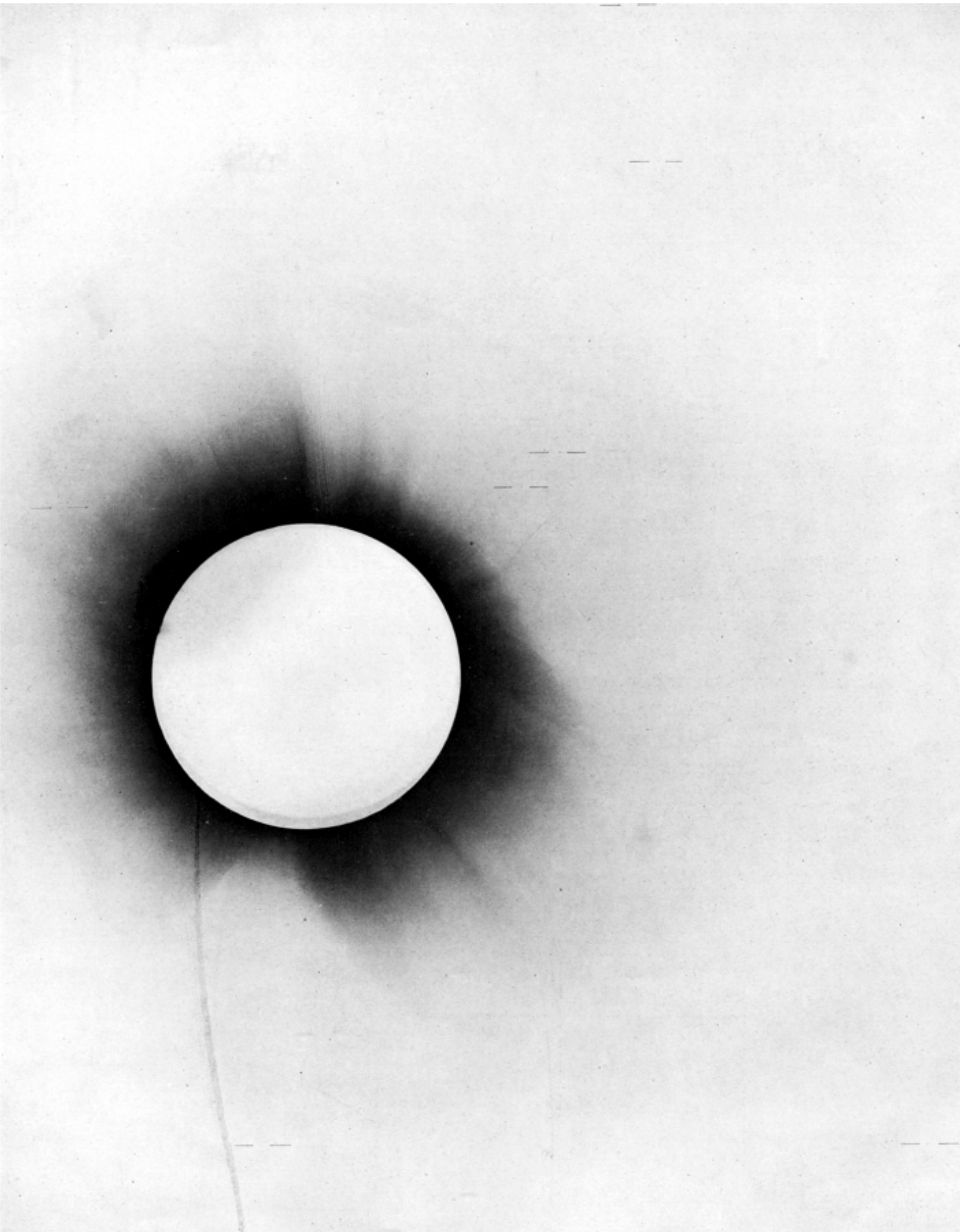
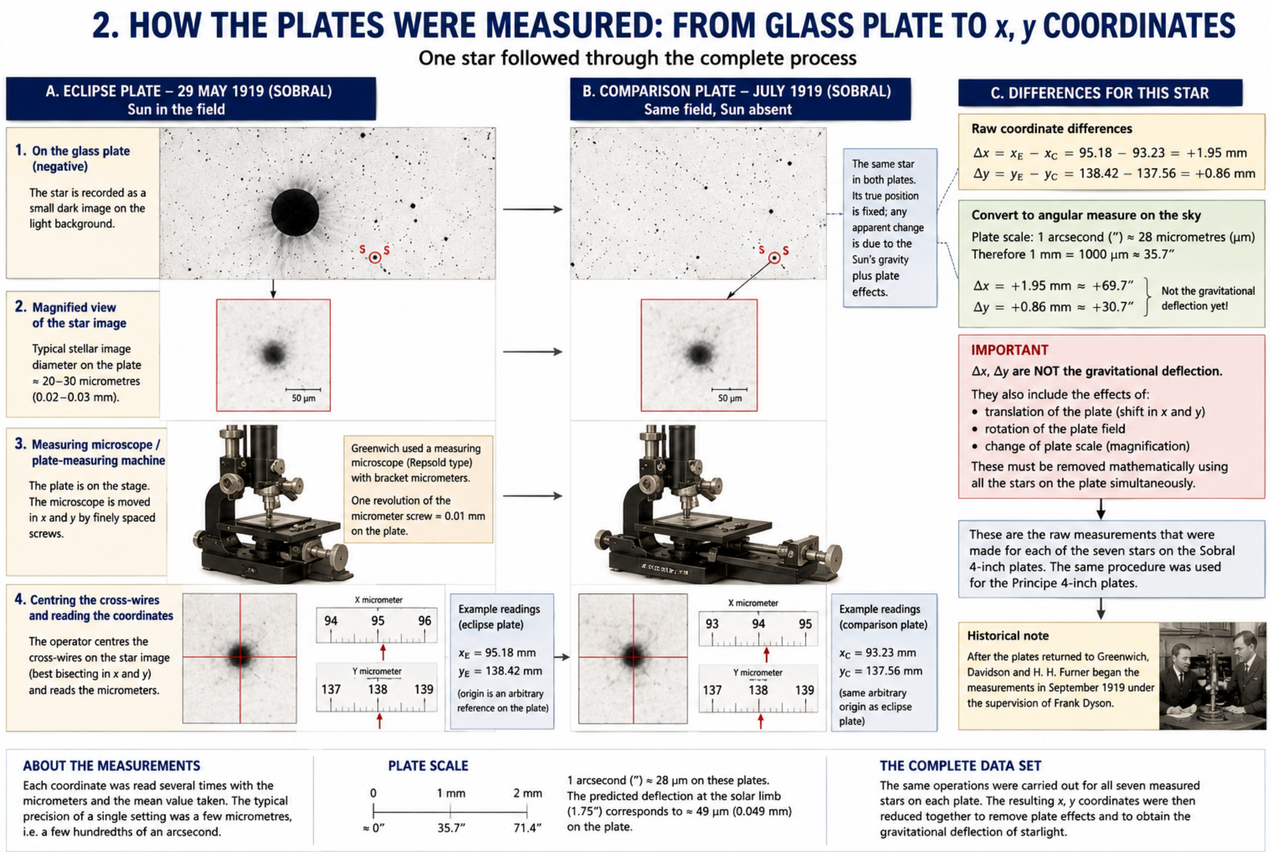
