Before we delve into the work of Eddington, there was an eight-year experimental prehistory after Einstein's 1911 prediction. The most useful modern historical study is Crispino & Paolantonio, *The first attempts to measure light deflection by the Sun*.
https://arxiv.org/pdf/1907.10687
https://arxiv.org/pdf/2004.11681

1911 — Einstein predicted that a ray grazing the Sun should be deflected by about 0.87″ and explicitly suggested that the effect might be detected photographically during a total solar eclipse. At this point an eclipse measurement would have tested Einstein's 1911 prediction, which happened to have essentially the same magnitude as the Newtonian calculation. It was not yet a test between 0.87″ and 1.75″, because Einstein did not obtain the 1.75″ prediction until 1915.

1911–12 — Erwin Finlay-Freundlich begins looking for evidence. Freundlich, working in Berlin and corresponding with Einstein, became the principal astronomer trying to turn the prediction into an observation. One idea was to remeasure photographs from earlier eclipses. He studied existing eclipse plates, including material from the Lick Observatory's 1905 and 1908 expeditions, but the stellar images were not sufficiently sharp for a meaningful sub-arcsecond determination.

10 October 1912 — The first purpose-designed attempt was made in Brazil. At Freundlich's request, Charles Dillon Perrine, director of the Argentine National Observatory at Córdoba, organised observations during the total eclipse in Brazil specifically intended to measure Einstein's predicted displacement. The Córdoba expedition established itself at Cristina, Minas Gerais. This appears to have been the first eclipse expedition deliberately equipped to measure Einstein's gravitational deflection of starlight. But rain/cloud prevented the required photographs, so there was no measurement of the 0.87″ prediction.

21 August 1914 — A much more serious attempt was made in the Crimea. Freundlich organised an expedition specifically to test the prediction during the total eclipse. Perrine's Córdoba group and a Lick Observatory expedition were also observing the eclipse from the region. But the timing could hardly have been worse, because the First World War had just begun. Freundlich, as a German in Russian territory, was detained and his equipment was seized. Weather also compromised observations by other groups. Again, no useful determination of Einstein's predicted deflection resulted.

But, had the 1912 or 1914 experiments succeeded, they would have disproved Einstein's own 1911 prediction.

Why? Because the real value is approximately 1.75″, not Einstein's then-predicted 0.87″. Einstein did not derive the full value until completing general relativity in November 1915. Crispino and Paolantonio make precisely this point.

There were further attempts after the 1915 prediction. Perrine attempted observations again during the 1916 eclipse, without obtaining a decisive measurement, and a Lick Observatory expedition attempted the measurement at the total eclipse of 8 June 1918. That attempt was also unsuccessful.

Dyson, Eddington and Davidson - **A Determination of the Deflection of Light by the Sun's Gravitational from Observations made at the Total Eclipse of May 29, 1919**.

This is a kind of crib sheet designed to simply track and explain key facts.

Purpose

The purpose of the expeditions was to determine what effect, if any, is produced by a gravitational field on the path of a ray of light traversing it.

