Townsfolk gathered at the Patrocínio plaza in Sobral, northeastern Brazil, ahead of the eclipse

No solar eclipse has been as momentous in the history of science as the one that occurred on May 29, 1919. That year, two separate expeditions of British astronomers were sent to photograph the eclipse and take measurements: one expedition voyaged to Sobral, an inland town in northeastern Brazil, and the other travelled to the island of Príncipe, then a Portuguese possession, off the coast of West Africa. Their mission was to determine whether starlight is bent as it traverses a region with a strong gravitational field, in this case the limb of the Sun, and to measure the angle of any detected deflection. Apart from possible surprises, the expeditions assumed that one of three possible results would occur: the path of light would be uninfluenced by gravitation, it would be deflected as predicted by calculations based on Isaac Newton's (1643–1727) law of universal gravitation, or it would bend according to Albert Einstein's (1879–1955) general theory of relativity by approximately double the amount calculated with Newtonian mechanics. Six months later, photos and calculations published by the British astronomers proved Einstein right.

The expeditions provided the first experimental evidence for the general theory of relativity that Einstein

When light BENT

Observations of the 1919 solar eclipse from Brazil and Africa provided the first experimental proof of Albert Einstein's theory of relativity

Marcos Pivetta and Rodrigo de Oliveira Andrade

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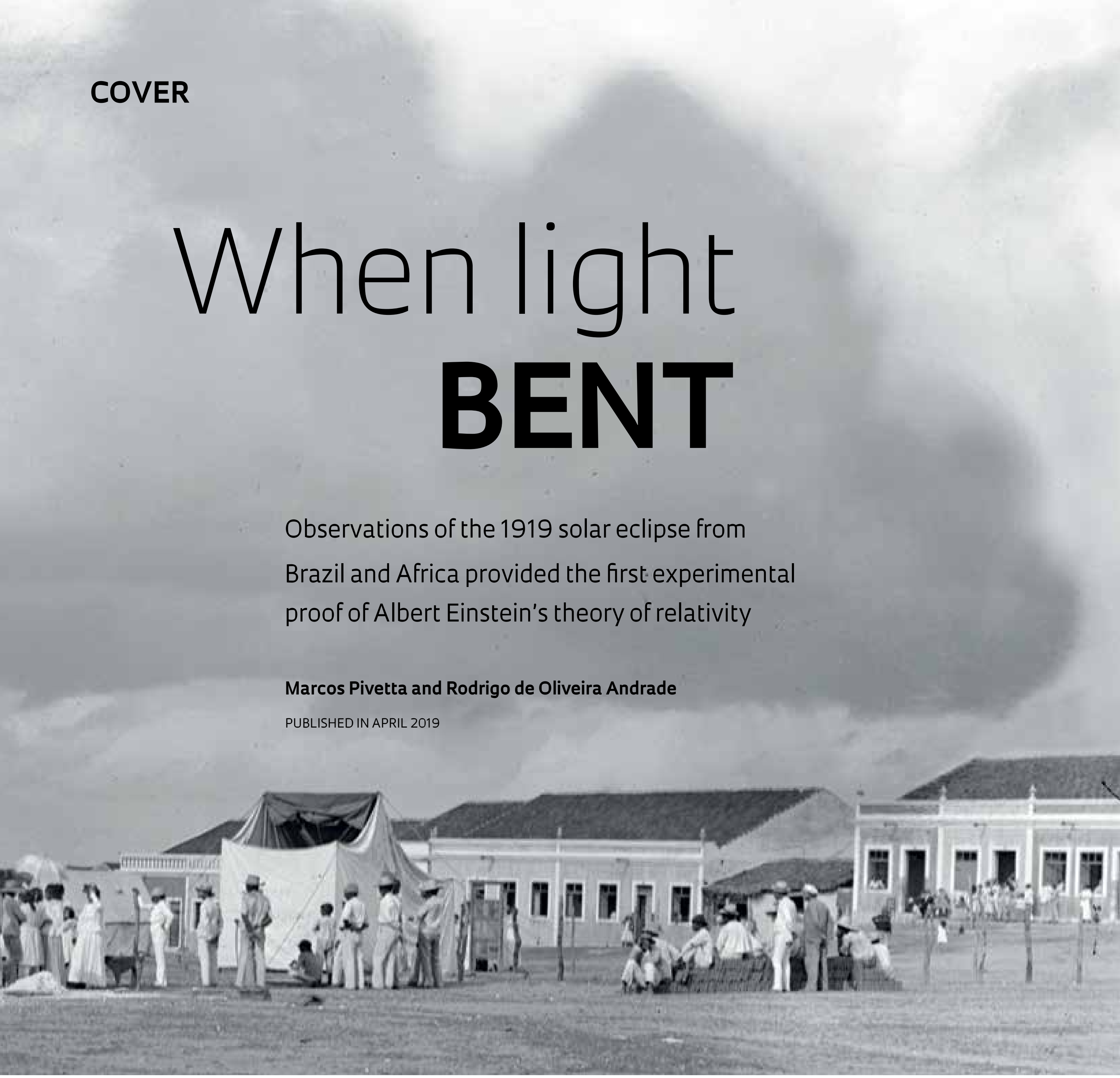

