Collisions that Make Waves in Space

Theoreticians at the **Max Planck Institute for Gravitational Physics (Albert Einstein Institute)** *in Golm near Potsdam have succeeded in calculating the shape and intensity of gravitational waves emitted by two black holes coalescing with one another. Their results are crucial for the success of the German-British gravitational wave detector GEO600, located in Hanover, which recently passed its first test. Physicists hope that it will enable them for the very first time to detect the existence of gravitational waves as predicted by Einstein.*

GEO600, located in Ruthe near Hanover. A rather inconspicuous hut is all that marks the presence of a high-tech facility.

At the end of October in the small town of Ruthe near Hanover, the scientists working with Karsten Danzmann from the Max Planck Institute for Quantum Optics felt their hearts give a leap. The researchers sent a laser beam into their gravitational wave detector for the first time. Travelling at the speed of light, the beam first hit an optical element that split it into two and redirected it in two vertically parallel directions. The two smaller beams were then

Pictures: Konrad-Zuse-Zentrum für Informationstechnik/MPI for Gravitational Physics – Benger / GEO600

reflected in a series of mirrors and brought together to a single point. That was it. The experiment ran unchanged for four days, without anything out of the ordinary happening. In fact, that is exactly what the team had hoped would be the case, because it showed that the GEO600 works. This may not sound very spectacular, but it represents the outcome of years of research, new developments, and sophisticated experiments. The goal of these efforts is to measure for the first time the gravitational waves predicted by Einstein.

According to the General Theory of Relativity, the gravity of a collection of matter, such as a star or a planet, can be described as a warping of space. This can be illustrated with the example of a billiard ball sitting on a rubber cloth and making an indentation in it. If another body finds its way into this hollow, it appears to be attracted by the ball and rolls towards it. If a body in space accelerates in such a way, it emits gravitational waves: warped space spreads out in every direction in waves. In the billiard ball analogy, waves would fan out from the location of the ball on the rubber cloth.

Einstein himself did not believe that anyone would ever be able to prove the existence of "his" gravitational waves. Today, however, that dream has come close to realization, even if only for the most extreme processes in the universe. The following example may serve to elucidate this. On its orbit around the sun the Earth emits gravitational waves that have a power of 200 Watts, while Jupiter manages to achieve the considerable sum of 5300 Watts. However, these are decidedly modest amounts in comparison to the real giants in the universe. For example, two compact neutron stars orbiting each other at a distance of one hundred kilometres over a period of one hundredth of a second generate a power equivalent to 1045 Watts. The power emitted in the form of gravitational waves from the explosion of a massive star, a supernova, is of a similar magnitude. These are the results the gravitational physicists are on the look-out for.

Waiting for a Brief Flicker

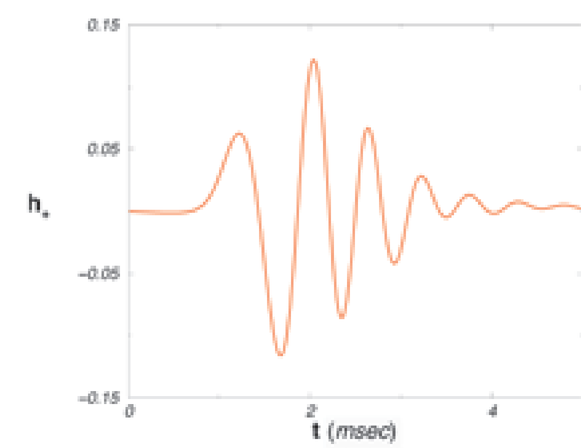
The proof works according to the following principle: gravitational waves spread out in space at the speed of light. Wherever they appear, space is compressed and stretched for a fraction of a second before taking on its original form again. It is this temporary distortion of space that the researchers hope to measure using laser interferometers such as the GEO600. At the heart of this apparatus is a very stable, high-performance laser. Using a semi-transparent mirror its beam is split into two beams that run away from one another to left and right. A mirror is situated at the end of each pathway, reflecting the light back. Both beams return to the semi-transparent mirror, which redirects them in such a way that they come together in a common point and overlap. The beams generate a so-called interference pattern at this point, whose brightness is measured by a special instrument.

