
Jan 2002
Features

Catching waves with Kip Thorne

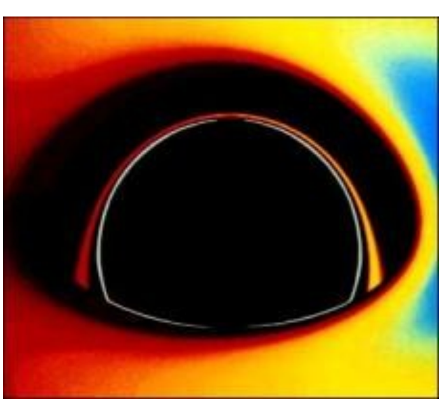
by The Plus Team

Kip Thorne has been at the forefront of black hole cosmology since the early 1960s, and currently heads one of the world's leading groups working in relativistic astrophysics. An important emphasis of his research is on black holes and gravitational waves, and developing the mathematics necessary to analyse these objects.

Professor Thorne gave a talk on "Warping Spacetime" and Rachel Thomas from the Plus team went along and spoke with him about it afterwards.

A little history

Have you ever wanted to witness the collision of two black holes? You can, if you just listen hard enough for the symphony of gravitational waves such events produce. Thorne is looking forward to the coming decade, when the next generation of gravitational wave detectors will reveal these hitherto unseen cosmic cataclysms.



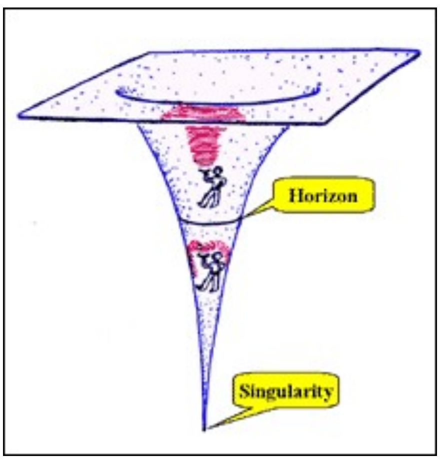
To date, the study of black holes has advanced using theoretical rather than experimental means, moving forward via the leaps of intellectual insight contributed by the major players in the field. The gravitational wave detectors being built by Thorne's colleagues will provide the first opportunity to test theoretical predictions made during the "Golden Age" of black hole theory, 1964 to 1974.

In this area of physics, the technology for actually testing theoretical predictions has always lagged behind; for example, it has only recently caught up enough to test some of the fundamental consequences of Einstein's theory of general relativity with high precisions.

In 1915 Einstein introduced the world to the idea that gravity was actually a warping effect of matter on spacetime , the 4 dimensional fabric that makes up our universe (there are 3 dimensions for space, and an extra dimension for time). The effects and manifestations of this warping, as predicted by general relativity, are much more complex than the familiar earthly effect of apples falling from trees.

When Karl Schwarzschild solved the Einstein field equation (the mathematical relationship between the curvature of spacetime and the presence of matter) for a special type of star, he discovered an object that was cut off from the rest of the universe − a black hole.

Schwarzchild discovered that there is a critical size for a star, which depends on the star's mass. If the star's volume shrinks down to this critical size, the star's mass warps spacetime so extremely that the curvature of spacetime measured at the star's surface is infinite.



The Schwarzchild singularity [Drawing used by permission of Kip Thorne]

Surprisingly, the Schwarzchild singularity is not actually a singularity in the terms defined by modern physics. Instead, it describes the "horizon" of an entity known as a "black hole". Anything that crosses the horizon and falls into the hole becomes forever trapped, with no information able to escape from within the hole's walls. In particular, no light can escape past the horizon, hence the name "black hole".

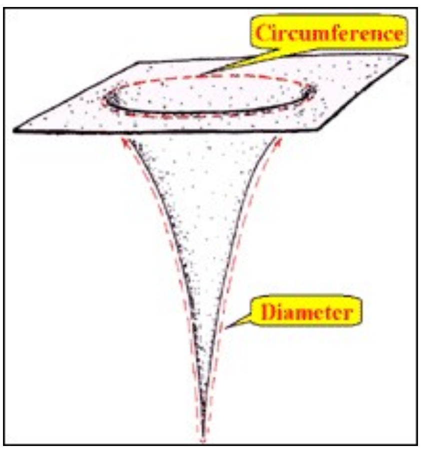
Even though the notion of a black hole is a direct consequence of general relativity, the world of physics (including Einstein himself) refused to admit that such an outrageous object could exist, and resisted the idea for over 50 years.