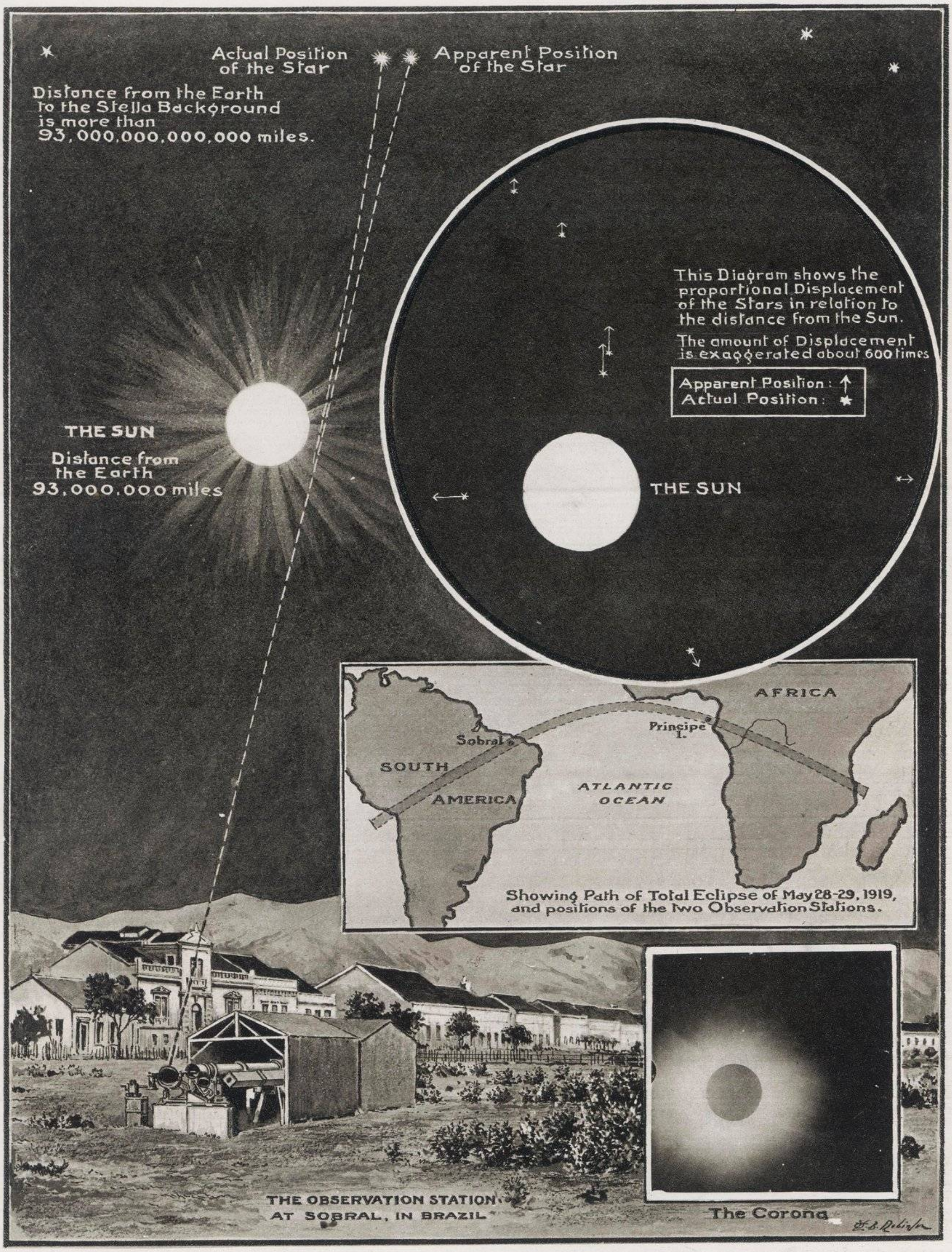
Three alternatives:-
- uninfluenced by gravitation
- energy or mass of light is subject to gravitation in the same way as ordinary matter. This means that the law of gravitation is strictly Newtonian, and the apparent displacement of a star close to the Sun's limb would amount to 0.87" outward
- Einstein's generalised relativity predicted an apparent displacement of a star at the limb amounting to 1.75" outwards.

"The Sun's limb" is a standard technical astronomical expression. It means the apparent edge of the Sun's visible disk as seen from the observer. So a light ray "grazing the solar limb", mean a ray whose closest apparent path passes essentially tangent to that visible edge. That is the reference case for the quoted maximum deflections.

N.nn" is arcseconds or the angular change in the star's apparent direction on the sky, as seen by the observer on

"STARLIGHT BENT BY THE SUN'S ATTRACTION": THE EINSTEIN THEORY.

DRAWN BY W. B. ROBINSON, FROM MATERIAL SUPPLIED BY DR. CROMMELIN.



THE CURVATURE OF LIGHT: EVIDENCE FROM BRITISH OBSERVERS' PHOTOGRAPHS AT THE ECLIPSE OF THE SUN.

The results obtained by the British expeditions to observe the total eclipse of the sun last May verified Professor Einstein's theory that light is subject to gravitation. Writing in our issue of November 15, Dr. A. C. Crommelin, one of the British observers, said: "The eclipse was specially favourable for the purpose, there being no fewer than twelve fairly bright stars near the limb of the sun. The process of observation consisted in taking photographs of these stars during totality, and comparing them with other plates of the same region taken when the sun was not in the neighbourhood. Then if the starlight is bent by the sun's attraction, the stars on the eclipse plates would seem to be pushed outward compared with those on the other plates. . . . The second Sobral camera and the one used at Principe agree in supporting (Einstein's theory). . . . It is of profound philosophical interest. Straight lines in Einstein's space cannot exist; they are parts of gigantic curves."—[*Drawing Copyrighted in the United States and Canada.*]

Earth. This is for a light ray that just grazes the visible limb of the Sun.

The word “outward” refers to the apparent position of the star on the sky. The light ray itself is bent toward the Sun by gravity, but when we extend the arriving ray backwards to infer where the star is, the star appears displaced away from the Sun.

And the angle is measured at the observer, i.e. it is the angle between the direction in which the star would appear without solar deflection and the direction in which it appears during the eclipse.

For scale, 0.87" is extraordinarily small. The apparent diameter of the Sun is about 1,900 arcseconds, so the Newtonian displacement is only about 1/2,200 of the Sun’s apparent diameter. Einstein’s 1.75" is about 1/1,100.

Imagine dividing the Moon's visible diameter into roughly 2,000 pieces: one piece is about an arcsecond.

