

THE SOLAR ECLIPSE THAT VALIDATED EINSTEIN'S THEORY OF RELATIVITY

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YOUNG REVIEWERS:



SHACHAR

AGE: 13



YOTAM

AGE: 13

This article describes one of the most important chapters in scientific history, which contributed to the modern understanding of the universe. Albert Einstein completed his theory of general relativity in 1915. This theory changed our understanding of the concepts of space, time and gravity, established by Isaac Newton. One prediction of the new theory was that light rays reaching us from distant stars, curve when they pass near the sun, because of the sun's gravity and the nature of space and time. This prediction was confirmed through astronomical observations measuring the light reaching Earth from distant stars. When this result was published, it ignited a big excitement and interest in the scientific community and the general public, and Einstein became a superstar overnight.

A DRAMATIC ANNOUNCEMENT

On November 7, 1919, a news article was published in the British paper London Times, under the sensational title, "A revolution in

SOLAR ECLIPSE

A phenomenon occurring when the moon is directly between the sun and the Earth, so that the moon casts a shadow on part of the Earth.

THEORY OF SPECIAL RELATIVITY

A theory developed by Albert Einstein, published in 1905, that introduced the notion of relativity of space and time measurements.

science—New theory of the universe—Newton's ideas have been refuted." The article reported the results of astronomical observations conducted by two expeditions earlier that same year, one located on Principe island, near the west coast of Africa, and the other in the city of Sobral in Brazil. From these two places, it was possible to observe a full **solar eclipse** on the same day. The aim of these observations was to check one of the predictions of Einstein's theory of general relativity. Einstein claimed that the paths of light rays coming from distant stars would become curved as they passed by the sun on their way toward Earth.

How could observations of curving light rays support Einstein's theory and change the way people viewed space, time, and gravity? Let us start with some background.

THE THEORY OF SPECIAL RELATIVITY

The year 1905 was one of the most productive years in the scientific career of the Jewish-German physicist Albert Einstein. That year, he formulated the **theory of special relativity**. This theory is based on two assumptions:

First, the theory applies to systems moving at a constant velocity with respect to each other. To make this simple, let us imagine a person sitting in a train car. The windows are covered, and no sound of the wheels on the tracks is heard. If the train moves at a constant velocity, there is no experiment that the person in the train could do to determine the velocity of the train, or to decide if it was moving or standing still with respect to the platform.

The second assumption tells us that the propagation of light behaves differently than the motion of other things. The velocity of light is always constant—It does not depend on the velocity of the light source or the velocity of the observer. To illustrate, when I am driving my car and ask how fast the neighboring car is going, the answer is dependent on my velocity. If the neighboring car is moving at the same velocity as my car, then it will seem to be at rest relative to my car. But, if I drive slower, the other car will appear to move away from me. Einstein's insight was that light behaves differently—the velocity of light is independent of the state of motion of whomever is measuring it and the velocity of the source from which that light is emitted.

Does this sound strange to you? Well, it gets even more strange! From these two assumptions it follows that, if two people are moving relative to one another and they measure the length of a certain object, they will get different results! Further, if they measure the time between two events, they will not agree on the time that pass between them. Sometimes, they will even not agree on which event happened first! Measurements of distance, time, and simultaneity of events are

relative, meaning they depend on the state of motion of whomever is conducting the measurements. The concepts of distance and time in Einstein's theory of special relativity are very different from the worldview proposed by the English mathematician and physicist Isaac Newton. According to Newton's theories, space and time, are separate entities and they are absolute—the results of time and distance in space measurements are independent of the motion of whomever is conducting them.

One of the famous conclusions from Einstein's theory is that mass and energy are equivalent to one another—a conclusion that is represented by the most famous formula in science, $E = mc^2$. E represents energy, m represents mass, and c is the velocity of light. According to this formula, a small amount of mass could be transformed into a huge amount of energy. In reactors that provide nuclear energy, these processes occur in a controlled way. In an atomic bomb, they occur in an uncontrolled manner, leading to a disastrous explosion. At the core of the sun, four nuclei of hydrogen fuse together in a complex process to become the nucleus of helium. The mass of a helium nucleus is slightly smaller than the mass of four hydrogen nuclei. The mass that is lost in this process becomes energy and is the source of the Sun's energy and, therefore, the source of life on earth.

THE THEORY OF GENERAL RELATIVITY

The theory of special relativity has two main limitations: first, this theory relates only to systems moving at constant velocity; it does not account for accelerated motion, which means motion that speeds up or slows down, or changes its direction like in a merry-go-around. The second limitation is that the special theory of relativity can not take into account the **gravitational force**, the central force that holds the moon in a fixed orbit around the earth and the planets in their orbits around the sun.