As long as this arrangement is not disturbed, the interference pattern illuminates evenly. However, if a gravitational wave sweeps over it, the space in each arm of the interferometer is compressed and stretched a short interval of time apart. At that moment, the two laser beams are no longer travelling through space that is flat but through space that is bent – much as a ship in a storm rides up over high waves. As a result, each beam travels a little further or a little less far than it did before. And this manifests as a brief flicker in the interference pattern.

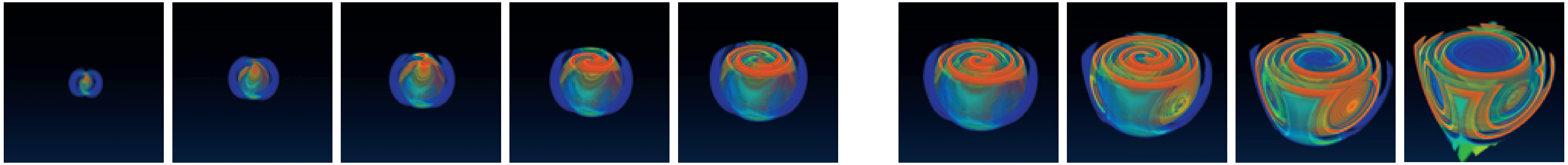
Whilst this may sound simple in principle, in actuality it is only just within the boundaries of what is technically feasible. If the laser beam travels a distance of one kilometre, a gravitational wave alters this pathway by as little as a billionth of the diameter of an atom, which itself measures a mere ten millionth of a millimetre. An incredible undertaking. But now the researchers want to get started. However, one gravitational wave detector on its own would not be sufficient to obtain reliable results. For one thing, it would be unable to localise a source in the sky. In addition, a flicker in the interference pattern would not constitute proof of a gravitational wave passing through. It might be caused by some other disturbance.

For this reason, other instruments of this kind are currently being set up around the world in addition to the GEO600. The American LIGO, with two facilities in Hanford and Livingston (USA) respectively, is due to undergo its first test run shortly. Each of these interferometers has arms that are four kilometres long. VIRGO, with three kilometre-long arms, is

One of the 600-metre-long pipes. They are suspended in such a way that they will not vibrate when exposed to external tremors.



Computer simulations at the Max Planck Institute for Gravitational Physics show the oscillation mode of a gravitational wave that arises when two black holes weighing ten solar masses merge.



This computer simulation shows gravitational waves speeding towards the Earth after the collision of two black holes. The waves are generated close to the centre of the collision and spread out like ripples on a pond.

currently under construction near the Italian town of Pisa. It will be completed in two to three years' time. Finally, a 300 metre-long interferometer named TAMA is already up and running in Mitaka, Japan. The latter is not sensitive enough, however, to provide evidence of genuine cosmic sources and serves principally to test new technical components.

GEO600 has two arms, each of which is 600 metres in length, its pipes are fully evacuated, and ultimately it will be equipped with the best optical components in the world. Together with LIGO it will be doing pioneering work. "We want to try the first coincidence test with LIGO from December 28th onwards", says Karsten Danzmann. The devices are to run for about two weeks. In the first instance the scientists want to study how they react to environmental influences, such as sun storms or particles of cosmic radiation. Whilst these do not generate gravitational waves, they may disturb the sensitive electronics in both instruments and give rise to what seems to be a gravitational signal. In addition, the physicists want to test a range of software packages that search for different cosmic gravitational signals.

