of bodies interacting under gravity.

It was a triumph of Newton's theory that the inverse-square law of universal gravitation could explain the laws of planetary motion obtained by Johannes Kepler more than a century earlier. So spectacular was this success that the idea of a Universe guided by Newton's laws of motion was to dominate scientific thinking for more than two centuries. Until, in fact, the arrival on the scene of an obscure patent clerk by the name of Albert Einstein.

2.2. The Einstein Revolution

A detailed account of the life of Albert Einstein can be found in Pais (1992). He was born in Ulm (Germany) on 14 March 1879, but his family soon moved to Munich, where he spent his school years. The young Einstein was not a particularly good student, and in 1894 he dropped out of school entirely when his family moved to Italy. After failing the entrance examination once, he was eventually admitted to the Swiss Institute of Technology in Zurich in 1896. Although he did fairly well as a student in Zurich, he was unable to get a job in any Swiss university, as he was held to be extremely lazy. He left academia to work in the Patent Office at Bern in 1902. This gave him a good wage and, since the tasks given to a junior patent clerk were not exactly onerous, it also gave him plenty of spare time to think about physics.

Einstein's special theory of relativity (Einstein 1905) stands as one of the greatest intellectual achievements in the history of human thought. It is made even more remarkable by the fact that Einstein was still working as a patent clerk at the time, and was only doing physics as a kind of hobby. What's more, he also published seminal works that year on the photoelectric effect and on Brownian motion. But the reason why the special theory of relativity stands head-and-shoulders above his own work of this time, and that of his colleagues in the world of mainstream physics, is that Einstein managed to break away completely from the concept of time as an absolute property that marches on at the same rate for everyone and everything. This idea is built into the Newtonian picture of the world, and most of us regard it as being so obviously true that it does not bear discussion.

The idea of relativity did not originate with Einstein. The principle of it had been articulated by Galileo nearly three centuries earlier. Galileo claimed that only relative motion matters, so there could be no such thing as absolute motion. He argued that if you were travelling in a boat at constant speed on a smooth lake, then there would be no experiment that you could do in a sealed cabin on the boat that would indicate to you that you were moving at all. Of course, not much was known about physics in Galileo's time, so the kinds of experiment he could envisage were rather limited.

Einstein's version of the principle of relativity simply turned it into the statement that all laws of nature have to be exactly the same for all observers in relative motion. In particular, Einstein decided that this principle must apply to the theory of electromagnetism, constructed by James Clerk Maxwell, which describes amongst other things the forces between charged bodies mentioned above. One of the consequences of Maxwell's theory is that the speed of light (in vacuum) appears as a universal constant c . Taking the principle of relativity seriously means that all observers have to measure the same value of c , whatever their state of motion. This seems straightforward enough, but the consequences are nothing short of revolutionary.

2.3. Thought Experiments

Einstein decided to ask himself specific questions about what would be observed in particular kinds of experiments involving the exchange of light signals. He worked a great deal with *gedanken* (thought) experiments of this kind. For example, imagine there is a flash bulb in the centre of a railway carriage moving

along a track. At each end of the carriage there is a clock, so that when the flash illuminates it we can see the time. If the flash goes off, then the light signal reaches both ends of the carriage simultaneously, from the point of view of passengers sitting in the carriage. The same time is seen on each clock.

Now picture what happens from the point of view of an observer at rest who is watching the train from the track. The light flash travels with the same speed in our reference frame as it did for the passengers. But the passengers at the back of the carriage are moving into the signal, while those at the front are moving away from it. This observer therefore sees the clock at the back of the train light up before the clock at the front does. But when the clock at the front does light up, it reads the same time as the clock at the back did! This observer has to conclude that something is wrong with the clocks on the train. This example demonstrates that the concept of simultaneity is relative. The arrivals of the two light flashes are simultaneous in the frame of the carriage, but occur at different times in the frame of the track. Other examples of strange relativistic phenomena include time dilation (moving clocks appear to run slow) and length contraction (moving rulers appear shorter). These are all consequences of the assumption that the speed of light must be the same as measured by all observers. Of course, the examples given above are a little unrealistic. In order to show noticeable effects, the velocities concerned must be a sizeable fraction of c . Such speeds are unlikely to be reached in railway carriages. Nevertheless, experiments have been done that show that time dilation effects are real. The decay rate of radioactive particles is much slower when they are moving at high velocities because their internal clock runs slowly. Special relativity also spawned the most famous equation in all physics

$$E = mc^2, \quad (3)$$

expressing the equivalence between matter and energy.

Remarkable though the special theory undoubtedly is, it is seriously incomplete. It deals only with bodies moving with constant velocity with respect to each other. Even Chapter 1 of the laws of Nature, written by Newton, had been built around the causes and consequences of velocities that change with time. Newton's second law is about the rate of change of momentum of an object, which in layman's terms is its acceleration. Special relativity is restricted to so-called inertial motions, i.e. the motions of particles that are not acted upon by any external forces. This means that special relativity cannot describe accelerated motion of any kind and, in particular, cannot describe motion under the influence of gravity.

2.4. The Equivalence Principle

Einstein had a number of deep insights in how to incorporate gravitation into relativity theory. For a start, consider Newton's theory of gravity embodied by equation (1). The force exerted on body B by body A depends on M_A and M_B . In this case mass has the role of a kind of gravitational charge, determining the strength of the pull. Consequently, this manifestation of mass is called the gravitational mass; the force produced depends on the active gravitational mass (in this case M_A and the force felt by B depends on its passive gravitational mass M_B). But we then have to use Newton's second law (2) to work out the acceleration. The acceleration of B depends then on M_B , but mass plays a

different role in this expression. In equation (2) we have the *inertial mass* of the particle which represents its reluctance to being accelerated. But Newton's third law of motion also states that if body A exerts a force on body B then body B exerts a force on body A which is equal and opposite. This means that m must also be the active gravitational mass (if you like, the gravitational charge) produced by the particle. In Newton's theory, all three of these masses - the inertial mass, the active and passive gravitational masses - are equivalent. But there seems to be no reason, on the face of it, why this should be the case. Couldn't they be different?