Resistance to the reality of black holes finally began to crumble in the 1960s. It was then that the theoretical study of black holes was accelerated into what Thorne calls the "Golden Age". During the years between 1964 and 1974, many major discoveries were made by Hawking, Penrose, Thorne and their contemporaries, and it is these predictions that he wants to put to the test.

So what *is* a black hole?

A hole in the ground is not made of soil, but instead from the empty space left after digging out the soil. In the same way, black holes are made not from matter, but from a warping of spacetime itself. To help us picture what a black hole looks like, Thorne uses the analogy of a blind ant who lives on a large trampoline with a heavy rock in the middle.

We human observers can see that the rock severely warps the surface of the trampoline, which represents the ant's universe. The tiny ant, on the other hand, will be unaware of this as it walks along the surface of the large trampoline, effectively experiencing it in only two dimensions.

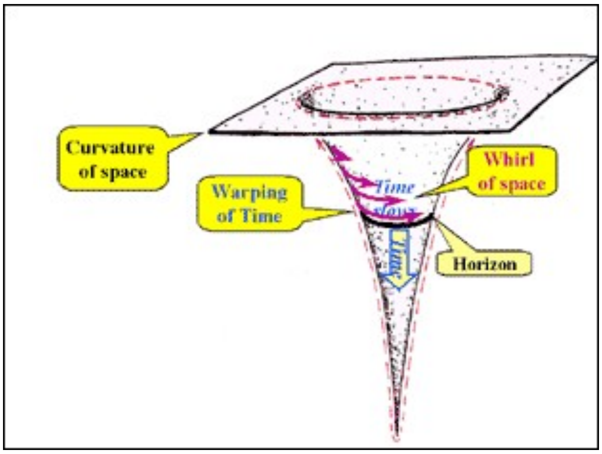


The diameter is greater than the circumference
[Drawing used by permission of Kip Thorne]

The extreme curvature of the fabric of the ant's universe has some surprising mathematical conseqences for geometry. Consider what happens when the ant walks around the trampoline's "black hole", measuring the circumference as it goes. In the normal (euclidean) geometry of flat space, the diameter of a circle is its circumference divided by pi. However, when the ant tries to measures the diameter of the "black hole" by walking across it (all the way down one side and up the other), it finds that the diameter is not less than the circumference but in fact many times larger.

It is difficult for the ant to get a good understanding of its universe by looking at the trampoline as a two−dimensional surface. Similarly, if we consider a black hole in our own universe, we might think of it as a sphere in our three−dimensional space. However, because space is curved by the mass of the black hole, it turns out that the only way we could see the entire curvature would be to picture it in a flat space with many more dimensions than four!

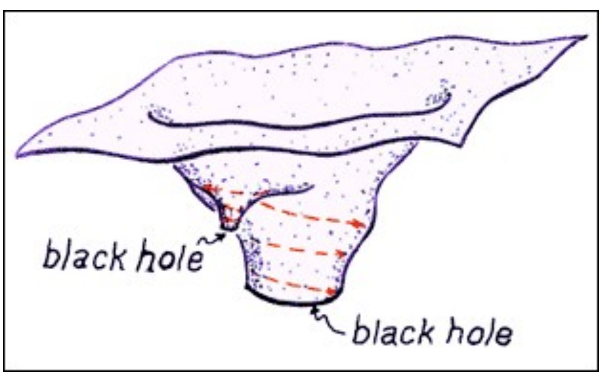
Needless to say, most humans don't have a clue what many−dimensional space might look like. To make the situation easier to visualise, physicists instead just concentrate on two dimensions of space (usually the "equatorial plane" that passes through the middle of the black hole), and examine this plane's curvature in a three−dimensional hyperspace. This gives us an extra mathematical dimension to understand the curvature, but it is not a real dimension that we can ever experience. It simply allows us to examine the warping of a two−dimensional slice of our own spacetime, just as we were able to examine the curvature of the blind ant's trampoline universe.