Aside - How did Einstein first determine 0.87"?

https://onlinelibrary.wiley.com/doi/abs/10.1002/andp.19113401005

Einstein started with his Principle of Equivalence which states that within a sufficiently small region of space and time, the effects observed in a laboratory at rest in a gravitational field are indistinguishable from those observed in a laboratory accelerating at the corresponding rate in the absence of gravity.

For example, an observer in a closed laboratory standing on Earth sees a released object accelerate towards the floor. An observer in an identical laboratory in gravity-free space, but moving upwards with the same acceleration, sees the same thing, i.e. the floor accelerates towards the released object. From experiments confined to the laboratory, the observer cannot distinguish the two situations.

The older expression was that “a gravitational field is indistinguishable from a spurious field of force produced by an acceleration of the axes of reference”, but it means exactly the same thing. “Axes of reference” means the coordinate system/reference frame from which a measurement is made. If that reference frame is accelerating, objects appear to experience forces even though no physical force is acting on them. These are what the sentence calls “spurious fields of force”, but today we would normally say inertial or fictitious forces.

In simple terms an accelerating laboratory with no gravitational field produce the same observed behaviour as a stationary laboratory with a gravitational field. The “spurious” force isn't saying gravity is unreal. It simply means that acceleration of your reference frame itself can create apparent forces in your description of motion.

Einstein then applied this reasoning to light. He imagined firing a horizontal beam of light across an upwardly accelerating lift. Relative to the lift, the light reaches the opposite wall at a point slightly lower than where a straight horizontal line drawn on the lift would meet it. To the observer in the accelerating lift, the light follows a downward-curving path. In 1911, by the equivalence principle, Einstein argued that light in a gravitational field must behave equivalently. Its trajectory must be deflected toward the gravitating body.

The important logical step is that acceleration makes light appear to curve, that acceleration is locally equivalent to gravity, therefore gravity must also deflect light. This established the *existence and direction* of the effect, but by itself is not yet the complete solar calculation.

In the 1911 paper he argued from the equivalence principle that clocks at different gravitational potentials run at different rates. Expressed using the coordinates of a stationary observer, this means that the coordinate velocity of light depends on gravitational potential.

Near the Sun,

$$\Phi = -GM_\odot/r$$

where Φ is the gravitational potential at the point where the light is passing. It is gravitational potential energy per unit mass, measured in J/kg, equivalently m^2/s^2. The negative sign reflects the convention that the potential is zero infinitely far from the Sun and becomes negative closer to it.

G is the universal gravitational constant,

$$6.67430 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$$

$M_\odot$ is the mass of the Sun, approximately 1.9885×10^{30} kg

r is the distance from the centre of the Sun to the point at which the gravitational potential is being calculated.

A spatial variation in propagation speed bends a ray. This is analogous mathematically to geometrical optics, when if the propagation speed varies from place to place, the direction of a ray changes. Einstein integrated this effect along the trajectory of a ray passing the Sun.

For a ray whose closest approach is R, his calculation gave

$$\alpha_{1911} \simeq 2GM_{\odot}/Rc^2$$

And for a grazing ray, $R = R_{\odot}$, gave approximately 0.87″ for the solar-limb prediction. The crucial historical point is that 0.87″ is actually Einstein's first prediction as well as the Newtonian value. The famous 1.75″ came only with the full general theory of relativity in 1915, when the effect associated with spatial curvature supplied the additional deflection.

So Einstein's 1911 accelerating-lift argument told him that gravity must affect light. He also realised that clocks run at different rates at different gravitational potentials. Expressed in the coordinates of a stationary observer, this can be described as the coordinate speed of light varying with gravitational potential.

This was already a remarkable prediction. But the underlying geometrical picture was incomplete. Einstein was essentially allowing gravity to affect time, while his treatment of the spatial geometry was still effectively Euclidean for this calculation.

Why is this mentioned as a Newtonian prediction?

Because it was Johann Georg von Soldner who had obtained essentially the same half-value in 1801 using Newtonian corpuscular mechanics, despite starting from a completely different physical picture. Einstein apparently did not derive his 1911 result from Soldner.

https://onlinelibrary.wiley.com/doi/epdf/10.1002/andp.202100203

If light consists of rapidly moving particles, and gravity acts on matter universally, shouldn't a light particle passing a massive body also be gravitationally deflected?
This was a perfectly reasonable question within the Newtonian corpuscular conception of light then still viable. Soldner explicitly treated a light ray as if it were a material body subject to gravitational attraction.

Imagine a light corpuscle approaching the Sun with velocity c. If there were no Sun, it would travel in a straight line, but as it passes the Sun, Newtonian gravity continuously accelerates it towards the Sun. If the corpuscle is moving enormously fast, it will not fall into the Sun. Instead, its otherwise straight trajectory is bent slightly, just as the trajectory of a comet passing the Sun is bent. In Newtonian mechanics the resulting path is an open hyperbolic orbit.