LIGO and GEO600 are part of the Ligo Science Collaboration group, which means that researchers from both facilities can access the entire set of data at any time. VIRGO is to join in the collaborative enterprise at a later date, and all four locations will be treated as a single global gravitational wave observatory. Only if these machines register a signal at about the same time is it likely that a gravitational wave is the cause. Four instruments have the added advantage that the direction from which the wave came can be approximately established. This method is similar to that used in land surveying, where a bearing of a particular point is taken from different locations. After the trial run early in 2002, the data will be evaluated and the temporary optical elements in GEO600 replaced with permanent ones. The German and American facilities will initiate regular observational operations towards the end of 2002.

The cosmic interpretation of the measured signals they hope to obtain will depend crucially on the quality of theoretical models. A group of young physicists (Baker, Brügmann, Campanelli, Lousto and Takahashi) at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute, AEI) in Golm, near Potsdam, has already made an outstanding contribution in this regard. The Lazarus team, as these scientists call themselves, has calculated the shape and intensity of gravitational waves that arise when two black holes merge into one another. An occurrence of this kind is preceded by a lengthy series of events. The process begins with two massive stars orbiting each other. When they have used up all their fuel, they eject their outer crust into space and become supernovas. Their cores, however, collapse and become black holes. These orbit one another as before, but since they emit gravitational waves, they lose momentum and gradually draw closer to each other. Eventually they collide and merge in a fraction of a second. Around three per cent of the mass of black holes is transformed into gravitational wave energy when this cosmic collision occurs.

Black Holes on the Computer

Although this is the most cataclysmic event in the universe imaginable, it remains completely invisible, as neither light nor radio waves nor X-rays are emitted in the process. Gravitational waves constitute the only evidence. Thus simulations are essential in order to establish the nature of the sources from the signal observed. Previous simulations of two colliding black holes were unable to show the entire process of coalescence. The basic problem was how to model the wave emissions and the inside of the black hole simultaneously. The Potsdam team achieved the crucial breakthrough by combining two separate methods: full numerical simulation of the collision and an approximation method taken from perturbation theory for calculating the radiation given off from the emerging black hole.

The results obtained by the Golm researchers are good news for their colleagues working with the GEO600. This is because they indicate that the gravitational waves are much stronger than had thus far been supposed. The frequency range is also more favourable. "Two black holes, which together are 18 times heavier than the Sun, emit gravitational waves with a frequency between 600 and 900 Hertz", explains Bernd Brügmann, a member of the Lazarus team. This frequency band is located exactly within the measuring range of the GEO600 and the other detectors.

Collisions between two black holes are extremely rare. Experts assume that such an event happens only once every 100,000 years in a galaxy such as our own Milky Way. Nonetheless, it literally makes waves that are so big that the evidence can be detected at distances of several hundred million light years. Since there is a very large number of galaxies within this radius around the Earth, astrophysicists calculate that they should be able to register a collision of two black holes once every two years.

"The Golm-Hanover connection is working extremely well", continues Danzmann. And on the 1st of January 2002 the experimentalists and the theoreticians were brought together administratively as well. The AEI now has two official sites, one in Golm and the other in Hanover; up until then, the Hanover site had officially been part of the Max Planck Institute for Quantum Optics in Garching, near Munich (cf. page 109 of this edition).

In addition to merging black holes, the researchers hope to detect two other kinds of events in particular. One of these are supernovae. In a galaxy such as the Milky Way, about two or three "heavy" stars explode every century. However, if as scientists hope, such events can be observed at distances as great as tens of millions of light years, then it should be possible to register several events of this sort every year. Merging neutron stars may be an even more attractive prospect. These are very compact residues of stellar material with diameters of about 20 kilometres, whose matter is so tightly compressed that a teaspoonful of it would weigh a billion metric tons on Earth. When such bodies orbit one another and merge in much the same way as black holes, very strong gravitational waves are emitted. It might be possible to register one of these events every year.

The discovery of gravitational waves would enable astrophysicists to open up a whole new observational window on the universe. "And detecting them would also be a landmark for Einstein's General Theory of Relativity", says Bernard Schutz, Director of the AEI in Golm. This is because gravitational waves are among the few phenomena predicted by the theory of relativity, for which no evidence has yet been found.

Thomas Bührke