

GENERAL RELATIVITY Pedro Ferreira

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EINSTEIN'S INSIGHT

In 1905, at the age of 26, Albert Einstein proposed his special theory of relativity. The theory reconciled the physics of moving bodies developed by Galileo Galilei and Newton with the laws of electromagnetic radiation. It posits that the speed of light is always the same, irrespective of the motion of the person who measures it. Special relativity implies that space and time are intertwined to a degree never previously imagined.

Starting in 1907, Einstein began trying to broaden special relativity to include gravity. His first breakthrough came when he was working in a patent office in Bern, Switzerland. "Suddenly a thought struck me," he recalled. "If a man falls freely, he would not feel his weight... This simple thought experiment... led me to the theory of gravity." He realised that there is a deep relationship between systems affected by gravity and ones that are accelerating.

The next big step forward came when Einstein was introduced to the mathematics of geometry developed by the 19th-century German mathematicians Carl Friedrich Gauss and Bernhard Riemann. Einstein applied their work to write down the equations that relate the geometry of space-time to the amount of

energy that it contains. Now known as the Einstein field equations, and published in 1916, they supplanted Newton's law of universal gravitation and are still used today, nearly a century later.

Using general relativity, Einstein made a series of predictions. He showed, for example, how his theory would lead to the observed drift in Mercury's orbit. He also predicted that a massive object, such as the sun, should distort the path taken by light passing close to it: in effect, the geometry of space should act as a lens and focus the light (see diagram).

Einstein also argued that the wavelength of light emitted close to a massive body should be stretched, or red-shifted, as it climbs out of the warped space-time near the massive object. These three predictions are now called the three classical tests of general relativity.

APPARENT POSITION

"Space tells matter how to move and matter tells space how to curve" John Archibald Wheeler

Einstein suggested that light rays skimming past the sun would be bent by its gravity. To test the idea, Arthur Eddington first photographed the Hyades stars at night. He then needed to photograph them when they were on the far side of the sun. For this picture, it only became possible to see the starlight when the glare of the sun was eliminated by a total solar eclipse. His images confirmed Einstein's prediction

EARTH

According to general relativity, space-time can be viewed as a smooth, flexible sheet that bends under the influence of massive objects

HYADES STAR CLUSTER, **150 LIGHT YEARS AWAY** ACTUAL

POSITIONS

APPARENT POSITION

The mass of the sun bends space-time, so bright rays from the Hyades cluster bend too. Viewed from Earth, the stars appear to have shifted



GRAVITY BEFORE EINSTEIN

In 1686, Isaac Newton proposed an incredibly powerful theory of motion. At its core was the law of universal gravitation, which states that the force of gravity between two objects is proportional to each of their masses and inversely proportional to the square of their distance apart. Newton's law is universal because it can be applied to any situation where gravity is important: apples falling from trees, planets orbiting the sun, and many, many more.

For more than 200 years, Newton's theory of gravity was successfully used to predict the motions of celestial bodies and accurately describe the orbits of the planets in the solar system. Such was its power that in 1846 the French astronomer Urbain Le Verrier was able to use it to predict the existence of Neptune.

There was, however, one case where Newton's theory didn't seem to give the correct answer. Le Verrier measured Mercury's orbit with exquisite precision and found that it drifted by a tiny amount - less than one-hundredth of a degree over a century - relative to what would be expected from Newton's theory. The discrepancy between Newton's theory and Mercury's orbit was still unresolved at the beginning of the 20th century.

Images of the 1919 solar eclipse proved that gravity bends starlight

HISTORY OF GENERAL RELATIVITY

Albert Einstein's general theory of relativity is one of the towering achievements of 20th-century physics. Published in 1916, it explains that what we perceive as the force of gravity in fact arises from the curvature of space and time.

Einstein proposed that objects such as the sun and the Earth change this geometry. In the presence of matter and energy it can evolve, stretch and warp, forming ridges, mountains and valleys that cause bodies moving through it to zigzag and curve. So although Earth appears to be pulled towards the sun by gravity, there is no such force. It is simply the geometry of space-time around the sun telling Earth how to move.

The general theory of relativity has far-reaching consequences. It not only explains the motion of the planets; it can also describe the history and expansion of the universe, the physics of black holes and the bending of light from distant stars and galaxies.