Soldner estimated a deviation of 0.84", and Einstein, obtained the same numerical answer (0.87") from quite different physical arguments.

Soldner was thinking as an astronomer concerned with positional accuracy. At the beginning of his paper he argues that as practical astronomy becomes more precise, theory must identify even very small effects that could alter the measured position of a celestial object. He then remarks that, if fixed stars could be observed sufficiently close to the Sun, this gravitational deflection would have to be taken into account.

So the idea of looking for gravitationally displaced stellar positions near the Sun was already more than a century old.

What changed in 1915, and why did the predicted deflection double?

Einstein's 1911 calculation had already established that gravity should affect light. Starting from the Principle of Equivalence, he argued that a gravitational field changes the rate of clocks and, when described using the coordinates of a stationary observer, changes the coordinate speed at which light propagates through different gravitational potentials. The calculation was incomplete, however, because Einstein had not yet constructed a theory in which the geometry of space as well as time was determined by gravity.

By November 1915 Einstein's general theory of relativity made a much more fundamental statement,

Gravity is not fundamentally a force acting between bodies within an independently existing Euclidean space and universal time. The distribution of mass and energy determines the geometry of spacetime, and freely moving matter and light follow paths determined by that geometry.

Near a massive body such as the Sun:
- clocks behave differently depending upon gravitational potential
- spatial measurements also don't have the relationships they would have in ordinary Euclidean geometry.

That second effect is what is meant by spatial curvature.

What does “spatial curvature” actually mean?

It does not mean that ordinary three-dimensional space is literally being bent like a rubber sheet into some external fourth spatial dimension. No external dimension is required. Curvature can be defined intrinsically, by measurements made within the space itself.

The familiar example is the surface of a sphere. On a flat plane, the circumference of a circle is

$$C = 2\pi r$$

On the surface of a sphere, if both circumference and radius are measured along the surface, that relationship is no longer exact.

Similarly, around the Sun, the relationship between radial distances and circumferences is not exactly the Euclidean relationship. The difference is extraordinarily small in the Sun's weak gravitational field, but it is real in general relativity. That is what “*space is curved*” means operationally. The rules relating measured distances and directions differ from Euclidean geometry.

General relativity does not say that a gravitational force grabs the photon and pulls it sideways in the Newtonian sense.

Light follows the locally straightest possible trajectories through spacetime, called null geodesics.

Because the spacetime geometry around the Sun is curved, a trajectory that is locally straight throughout its journey does not correspond to a globally straight line when compared with the geometry far from the Sun. The result is the observed deflection.

Mathematically...

Einstein's crucial 1915 step was to replace the fixed geometry of special relativity with a metric whose values depend upon the distribution of mass and energy.

The metric defines how measurements of time, distance and direction are related at every point in spacetime. Around the Sun, both its time and spatial components differ slightly from their values in flat spacetime.

We can start with a flat two-dimensional sheet, if you move a tiny distance dx horizontally and dy vertically, Pythagoras gives the actual distance

$$ds^2 = dx^2 + dy^2.$$

In three-dimensional Euclidean space:

$$ds^2 = dx^2 + dy^2 + dz^2.$$

So ds is the actual physical interval between two neighbouring points, while dx, dy, dz describe their coordinate differences.

Einstein's special relativity combines space and time. In one common sign convention,

$$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2.$$

Here:
dt is a small difference in time
dx, dy, dz are small differences in spatial coordinates
c is the speed of light
ds^2 is the the spacetime interval.

So far, spacetime is flat.

In general relativity, the relationship depends on the gravitational field. Einstein therefore writes the general relationship compactly (in tensor notation), as

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$$

which is essentially a generalised Pythagoras theorem for spacetime.

Now unpack the notation.

x^μ simply represents the four spacetime coordinates,

$$x^\mu = (ct, x, y, z).$$

The Greek index μ therefore means one of the four spacetime coordinates. Similarly for ν.

The $g_{\mu\nu}$ is the metric tensor. In practical terms, it is a set of numbers that tells you how coordinate differences are converted into actual spacetime intervals at that location.

The repeated indices mean that we sum over all four coordinates. So

$g_{\mu\nu}\, dx^{\mu}\, dx^{\nu}$ is shorthand for a collection of terms involving *dt, dx, dy, dz.*

$g_{\mu\nu}$ matters for the Sun. Without, the metric has the simple flat-spacetime form, but with the Sun the metric changes.

The Sun's mass-energy determines $g_{\mu\nu}$, and therefore changes the geometrical relationship between time, distance and direction around it.

This is the mathematical meaning behind the verbal statement "the Sun curves spacetime".

It means that the $g_{\mu\nu}$ describing spacetime around the Sun, is not the flat-spacetime metric. But for light (photons),

$$ds^2 = 0.$$

This does not mean that the photon goes nowhere. It means that the spacetime interval along a light ray is a null interval.