Einstein decided that this equivalence must be the consequence of a deeper principle called the principle of equivalence. In his own words, this means that 'all local, freely-falling laboratories are equivalent for the performance of all physical experiments'. What this means is essentially that one can do away with gravity as a separate force of nature and regard it instead as a consequence of moving between accelerated frames of reference.

To see how this is possible, imagine a lift equipped with a physics laboratory. If the lift is at rest on the ground floor, experiments will reveal the presence of gravity to the occupants. For example, if we attach a weight on a spring to the ceiling of the lift, the weight will extend the spring downwards. Next, imagine that we take the lift to the top of a building and let it fall freely. Inside the freely-falling lift there is no perceptible gravity. The spring does not extend, as the weight is always falling at the same rate as the rest of the lift, even though the lift's speed might be changing. This is what would happen if we took the lift out into space, far away from the gravitational field of the Earth. The absence of gravity therefore looks very much like the state of free-fall in response to a gravitational force. Moreover, imagine that our lift was actually in space (and out of gravity's reach), but there was a rocket attached to it. Firing the rocket would make the lift accelerate. There is no up or down in free space, but let us assume that the rocket is attached so that the lift would accelerate in the opposite direction from before, i.e. in the direction of the ceiling.

What happens to the spring? The answer is that the acceleration makes the weight move in the reverse direction relative to the lift, thus extending the spring towards the floor. (This is like what happens when a car suddenly accelerates - the passenger's head is flung backwards.) But this is just like what happened when there was a gravitational field pulling the spring down. If the lift carried on accelerating, the spring would remain extended, just as if it were not accelerating but placed in a gravitational field. Einstein's idea was that these situations do not merely appear similar: they are completely indistinguishable. Any experiment performed in an accelerated lift in space would give exactly the same results as one performed in a lift upon which gravity is acting. To complete the picture, now consider a lift placed inside a region where gravity is acting, but which is allowed to fall freely in the gravitational field. Everything inside becomes weightless, and the spring is not extended. This is equivalent to the situation in which the lift is at rest and where no gravitational forces are acting. A freely-falling observer has every reason to consider himself to be in a state of inertial motion.

Einstein now knew how he should construct the general theory of relativity. But it would take him another ten years to produce the theory in its final form

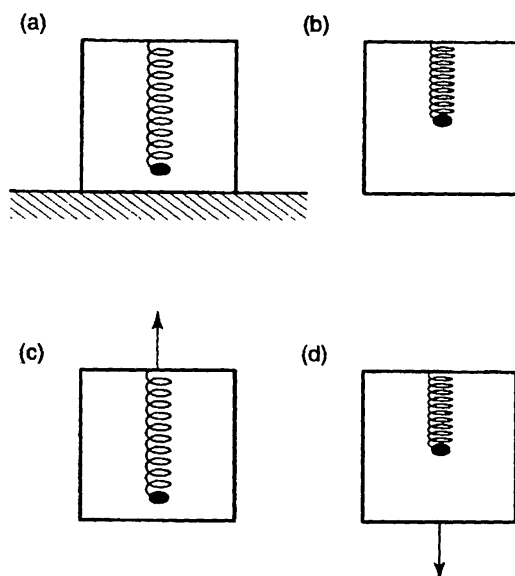


Figure 1. Thought-experiment illustrating the equivalence principle. A weight is attached to a spring, which is attached to the ceiling of a lift. In (a) the lift is stationary, but a gravitational force acts downwards; the spring is extended by the weight. In (b) the lift is in deep space, away from any sources of gravity, and is not accelerated; the spring does not extend. In (c) there is no gravitational field, but the lift is accelerated upwards by a rocket; the spring is extended. The acceleration in (c) produces the same effect as the gravitational force in (a). In (d) the lift is freely-falling in a gravitational field, accelerating downwards so no gravity is felt inside; the spring does not extend because in this case the weight is weightless and the situation is equivalent to (b).

(Einstein 1915a,b). What he had to find was a set of laws that could deal with any form of accelerated motion and any form of gravitational effect. To do this he had to learn about sophisticated mathematical techniques, such as tensor analysis and Riemannian geometry, and to invent a formalism that was truly general enough to describe all possible states of motion. He got there in 1915, and his theory is embodied in the expression

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}; \quad (4)$$

the entities G and T are tensors defined with respect to four-dimensional coordinates x_μ . The right-hand-side contains the Einstein tensor which describes the curvature of space and the tensor T is the energy-momentum tensor which describes the motion and properties of matter. Understanding the technicalities of the general theory of relativity is a truly daunting task, and calculating anything useful using the full theory is beyond all but the most dedicated specialists. While the application of Newton's theory of gravity requires one equation to be

solved, Einstein's theory (4) represents ten independent non-linear equations which are all non-linear. Because of the equivalence between mass and energy embodied in special relativity through equation (3), all forms of energy gravitate. The gravitational field produced by a body is itself a form of energy, and it also therefore gravitates. This non-linearity leads to unmanageable mathematical complexity when it comes to solving the equations. But the crucial aspect of this theory is that it relates the properties and distribution of matter to the curvature of space. This is what the 1919 expeditions were intended to test.

3. The Bending of Light: From Principles to Principle

3.1. Curvature and the Equivalence Principle

The idea that space could be warped is so difficult to grasp that even physicists don't really try to visualise such a thing. Our understanding of the geometrical properties of the natural world is based on the achievements of generations of Greek mathematicians, notably the formalised system of Euclid - Pythagoras' theorem, parallel lines never meeting, the sum of the angles of a triangle adding up to 180 degrees, and so on. All of these rules find their place in the canon of Euclidean geometry. But these laws and theorems are not just abstract mathematics. We know from everyday experience that they describe the properties of the physical world extremely well. Euclid's laws are used every day by architects, surveyors, designers and cartographers - anyone, in fact, who is concerned with the properties of shape, and the positioning of objects in space. Geometry is real.

