How researchers listen for gravitational waves

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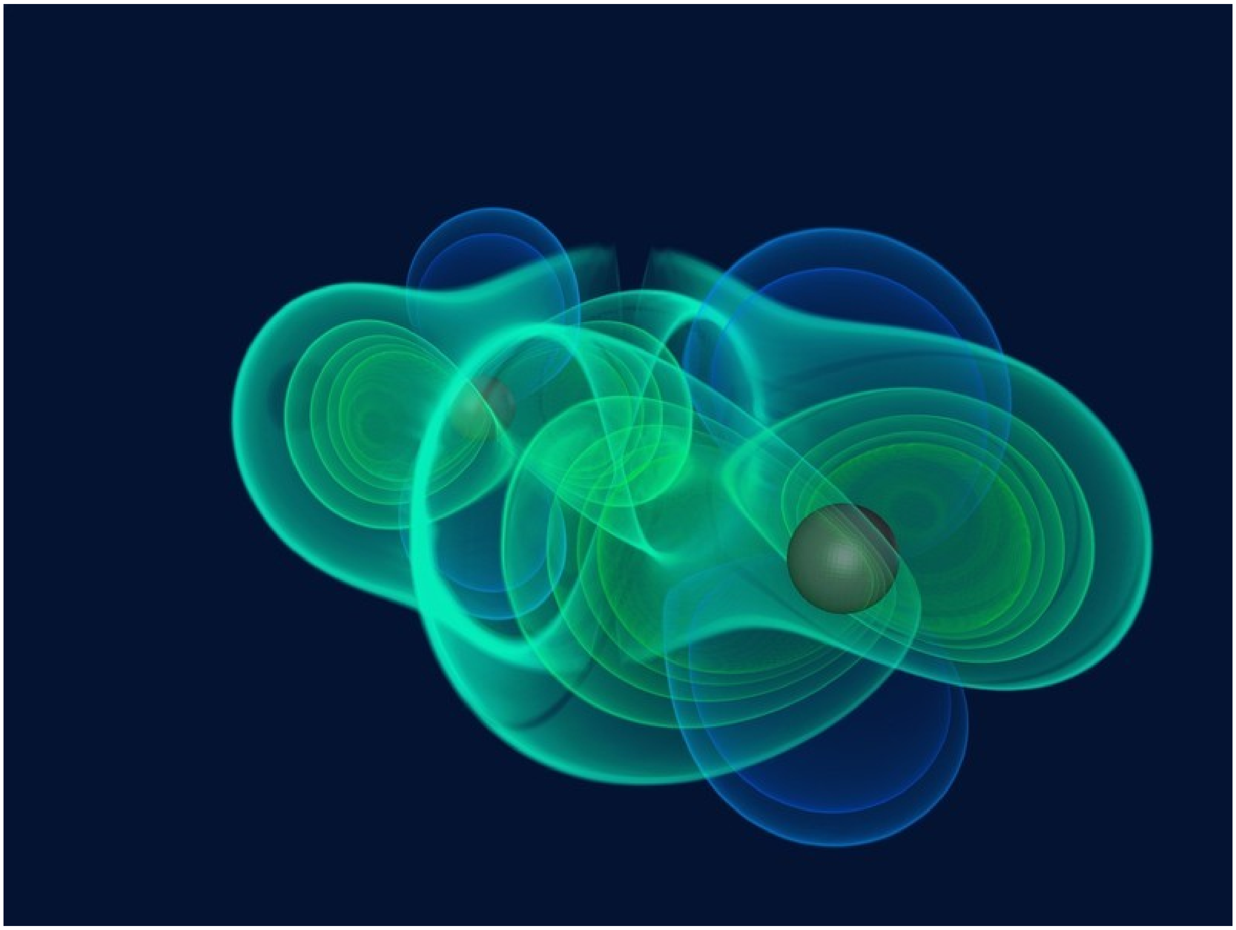


Cosmic collision: Gravitational waves are generated when black holes encircle each other and even collide – simulated here on a computer. Credit: MPI for Gravitational Physics / Institute for Theoretical Physics, Frankfurt / Zuse Institute Berlin

A century ago, Albert Einstein postulated the existence of gravitational waves in his General Theory of Relativity. But until now, these distortions of space-time have remained stubbornly hidden from direct observation. At the Max Planck Institute for Gravitational Physics in Hanover, researchers are on the trail of this phenomenon with the GEO600 detector. At the heart of the installation is a laser.

