FUNDAMENTAL PHYSICS

Gravitational Waves Should Permanently Distort Space-Time

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The "gravitational memory effect" predicts that a passing gravitational wave should forever alter the structure of space-time. Physicists have linked the phenomenon to fundamental cosmic symmetries and a potential solution to the black hole information paradox.

A black hole collision should forever scar space-time.

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Alfred Pasieka / Science Source

The first detection of gravitational waves in 2016 provided decisive confirmation of Einstein's general theory of relativity. But another astounding prediction remains unconfirmed: According to general relativity, every gravitational wave should leave an indelible imprint on this so-called “memory effect.”

“The memory effect is absolutely a strange, strange phenomenon,” said Paul Lasky, an astrophysicist at Monash University in Australia. “It’s really deep stuff.”

Their goals are broader than just glimpsing the permanent space-time scars left by a passing gravitational wave. By exploring the links between matter, energy and space-time, physicists hope to come to a better understanding of Stephen Hawking’s black hole information paradox, which has been a major focus of theoretical research for going on five decades. “There’s an intimate connection between the memory effect and the symmetry of space-time,” said Kip Thorne, a physicist at the California Institute of Technology whose work on gravitational waves earned him part of the 2017 Nobel Prize in Physics. “It is connected ultimately to the loss of information in black holes, a very deep issue in the structure of space and time.”

A Scar in Space-Time

Why would a gravitational wave permanently change space-time’s structure? It comes down to general relativity’s intimate linking of space-time and energy.

First consider what happens when a gravitational wave passes by a gravitational wave detector. The Laser Interferometer Gravitational-Wave Observatory (LIGO) has two arms positioned in an L shape. If you imagine a circle circumscribing the arms, with the center of the circle at the arms’ intersection, a gravitational wave will periodically distort the circle, squeezing it vertically, then horizontally, alternating until the wave has passed. The difference in length between the two arms will oscillate — behavior that reveals the distortion of the circle, and the passing of the gravitational wave.

According to the memory effect, after the passing of the wave, the circle should remain permanently deformed by a tiny amount. The reason why has to do with the particularities of gravity as described by general relativity.

The objects that LIGO detects are so far away, their gravitational pull is negligibly weak. But a gravitational wave has a longer reach than the force of gravity. So, too, does the property responsible for the memory effect: the gravitational potential.

In simple Newtonian terms, a gravitational potential measures how much energy an object would gain if it fell from a certain height. Drop an anvil off a cliff, and the speed of the anvil at the bottom can be used to reconstruct the “potential” energy that falling off the cliff can impart.

But in general relativity, where space-time is stretched and squashed in different directions depending on the motions of bodies, a potential dictates more than just the potential energy at a location — it dictates the shape of space-time.

How, exactly, will a passing wave distort space-time? The possibilities are literally infinite, and, puzzlingly, these possibilities are also equivalent to one another. In this manner, space-time is like an infinite game of Boggle. The classic Boggle game has 16 six-sided dice arranged in a four-by-four grid, with a letter on each side of each die. Each time a player shakes the grid, the dice clatter around and settle into a new arrangement of letters. Most configurations are distinguishable from one another, but all are equivalent in a larger sense. They are all at rest in the lowest-energy state that the dice could possibly be in. When a gravitational wave passes through, it shakes the cosmic Boggle board, changing space-time from one wonky configuration to another. But space-time remains in its lowest-energy state.

Super Symmetries

That characteristic — that you can change the board, but in the end things fundamentally stay the same — suggests the presence of hidden symmetries in the structure of space-time. Within the past decade, physicists have explicitly made this connection.

The story starts back in the 1960s, when four physicists wanted to better understand general relativity. They wondered what would happen in a hypothetical region infinitely far from all mass and energy in the universe, where gravity's pull can be neglected, but gravitational radiation cannot. They started by looking at the symmetries this region obeyed.