It seems self-evident, therefore, that these properties of space that we have grown up with should apply beyond the confines of our buildings and the lands we survey. They should apply to the Universe as a whole. Euclid's laws must be built into the fabric of the world. Or must they? Although Euclid's laws are mathematically elegant and logically compelling, they are not the only set of rules that can be used to build a system of geometry. Mathematicians of the 19th century, such as Gauss and Riemann, realised that Euclid's laws represent only a special case of geometry wherein space is flat. Different systems can be constructed in which these laws are violated.

Consider, for example, a triangle drawn on a flat sheet of paper. Euclid's theorems apply here, so the sum of the internal angles of this triangle must be 180 degrees (equivalent to two right-angles). But now think about what happens if you draw a triangle on a sphere instead. It is quite possible to draw a triangle on a sphere that has three right angles in it. For example, draw one point at the 'north pole' and two on the 'equator' separated by one quarter of the circumference. These three points form a triangle with three right angles that violates Euclidean geometry.

Thinking this way works fine for two-dimensional geometry, but our world has three dimensions of space. Imagining a three-dimensional curved surface is much more difficult. But in any case it is probably a mistake to think of 'space' at all. After all, one can't measure space. What one can measure are distances between objects located in space using rulers or, more realistically in an astronomical context, light beams. Thinking of space as a flat or curved piece of paper encourages one to think of it as a tangible thing in itself, rather

than simply as where the tangible things are not. Einstein always tried to avoid dealing with entities such as 'space' whose category of existence was unclear. He preferred to reason instead about what an observer could actually measure with a given experiment.

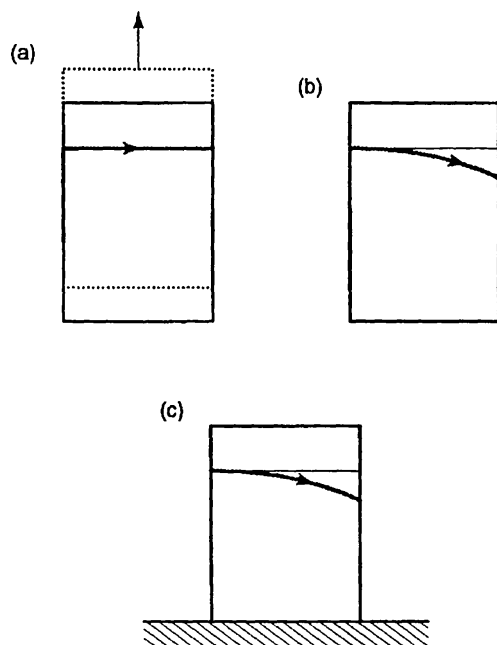


Figure 2. The bending of light. In (a), our lift is accelerating upwards, as in Figure 1(c). Viewed from outside, a laser beam follows a straight line. In (b), viewed inside the lift, the light beam appears to curve downwards. The effect in a stationary lift situated in a gravitational field is the same, as we see in (c).

Following this lead, we can ask what kind of path light rays follow according to the general theory of relativity. In Euclidean geometry, light travels on straight lines. We can take the straightness of light paths to mean essentially the same thing as the flatness of space. In special relativity, light also travels on straight lines, so space is flat in this view of the world too. But remember that the general theory applies to accelerated motion, or motion in the presence of gravitational effects. What happens to light in this case? Let us go back to the thought experiment involving the lift. Instead of a spring with a weight on the end, the lift is now equipped with a laser beam that shines from side to side. The lift is in deep space, far from any sources of gravity. If the lift is stationary, or moving with constant velocity, then the light beam hits the side of the lift exactly opposite to the laser device that produces it. This is the prediction of the special theory of relativity. But now imagine the lift has a rocket which switches on and accelerates it upwards. An observer outside the lift who is at

rest sees the lift accelerate away, but if he could see the laser beam from outside it would still be straight. He is not accelerating, so the special theory applies to what he sees. On the other hand, a physicist inside the lift notices something strange. In the short time it takes light to travel across, the lift's state of motion has changed (it has accelerated). This means that the point at which the laser beam hits the other wall is slightly below the starting point on the other side. What has happened is that the acceleration has 'bent' the light ray downwards.

Now remember the case of the spring and the equivalence principle. What happens when there is no acceleration but there is a gravitational field, is exactly the same as in an accelerated lift. Consider now a lift standing on the Earth's surface. The light ray must do exactly the same thing as in the accelerating lift: it bends downward. The conclusion we are led to is that gravity bends light. And if light paths are not straight but bent, then space is not flat but curved.

3.2. Newton and Soldner

The story so far gives the impression that nobody before Einstein considered the possibility that light could be bent. In fact, this is not the case. It had been reasoned before, by none other than Isaac Newton himself, that light might be bent by a massive gravitating object. In a rhetorical question posed in his *Opticks*, Newton wrote:

“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?”

In other words, he was arguing that light rays themselves should feel the force of gravity according to the inverse-square law. As far as we know, however, he never attempted to apply this idea to anything that might be observed. Newton's query was addressed in 1801 by Johann Georg von Soldner. His work was motivated by the desire to know whether the bending of light rays might require certain astronomical observations to be adjusted. He tackled the problem using Newton's corpuscular theory of light, in which light rays consist of a stream of tiny particles. It is clear that if light does behave in this way, then the mass of each particle must be very small. Soldner was able to use Newton's theory of gravity to solve an example of a ballistic scattering problem.

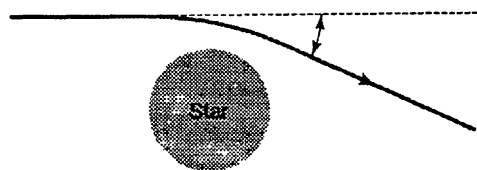


Figure 3. The ballistic scattering problem. A small body passing close to a massive one is deflected through a small angle on its way.