After completing the special theory of relativity, Einstein began searching for a theory that would be free of these two limitations. His 10-year search led to the **theory of general relativity**. The main idea of this theory is that the gravitational force—the attraction force between two objects—is not a force, as in Newton's theory, but a feature of space, or more accurately, of space and time. In Einstein's new theory, space and time are combined into one entity—space-time. In Newton's theory, space and time are the "stage" on which all physical processes occur. In Einstein's theory, space and time *take part* in these processes and are influenced by them. According to Einstein, massive objects in the universe that has mass, like planets and stars, curve the space-time around them. This means that objects and light rays that are moving through the universe are moving through curved space-time. It is very hard to explain this concept in a way that

GRAVITATIONAL FORCE

One of the basic forces in nature. This is an attraction force acting between objects, and it is influenced by their masses and the distance between them.

THEORY OF GENERAL RELATIVITY

A theory published by Einstein in 1915 that is an extension of the theory of special relativity to deal with systems moving at changing velocity and with gravity.

is easy to understand. Even physicists who study such phenomena have difficulties with imagining curved space-time. These concepts are best described in the language of mathematics, using methods developed by mathematicians back in the nineteenth century. Using these methods, in 1915 Einstein found the equations describing the influence of mass on the structure of space-time, and the equations of motion that follow from this influence. These equations are Einstein's greatest achievement and are the basis for everything we know about the universe—how it started, how it developed, and what is its structure.

OBSERVATIONS OF A SOLAR ECLIPSE VERIFIED EINSTEIN'S THEORY

When Einstein began to develop his theory of general relativity, he already knew that light beams are curved near the sun. Even before he had the final theory, Einstein calculated how much these light beams curve but, although he did not know it at the time, he got a result that was two times smaller than the correct value. In 1913, Einstein sent a letter to the astronomer George Hale, who was the director of Mount Wilson Observatory, the biggest observatory in the United States. Einstein asked Hale if there was a way to observe the stars near the sun during the daytime. Hale answered that the only way to observe these stars is during a full solar eclipse.

You might still be wondering why a solar eclipse was needed to prove Einstein's theory. First, it is important to remember that, to see the effect of the sun's gravity on the light from distant stars, the sun must be between us and the stars we are observing—meaning it should be done at daytime. Normally, it is impossible to see stars in daytime because the sun is so bright! But, during a solar eclipse when the sky is dark, those stars would be visible. A solar eclipse occurs because the plane of the moon's orbit around the earth is bent relative to the plane of earth's orbit around the sun. Occasionally, the earth, the moon, and the sun cross paths in such a way that they form a straight line. When this happens, the moon hides the sun, and a solar eclipse occurs. But the moon is too small to cast a shadow on the whole earth, and therefore there are areas where a full solar eclipse occurs, and in other areas it is only partial.

Einstein reasoned that, if astronomers compared photographs of the stars taken during a solar eclipse, when the sun was present between the Earth and the stars, to photographs of the same stars taken during nighttime when the sun was not between the Earth and the stars, the positions of the stars should appear to be shifted. If the positions of the stars differed between the two photographs, this would indicate that the sun's gravitational field was curving the path of the light from those stars (Figure 1).

Figure 1

When light rays from a distant star pass by the gravitational field of the sun, the rays curve. An observer on earth would see the location of the star as shifted when the sun is in the path of the star's light compared to when the sun is in a different area of the sky, not in the light's path.

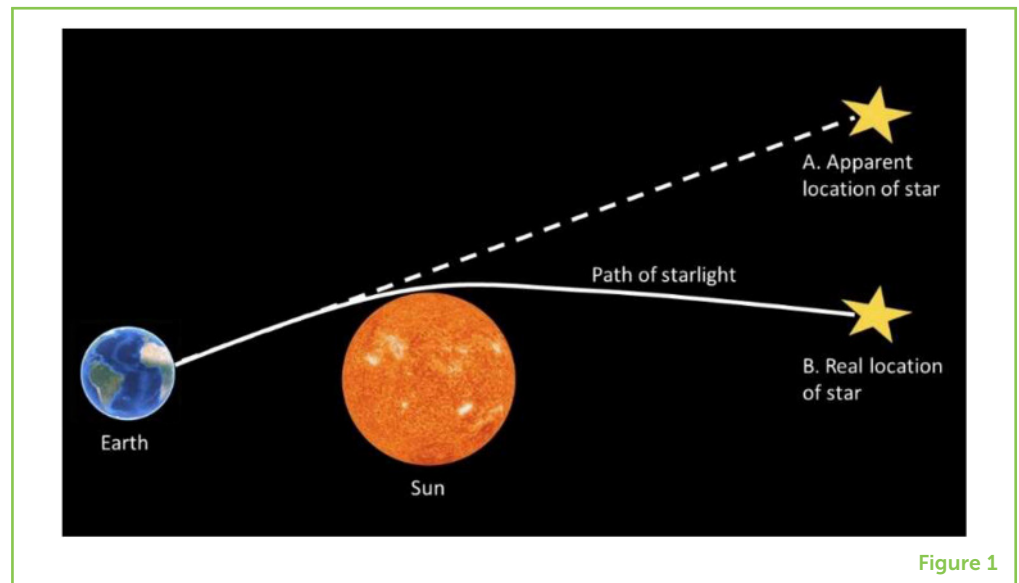


Figure 1

Figure 2

The solar eclipse of 1919 and the stars around it. The locations of the stars seen in this photo were compared to photos taken when the sun was in a different part of the sky. By doing so, researchers found that the positions of the stars appeared to have shifted. This happens because the sun's gravity bends the stars' light rays, as shown in Figure 1.