Black hole parameters
[Drawing used by permission of Kip Thorne]

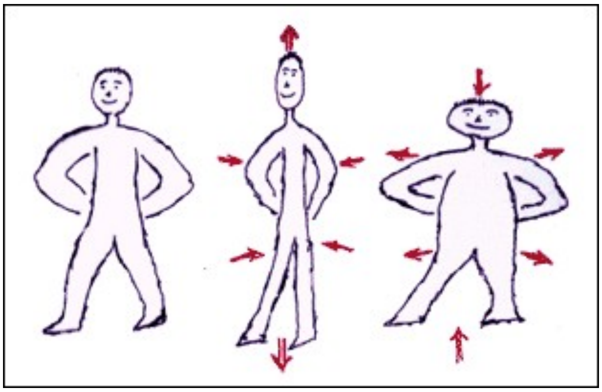
In the physicists' model, there are three parameters that describe the warping of spacetime − the curvature of space, the warping of time and the whirl of space. These properties can be described mathematically, and by solving the Einstein field equation we can predict what these three parameters will be in various circumstances. This helps us to picture black holes and other relativistic phenomena. The picture at the right shows curvature, warping and whirl for a spinning black hole which drags the surrounding space with it as it spins.

Colliding black holes



A small black hole orbiting a large black hole
[Drawing used by permission of Kip Thorne]

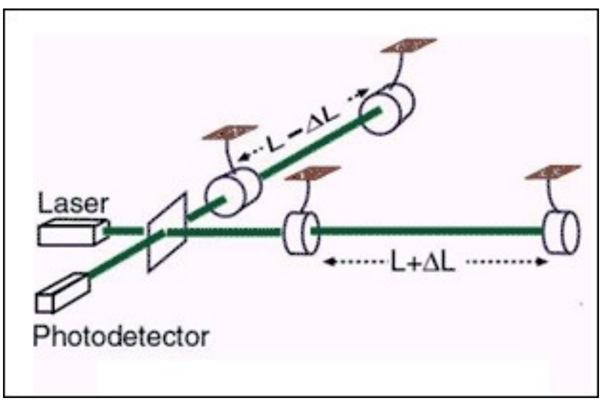
As a small black hole orbits a larger black hole, it creates gravitational waves which carry all the information required to describe the warped spacetime around the two holes, the so−called "spacetime map".



Stretching and squeezing
[Drawing used by permission of Kip Thorne]

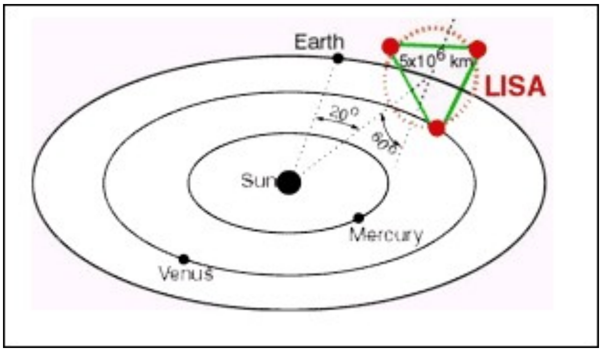
These waves are tidal waves, similar to ripples on the surface of a pond. A cork on a pond's surface will be moved both back and forth and up and down by the ripples. Similarly, gravitational waves also produces motion in two directions by stretching and squeezing space. Gravitational waves are very weak, however, stretching and squeezing space by the width of just 1/10,000 of an atom when they reach the Earth.

Thorne is working with colleagues on a programme of gravity wave detection using a technique known as laser interferometry. This method involves splitting a laser beam into two perpendicular beams, bouncing each of these two beams off a mirror, and then recombining the two beams when they meet.