Consequently, once you know the Sun's $g_{\mu\nu}$, you can calculate the paths satisfying the appropriate null-geodesic equations. Those paths are not straight lines in the ordinary Euclidean sense.

That ultimately produces

$$\alpha_{GR} \simeq 4GM_{\odot}/R_{\odot}c^2 = 1.75''$$

So general relativity described gravity not as a force acting within otherwise ordinary space, but as curvature of four-dimensional spacetime produced by mass-energy. Light follows the straightest possible paths (so-called null geodesics) through this curved spacetime.

For the Sun, the curvature of the spatial part of spacetime contributes an additional deflection approximately equal to the effect already obtained in 1911.

The equation of α_{GR} is often presented as a leading-order weak-field GR (General Relativity) result.

"Weak-field" means that the gravitational field is sufficiently weak that the dimensionless quantity $GM_\odot/R_\odot c^2$ is much smaller than 1.

"Leading-order term" means that the equation here is not complete, but the first term is dominant and a very good approximation (the second-order correction is only of order 10 microarcseconds, roughly 0.00001").

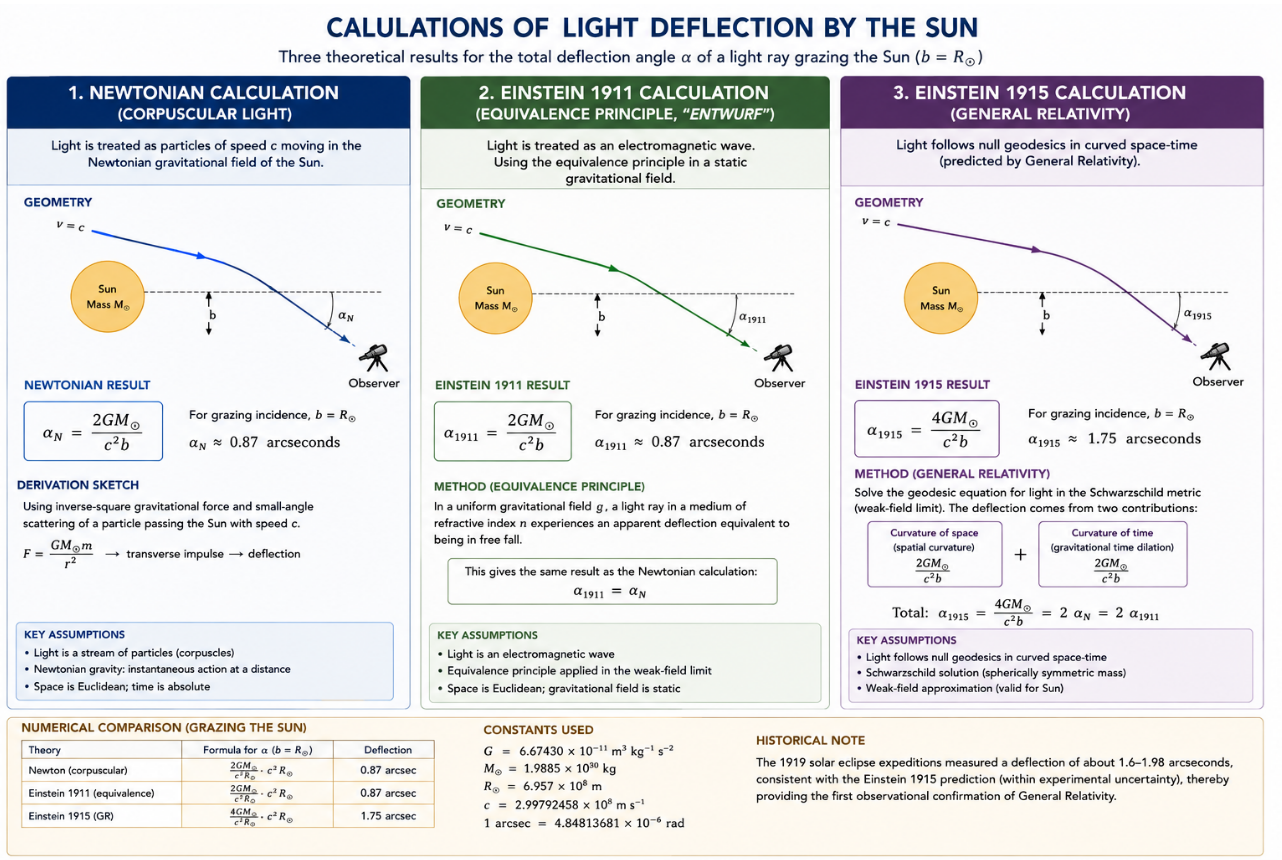
Remember - the assumption was that the electromagnetic energy of a beam of light would be subject to gravitation in precisely the same way as ordinary matter, so both Newton and Einstein predicted a displacement, the question was how much.