Isaac Newton strolled not through paradise, but through an English park. He nevertheless had a run-in with an apple - or to be more precise: it hit Newton on the head. Or did it roll in front of his feet? Difficult to say. There is some doubt as to whether there is any truth in the story of the falling apple. But like most legends, it is at least a good fabrication. Henry Pemberton told it for the first time in 1728 in his biography of the famous physicist.

Fact is that the University of Cambridge was closed from 1665 to 1666 because of the plague and the professor had a lot of time on his hands to contemplate. In any case, the encounter with the apple proved fruitful for Newton. It is said to have made him think that one and the same physical phenomenon was behind the motion of a stone tossed into the air, the orbit of the Moon around the Earth, and the motion of an apple falling to the ground: gravity.

Thus, the middle of the 17th century marks the beginning of the history of gravitation – the force which reaches into the furthest corners of the universe and keeps the world together. Put more precisely: "Two point masses attract each other with a force which points along the line intersecting them, is directly proportional to the product of their masses and indirectly proportional to the square of the distance between them." The Newtonian law of gravitation is wonderfully compatible with our everyday life. It explains why the Earth orbits the Sun and also why mobile phones (the most expensive ones, of course!) fall to the ground and break. So far, so good, if there wasn't just one little snag: the applicability of the law of gravitation is limited.

When the astronomers in the 19th century observed the motion of the planets with increasingly better instruments, they noticed that the point of Mercury's orbit closest to the Sun (perihelion) shifts in space. Although this effect occurs with all planets, as they pull at each other with their reciprocal gravitational force – the precession of the Mercurial perihelion turned out to be particularly clear and also greater than was to be expected according to Newtonian physics: per century, it amounts to around 1/80th of a degree. Was this the effect of an unknown celestial body in hiding? Or was it even the case that the construct of the classical theory of gravitation had a design fault?

In 1907, a "second class expert" at the patent office in Bern was giving intense thought to gravity. Two years earlier, he had submitted five articles to the journal Annalen der Physik, one of which was titled "On the Electrodynamics of Moving Bodies". In the article, the hobby researcher shook the foundations of physics just as he did with the three-page addendum "Does the Inertia of a Body Depend upon its Energy Content?"

The two publications are later called the Special Theory of Relativity. The ingenious author is named Albert Einstein, 1905 is deemed to be his annus mirabilis (miraculous year). On 20 July he celebrates his publications with his wife, Mileva. He describes the end of the exuberant celebration in a postcard to his friend Conrad Habicht: "Completely drunk, unfortunately both under the table."

The Special Theory of Relativity breaks with the Newtonian dogma of absolute time, among other things, and refutes the claim that velocities would always add together directly. In addition, the change in the gravitational effect of a body should be detectable immediately in the whole universe according to Newtonian theory. This means: gravity acts everywhere immediately. This was not really compatible with Einstein's statement, which stated that there was a natural speed limit for the propagation of the effects of any kind of force – the speed of light (c = 300,000 km/s).

The physicist thus put the laws of gravitation onto a new footing. He later recalled: "It was 1907 when I had the happiest thought of my life (...) … the gravitational field has ... only a relative existence. For if one considers an observer in free fall, for instance from the roof of a house, there exists for him during his fall no gravitational field – at least in his immediate vicinity. All objects dropped by this observer actually remain in a state of rest or uniform motion, regardless of their chemical or physical nature."

Einstein's trick can be explained in very simple terms: he simulates gravity using acceleration, since acceleration generates forces as well, as occur in a rapidly accelerating lift, for example. If the lift car was soundproof and lightproof, people could think that terrestrial gravity had suddenly increased. But is gravity a force at all, as Newton expressed it?

The realization that gravitation is at least partially a question of the reference system leads Albert Einstein to the revolutionary ideas which he presented in 1915 after eight years of work in his General Theory of Relativity. Tiny deviations from the Newtonian model result from the General Theory of Relativity for the motions of the planets. They occur most clearly for the rapidly orbiting Mercury close to the Sun. The perihelion precession can be explained and calculated exactly: "For some days I was beside myself with merry excitement," wrote Einstein after he had solved this mystery.