PHYSICIST, SUPERSTAR

In 1919, the English astronomer Arthur Eddington travelled to the island of Príncipe off the coast of west Africa to see if he could detect the lensing of light predicted by general relativity. His plan was to observe a bright cluster of stars called the Hyades as the sun passed in front of them, as seen from Earth. To see the starlight, Eddington needed a total solar eclipse to blot out the glare of the sun.

If Einstein's theory was correct, the positions of the stars in the Hyades would appear to shift



By 1930, Albert

Arthur Eddington

were famous for

general relativity

their work on

Einstein and

by about 1/2000th of a degree.

To pinpoint the position of the Hyades in the sky, Eddington first took a picture at night from Oxford. Then, on 29 May 1919, he photographed the Hyades as they lay almost directly behind the sun during the total eclipse that Príncipe experienced that day. Comparing the two measurements, Eddington was able to show that the shift was as Einstein had predicted and too large to be explained by Newton's theory.

Following the eclipse expedition,

there was some controversy that Eddington's analysis had been biased towards general relativity. Matters were put to rest in the late 1970s when the photographic plates were analysed again and Eddington's analysis was shown to be correct.

Eddington's result turned Einstein into an international superstar: "Einstein's theory triumphs" was the headline of The Times of London. From then on, as more consequences of his theory have been discovered, general relativity has become entrenched in the popular imagination, with its descriptions of expanding universes and black holes.

In 1959, the American physicists **Robert Pound and Glen Rebka** measured the gravitational redshifting of light in their laboratory at Harvard University, thereby confirming the last of the three classical tests of general relativity.

"No black holes have been seen directly yet, though there is overwhelming evidence that they exist"

BLACK HOLES

Shortly after Einstein proposed his general theory of relativity, a German physicist called Karl Schwarzschild found one of the first and most important solutions to Einstein's field equations. Now known as the Schwarzschild solution, it describes the geometry of space-time around extremely dense stars - and it has some very strange features.

For a start, right at the centre of such bodies, the curvature of space-time becomes infinite - forming a feature called a singularity. An even stranger feature is an invisible spherical surface, known as the event horizon, surrounding the singularity. Nothing, not even light, can escape the event horizon. You can almost think of the Schwarzschild singularity as a hole in the fabric of space-time.

In the 1960s, the New Zealand mathematician Roy Kerr discovered a more general class of solutions to Einstein's field equations. These describe dense objects that are spinning, and they are even more bizarre than Schwarzschild's solution.

The objects that Schwarzschild and Kerr's solutions describe are known as black holes. Although no black holes have been seen directly, there is overwhelming evidence that they exist. They are normally detected through the effect they have on nearby astrophysical bodies such as stars or gas.

The smallest black holes can be found paired up

with normal stars. As a star orbits the black hole, it slowly sheds some of its material and emits X-rays. The first such black hole to be observed was Cygnus X-1, and there are now a number of well-measured X-ray binaries with black holes of about 10 times the mass of the sun.

Evidence for much larger black holes came in the 1960s when a number of very bright and distant objects were observed in the sky. Known as quasars, they arise from the havoc black holes seem to create at the cores of galaxies. Gas at the centre of a galaxy forms a swirling disc as it is sucked into the black hole. Such is the strength of the black hole's pull that the swirling gas emits copious amounts of energy that can be seen many billions of light years away. Current estimates place these black holes at between a million and a billion times the mass of the sun. As a result, they are called supermassive black holes.

The evidence now points to there being a supermassive black hole at the centre of every galaxy, including our own. Indeed, observations of the orbits of stars near the centre of the Milky Way show that they are moving in very tightly bound orbits. These can be understood if the space-time they live in is deeply distorted by the presence of a supermassive black hole with more than 4 million times the mass of the sun.

Despite their names, British physicist Stephen Hawking has pointed out that black holes may not be completely black. He argues that, near the event horizon, the quantum creation of particles and antiparticles may lead to a very faint glow. This glow, which has become known as Hawking radiation, has not been detected yet because it is so faint. Yet, over time, Hawking radiation would be enough to remove all the energy and mass from a black hole, causing all black holes to eventually evaporate and disappear.