They already knew the symmetries of the world according to special relativity, where space-time is flat and featureless. In such a smooth world, everything looks the same regardless of where you are, which direction you're facing, and the speed at which you're moving. These properties correspond to the translational, rotational and boost symmetries, respectively. The physicists expected that infinitely far from all the matter in the universe, in a region referred to as "asymptotically flat," these simple symmetries would reemerge.

To their surprise, they found an infinite set of symmetries in addition to the expected ones. The new "supertranslation" symmetries indicated that individual sections of space-time could be stretched, squeezed and sheared, and the behavior in this infinitely distant region would remain the same.

In the 1980s, Abhay Ashtekar, a physicist at Pennsylvania State University, discovered that the memory effect was the physical manifestation of these symmetries. In other words, a supertranslation was exactly what would cause the Boggle universe to pick a new but equivalent way to warp space-time.

His work connected these abstract symmetries in a hypothetical region of the universe to real effects. "To me that's the exciting thing about measuring the memory effect — it's just proving these symmetries are really physical," said Laura Donnay, a physicist at the Vienna University of Technology.

The point of the Boggle game is to search the seemingly random arrangement of letters on the grid to find words. Each new configuration hides new words, and hence new information.

Like Boggle, space-time has the potential to store information, which could be the key to solving the infamous black hole information paradox. Briefly, the paradox is this: Information cannot be created or destroyed. So where does the information about particles go after they fall into a black hole and are re-emitted as information-less Hawking radiation?

In 2016, Andrew Strominger, a physicist at Harvard University, along with Stephen Hawking and Malcolm Perry realized that the horizon of a black hole has the same supertranslation symmetries as those in asymptotically flat space. And by the same logic as before, there would be an accompanying memory effect. This meant the infalling particles could alter space-time near the black hole, thereby changing its information content. This offered a possible solution to the information paradox. Knowledge of the particles' properties wasn't lost — it was permanently encoded in the fabric of space-time.

"The fact that you can say something interesting about black hole evaporation is pretty cool," said Sabrina Pasterski, a theoretical physicist at Princeton University. "The starting point of the framework has already had interesting results. And now we're pushing the framework even further."

Pasterski and others have launched a new research program relating statements about gravity and other areas of physics to these infinite symmetries. In chasing the connections, they've discovered new, exotic memory effects. Pasterski established a connection between a different set of symmetries and a spin memory effect, where space-time becomes gnarled and twisted from gravitational waves that carry angular momentum.

A Ghost in the Machine

Alas, LIGO scientists haven't yet seen evidence of the memory effect. The change in the distance between LIGO's mirrors from a gravitational wave is minuscule — about one-thousandth the width of a proton — and the memory effect is predicted to be 20 times smaller.

LIGO's placement on our noisy planet worsens matters. Low-frequency seismic noise mimics the memory effect's long-term changes in the mirror positions, so disentangling the signal from noise is tricky business.

Earth's gravitational pull also tends to restore LIGO's mirrors to their original position, erasing its memory. So even though the kinks in space-time are permanent, the changes in the mirror position — which enables us to measure the kinks — are not. Researchers will need to measure the displacement of the mirrors caused by the memory effect before gravity has time to pull them back down.

thought up clever workarounds. "What you can do is effectively stack up the signal from multiple mergers," said Lasky, "accumulating evidence in a very statistically rigorous way."

Lasky and Schmidt have independently predicted that they'll need over 1,000 gravitational wave events to accumulate enough statistics to confirm they've seen the memory effect. With ongoing improvements to LIGO, as well as contributions from the VIRGO detector in Italy and KAGRA in Japan, Lasky thinks reaching 1,000 detections is a few short years away.

"It is such a special prediction," said Schmidt. "It's quite exciting to see if it's actually true."

Correction: *December 9, 2021*
The original version of this article attributed the original discovery of the connection between supertranslation symmetries and the memory effect to Andrew Strominger in 2014. In fact, that connection had previously been known. The 2014 discovery by Strominger was between supertranslation symmetries, the memory effect and a third topic.