A small particle moving past a large gravitating object feels a force from the object that is directed towards the centre of the large object. If the particle is moving fast, so that the encounter does not last very long, and the mass of the particle is much less than the mass of the scattering body, what happens is that the particle merely receives a sideways kick which slightly alters the direction of its motion. The size of the kick, and the consequent scattering angle, is quite easy to calculate because the situation allows one to ignore the motion of the scatterer. Although the two bodies exert equal and opposite forces on each other, according to Newton's third law, the fact that the scatterer has a much larger mass than the 'scatteree' means that the former's acceleration is very much lower. This kind of scattering effect is exploited by interplanetary probes, which can change course without firing booster rockets by using the gravitational 'slingshot' supplied by the Sun or larger planets. When the deflection is small, the angle of deflection predicted by Newtonian arguments, θ_N turns out to be

$$\theta_N = \frac{2GM}{rc^2}, \quad (5)$$

where r is the distance of closest approach between scattering object and scattered body.

Unfortunately, this calculation has a number of problems associated with it. Chief amongst them is the small matter that light does not actually possess mass at all. Although Newton had hit the target with the idea that light consists of a stream of particles, these photons, as they are now called, are known to be massless. Newton's theory simply cannot be applied to massless particles: they feel no gravitational force (because the force depends on their mass) and they have no inertia. What photons do in a Newtonian world is really anyone's guess. Nevertheless, the Soldner result is usually called the Newtonian prediction, for want of a better name.

Unaware of Soldner's calculation, in 1907 Einstein began to think about the possible bending of light. By this stage, he had already arrived at the equivalence principle, but it was to be another eight years before the general theory of relativity was completed. He realised that the equivalence principle in itself required light to be bent by gravitating bodies. But he assumed that the effect was too small ever to be observed in practice, so he shelved the calculation. In 1911, still before the general theory was ready, he returned to the problem. What he did in this calculation was essentially to repeat the argument based on Newtonian theory, but incorporating equation (3). Although photons don't have mass, they certainly have energy, and Einstein's theory says that even pure energy has to behave in some ways like mass. Using this argument, and spurred on by the realisation that the light deflection he was thinking about might after all be measurable, he calculated the bending of light from background stars by the Sun.

For light just grazing the Sun's surface, i.e. with r equal to the radius of the Sun $R_\odot$ and M is the mass of the Sun $M_\odot$, equation (5) yields a deflection of 0.87 seconds of arc; for reference, the angle in the sky occupied by the Sun is around half a degree. This answer is precisely the same as the Newtonian value obtained more than a century earlier by Soldner.

The predicted deflection is tiny, but according to the astronomers Einstein consulted, it could just about be measured. Stars appearing close to the Sun

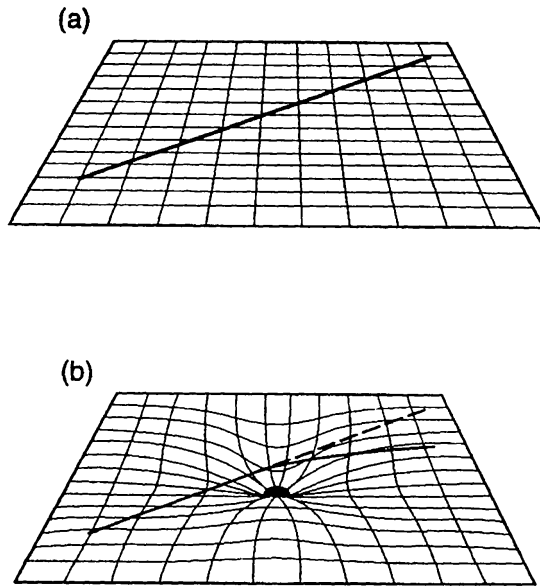


Figure 4. Curved space and the bending of light. In this illustration, space is represented as a two-dimensional surface. In the absence of any gravitating bodies, light travels in a straight line like a ball rolling on a smooth, flat table-top (a). When a massive body is placed in the way, space becomes curved: the closer you get to the body, the more curved it is (b). The effect on light is as if the ball were rolling across a table-top with a dip in the middle: it is deflected away from a straight line.

would appear to be in slightly different positions in the sky than they would be when the Sun was in another part of the sky. It was hoped that this kind of observation could be used to test Einstein's theory. The only problem was that the Sun would have to be edited out of the picture, otherwise stars would not be visible close to it at all. In order to get around this problem, the measurement would have to be made at a very special time and place: during a total eclipse of the Sun.

3.3. A Crucial Correction

But this isn't quite where we take up the story of the famous eclipse expeditions of 1919. There is a twist in the tale. In 1915, with the full general theory of relativity in hand, Einstein returned to the light-bending problem. And he soon realised that in 1911 he had made a mistake. The correct answer was not the same as the Newtonian result, but twice as large.

What had happened was that Einstein had neglected to include all effects of curved space in the earlier calculation. The origin of the factor two is quite straightforward when one looks at how a Newtonian gravitational potential dis-

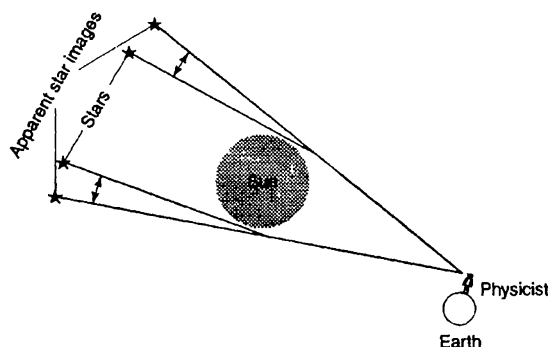


Figure 5. The bending of light by the Sun. Light from background stars follows paths like that shown in Figure 4. The result is that the stars are seen in slightly different positions in the sky when the Sun is in front of them, compared to their positions when the Sun is elsewhere.