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had published four years prior, which suggested that matter and energy cause warps in the spacetime fabric and that they could also deflect the path of light traveling through it. In lending support to Einstein's ideas, the results from the eclipse expeditions gave humanity a new understanding of the universe. They also helped make the German physicist one of the most respected and celebrated scientists of the twentieth century.

Today, one hundred years after the 1919 eclipse, there is a consensus in the scientific community that general relativity more accurately predicts the trajectory (deflection) of starlight than the calculations based on Newton's theory of gravity. For decades, however, astrophysicists, physicists, and historians of science debated whether the data from the 1919 observations were sufficiently robust to endorse Einstein's ideas, as indeed they eventually proved to be. Some critics argued that the measurements had not been accurate enough to decide which of the two theories was right; others contended that British astronomer Arthur Stanley Eddington (1882–1944), the then director of the University of Cambridge Observatory who headed up the Príncipe expedition, had deliberately discarded the data from the Sobral observations that appeared to support Newton's

Chasing stars

The first decades of the twentieth century saw several attempts by astronomers to capture the deflection of starlight, largely without success

1911

German astronomer Erwin Finlay-Freundlich attempted to measure the deflection with photographic plates of a solar eclipse taken at the **Lick Observatory** in the US

1912

Researchers from the Argentine Observatory led by **Charles Perrine** planned to record a solar eclipse from the vantage point of the Serra da Mantiqueira highlands in Minas Gerais, southeastern Brazil. Bad weather prevented them from taking any photographs

1914

The outbreak of **World War I** thwarted Finlay-Freundlich's second attempt to record an eclipse, this time in Crimea, Russia

1916

The Argentine Observatory managed to record a solar eclipse in Tucacas, Venezuela, but no photograph was usable for proving Einstein's ideas