The General Theory of Relativity is ultimately a field theory – just like Maxwell's electrodynamics. In his equations, the Scottish physicist and mathematician James Clerk Maxwell links electric and magnetic field with charges and currents. Today, we experience the consequences of electrodynamics as a matter of course: they bring radio and television into our homes – as electromagnetic waves. The waves are generated by the acceleration of electric charges. Although distinct in many points, the General Theory of Relativity and electrodynamics have several formal things in common.

In electrodynamics, the fields result from the charge distribution, and for their part influence the charged particles, which in turn have an effect on the fields. In the General Theory of Relativity, the distribution of matter determines the geometry of space-time, which has an effect on the distribution of matter, which ultimately changes the geometry.

The two theories have something else in common: for Maxwell, perturbations in electromagnetic fields travel from their point of origin, an electric charge, for example, with the speed of light. For Einstein, the accelerated motion of masses in a gravitational field lead to perturbations that move through space at the speed of light. In both cases, the word perturbations can be replaced by another one: waves.

Field research: In Ruthe, near Hanover, GEO600 extends both its 600-metre arms. Its heart is the building in the centre which houses the laser system (rear, left). Credit: Harald Lück / MPI for Gravitational Physics / Leibniz Universität Hannover

If you jump up and down on a trampoline, you lose energy (not only in the form of calories) and generate waves in space-time. A person has a low mass and jumps relatively slowly, however. The gravitational waves emitted by the person are therefore immeasurably small.

Space is home to large masses, however – and even a trampoline: space-time. Everything is in motion here, because not a single celestial body remains at rest in one location. Earth bends space as it orbits the Sun, radiating gravitational waves with a power of 200 watts. But even these gravitational waves are still too weak to be tracked down with a detector.

Fortunately, much more violent tremors of space-time occur in the universe: when two neutron stars or black holes orbit each other extremely rapidly or even collide with each other. Or when a massive star explodes as a supernova. Such cosmic events generate gravitational waves with energies of around 1045 watts.

The two American astronomers Russell Hulse and Joseph Taylor actually showed that the orbital period of the two neutron stars PSR 1913+16 decreases because the binary system loses energy – and emits it as gravitational waves. The researchers were awarded the Nobel Prize for Physics for this in 1993. But how can these waves in space-time be detected? How do they make themselves felt?

For this purpose, imagine a virtual rubber sheet, which two experimenters – let's call them Albert and Isaac – each hold at two opposite corners. Albert and Isaac now pull simultaneously at the sheet by taking two or three steps backwards. As they move away from each other, their arms remain close to their body. The rubber sheet becomes longer and narrower at the same time.

Next, Albert and Isaac move towards each other again, extending their arms away from their body as they do so: the rubber sheet becomes shorter and wider at the same time. Finally, the two experimenters return to their original position. During the experiment, a portrait of Albert Einstein painted on the rubber sheet would expand and compress as if a gravitational wave spreading from the bottom to the top through the plane of the rubber sheet had distorted space.

In a second experiment, we paint two circles onto the rubber sheet as far away from each other as possible. We call one start/finish, the other turning point. We then organize an army of well-trained ants. We put all of them in the circle start/finish and let one after the other run to the turning point and back again at regular time intervals. Since the ants are moving with constant speed, they all arrive back at the finish circle at the same time intervals and separation as they left it at the start.

Now Albert and Isaac stretch the rubber sheet to double its size. This also causes the marching formation of the ant army to be stretched out, the separations between the ants increase: the ants arrive back at the finish separated by twice their original separation time. This time delay is only a temporary occurrence, however, because it applies only to those ants which are just en route. If the sheet remains stretched by a factor of two, the ants starting out also return at the same time intervals again. The (simulated) gravitational wave has the effect that the ants follow each other at times faster, at times slower than expected.

As described above, a gravitational wave changes the separation between the objects contained in space at right angles to the direction of propagation. It is extremely difficult to measure this. Let's imagine the worst-case scenario in our galaxy: the explosion of a massive star. The gravitational waves emitted by this collapse would – when they arrive at our solar system after a propagation time of a few thousand years – change the distance between Sun and Earth (1.5 x 1011 metres) by only the diameter of a hydrogen atom (10-10 metres) in a few ten thousandths of a second.