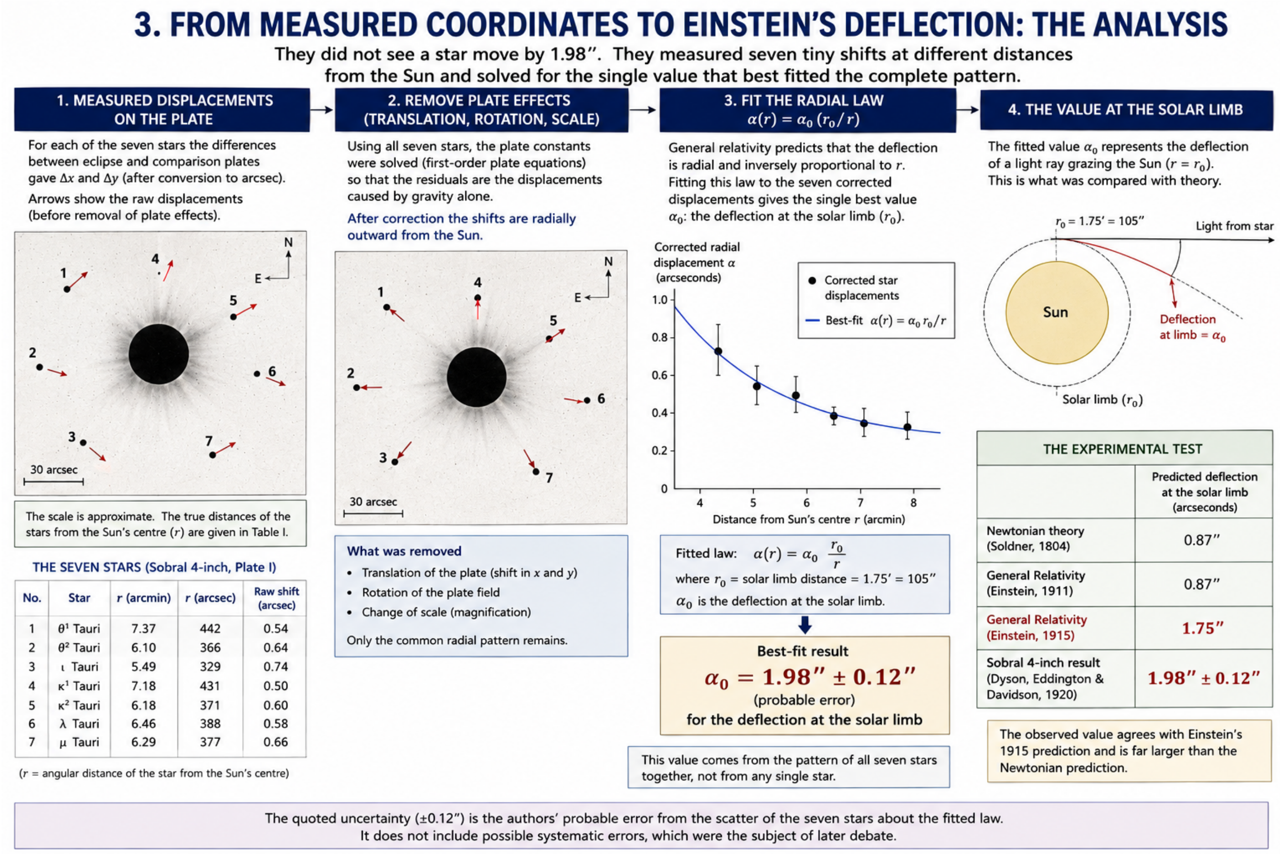