Now, the task was to observe a ray of light from a star passing near the Sun. And that meant the measurement must be made during a total eclipse of the Sun.

Remember - Einstein's theory was also confirmed by the motion of the perihelion of Mercury.
But his theory also predicted a displacement to the red of the Fraunhofer lines on the Sun amounting to about 0.008 A in the violet. Which had not been observed. The experiment

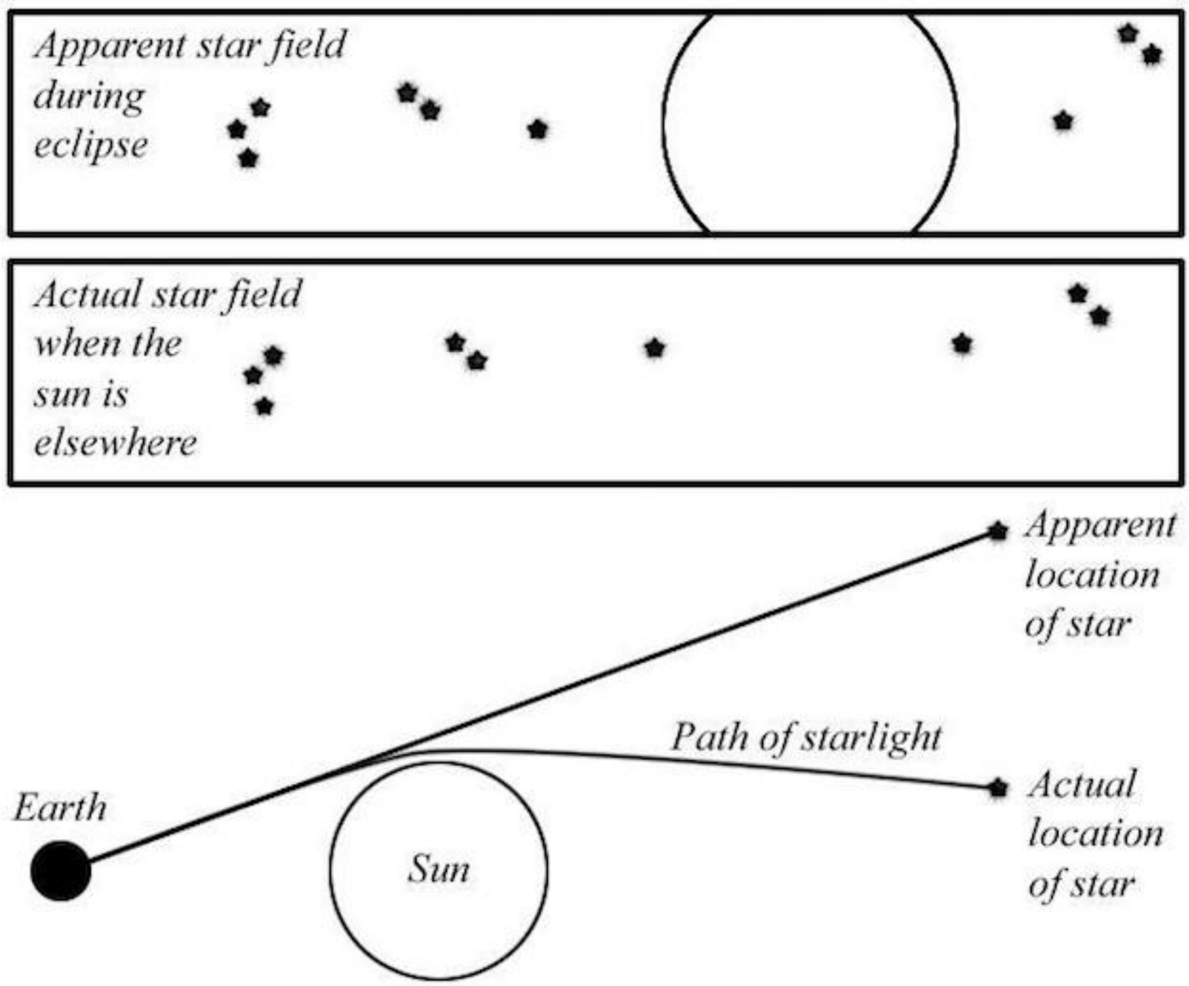
was straightforward in principle, measure a particular atomic line in the laboratory, then measure the corresponding Fraunhofer line in sunlight, and see whether the solar line is displaced slightly towards the red. However, the predicted displacement was extremely small, and the Sun is not a clean laboratory source. Motions of solar gas produce Doppler shifts, pressure and convection affect spectral lines, different lines form at different heights, rotation contributes shifts, and line profiles can be asymmetric. Consequently, around 1919 the expected systematic gravitational redshift had not been established convincingly.