torts the metric of space-time. In flat space (which holds for special relativity), the infinitesimal in four dimensional space-time ds is related to time intervals dt and distance intervals dl via

$$ds^2 = c^2 dt^2 - dl^2; \quad (6)$$

light rays follow paths in space-time defined by $ds^2 = 0$ which are straight in this case. of course, the point about the general theory is that light rays are no longer straight. In fact, around a spherical distribution of mass M the metric changes to that, in the weak field limit, it becomes

$$ds^2 = \left(1 + \frac{2GM}{rc^2}\right) c^2 dt^2 - \left(1 - \frac{2GM}{rc^2}\right) dl^2. \quad (7)$$

Since the corrections of order GM/rc^2 are small, one can solve the equation $ds^2 = 0$ by expanding each bracket in a power series. Einstein's original calculation had included only the first term. The second, which arises from the space curvature, doubles the net deflection. The angular deflection predicted by Einstein's equations is therefore

$$\theta_E = \frac{4GM}{rc^2}, \quad (8)$$

which yields 1.74 arc seconds for $M = M_\odot$ and $r = R_\odot$, compared to the 0.87 arc seconds obtained using Newtonian theory. Not only is this easier to measure, being larger, but it also offers the possibility of a definitive test of the theory since it differs from the Newtonian value.

In 1912, an Argentinian expedition had been sent to Brazil to observe a total eclipse. Light-bending measurements were on the agenda, but bad weather prevented them making any observations. In 1914, a German expedition, organised by Erwin Freundlich and funded by Krupp, the arms manufacturer, was sent to the Crimea to observe the eclipse due on 21 August. But when the First

World War broke out, the party was warned off. Most returned home, but others were detained in Russia. No results were obtained. The war made further European expeditions impossible. One wonders how Einstein would have been treated by history if either of the 1912 or 1914 expeditions had been successful. Until 1915, his reputation was riding on the incorrect value of 0.87 arc seconds. As it turned out, the 1919 British expeditions to Sobral and Principe were to prove his later calculation to be right. And the rest, as they say, is history.

4. Eddington and the Expeditions

The story of the 1919 expeditions revolves around an astronomer by the name of Arthur Stanley Eddington. His life and work is described by Douglas (1957) and Chandrasekhar (1983). Eddington was born in Cumbria in 1882, but moved with his mother to Somerset in 1884 when his father died. He was brought up as a devout Quaker, a fact that plays an important role in the story of the eclipse expedition. In 1912, aged only 30, he became the Plumian Professor of Astronomy and Experimental Philosophy at the University of Cambridge, the most prestigious astronomy chair in Britain, and two years later he became director of the Cambridge observatories. Eddington had led an expedition to Brazil in 1912 to observe an eclipse, so his credentials made him an ideal candidate to measure the predicted bending of light.

Eddington was in England when Einstein presented the general theory of relativity to the Prussian Academy of Sciences in 1915. Since Britain and Germany were at war at that time, there was no direct communication of scientific results between the two countries. But Eddington was fortunate in his friendship with the astronomer Willem De Sitter, later to become one of the founders of modern cosmology, and who was in neutral Holland at the time. De Sitter received copies of Einstein's papers, and wasted no time in passing them onto Eddington in 1916. Eddington was impressed by the beauty of Einstein's work, and immediately began to promote it. In a report to the Royal Astronomical Society in early 1917, he particularly stressed the importance of testing the theory using measurements of light bending. A few weeks later, the Astronomer Royal, Sir Frank Watson Dyson, realised that the eclipse of 29 May 1919 was especially propitious for this task. Although the path of totality ran across the Atlantic ocean from Brazil to West Africa, the position of the Sun at the time would be right in front of a prominent grouping of stars known as the Hyades. When totality occurred, the sky behind the Sun would be glittering with bright stars whose positions could be measured. Dyson began immediately to investigate possible observing sites. It was decided to send not one, but two expeditions. One, led by Eddington, was to travel to the island of Principe off the coast of Spanish Guinea in West Africa, and the other, led by Andrew Crommelin (an astronomer at the Royal Greenwich Observatory), would travel to Sobral in northern Brazil. An application was made to the Government Grant Committee to fund the expeditions, £100 for instruments and £1000 for travel and other costs. Preparations began, but immediately ran into problems.

Although Britain and Germany had been at war since 1914, conscription into the armed forces was not introduced in England until 1917. At the age of 34, Eddington was eligible for the draft, but as a Quaker he let it be known that

he would refuse to serve. The climate of public opinion was heavily against conscientious objectors. Eddington might well have been sent with other Quaker friends to a detention camp and spent the rest of the war peeling potatoes. Dyson, and other prominent Cambridge academics, went to the Home Office to argue that it could not be in the nation's interest to have such an eminent scientist killed in the trenches of the Somme. After much political wrangling, a compromise was reached. Eddington's draft was postponed, but only on condition that if the war ended by 29 May 1919, he must lead the expedition to Principe.

Even with this hurdle out of the way, significant problems remained. The expeditions would have to take specialised telescopes and photographic equipment. But the required instrument-makers had either been conscripted or were engaged in war work. Virtually nothing could be done until the armistice was signed in November 1918. Preparations were hectic, for the expeditions would have to set sail in February 1919 in order to arrive and set up camp in good time. Moreover, reference plates would have to be made. The experiment required two sets of photographs of the appropriate stars. One, of course, would be made during the eclipse, but the other set (the reference plates) had to be made when the Sun was nowhere near that part of the sky. In order to correct for possible systematic effects the reference plates should ideally be taken at the same site and at the same elevation in the sky: this would mean waiting at the observation site until the stars behind the Sun during the eclipse would be at the same position in the sky before dawn. This was not too much of a problem at Sobral, where the eclipse occurred in the morning but at Principe, Eddington would have to wait for several months to take his reference plates.

In the end the expeditions set off on time (in February 1919) and back home the astronomical community, particularly in Britain, chewed its collective nails. There were several possible outcomes. They might fail to measure anything, due to bad weather or some other mishap. They might measure no deflection at all, which would contradict all the theoretical ideas of the time. They might find the Newtonian value, which would humiliate Einstein. Or they might vindicate him, by measuring the crucial factor of two. Which would it be?