Negative of the 1919 solar eclipse taken from the report of Sir Arthur Eddington on the expedition to verify Einstein's prediction of the bending of light around the sun.



The eclipse and comparison plates contained images of the same stars, photographed with and without the Sun in the field.
Using a precision plate-measuring microscope, the observer centred cross-wires on each stellar image and measured its x and y coordinates on both plates.
Subtracting these coordinates gave the apparent displacement of each star, but not yet its gravitational deflection: the differences also contained changes in plate position, rotation and scale.
These geometrical effects therefore had to be determined from the complete set of stellar measurements and removed mathematically before the much smaller gravitational displacement could be extracted.



From measured coordinates to the solar-limb deflection. The seven useful Sobral stars were measured on both eclipse and comparison plates, giving small differences in x and y. These raw differences also contained plate translation, rotation and changes of scale, which were solved for and removed using the complete set of stars. The remaining displacements were then tested for the radial 1/r pattern predicted by Einstein, and the best-fitting value was expressed as the equivalent deflection for a ray grazing the Sun. The preferred Sobral 4-inch result was 1.98″ ± 0.12″ probable error, compared with 1.75″ predicted by general relativity and about 0.87″ from the Newtonian/1911 calculation.

The 1.98″ value was not the measured displacement of any one star. It was the solar-limb value inferred from the combined pattern of all seven stars.

The 6 November 1919 announcement

The results were formally announced on 6 November 1919 at a special joint meeting of the Royal Society and the Royal Astronomical Society in London. The results were presented by Frank Dyson, the Astronomer Royal, Arthur Eddington and Andrew Crommelin. Dyson presented the principal experimental results, with Crommelin reporting on the Sobral expedition and Eddington discussing the Príncipe observations and their implications.