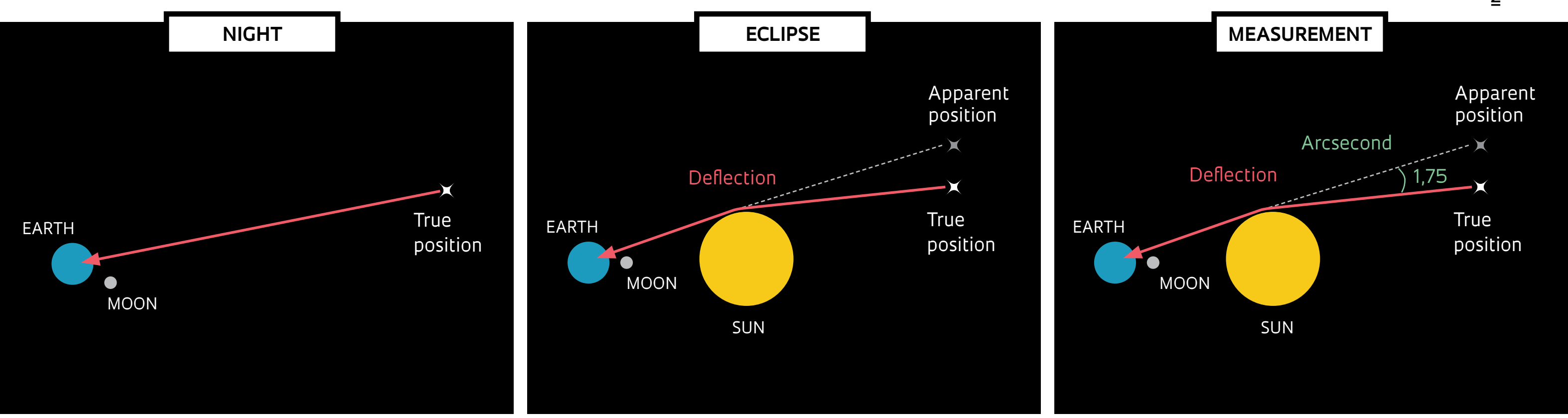
ILLUSTRATION ZÉ VICENTE

theory. "Eddington was not only an enthusiast of Einstein's ideas, but was keen to experimentally verify his theory as a gesture toward a reconciliation between the United Kingdom (UK) and Germany after World War I [1914–1918]," says physicist Luiz Nunes de Oliveira of the São Carlos Institute of Physics at the University of São Paulo (IFSC-USP). "But there is no evidence that the data was fudged."

Irish astrophysicist and historian of science Daniel Kennefick, of the University of Arkansas, also dismisses claims that Eddington skewed the data in Einstein's favour. "Not only was Eddington not in Sobral and therefore not personally involved in taking the measurements, but he also had no hand in analysing the data from that end of the expedition. Those analyses were done by Frank Dyson [1868–1939] and his assistants at the Greenwich Observatory in London," argues Kennefick, who is launching a book on

INFOGRAPHIC ANA PAULA CAMPOS

WHY LIGHT BENDS



Starlight travels in a straight line across the universe until reaching the Earth, so a star photographed at night will be seen at its true position

During an eclipse, starlight is deflected as it passes near the Sun. According to Einstein's general theory of relativity, the Sun's sheer mass causes the spacetime fabric to curve around it, and a light ray crossing this region will shift its course

Einstein predicted that light would bend at an angle of 1.75 arcseconds, roughly twice the amount that other physicists had predicted using Newton's law of gravity

1918

The Lick Observatory team was unable to photograph a solar eclipse in the US because its equipment had been held up in Russia since 1914

1919

The path of the eclipse that confirmed Einstein's predictions crossed over the equator. The eclipse was observed from Sobral and the island of Príncipe, off the West coast of Africa

1922

Photographs of a solar eclipse made on Christmas Island corroborated the data obtained years earlier at Sobral

SOURCE EARMAN, J. & GLYMOUR, C. RELATIVITY AND ECLIPSES: THE BRITISH ECLIPSE EXPEDITIONS OF 1919 AND THEIR PREDECESSOR

the 100th anniversary of the eclipse (*see interview on page 10*).

Star fields—the name astronomers give to discrete areas of the sky populated by stars—are continually shifting in space. However, the relative position between individual stars is always the same on a small time scale of, say, a few months. "If we take a photo today and another in three months' time, the stars in a given field line up perfectly," explains astronomer Augusto Damineli of USP. "But around a solar eclipse, the stars will appear to be slightly offset in relation to a photo of the same star field taken at night. The closer a star is to the Sun, the more its light rays are bent during an eclipse." This was the predicted but not yet experimentally observed effect that the British expeditions were able to confirm.

In his book *Opticks*, first published in 1704, Newton also suggests that light is bent by gravity, but provides no calculations for the angle of deflection. According to Newton, gravity is a force acting between point masses that is proportional to their mass and inversely proportional to the square of their separation distance. In Newton's time, the nature of light was unknown. There were then two competing hypotheses: that light consisted of corpuscles (particles) or that it was a type of a wave. Assuming light to be corpuscular, British astronomer John Michell (1724–1793) and French scientist Pierre-Simon Laplace (1749–1827) independently calculated the effects of gravity on light near the end of the eighteenth century. However, during the course of the nineteenth century, it was established that light was a form of an electromagnetic wave. "When light came to be understood as a type of wave, rather than matter, it became completely uncertain whether it would be affected by gravity," says Daniel Vanzella of the São Carlos Institute of Physics at USP (IFSC-USP). "That remained an open question for more than 100 years."