Figure 2

A German astronomical expedition was planning to perform observations during a full solar eclipse on August 21, 1914 in the Crimea area in Russia. But then the first world war began and the expedition was taken prisoner and its equipment was confiscated.

Researchers finally got another opportunity during a solar eclipse on May 29, 1919 (Figure 2). At that time, Einstein already had the final theory of general relativity and, based on this, predicted that the rate of curving is twice stronger than what he assumed previously. As stated earlier, these observations were obtained from two locations, Sobral and Principe. After some months of analyzing the observations, which was not a simple task, using the resources that were available at the time, the directors of expeditions, Arthur Eddington and Charles Davidson, along with the royal astronomer Sir Frank Dyson stated

that, "The results of the expeditions to Sobral and Principe leave almost no doubt in the fact that the curving of light around the sun is indeed occurring, and that its rate is matching that which is required by Einstein's theory of relativity." The fact that this prediction of the general theory of relativity was confirmed by independent measurements at two distant locations helped to convince the scientific community that this conclusion is actually true.

IMPACT OF EINSTEIN'S THEORIES

This was an extremely important result. It not only provided a confirmation of Einstein's theory of general relativity, but it also helped scientists to understand a valuable astronomical phenomenon called **gravitational lensing**, which can help scientists to study the universe. The amount that light waves curve as they pass near the sun is very small. Objects with much larger masses, like black holes or even whole galaxies, can cause in much stronger curving, to the point that sources of light behind these massive objects can be seen through our telescopes. Einstein noticed the possibility of gravitational lensing back in 1912, but he only published his ideas and the related calculations 24 years later.

The sensational title of the news article reporting the success of the British expeditions resulted in much excitement in the scientific community. It also caused excitement in the general public, which was amplified because of the period when the article was published—only a few years after World War I, which took the lives of millions of victims and resulted in great destruction. The article reminded people of the intelligence of the human mind and showed them that there could be international cooperation in science. This aroused new hope. The general public's interest in, and admiration of, Einstein were sky high, and he became a superstar overnight. Einstein enjoyed this status until the end of his life, and he is still well-known and respected today.

AUTHOR'S NOTE

Hanoch Gutfreund also shares exciting insights on the importance of a unique manuscript, which was auctioned in November 2021. This manuscript shows how Albert Einstein and his lifelong friend, Michele Besso, worked together to examine the consequences of a preliminary theory published by Einstein in 1913. The result of their work helped Einstein to complete his General Theory of Relativity 2 years later. Find out more here!

GRAVITATIONAL LENSING

A phenomenon in which the gravitational force of an object with high mass curves light rays from sources located behind those objects, so that they are visible to our telescopes.

ADDITIONAL READING

At the hundredth year of the affair which is the topic of this article, two books were published, describing its scientific and historic contexts: S. James Gates, Jr. and Cathie Pelletier, *Proving Einstein Right—The Daring Expeditions That Changed How We Look at the Universe*, Hachette Book Group, 2019. Daniel Kennefick, *No Shadow of a Doubt—the 1919 Eclipse That Confirmed Einstein's Theory of Relativity*, Princeton University Press, 2019.

SUBMITTED: 25 July 2021; **ACCEPTED:** 31 March 2022;
PUBLISHED ONLINE: 04 May 2022.

EDITOR: Idan Segev, Hebrew University of Jerusalem, Israel

SCIENCE MENTORS: Osnat Cohen and Adva Ben-Natan

CITATION: Gutfreund H (2022) The Solar Eclipse That Validated Einstein's Theory of Relativity. *Front. Young Minds* 10:747040. doi: 10.3389/frym.2022.747040

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YOUNG REVIEWERS

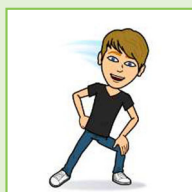
SHACHAR, AGE: 13

Hi, I am Shachar, a 13 year old living in Modi'in. I have a dog which only likes eating, and an old cat which does not eat at all (and if she does, she vomits).



YOTAM, AGE: 13

My name is Yotam, I am a student in the 7th grade—the first year in middle school. I like learning mathematics and science, and I am very interested in computer science and programs. Another big love of mine is music, especially rock and classical music. I also play the guitar: electrical, classical, and acoustic, and I am a member in a band where I play with my friends.



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Hanoch Gutfreund is a Professor Emeritus of Theoretical Physics at the Hebrew University of Jerusalem. His work focuses on research in solid-state physics, statistical physics, and neural computation (the interface between physics and brain research). He has previously held various academic and administrative positions at the University—head of the Institute of Physics, head of the Institute of Advanced Studies, rector, and president. He has served in various university and public positions in Israel and abroad, related to education and science policy. In recent years, he has served as the academic director of the Albert Einstein Archive at the Hebrew University. He is responsible for preserving Einstein's legacy in Israel and around the world. *hanoch.gutfreund@mail.huji.ac.il