HOW GENERAL RELATIVITY SHAPES OUR UNIVERSE

Einstein's general theory of relativity has revealed that the universe is an extreme place. We now know it was hot and dense and has been expanding for the past 13.7 billion years. It is also populated with incredibly warped regions of space-time called black holes that trap anything falling within their clutches.



THE EXPANDING UNIVERSE

One of general relativity's most striking predictions arises if we consider what happens to the universe as a whole.

Shortly after Einstein published his theory, Russian meteorologist and mathematician Alexander Friedmann and Belgian priest Georges Lemaître showed that it predicted that the universe should evolve in response to all the energy it contains. They argued that the universe should start off small and dense, and expand and dilute with time. As a result, galaxies should drift away from each other.

Einstein was initially sceptical of Friedmann and Lemaître's conclusion, favouring a static universe. But a discovery by the American astronomer Edwin Hubble changed his mind.

Hubble analysed how galaxies recede from the Milky Way. He found that distant galaxies move away faster than those that are relatively nearby. Hubble's observations showed that the universe was indeed expanding. This model of the cosmos later became known as the big bang.

Over the past 20 years, a plethora of powerful observations by satellites and large telescopes have further firmed up the evidence for an expanding and evolving universe. We have obtained an accurate measure of the expansion rate of the universe and of the temperature of the "relic radiation" left over from the big bang, and we have been able to observe young galaxies when the universe was in its infancy. It is now accepted that the universe is about 13.7 billion years old.

GRAVITATIONAL WAVES

According to general relativity, even empty spacetime, devoid of stars and galaxies, can have a life of its own. Ripples known as gravitational waves can propagate across space in much the same way that ripples spread across the surface of a pond.

One of the remaining tests of general relativity is to measure gravitational waves directly. To this end, experimental physicists have built the Laser Interferometer Gravitational-Wave Observatory (LIGO) at Hanford, Washington, and Livingston, Louisiana. Each experiment consists of laser beams that are reflected between mirrors placed up to 4 kilometres apart. If a gravitational wave passes through, it will slightly distort space-time, leading to a shift in the laser beams. By monitoring time variations in the laser beams, it is possible to search for the effects of gravitational waves.

No one has yet detected a gravitational wave directly, but we do have indirect evidence that they exist. When pulsars orbit very dense stars, we expect them to emit a steady stream of gravitational waves, losing energy in the process so that their orbits gradually become smaller. Measurement of the decay of binary pulsars' orbits has confirmed that they do indeed lose energy and the best explanation is that these pulsars are losing energy in the form of gravitational waves.

Pulsars are not the only expected source of gravitational waves. The big bang should have created gravitational waves that still propagate through the cosmos as gentle ripples in space-time. These



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primordial gravitational waves are too faint to be detectable directly, but it should be possible to see their imprint on the relic radiation from the big bang - the cosmic microwave background. Experiments are now under way to search for these signatures.

Gravitational waves should also be emitted when two black holes collide. As they spiral in towards each other, they should emit a burst of gravitational waves with a particular signature. Provided the collision is sufficiently close and sufficiently violent, it may be possible to observe them with instruments on Earth.

A more ambitious project is the Laser Interferometer Space Antenna (LISA), made up of a trio of satellites that will follow the Earth in its orbit around the sun. They will emit precisely calibrated laser beams towards each other, much like LIGO. Any passing gravitational wave will slightly distort space-time and lead to a detectable shift in the laser beams. NASA and the European Space Agency hope to launch LISA in the next decade.

The LIGO detectors (left) are looking for gravitational waves ringing through space

TIME TRAVEL

Einstein's theory allows for the intriguing possibility of time travel. One suggested way of achieving this involves the construction of tunnels called wormholes that link different parts of space at different times. It is possible to build wormholes - in theory. But unfortunately they would require matter with negative energy, and other unnatural physical circumstances, not only to open them up but also to allow them to be traversed. Another possibility is to create a large region of space that rotates, or use hypothetical objects called cosmic strings. The possibility of time travel can lead to physical paradoxes, such as the grandfather paradox in which the time traveller goes back in time and kills her grandfather before he has met her grandmother. As a result, one of her parents would not have been conceived and the time traveller herself would not exist. It has been argued, however, that physical paradoxes such as these are, in practice, impossible to create.



FRONTIERS OF GENERAL RELATIVITY

General relativity predicts that the universe is full of exotic phenomena. Space-time can tremble like the surface of a pond and it seems to be full of a mysterious form of energy that is pushing it apart. It is also conceivable for space-time to be so warped that it becomes possible to travel backwards in time.