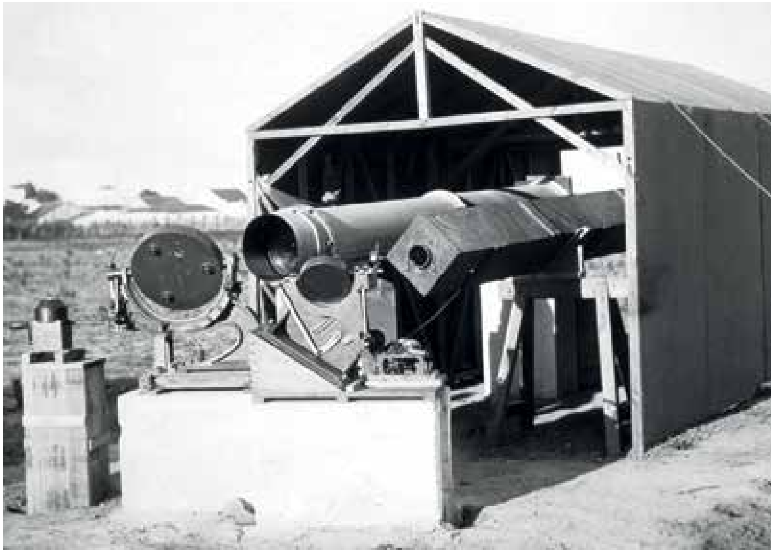
Einstein began to make a name for himself in the scientific community when he introduced a new conception of space and time in 1905. "With the publication of his special theory of relativity, space and time ceased to be understood as absolute," explains astronomer Reinaldo Ramos de Carvalho of the Brazilian National Institute for Space Research (INPE) in São José dos Campos. Einstein posited that space could deform, shrink, and even collapse, forming black holes, and that time could expand. However, the initial and incomplete version of his theory still yielded the same value for light deflection as Newtonian gravitation: 0.87 arcseconds. It was only after publishing his theory of general relativity in 1915 that Einstein took his ideas a step further.

He proposed that gravity was not a force exerted between masses, as Newton described it, but rather the effect of a property of energy: that of deforming spacetime and everything that moves across it, even waves, such as light. "Space as described by Newton was flat. But in Einstein's general relativity, spacetime is curved near bodies possessing significant energy or mass," explains physicist George Matsas of the Institute for Theoretical Physics at São Paulo State University (IFT-UNESP). After factoring in the assumption of spacetime curvature, Einstein's figure for light deflection virtually doubled to 1.75 arcseconds.

THE WORLD'S EYES ON SOBRAL

When general relativity was unveiled, astronomers from around the world were eager to test the theory through observation of solar eclipses, which would provide the opportunity to photograph stars near the Sun's corona and determine whether their light would be deflected due to proximity to the Sun. However, because of bad weather or difficulties stemming from World War I, none succeeded in obtaining data that could substantiate Einstein's ideas until the eclipse of 1919 (*see the timeline on page above*).

In mid-1918, researchers at the Brazilian National Observatory in Rio de Janeiro, who were anticipating an eclipse the following year, determined that Sobral, a small town approximately 200 kilometres from Fortaleza, would provide optimal geographical conditions for observation. Astronomer Henrique Charles Morize (1860–1930), the then director of the institution, pre-



The 13-inch telescope used by the Sobral expedition to document the eclipse

pared a detailed report on the region and sent it to scientific institutions around the world, including the Royal Astronomical Society in London.

Frank Dyson, president of the society, had been exposed to Einstein's theories through Arthur Eddington, the institution's secretary. Eddington was then a rising star in the European astronomical community, says historian Matthew Stanley, a professor in the Department of History of Science at Harvard. "His work in statistical cosmology had established his reputation as a creative and talented scientist, and his later work in stellar structure was a crucial element in the development of theoretical astrophysics as a field," Stanley wrote in an article in the journal Isis in 2003. "Both Eddington and Dyson knew that the May 1919 eclipse would be special," says Oliveira. "The Sun would pass across a large cluster of stars in the constellation of Taurus, so there would be plenty of bright lights to observe." The eclipse would provide a window of only a few minutes to photograph stars near the Sun's edge, 150 light-years away from Earth (a light-year equals 9.5 trillion kilometres).