What they announced was more cautious than the legend that subsequently developed. The preferred Sobral 4-inch photographs gave 1.98″, while the less precise Príncipe observations gave 1.61″. Both supported Einstein's general-relativistic prediction of approximately 1.75″ rather than the approximately 0.87″ value associated with the Newtonian calculation and Einstein's 1911 result.

The troublesome Sobral astrographic photographs gave a substantially smaller value, but the investigators regarded them as unreliable because the telescope had changed focus and scale during the eclipse. Their eventual published conclusion was that the Sobral and Príncipe results left “little doubt” that the deflection was of the amount required by Einstein's theory.

The reaction at the meeting was enthusiastic but not simply unquestioning. J. J. Thomson, President of the Royal Society and discoverer of the electron, described the result as of extraordinary interest and regarded it as the most important result concerning gravitation since Newton.

Scientific discussion nevertheless continued over the reliability of the very small photographic displacements and possible systematic effects; within weeks, for example, Alexander Anderson proposed atmospheric refraction as a possible explanation, which Eddington and subsequently Arthur Schuster analysed and rejected.

The transformation into a world event occurred the following morning. *The Times* of 7 November reported the meeting under the famous headlines:

REVOLUTION IN SCIENCE
NEW THEORY OF THE UNIVERSE
NEWTONIAN IDEAS OVERTHROWN

That was much stronger language than the astronomers themselves had used. Einstein's theory did not overthrow Newtonian gravity in the sense of making it useless. Newton's equations remain the extremely accurate weak-field, low-velocity approximation. What the eclipse observations indicated was that Newtonian gravitation was not the complete description of gravity.

What later experiments found

The 1919 eclipse observations were historically decisive, but they were not a precision test by modern standards. Later eclipse expeditions repeated the photographic experiment with improving instruments and generally supported the general-relativistic prediction, but eclipse photography remained intrinsically difficult, e.g. atmospheric seeing, temperature changes, optical distortion and photographic plate scale all limited the attainable accuracy.

Early eclipse measurements typically constrained the relativistic result only at the level of tens of percent.

The decisive improvement came when astronomers no longer needed an eclipse.

Compact extragalactic radio sources could be observed as their apparent positions approached the Sun, and very-long-baseline interferometry (VLBI) could compare their positions using radio telescopes separated by thousands of kilometres. By 1984, VLBI measurements gave the relativistic parameter

$$\gamma = 1.008 \pm 0.005,$$

where general relativity predicts exactly $\gamma=1$.

γ is the Parameterised Post-Newtonian (PPN) parameter measuring the amount of spatial curvature produced by mass. General relativity predicts $\gamma=1$, whilst the old Newtonian/Einstein-1911 light-deflection value corresponds effectively to $\gamma=0$. Measuring solar light deflection therefore provides a direct experimental test of the spatial-curvature component of general relativity.

By 1991, solar gravitational deflection could be measured with positional accuracy better than 1 milliarcsecond, compared with the arcsecond-scale accuracy of the eclipse experiments.

Large VLBI datasets subsequently improved the test still further, while independent measurements of the closely related gravitational time delay of radio signals provided even tighter constraints. The 2002 Cassini experiment, for example, measured the parameter γ with an uncertainty of about $2.3\times10{-}5$, again consistent with general relativity.

Thus 1919 was historically decisive, but not a precision test by modern standards. Its importance was that two independent eclipse expeditions obtained results favouring Einstein's 1.75″ prediction over the approximately 0.87″ Newtonian/1911 value. During the following century, increasingly precise and quite different experimental techniques confirmed the same relativistic description of the propagation of light through the Sun's gravitational field.

Historical Discussion - Everything is never plain sailing

There was **immediate technical criticism** of the 1919 results, although the famous accusation that Eddington had selectively discarded inconvenient data is a **much later controversy**.

The **1919–20 controversy** was normal scientific argument. Were the displacements real? Could atmospheric refraction or instrumental effects explain them? How reliable were these very difficult photographic measurements?