Albert Einstein therefore thought it was impossible to detect gravitational waves. And yet a number of scientists nevertheless conjured up instruments that were expected to succeed here. The first generation of instruments consisted of aluminium cylinders, weighing several tons, equipped with sensors. Pulses of gravitational waves should cause them to oscillate like the clapper of a church bell. However, these resonance detectors produced no results despite their having highly sensitive amplifiers.

The researchers therefore designed receivers which were even much more sensitive. Their principle is based on the thought experiment with the rubber sheet. For this purpose, we replace the start/finish circle with a laser, the turning point with a mirror, and imagine the ants to be the wave crests of a light signal. In order to detect the tiny delays in the arrival time, a second beam path must be arranged perpendicular to the first one so that the light waves of these two arms superpose.

Such a Michelson interferometer has been around since 1882; it was originally built to test the constancy of the speed of light. Equipped with state of the art technology, it is perfect for detecting gravitational waves. The GEO600 installation, which stands in a field in Ruthe near Hanover, operates according to the principle of the Michelson interferometer.

Below ground: At GEO600, the light beams travel underground through corrugated stainless steel tubes with a diameter of 60 centimetres and walls 0.9 millimetres thick (right). The installation is vibration cushioned and completely evacuated. Credit: MPI for Gravitational Physics / University of Hanover

The light is produced by several diode lasers, which are similar to those in a CD player. A small crystal converts the light into an infrared laser beam, whose power amounts to only ten watts after high-precision preparation and filtering – much more than a laser pointer, but also much too weak for useful measurements.

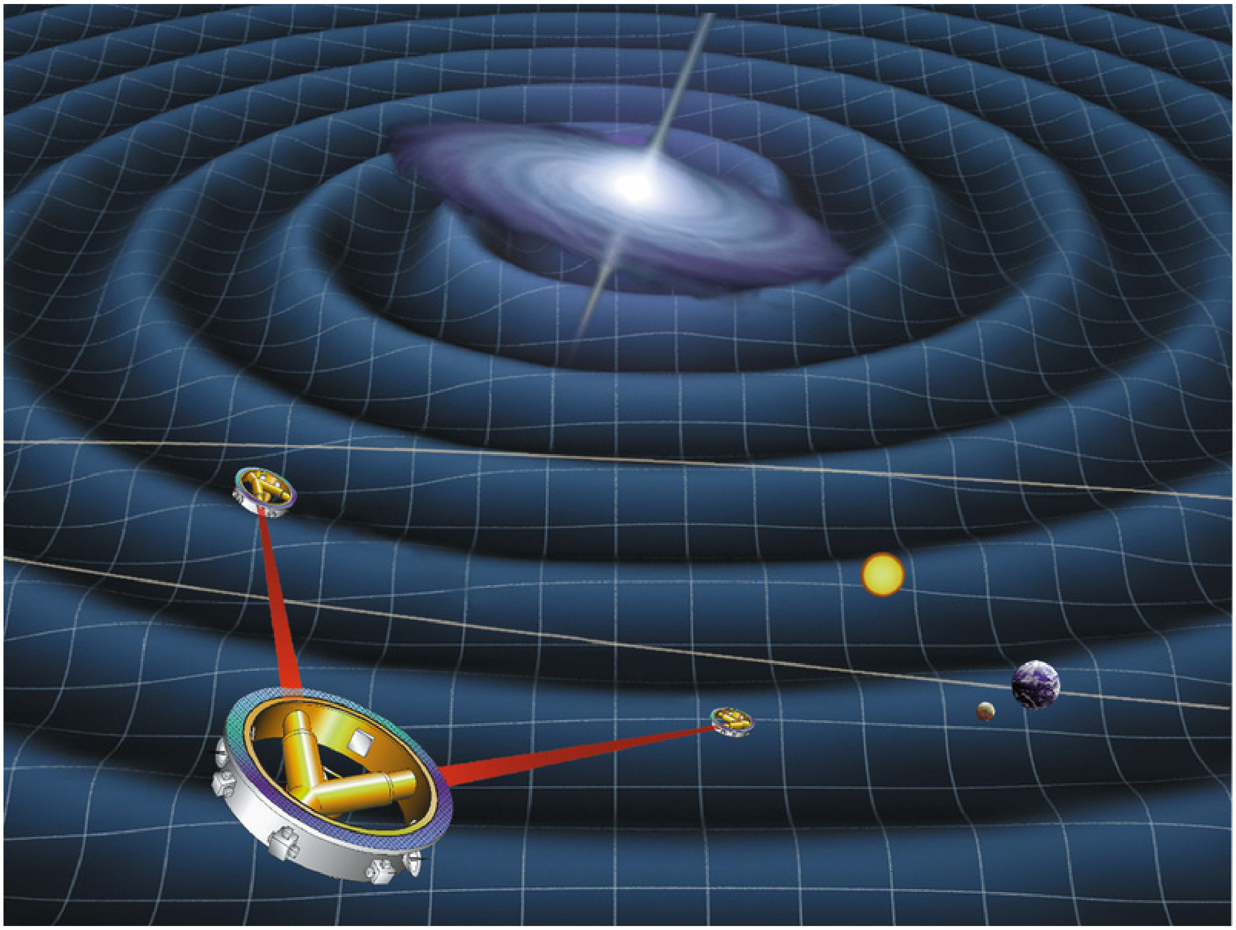
The researchers therefore employ "light recycling": a mirror returns all the unused light back towards the laser, which directs it again towards the interferometer. This cycle is repeated several times and amplifies not only the circulating light power to several 1000 watts, but also increases the sensitivity of the detector as well. The laser is also extremely stable: it produces light that always has the same amplitude and frequency for months and years.