The June 1919 issue of *Observatory* magazine, which carries news of Royal Astronomical Society meetings and certain other matters, contains a Stop-Press item. Two telegrams had arrived. One was from Crommelin in Sobral: 'ECLIPSE SPLENDID'. The other, from Eddington, was disappointing: 'THROUGH CLOUD. HOPEFUL'. The expeditions returned and began to analyse their data. The community waited.

4.1. Measurement and Error

The full details of both expeditions can be read in the account published in *Philosophical Transactions of the Royal Society* (Dyson et al. 1920). The main items of experimental equipment were two astrographic object glasses of about 10 inches in diameter, one from Oxford and one from the Royal Greenwich Observatory. These lenses are specially designed to measure star positions over a relatively large piece of the sky and were therefore ideal for the kind of experiment being done during the eclipse. The objectives were removed from the observatories in which they were usually housed and steel tubes were built to

form temporary telescopes for the expeditions. Almost as an afterthought, it was decided to take a much smaller objective lens, 4 inches in diameter, to the Sobral site as a kind of backup.

The expeditions also took two large coelostats, mirrors used especially for solar observations. The reason for the mirrors was that no mechanical devices were available to drive the steel tubes containing the object glasses to compensate for the rotation of the Earth. The tubes had to be as long as the focal length of the lens, which in this case was about 3.5 metres, so they were difficult to move once set up. If a telescope is not moved by such a driver during the taking of a photograph, the stars move on the sky during the exposure and the images turn into streaks. In the eclipse experiment, the trick used was to keep the telescope, still but to have it pointing downwards towards the coelostat which reflects the light into the telescope lens. The mirror is much small (about 16 inches across) and a relatively small clockwork device can be used to move it to correct for the Earth's rotation instead of moving the whole telescope.

It is clear that both expeditions had encountered numerous technical problems. The day of the eclipse arrived at Principe with heavy cloud and rain. Eddington was almost washed out, but near totality the Sun began to appear dimly through cloud and some photographic images could be taken. Most of these were unsuccessful, but the Principe mission did manage to return with two useable photographic plates. Sobral had better weather but Crommelin had made a blunder during the setting up of his main telescope. He and his team had set the focus overnight before the eclipse when there were plenty of bright stars around to check the optical performance of the telescope. However, when the day of the eclipse dawned and the temperature began to rise his team watched with growing alarm as both the steel tube and the coelostat mirror began to expand with the heat. As a result, most of the main Sobral plates were badly blurred. On the other hand, the little 4-inch telescope taken as a backup performed very well and the plates obtained with it were to prove the most convincing in the final analysis.

There were other problems too. The light deflection expected was quite small: less than two seconds of arc. But other things could cause a shifting of the stars' position on a photographic plate. For one thing, photographic plates can expand and contract with changes in temperature. The emulsion used might not be particularly uniform. The eclipse plates might have been exposed under different conditions from the reference plates, and so on. The Sobral team in particular realised that, having risen during the morning, the temperature fell noticeably during totality, with the probable result that the photographic plates would shrink. The refractive properties of the atmosphere also change during an eclipse, leading to a false distortion of the images. And perhaps most critically of all, Eddington's expedition was hampered by bad luck even after the eclipse. Because of an imminent strike of the local steamship operators, his team was in danger of being completely stranded. He was therefore forced to leave early, before taking any reference plates of the same region of the sky with the same equipment. Instead he relied on one check plate made at Principe and others taken previously at Oxford. These were better than nothing, but made it impossible to check fully for systematic errors and laid his results open to

considerable criticism. All these problems had to be allowed for, and corrected if possible in the final stage of data analysis.

Scientific observations are always subject to errors and uncertainty of this kind. The level of this uncertainty in any experimental result is usually communicated in the technical literature by giving not just one number as the answer, but attaching to it another number called the 'standard error', an estimate of the range of possible errors that could influence the result. If the light deflection measured was, say, 1 arc second, then this measurement would be totally unreliable if the standard error were as large as the measurement itself, 1 arc second. Such a result would be presented as 1 ± 1 arc second, and nobody would believe it because the measured deflection could well be produced entirely by instrumental errors. In fact, as a rule of thumb, physicists never usually believe anything unless the measured number is larger than two standard errors. The expedition teams analysed their data, with Eddington playing the leading role, cross-checked with the reference plates, checked and double-checked their standard errors. Finally, they were ready.

4.2. Results and Reaction

A special joint meeting of the Royal Astronomical Society and the Royal Society of London was convened on 6 November 1919. Dyson presented the main results, and was followed by contributions from Crommelin and Eddington. The results from Sobral, with measurements of seven stars in good visibility, gave the deflection as 1.98 ± 0.16 arc seconds. Principe was less convincing. Only five stars were included, and the conditions there led to a much larger error. Nevertheless, the value obtained by Eddington was 1.61 ± 0.40 . Both were within two standard errors of the Einstein value of 1.74 and more than two standard errors away from either zero or the Newtonian value of 0.87.

The reaction from scientists at this special meeting was ambivalent. Some questioned the reliability of statistical evidence from such a small number of stars. This skepticism seems in retrospect to be entirely justified. Although the results from Sobral were consistent with Einstein's prediction, Eddington had been careful to remove from the analysis all measurements taken with the main equipment, the astrographic telescope and used only the results from the 4-inch. As I have explained, there were good grounds for this because of problems with the focus of the larger instrument. On the other hand, these plates yielded a value for the deflection of 0.93 seconds of arc, very close to the Newtonian prediction. Some suspected Eddington of cooking the books by leaving these measurements out. Others, such as Ludwick Silberstein, admonished the audience. Silberstein pointed a finger at the portrait of Newton that hangs in the meeting room, and warned: 'We owe it to that great man to proceed very carefully in modifying or retouching his Law of Gravitation.' On the other hand, the eminent Professor J.J. Thomson, discoverer of the electron and Chair of the meeting, was convinced, stating

"This is the most important result obtained in connection with the theory of gravitation since Newton's day."

