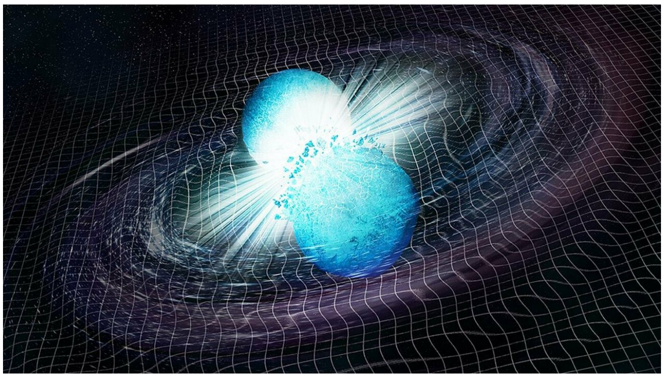
How to use gravitational waves to measure the expansion of the universe

29 March 2019, by Louise Lerner



A neutron star collision causes detectable ripples in the fabric of spacetime, which are called gravitational waves. Credit: Aurore Simonnet

On the morning of Aug. 17, 2017, after traveling for more than a hundred million years, the aftershocks from a massive collision in a galaxy far, far away finally reached Earth.

These ripples in the fabric of spacetime, called gravitational waves, tripped alarms at two ultra-sensitive detectors called LIGO, sending texts flying and scientists scrambling. One of the scientists was Prof. Daniel Holz at the University of Chicago. The discovery had provided him the information he needed to make a groundbreaking new measurement of one of the most important numbers in astrophysics: the Hubble constant, which is the rate at which the universe is expanding.

The Hubble constant holds the answers to big questions about the universe, like its size, age and history, but the two main ways to determine its value have produced significantly different results. Now there was a third way, which could resolve one of the most pressing questions in astronomy—or it could solidify the creeping suspicion, held by many in the field, that there is something substantial missing from our model of the universe.

"In a flash, we had a brand-new, completely independent way to make a measurement of one of the most profound quantities in physics," said Holz. "That day I'll remember all my life."

As LIGO turns back on April 1, Holz and other scientists are preparing for more data that could shed light on some of the universe's biggest questions.

Universal questions

We've known the universe is expanding for a long time (ever since eminent astronomer and UChicago alum Edwin Hubble made the first measurement of the expansion in 1929, in fact) but in 1998, scientists were stunned to discover that the rate of expansion is not slowing as the universe ages, but actually accelerating over time. In the following decades, as they tried to precisely determine the rate, it has become apparent that different methods for measuring the rate produce different answers.

One of the two methods measures the brightness of supernovae–exploding stars– in distant galaxies; the other looks at tiny fluctuations in the cosmic microwave background, the faint light left over from the Big Bang. Scientists have been working for two decades to boost the accuracy and precision for each measurement, and to rule out any effects which might be compromising the results; but the two values still stubbornly disagree by almost 10 percent.

Because the supernova method looks at relatively nearby objects, and the cosmic microwave background is much more ancient, it's possible that both methods are right—and that something profound about the universe has changed since the beginning of time.

"We don't know if one or both of the other methods have some kind of systematic error, or if they actually reflect a fundamental truth about the universe that is missing from our current models," said Holz. "Either is possible."

Holz saw the possibility for a third, completely independent way to measure the Hubble constant—but it would depend on a combination of luck and extreme feats of engineering.

The 'standard siren'

In 2005, Holz wrote a paper with Scott Hughes of Massachusetts Institute of Technology suggesting that it would be possible to calculate the Hubble constant through a combination of gravitational waves and light. They called these sources "standard sirens," a nod to "standard candles", which refers to the supernovae used to make the Hubble constant measurement.

But first it would take years to develop technology that could pick up something as ephemeral as ripples in the fabric of spacetime. That's LIGO: a set of enormous, extremely sensitive detectors that are tuned to pick up the gravitational waves that are emitted when something big happens somewhere in the universe.

The Aug. 17, 2017 waves came from two extremely heavy neutron stars, which had spiraled around and around each other in a faraway galaxy before finally slamming together at close to the speed of light. The collision sent gravitational waves rippling across the universe and also released a burst of light, which was picked up by telescopes on and around Earth.

That burst of light was what sent the scientific world into a tizzy. LIGO had picked up gravitational wave readings before, but all the previous ones were from collisions of two black holes, which can't be seen with conventional telescopes.

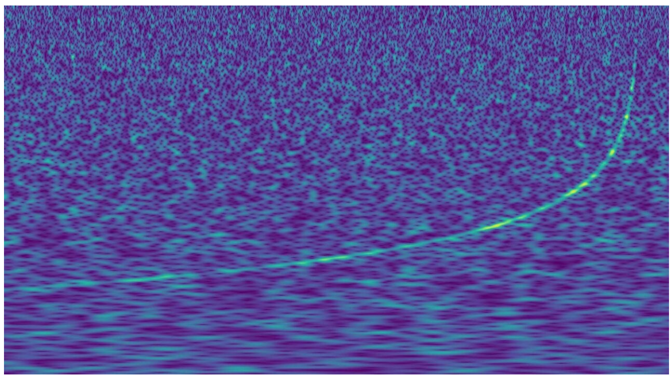
But they could see the light from the colliding neutron stars, and the combination of waves and light unlocked a treasure trove of scientific riches. Among them were the two pieces of information Holz needed to make his calculation of the Hubble constant.

How does the method work?

To make this measurement of the Hubble constant (named after pioneering scientist and UChicago alum Edwin Hubble), you need to know how fast an object—like a newly collided pair of neutron stars—is receding away from Earth, and how far away it was to begin with. The equation is surprisingly simple. It looks like this: The Hubble constant is the velocity of the object divided by the distance to the object, or H=v/d.

Somewhat counterintuitively, the easiest part to calculate is how fast the object is moving. Thanks to the bright afterglow given off by the collision, astronomers could point telescopes at the sky and pinpoint the galaxy where the neutron stars collided. Then they can take advantage of a phenomenon called redshift: As a faraway object moves away from us, the color of the light it's giving off shifts slightly towards the red end of the spectrum. By measuring the color of the galaxy's light, they can use this reddening to estimate how fast the galaxy is moving away from us. This is a century-old trick for astronomers.

The more difficult part is getting an accurate measure of the distance to the object. This is where gravitational waves come in. The signal the LIGO detectors pick up gets interpreted as a curve, like this:



The signal picked up by the LIGO detector in Louisiana, as it caught the waves from two neutron stars colliding far away in space, forms a distinctive curve. Credit: LIGO

The shape of the signal tells scientists how big the two stars were and how much energy the collision gave off. By comparing that with how strong the waves were when they reached Earth, they could infer how far away the stars must have been.

The initial value from just this one standard siren came out to be 70 kilometers per second per megaparsec. That's right in between the other two methods, which find about 73 (from the supernova method) and 67 (from the cosmic microwave background).

Of course, that's only a single data point. But the LIGO detectors are turning back on after an upgrade to boost their sensitivity. While nobody knows precisely how often neutron stars collide, Holz co-authored a paper estimating that the gravitational wave method may provide a revolutionary, extremely precise measurement of the Hubble constant within five years.

"As time goes on, we'll observe more and more of these binary neutron star mergers, and use them as standard sirens to steadily improve our estimate of the Hubble constant. Depending on where our value falls, we might confirm one method or the other. Or we might find an entirely different value," Holz said. "No matter what we find, it's gonna be interesting—and will be an important step in learning more about our universe."

Provided by University of Chicago
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