The two arms of the interferometer are each formed by tubes 600 metres long and installed in trenches. The idea is that the laser beams can travel along the tubes without being disturbed by external influences. In reality, vibrations caused by traffic, natural seismic movement or the waves in the North Sea must be eliminated. Seismometers measure the oscillations, which are then compensated by piezoelectric actuators.

In addition to this active system, all optical components are equipped with a passive one: dual-layered dampers made of rubber and stainless steel. Leaf springs and multi-stage pendulums also act as vibration dampers. In order to keep the thermal fluctuations in the air density within the installation as low as possible, the interferometer has been housed in evacuated stainless steel tubes; turbomolecular pumps generate an ultra-high vacuum better than 10-11 bar.

GEO600 is a bilateral project headed by the Max Planck Institute for Gravitational Physics and the Leibniz Universität Hannover for Germany, and the Universities of Glasgow and Cardiff for Great Britain. The installation is one of several terrestrial listening posts whose task will be to listen to the concert of the stars.

At the end of 2015, the USA will put into operation aLIGO at two locations 3000 kilometres apart – second generation interferometric detectors, each with an arm length of four kilometres, which use many of the measuring technologies developed at GEO600. Near the Italian city of Pisa, Virgo is being expanded to have measuring arms three kilometres in length, and Japanese scientists are currently building the subterranean detector KAGRA of the same size. A first successful reception of the messages from space is expected during the next few years.



The future lies in space: Tremors can never be completely avoided in ground-based detectors and they disturb the measurement of gravitational waves below ten hertz. An international team of scientists is therefore planning the eLISA (evolved Laser Interferometer Space Antenna) project. Starting in 2034, three satellites are to follow behind Earth at a distance of 50 million kilometres and thus create a triangle with a side length millions of kilometres long. This space laser interferometer will be able to receive low-frequency gravitational waves from throughout the visible universe. Credit: NASA / JPL-Caltech

However, the astronomers are now already thinking ahead to the year 2034 when the eLISA interferometer is to listen from space for low-frequency gravitational waves from the whole visible universe and thus supplement the ground-based detectors.

Key statements of the Special Theory of Relativity

- There is no ether to carry light and radio waves.
- All physical laws have the same form in all systems moving uniformly with respect to each other.
- Space and time are inseparably linked to each other.
- There is no absolute simultaneousness.
- The speed of light is a universal constant and independent of the motion relative to the light source.
- Energy and mass are equivalent, mass is a direct measure of the energy contained in a body. And: light transmits mass. ...

Key statements of the General Relativity Theory

- Gravity is not a force in the conventional sense, but a property of the geometry of space-time.
- Matter bends space-time, the extent of the curvature increasing with the mass of a body and decreasing with increasing separation from it. Space and time are dynamic quantities and determine in turn the motion of matter.
- Time plays an important role in the General Theory of Relativity. A clock ticks more slowly near a massive celestial body than further away from it in regions which are affected less by its gravity.

Provided by Max Planck Society

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