Can you hear black holes collide?

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An overlay of the results of a supercomputer simulation of colliding black holes and a piece of gravitational-wave detector equipment.

A team of gravitational-wave researchers from four universities has been selected to exhibit at the prestigious Royal Society Summer Science Exhibition.

Researchers from the Universities of Glasgow, Birmingham, Cardiff and Southampton are joining forces with colleagues from the Albert Einstein Institute in Potsdam, Germany, and designers from Milde Science Communication to showcase the exciting science associated with Einstein's general theory of relativity, black holes and gravitational waves.

The exhibit, entitled: ‘Can you hear black holes collide?’ introduces the main ideas behind Einstein’s relativistic theory of gravity. Through a number of hands-on exhibits visitors get an understanding of how space and time are flexible, and why this leads to gravity. Black holes are explained and a table-top laser-interferometer is used to demonstrate the technology used to search for gravitational waves - the tiny ripples in space and time that bathe the Earth. State-of-the-art supercomputer simulations of colliding black holes are demonstrated. The challenging task of digging weak gravitational-wave signals out of noisy detector data is introduced via a fun game where visitors can test their skill at listening for actual black hole signals.

Running from 30 June – 3 July 2008, the Royal Society Summer Science exhibition is a premier annual showcase for scientific excellence in the UK. Research teams are invited to bid to provide an exhibit on their work, and after a stiff competition the best are selected for display to scientists, the media and the general public.

Gravity is geometry

With his theories of relativity Einstein laid the foundation for much of modern physics. His special theory of relativity is based on the idea that the speed of light is constant regardless of the motion of the observer. It tells us that measurements involving space and time lead to surprising results if one travels near the speed of light. Time appears to slow down and objects seem to contract. This shows that space and time are not the rigid concepts that we are used to in everyday life. In the general theory of relativity, which reconciles the principles of relativity with gravitation, space and time become even more flexible – changing as the world changes around them.

Black holes

In Einstein’s theory gravity is no longer simply a force that pulls falling apples to the ground. Instead, gravity is geometry. The presence of matter alters the geometry of space and time, and the geometry in turn determines how matter moves. One of the most fascinating predictions of general relativity is the existence of black holes. Black holes are made from matter, but they are not matter. They are formed when massive stars run out of nuclear fuel and collapse under their own weight. The collapse leads to a region of extreme space-time curvature. Objects can fall into this region – the black hole – but nothing can escape. Not even light.

We have strong astronomical evidence that black holes are common in the Universe. Their presence may be central to the formation of galaxies. In fact, we believe that virtually all galaxies harbour a gigantic black hole in their centres. Yet we do not know how these black holes work. Apart from having relatively good estimates of their masses and some evidence that they may rotate very fast, we know very little. Black holes are dynamical objects that interact with the environment. They may form binary systems where two black holes orbit each other. According to general relativity, such systems will evolve towards a final black-hole collision – an event involving extreme space-time deformations.

Waves of gravity

Einstein's geometric theory of gravity predicts that changes in gravity propagate through the Universe in the form of waves. These gravitational waves, often thought of as “ripples” in space and time, are created whenever masses accelerate. They have not yet been detected directly, but we have strong indirect evidence that they exist. The best evidence comes from a double neutron star system called PSR1913+16. As the stars orbit each other the system radiates gravitational waves and loses energy. Observations, now spanning more than three decades, show that the orbit of the double neutron star system shrinks at exactly the rate predicted by general relativity.

Gravitational waves convey less a picture than a sound. Just as sound waves contain information about the musical instrument that created them, the gravitational waves carry an imprint of the event in which they were generated.

The strongest gravitational-wave signals come from the most violent events in the Universe, involving the acceleration of large masses in small regions of space. Because of their small size to mass ratio, black holes are particularly promising sources. If we could detect these signals, we would be able to find black holes and study them in detail.

However, even though the events that generate the waves may be extremely powerful, the waves wane with distance. Since most cosmological events occur far from the Earth the gravitational waves that bathe our planet are very weak.

In order to catch these waves we must develop very sensitive detectors. One must be able to detect changes of about a thousandth of the diameter of the proton in a kilometer-sized detector. This is like comparing the width of a human hair to the distance to the nearest star! Cutting edge laser interferometers has been developed to detect these tiny stretches in space-time. An international network of extremely sensitive detectors is now tracking the changes in the space-time geometry, listening for tiny changes in gravity.

Sophisticated tools are needed to dig the very weak signals out of the detector noise. This poses further challenges. The development of such analysis tools requires a good theoretical understanding of gravitational-wave sources. Unfortunately, even though the mathematical equations of general relativity, encoding the interaction between matter and space-time geometry, are easy to write down they are notoriously difficult to solve. In most situations one has to resort to simplifications or costly supercomputer simulations.

After several decades of effort, there has recently been great progress on simulating the inspiral and final merger of two black holes. The results of these simulations provide insights into the detailed interaction of two black holes. They also provide researchers analysing the detector output with reliable signal templates.

Gravitational-wave astronomy

We study gravity, but gravity is also the messenger. By detecting gravitational waves from black holes we hope to measure black-hole parameters, provide accurate maps of the shape of space-time, and test Einstein's theory with high precision.

At the end of the day, the weak interaction between gravitational waves and matter may be a blessing. The gravitational waves that reach our detectors are virtually unaltered since their generation. This means that we will be able to study regions of space that cannot be investigated with the traditional tools of astronomy. Gravitational-wave astronomy will open a new window through which we will probe that dark side of our fascinating Universe.

Further details on the event can be found at: www.summerscience.org.uk and on the exhibit itself at the 'Can you hear black holes collide?' website: www.soton.ac.uk/maths/blackholes.html

More on black holes and gravitational waves:
www.einstein-online.info
www.ligo.org

Source: University of Glasgow