It was after this successful experiment that Einstein's law of gravitation was seen to predict the true deviations from the Newtonian law, both for the relatively slow-moving planet Mercury and for the fast-moving waves of light.



Aside - Why did they decide to do this experiment?

The initiative was substantially institutional, and Frank Watson Dyson, the Astronomer Royal, was central. Einstein's 1915 general relativity provided an unusually clean astronomical test, i.e. light passing close to the Sun should be deflected by about 1.75″, whereas the earlier Einstein/Newtonian-type calculation gave about 0.87″. The difficulty was observational, because stars sufficiently close to the Sun cannot normally be photographed because of daylight and the Sun's glare. A total solar eclipse temporarily removes that problem.



The decisive step came in March 1917. Examination of photographs taken with the Greenwich astrographic telescope during the 1905 eclipse at Sfax showed that such an instrument should be capable of recording stars sufficiently faint for the experiment.

Astronomers then examined the circumstances of forthcoming eclipses and recognised that 29 May 1919 was exceptionally favourable: during totality the Sun would lie in the rich Hyades star field, providing an unusually large number of comparatively bright stars around it. They estimated that about twelve stars could be photographed under reasonable conditions. The coincidence of a total eclipse with such an exceptionally favourable stellar field was extremely rare. Eddington later remarked that such an opportunity might otherwise require a wait of thousands of years.

So the logic was very practical. The 1905 photographs showed that the required stars could be photographed, and the 1919 eclipse provided an exceptionally rich star field.

On 10 November 1917, the Joint Permanent Eclipse Committee of the Royal Society and Royal Astronomical Society decided, if circumstances permitted, to send expeditions to Sobral and Príncipe. A subcommittee comprising Dyson, Eddington, Alfred Fowler and H. H. Turner organised the project. This was still during the First World War, and whether the expeditions could actually leave Britain remained uncertain until late 1918.

Who actually did what?

Frank Watson Dyson was Astronomer Royal and Director of the Royal Observatory Greenwich, and was the principal organiser of the experiment. He did not travel to either eclipse site. The Greenwich Observatory supplied instruments and staff, and Dyson subsequently played a major role in the analysis and interpretation of the Sobral observations. Modern historical work particularly stresses that the project should not simply be regarded as Eddington's personal experiment.

Arthur Stanley Eddington was Director of Cambridge Observatory and one of Britain's leading experts on Einstein's relativity. He helped organise the project and travelled to Príncipe. His companion was Edwin Turner Cottingham, a skilled instrument maker/clock mechanic associated with Cambridge Observatory. Cottingham's technical expertise was important, since he knew how to operated and maintained the coelostat system while Eddington dealt with the telescope and photographic plates.

Andrew Claude de la Cherois Crommelin and Charles Rundle Davidson, were both astronomers from the Royal Observatory Greenwich. In Sobral they, not Eddington, obtained the photographs from which the experiment's best result, 1.98″ ± 0.12″ probable error, was ultimately derived. Contemporary reports explicitly identify Crommelin and Davidson as the Sobral observers.

The original plan was actually for Davidson and Father Aloysius Cortie to go to Sobral, but Cortie could not spare the necessary time and was replaced by Cornelian.

We do not know who first identified the 29 May 1919 eclipse and the Hyades field as the exceptional opportunity.

Preparations

The section in the original paper mixes scientific planning, expedition administration and engineering construction.

Each has its importance as a historical description of a major experiment of the time.

In March 1917, astronomers recognised that the total solar eclipse of 29 May 1919 offered an unusually favourable opportunity to measure the gravitational deflection of starlight. During the eclipse the Sun would lie in front of an unusually rich field of relatively bright stars in the Hyades.

The feasibility of photographing these stars was not simply assumed, but photographs obtained during the 1905 total eclipse at Sfax, Tunisia, showed that if conditions in 1919 were at least as good as those at Sfax, approximately twelve useful stars should appear on the plates.

Before the expedition, therefore, the astronomers already knew the positions and photographic magnitudes of the candidate stars and calculated the gravitational displacement expected for each one. Einstein's 1915 prediction was taken as a radial displacement

$$\alpha(r) \simeq 1.75'' \, r_0/r$$

where $\alpha(r)$ predicted angular displacement of the star, r_0 the apparent angular radius of the Sun, and r the apparent angular distance of that particular star from the centre of the Sun.

Thus 1.75″ applied only to a hypothetical ray grazing the solar limb, for which $r = r_0$. The actual stars were farther from the Sun, $r > r_0$, and were therefore expected to show smaller displacements.

Selection of the observing sites

The path of totality crossed northern Brazil, the Atlantic, Príncipe and central Africa. Possible observing stations were investigated principally for weather conditions and the altitude of the Sun.