For a skeptical slant on Eddington's experiment, see Collins & Pinch (1998).

Einstein himself had no doubts. He had known about the results from the English expeditions before the formal announcement in November 1919. On 27 September, he had written an excited postcard to his mother:

“ . . . joyous news today. H.A. Lorentz telegraphed that the English expeditions have actually measured the deflection of starlight from the Sun.”

He later down-played his excitement in a puckish remark about his friend and colleague, the physicist Max Planck:

“He was one of the finest people I have ever known . . . but he didn’t really understand physics, [because] during the eclipse of 1919 he stayed up all night to see if it would confirm the bending of light by the gravitational field. If he had really understood [the general theory of relativity], he would have gone to bed the way I did.”

In 1922, another eclipse, viewed this time from Australia, yielded not a handful, but scores of measured position-shifts and much more convincing statistical data. But even so, the standard error on these later measurements was of similar size, around 0.20 arc seconds. Measurements of this kind using optical telescopes to measure light deflection continued until the 1950s, but never increased much in accuracy because of the fundamental problems in observing stars through the Earth’s atmosphere. More recently, similar measurements have been made, not using optical light but radio waves. These have the advantage that they are not scattered by the atmosphere like optical light is. The light-bending measurement for radio sources rather than stars can be made almost at will, without having to wait for an eclipse. For example, every year the distant quasar 3C279 passes behind the Sun, producing a measurable deflection. These measurements confirm the Einstein prediction and it is now accepted by the vast majority of physicists that light is bent in the manner suggested by the general theory of relativity; a quantitative summary of many experimental tests can be found in Bertotti et al. (1962).

Moreover, other predictions of the general theory also seem to fit with observations: the orbital spin of the binary pulsar (Taylor et al. 1979) is a notable example because it led to the award of the 1993 Nobel Prize. Nowadays, astronomers even use the bending as a measurement tool, so confident are they of its theoretical basis. For example, distant galaxies can act as giant gravitational lenses, forming multiple images of background objects such as quasars. This effect was first detected by Walsh et al. (1979) and now is part of the standard astronomers’ toolkit; see, e.g., Peacock (2000).

5. Discussion

5.1. Einstein the Icon

The eclipse expeditions of 1919 certainly led to the eventual acceptance of Einstein’s general theory of relativity in the scientific community. This theory is now an important part of the training of any physicist and is regarded as the best we have for describing the various phenomena attributable to the action

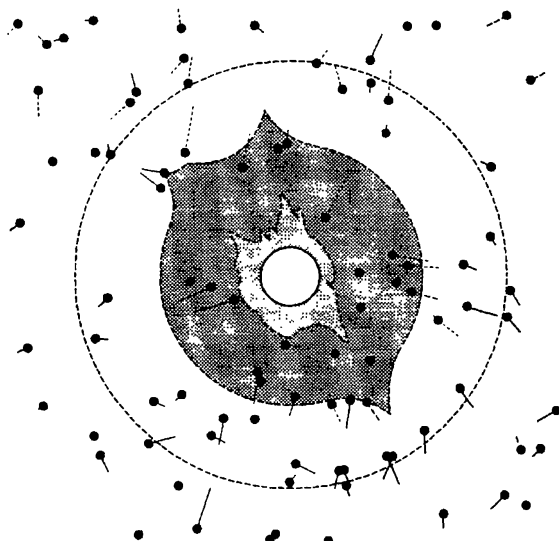


Figure 6. Changes in star positions recorded during the eclipse of 1922 and published in Campbell & Trumper (1923). The eclipsed Sun is represented by the circle in the centre of the diagram, surrounded by a representation of the coronal light. Images too close to the corona cannot be used. The recorded displacements of other stars are represented by lines (not to scale)

of gravity. The events of 1919 also established Einstein, rightly, as one of the century's greatest intellects. But it was to do much more than that, propelling him from the rarefied world of theoretical physics into the domain of popular culture. How did this happen?

Einstein, and his theory of relativity, had appeared in newspapers before 1919, mainly in the German-speaking world. He had himself written an article for *Die Vossische Zeitung* in 1914. But he had never experienced anything like the press reaction to the announcements at the Royal Society meeting in 1919. Indeed, as Abraham Pais notes in his superb biography of Einstein, the New York Times index records no mention at all of Einstein until 9 November 1919. From then until his death in 1955, not a year passed without a mention of Einstein's name.

Some of the initial attention also rubbed off on Eddington. He ran a series of lectures in Cambridge on Einstein's theory. Hundreds turned up and the lectures were packed. Eddington became one of the foremost proponents of the new theory in England, and went on to inspire a generation of astrophysicists in Cambridge and beyond. But this was nothing compared to what happened to Albert Einstein.

The London Times of 7 November 1919 carried a long article about the Royal Society meeting, headlined 'REVOLUTION IN SCIENCE. NEW THEORY OF THE UNIVERSE'. Two days later, the New York Times appeared with the headline 'LIGHTS ALL ASKEW IN THE HEAVENS'. But these splashes were not to be short-lived. Day after day, the global media ran editorials and

further features about Einstein and his theory. The man himself was asked to write an article for the *London Times*, an offer he accepted 'with joy and gratefulness'. Gradually, the press reinforced the role of Einstein as genius and hero, taking pains to position him on one side of an enormous intellectual gulf separating him from the common man. He emerged as a saintly, almost mythical character who was afforded great respect by scientists and non-scientists alike.

As years passed his fame expanded further still, into parts of popular culture that scientists had never occupied before. Einstein was invited to appear in *Variety* at the London Palladium (doing what one can only guess). He featured in popular songs, movies and advertisements. Eventually, this attention wore him down. Towards the end of his life he wrote to a friend:

“Because of the peculiar popularity which I have acquired, anything I do is likely to develop into a ridiculous comedy. This means that I have to stay close to home and rarely leave Princeton.”