Laser interferometry
[Drawing used by permission of Kip Thorne]

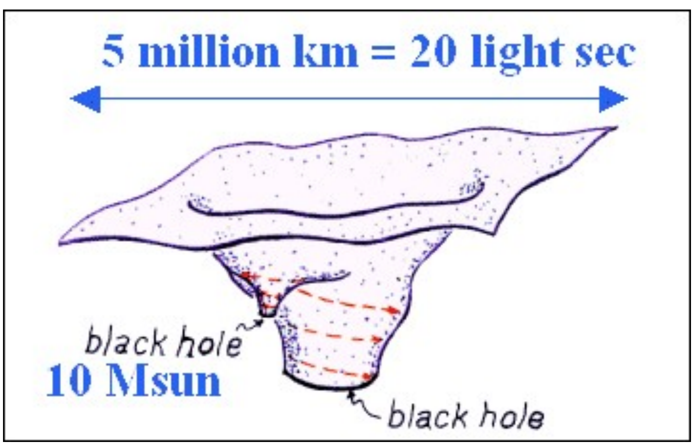
If the lengths of the two paths of the light differ, then the recombined beams will form interference patterns from which the differing lengths of the two paths can be deduced. As a gravity wave passes through the L−shape of the interferometer, it will displace the mirrors (attached to large masses) at the end of each arm, altering the distances travelled by the beams and producing an interference of the light.



LISA [Drawing used by permission of Kip Thorne]

LISA, the Laser Interferometer Space Antenna due to be launched in 2011, is an interferometer on a massive scale. It will consist of three separate space craft, arranged in space to form a triangle with sides 5 million kms long. At this distance, it will take approximately 20 seconds for light to travel between the space craft. When passing gravitational waves stretch and squeeze space, affecting the distance travelled by the light beams between the space craft, this can be measured by the resulting interference of the light beams.

Of course, making the measurements is a very subtle business. Suppose LISA is trying to detect the waves produced by a system of black holes 3 billion light years away, consisting of a small black hole, weighing just ten times the mass of the sun, orbiting a large black hole weighing one million times the mass of the sun. As the gravitational waves will be very weak after travelling 3 billion light years to our solar system, LISA will need to measure distance variations of just 10^{-10} cms. LISA should be up to this daunting task, and the waves it detects will carry detailed maps of the big hole's space curvature, time warping and whirl.



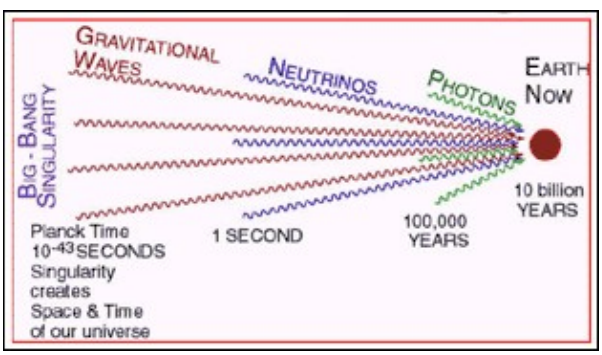
[Drawing used by permission of Kip Thorne]

It is thought that colliding black holes will merge into a single hole. Moreover, Hawking's Second law of black hole mechanics predicts that after such collisions, the horizons must increase. In other words, it is thought that the surface area of the final black hole's horizon must be larger than the sum of the surface areas of the two colliding holes' horizons.

The 4 kilometer long, L−shaped, LIGO gravitational wave detector in Hanford, Washington
[Photo used by permission of the LIGO Project, California Institute of Technology]

The observational tests of this and other predictions will begin this year with Earth−based gravity wave detectors (LIGO in Hanford, Washington, along with a UK−German companion detector in Hanover and a French−Italian companion detector in Pisa), and will be aided by the eventual launch of LISA.

All of these predictions and observations are restricted to the surface of the black hole. They can tell us nothing about the singularity that lies hidden beneath the horizon. However, there is one singularity we can study − the Big Bang which gave birth to our universe.



Looking back to the Big Bang [Drawing used by permission of Kip Thorne]

From the Earth, astronomers have observed cosmic background radiation enabling us to see back to just 100,000 years after the Big Bang. Observation of neutrinos can take us back to when the universe was only one second old. However, gravitational waves offer the only direct tool to probe what the universe was like when it was less than one second old.

Professor Thorne is very excited about the future for gravitational wave detection. He looks forward to testing theoretical predictions about black holes, and to a time when gravitational waves show us the very birth of our galaxy itself.

Plus is part of the family of activities in the Millennium Mathematics Project, which also includes the NRICH and MOTIVATE sites.