EYES ON THE SKY

To determine which theory—Newton's or Einstein's—was correct, the Royal Astronomical Society organized expeditions to regions providing ideal observation conditions. Eddington led an expedition to the island of Príncipe, 300 kilometres off the coast of Africa. The other team, consisting of two members of the Greenwich Observatory—Charles Davidson and Andrew Crommelin—went to Sobral, with Dyson coordinating the expedition from overseas.

The Greenwich team arrived in Brazil on March 23, 1919. They disembarked at the port of Belém, Pará, where they waited a few weeks as Henrique Morize from the Brazilian National Observatory made arrangements for their arrival in Sobral. By courtesy of the Brazilian government, their gear was waved through customs without inspection, as reported by the British researchers in an article later published in the *Philosophical Transactions of the Royal Society*.

Although a source of controversy, Eddington's and Dyson's conclusions were proven correct in later decades

Davidson and Crommelin brought two astrographic telescopes coupled to mirror systems known as coelostats, which are mounted such that they can track the Sun's movement across the sky and reflect the Sun's image back to the telescope. The main telescope brought from the Royal Greenwich Observatory offered a very wide field of vision, in theory allowing them to photograph a large number of stars around the Sun during the eclipse. The telescope had a 13-inch aperture and was mounted to a 16-inch coelostat. A smaller telescope was borrowed from the British Jesuit astronomer Aloysius Cortie (1859–1925) as a kind of backup, with a 4-inch aperture and 8-inch coelostat.

The scientists arrived in Sobral on April 30, 1919, and were welcomed by the then mayor, Jácome de Oliveira. "They then met Colonel Vicente Saboya, who offered the foreign visitors one of his houses," says physicist Emerson Ferreira de Almeida of Vale do Acaraú State University, in Sobral. "The observations would be made at the town's Jockey Club." Two other expeditions with more modest equipment, one Brazilian and the other American, joined the English astronomers a few days later in Sobral, although their measurements were neither intended nor later used to verify the validity of Einstein's theory of relativity (*see article on page12*).

Across the Atlantic, Eddington and his team had arrived at the port of Santo António in Príncipe on April 23, 1919. In their baggage, they carried a telescope borrowed from the Cambridge Observatory, similar to the larger one sent to Sobral. The day of the eclipse was marked by poor weather, and the overcast sky compromised the quality of the images. On some plates, the stars appeared clearer, while on other plates they disappeared in the cloudy sky. "That day also dawned cloudy in Sobral," says astronomer Carlos Veiga of the Center for Astronomy and Astrophysics at the Brazilian National Observatory. "But the clouds gradually began to thin, and the sky cleared." Shortly before 9:00 a.m., the moon's disk began to slide over the Sun's, completely obscuring it within minutes. The eclipse lasted exactly 5 minutes and 13 seconds.

The Greenwich team would remain in Sobral until July to photograph the same star field at night without the influence of the Sun's gravitational pull. Eddington returned from Príncipe to England ahead of the Sobral team and produced images of the same star field in the Oxford sky, although the comparison plates would have best been taken at the site where the eclipse plates had been captured.