A. Anderson, “The Deflection of Light during a Solar Eclipse,” *Nature* 104 (1920), p. 436.
A. S. Eddington, “The Deflection of Light during a Solar Eclipse,” *Nature* 104 (1919), p. 372.
Arthur Schuster, “The Deflection of Light during a Solar Eclipse,” *Nature* 104 (1920), p. 468.

A particularly useful contemporary exchange is in *Nature* immediately after the November 1919 announcement. Alexander Anderson of University College Galway proposed that the apparent stellar displacement might have been caused by atmospheric refraction associated with temperature changes in the Moon's shadow, rather than gravity. Eddington responded in December 1919, arguing that the proposed atmospheric effect would be too small. Arthur Schuster then independently analysed Anderson's suggestion and concluded that the effect was vastly too small to explain the observations.

It is normal that the results were questioned almost immediately, but the contemporary controversy concerned possible experimental and atmospheric errors.

The accusation that Eddington deliberately selected the data to favour Einstein belongs largely to a later historiographical controversy.

The much more famous “Eddington cooked the data because he wanted Einstein to win” controversy came in 1980, when John Earman and Clark Glymour argued that the rejection of the troublesome Sobral astrograph result was methodologically questionable. A later modern reanalysis by Gilmore and Tausch-Pebody argues that the 1919 decision to give the defective astrographic plates little weight was technically justified.

In the Gerard Gilmore and Gudrun Tausch-Pebody's paper, *The 1919 eclipse results that verified general relativity and their later detractors: a story re-told*, they do more than simply defend Eddington. They take the numerical data published in the 1920 report and reanalyse them using modern least-squares and statistical methods.

The published version appeared in the Royal Society's *Notes and Records*. https://arxiv.org/pdf/2010.13744

John Earman and Clark Glymour argued that the 1919 investigators had unjustifiably rejected the Sobral astrograph result, which was close to the old 0.87″ prediction, while accepting the Sobral 4-inch and poorer-quality Príncipe observations that supported Einstein. This subsequently developed into the much stronger popular claim that Eddington's theoretical commitment to relativity influenced his selection of the evidence. Gilmore and Tausch-Pebody argue that this later interpretation is based on a faulty statistical treatment of the observations.

The original analysis was essentially a problem in differential astrometry. For every star the investigators measured its change of x and y position between eclipse and comparison photographs. They then had to separate the gravitational displacement from ordinary differences between the two photographic plates, i.e. translation, rotation and, crucially, change of scale.

The 1919 astronomers solved these using the contemporary method of normal equations. Gilmore and Tausch-Pebody solve the same published measurements by modern least squares.

There was no significant mathematical error in the original reduction.

But the original report quoted errors as “probable errors”, which are smaller numerically than the modern standard deviation. For normally distributed errors, Gilmore and Tausch-Pebody multiply the probable error by about 1.48 to obtain the equivalent standard deviation.

Thus the preferred Sobral result becomes approximately 1.98″ ± 0.18″ rather than 1.98″ ± 0.12″ when expressed using the modern convention.

Príncipe becomes approximately 1.61″ ± 0.45″.

The defective Sobral astrograph is entirely different. The original authors deliberately did not quote a final uncertainty for it, because the errors were dominated by poorly determined systematic effects. Gilmore and Tausch-Pebody's modern analysis finds roughly 0.95″ ± 0.90″, but they stress that even this ±0.90″ cannot properly be treated as an ordinary Gaussian uncertainty because the errors are non-normal and the systematic errors are unknown.

The defective eclipse photographs were out of focus and distorted, whereas the later comparison photographs returned to focus without the telescope having been readjusted. The observers suspected unequal solar heating of the 16-inch coelostat mirror. Gilmore and Tausch-Pebody found that the measurements themselves were changing during the eclipse.

Overall, using the two accepted datasets they obtain an indicative weighted result of 1.93″ ± 0.17″.

The mistake of John Earman and Clark Glymour was to treat the spread in the defective Sobral astrograph measurements as though it supplied a normal statistical error gives that dataset an unjustifiably large weight. They did not consider dispersion, uncertainty and systematic error as having different origins. They just considered the astrograph measurements as though it supplied a normal statistical error gives that dataset an unjustifiably large weight.

The original observers, by contrast, recognised that the dominant uncertainty was an unresolved instrumental systematic, particularly plate scale, which could not legitimately be averaged away.