No scientist working today would begrudge the fame that settled on Einstein. His achievements were stunning, with all the hallmarks of genius stamped upon them. But while his scientific contributions were clearly a necessary part of his canonisation, they are not sufficient to explain the unprecedented public reaction.

One of the other factors that played a role in this process is obvious when one looks at the other stories in the *London Times* of 7 November 1919. On the same page as the eclipse report, one finds the following headlines: 'ARMISTICE AND TREATY TERMS'; 'GERMANS SUMMONED TO PARIS'; 'RECONSTRUCTION PROGRESS'; and 'WAR CRIMES AGAINST SERBIA'. To a world wearied by a terrible war, and still suffering in its aftermath, this funny little man and his crazy theories must have been a welcome distraction, even if his ideas themselves went way over the heads of ordinary people. Here too was token of a much-needed reconciliation between Britain and Germany. In his *Times* article, Einstein stressed that science cuts across mere national boundaries, hinting that if politicians behaved more like scientists there would be no more pointless destruction on the scale that Europe had just experienced.

But there was a more human side to the Einstein phenomenon. The image of the man himself seemed to fit the public idea of what a scientist should be. He was a natural born cliché, the stereotypical absent-minded professor. With his kindly, instantly recognisable face, gentle personal manner and vaguely sham-bolic appearance, he looked like everyone's favourite uncle. Though a genius, he lacked arrogance. His political views, such as his widely publicised pacifism, meant there was always a distance between him and the establishment that had led Europe into disastrous conflict. Perhaps even the overthrow of Newton's theory of gravity was seen as a healthy kick up the backside of the old order. He filled a role that the public needed.

5.2. Science and the Media

Newton's theory of gravity was not shown to be 'wrong' by the eclipse expedition. It was merely shown that there were some phenomena it could not describe, and for which a more sophisticated theory was required. But Newton's theory still yields perfectly reliable predictions in many situations, including, for example,

the timing of total solar eclipses. When a theory is shown to be useful in a wide range of situations, it becomes part of our standard model of the world. But this doesn't make it true, because we will never know whether future experiments may supersede it. It may well be the case that physical situations will be found where general relativity is supplanted by another theory of gravity. Indeed, physicists already know that Einstein's theory breaks down when matter is so dense that quantum effects become important. Einstein himself realised that this would probably happen to his theory.

There are many parallels between the events of 1919 and coverage of similar topics in the newspapers of 1999. One of the hot topics for the media in January 1999, for example, has been the discovery by an international team of astronomers that distant exploding stars called supernovae are much fainter than had been predicted (e.g. Riess et al 1998; Perlmutter et al. 1999). To cut a long story short, this means that these objects are thought to be much further away than expected. The inference then is that not only is the Universe expanding, but it is doing so at a faster and faster rate as time passes. In other words, the Universe is accelerating. The only way that modern theories can account for this acceleration is to suggest that there is an additional source of energy pervading the very vacuum of space. These observations therefore hold profound implications for fundamental physics.

As always seems to be the case, the press present these observations as bald facts but as astrophysicists know very well they are far from unchallenged by the astronomical community. Lively debates about these results occur regularly at scientific meetings, and their status is far from established. In fact, only a year or two ago, precisely the same team was arguing for exactly the opposite conclusion based on their earlier data. But the media don't seem to like representing science the way it actually is, as an arena in which ideas are vigorously debated and each result is presented with caveats and careful analysis of possible error. They prefer instead to portray scientists as priests, laying down the law without equivocation. The more esoteric the theory, the further it is beyond the grasp of the non-specialist, the more exalted is the priest. It is not that the public want to know - they want not to know but to believe.

Things seem to have been the same in 1919. Although the results from Sobral and Principe had then not received independent confirmation from other experiments, in much the same way as the new supernova experiments have not, they were still presented to the public at large as being definitive proof of something very profound. That the eclipse measurements later received confirmation is not the point. This kind of reporting can elevate scientists to the priesthood, at least temporarily, but does nothing to bridge the ever-widening gap between what scientists do and what the public think they do. The distorted image of scientist-as-priest is likely to lead only to alienation and further loss of public respect. Science is not a religion, and should not pretend to be one.

References

- Bertotti, B., Brill, D.R., & Krotkov, R. 1962 in *Gravitation: an Introduction to Current Research*, ed. L. Witten (New York: John Wiley & Sons), 1
 Campbell, W.W. & Trumpler, R. 1923 *Lick Obs. Bull.*, 11, 41

- Chandrasekhar, S. 1983 Eddington. The Most Distinguished Astrophysicist of His Time (Cambridge: CUP) 1983
- Coles, P. 1999 Einstein and the Total Eclipse (Cambridge: Icon Books)
- Coles, P. 2000 Einstein and the Birth of Big Science (Cambridge: Icon Books)
- Collins, H.M. & Pinch, T. 1998 The Golem: What You Should Know About Science (Cambridge: CUP)
- Douglas, A.V. 1957 The Life of Arthur Stanley Eddington (London: Thomas Nelson & Sons)
- Dyson, F.W., Eddington, A.S., & Davidson, C., 1920 Philosophical Transactions of the Royal Society of London, Series A, 220, 291.
- Einstein, A. 1905 Annalen der Physik, 17, 891
- Einstein, A. 1915a Preuss. Akad. Wiss. Berlin, Sitzber., 778
- Einstein, A. 1915b Preuss. Akad. Wiss. Berlin, Sitzber., 844
- Pais, A. 1992, 'Subtle is the Lord ...' The Science and the Life of Albert Einstein (Oxford: OUP)
- Peacock, J.A. 2000 Cosmological Physics (Cambridge: CUP)
- Perlmutter, S. et al. 1999, ApJ, 517, 565
- Riess, A. et al. 1998, AJ, 116, 1009
- Taylor, J.H., Fowler, L.A. & McCullach, R.M. 1979 Nature, 277, 437
- Walsh, D., Carswell, R.F. & Weymann, R.J. 1979 Nature, 279, 381