THE DARK UNIVERSE

The expanding universe predicted by general relativity has become firmly entrenched in modern science. As our ability to observe distant galaxies and map out the cosmos has improved, our picture of the universe has revealed some even more exotic features.

For a start, astronomers have been able to measure how fast distant spiral galaxies spin, and this shows that the outskirts of galaxies are rotating far too quickly to be reined in by the mass of the stars and gas at their centres. More matter is needed in galaxies to generate enough gravity to prevent galaxies from flying apart.

The popular explanation is that galaxies contain large quantities of other forms of matter - known as "dark matter" because it does not emit or reflect light. Dark matter is thought to clump around galaxies and clusters of galaxies in gigantic balls known as halos. Dark matter halos can be dense enough to significantly distort space-time and bend the path of any light rays that pass close by. This gravitational lensing has been observed in a number of clusters of galaxies, and is one of the strongest pieces of evidence for the existence of dark matter.

But that's not all. Cosmologists have been able to figure out how fast the universe expanded at different times in its history. This is done by measuring the distance to exploding stars called supernovae, and how quickly they are receding due to the expansion of space-time. The ground-breaking results from these observations, which emerged just over a decade ago, is that the expansion of the universe seems to be speeding up.

One explanation for this accelerating expansion is that the universe is permeated by an exotic form of energy, known as dark energy. Unlike ordinary matter and dark matter, which bend space-time in a way that draws masses together, dark energy pushes space apart, making it expand ever more quickly over time.

If we weigh up all the forms of matter and energy in the universe we end up with a striking conclusion: only 4 per cent of the universe is in the form of the matter we are familiar with. Around 24 per cent is dark matter and 72 per cent is dark energy.

This result emerged from the marriage of the general theory of relativity and modern astronomy and it has become a prime focus of physics. Experimenters and theorists are directing their efforts at trying to answer the burning questions: what exactly are dark matter and dark energy? And why do they have such strange properties?



The group of galaxies known as the Bullet cluster provides good evidence for dark matter (added in blue)





Pedro Ferreira is professor of astrophysics at the University of Oxford. He works on the origin of large-scale structures in the universe, on the general theory of relativity and on the nature of dark matter and dark energy



THE BIG UNSOLVED PROBLEM **QUANTUM GRAVITY**

General relativity is only one of the pillars of modern physics. The other is quantum mechanics, which describes what happens at the atomic including the graviton, the particle and subatomic scale. Its modern incarnation, quantum field theory, has been spectacularly successful at describing and predicting the behaviour of fundamental particles and forces.

The main challenge now is to combine the two ideas into one overarching theory, to be known as quantum gravity. Such a theory would be crucial for explaining the first moments of the big bang, when the universe was dense, hot and small, or what happens near the singularity at the cores of black holes, where the effects of quantum physics may compete with those of general relativity.

Although there is as yet no final theory of quantum gravity, there are several candidate theories being actively explored. One is string theory, which describes the fundamental constituents of matter not as pointlike particles but as microscopic

vibrating strings. Depending on how they vibrate, the strings will be perceived as different particles thought to carry the gravitational force.

Another possibility is that spacetime is not smooth but built up of discrete building blocks that interact with each other. As a result, if we were able to peer at its fine structure, it might look like a frothy space-time foam. In such theories, what we perceive as the space-time that bends and warps smoothly in the presence of matter is merely an emergent phenomenon masking more radical behaviour on small scales.

The quest for the theory of quantum gravity is arguably the biggest challenge facing modern physics. One of the difficulties is that it only really manifests itself at extremely high energies, well beyond our experimental reach. Physicists now face the task of devising experiments and astronomical observations that can test candidate theories of quantum gravity in the real world.

RECOMMENDED READING

The State of the Universe by Pedro G. Ferreira (Phoenix) Black Holes and Time Warps: Einstein's Outrageous Legacy by Kip Thorne (Papermac) Gravity: An Introduction to Einstein's General Theory of Relativity by James B. Hartle (Addison-Wesley) Time Travel in Einstein's Universe by Richard Gott (Phoenix) Was Einstein Right? Putting General Relativity to the Test by Clifford Will (Basic Books)

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