A station near Lake Tanganyika was rejected because the Sun would be too low in the sky, and atmospheric refraction would then introduce comparatively large positional corrections. Meteorological information indicated that Sobral in northern Brazil was the best Brazilian site. Príncipe, an island off the west coast of Africa, provided a second suitable site.

On 10 November 1917, the Joint Permanent Eclipse Committee decided, if circumstances permitted, to send expeditions to both Sobral and Príncipe.

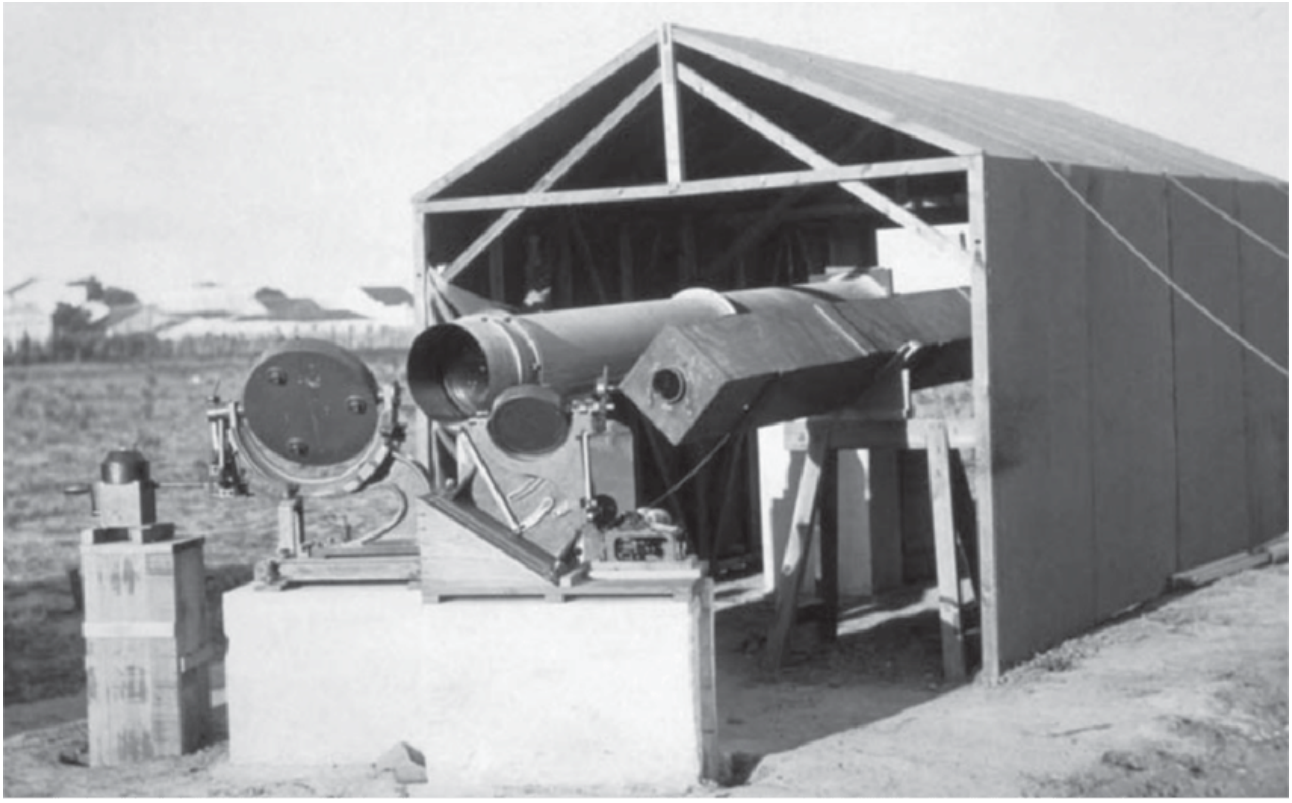
The principal optical instruments

The two expeditions were intended to use essentially comparable optical systems.

The crucial components borrowed from the observatories were not complete telescopes but the objective lenses, or “object glasses,” from existing astrographic telescopes:

- Sobral: the object glass from the Greenwich astrographic telescope
- Príncipe: the object glass from the Oxford astrographic telescope.

Each astrographic objective had a nominal aperture of approximately 13 inches (33 cm) and a focal length of 3.43 m (11 ft 3 in). For the eclipse observations the effective aperture was reduced, or stopped down, to 8 inches.



The 16-inch lens and large coelostat (on the left) and the smaller 4-inch telescope in a square box (on the right), with its much smaller coelostat on location at Sobral, Brazil. (Courtesy of the Science Museum, London.)

An astrograph is a telescope specifically designed for accurate astronomical photography and measurement of star positions, rather than primarily for visual observation.

What this means in practice is that an astrograph had a wide, well-corrected field of view. It was designed to produce sharp stellar images not merely on the optical axis but across a relatively large photographic plate. This is crucial because Eddington's experiment compared the positions of several stars spread across the field.