DIFFERING RESULTS

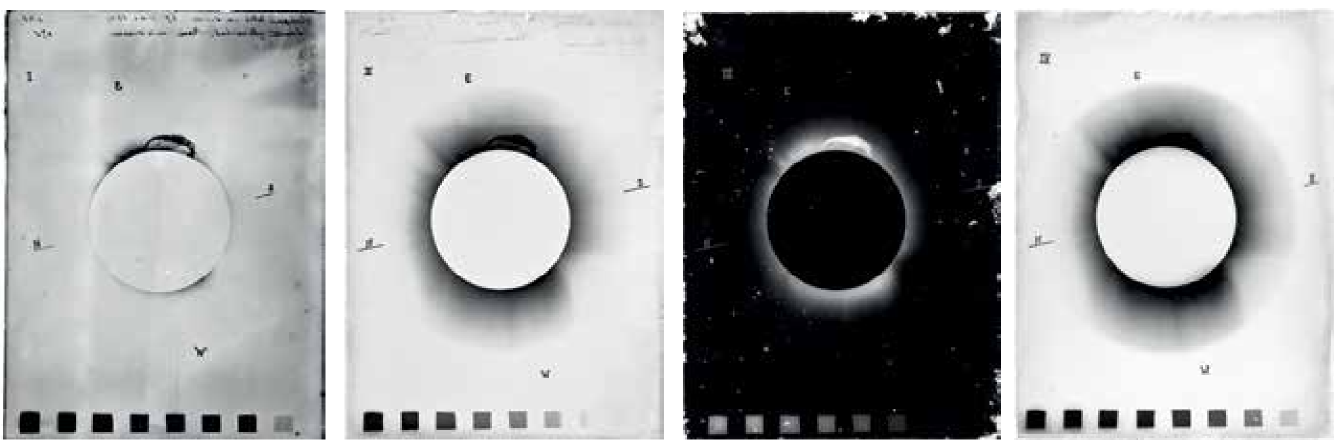
The astronomers produced three sets of photographic plates to measure the deflection of starlight near the Sun's limb. At Sobral, the main telescope recorded 12 stars and the backup telescope recorded 7. The telescope used at Príncipe captured five stars. The plates from all three revealed some degree of deflection during the eclipse, confirming both Newton's and Einstein's ideas. However, each of the three instruments captured different deflection figures, with different error margins. Two agreed with Einstein's calculations, but one instrument was closer to the Newtonian prediction.

The most reliable calculations were derived from the clearest images of the eclipse—ironically, these were obtained with the smaller telescope at Sobral. Back in the UK, the team analysed the plates and calculated the deflection to be 1.98 arcseconds (with 0.12 arcseconds of error), more than Einstein's figure. All images produced by the larger telescope at Sobral were blurred or out of focus. "This may have been caused by the effect of the Sun's heat on the mirror array," suggests USP physicist Ramachrisna Teixeira. The Sobral team was still able to analyse these poorer-quality plates and arrived at a deflection of 0.86, consistent with predictions based on Newton's law of gravity. However, the poor quality of the images led the British astronomers to discount the larger telescope's deflection values from their final analysis.

At Príncipe, due to bad weather, the images of many stars were either lost in the diffuse halo created by the Sun's light, or they were covered by the moon's disk. Atmospheric turbulence further compromised the quality of the photographic plates. Despite their suboptimal conditions, Eddington was able to analyse the eclipse plates and compare them with check plates he took of the same star field in Oxford. The result was a deflection of 1.61 arcseconds, with a margin of error of 0.30 arcseconds, slightly lower than Einstein's prediction. "The greatest weight must be attached to those obtained with the 4-inch lens at Sobral. From the superiority of the images and the larger scale of the photographs, it was recognized that these [results] would prove to be the most trustworthy," Dyson, Eddington, and Davidson announced in a written statement during a meeting of the Royal Astronomical Society in London, on November 6, 1919, declaring that Einstein's prediction had been confirmed.

While their findings became a source of controversy, Dyson's and Eddington's conclusions were ultimately proven correct. Several other eclipses were observed over the following decades, and the resulting measurements consistently pointed to a deflection close to Einstein's. Confirmation of his theory helped open new and wide avenues of research in fields such as physics, astronomy, and cosmology. "The German physicist's ideas found especially fertile ground in Soviet physicist Alexander Friedmann [1888–1925], who, building on Einstein's theory, proposed that galaxies were moving away from us because spacetime, that is, the universe, was expanding," says Carvalho.

General relativity also provided the groundwork for important concepts in astrophysics, including black holes (extremely compact regions in spacetime where gravity is so strong that not even light can escape it) and gravitational waves—disturbances in the curvature of spacetime that propagate as waves. Gravitational waves would only be confirmed in early 2016. ■



Photographic plates produced by the Brazilian team for spectroscopic observations of the Sun's corona

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