PennState

A 'bang' in LIGO detectors signals most massive gravitational-wave source yet

A binary black hole merger likely produced gravitational waves equivalent to the energy of eight suns in a mere 10 milliseconds

Artist's impression of binary black holes about to collide. Gravitational waves from what may be the most massive black hole merger yet observed have been detected by the National Science Foundation's Laser Interferometer Gravitational-wave Observatory (LIGO). ***IMAGE: MARK MYERS, ARC CENTRE OF EXCELLENCE FOR GRAVITATIONAL WAVE DISCOVERY (OZGRAV)***

September 02, 2020

UNIVERSITY PARK, Pa. — Gravitational waves from what may be the most massive black hole merger yet observed have been detected by the National Science Foundation's Laser Interferometer Gravitational-wave Observatory (LIGO). Produced by extreme astrophysical phenomena, these reverberations ripple forth and shake the fabric of space-time. The product of the merger is the first clear detection of an “intermediate-mass” black hole, with a mass between 100 and 1,000 times that of the sun.

The research team, which includes Penn State scientists, detected the signal, labeled GW190521, on May 21, 2019, with LIGO, a pair of identical, 4-kilometer-long interferometers in the United States; and Virgo, a 3-kilometer-long detector in Italy.

The signal seen by the detectors, which resembles about four short wiggles, is extremely brief in duration, lasting less than one-tenth of a second. From what the researchers can tell, GW190521 was generated by a source that is roughly 5 gigaparsecs, around 17 billion light years, away, when the universe was about half its age, making it one of the most distant gravitational-wave sources detected so far.

As for what produced this signal, based on a powerful suite of state-of-the-art computational and modeling tools, scientists think that GW190521 was most likely generated by a binary black hole merger with unusual properties.

"The signal that very massive black hole binaries leave in the data is very short,” said Ryan Magee, a graduate student at Penn State and a LIGO team member. “Unfortunately, this can make it difficult to distinguish between short duration noise transients, or glitches, and gravitational-wave candidates."

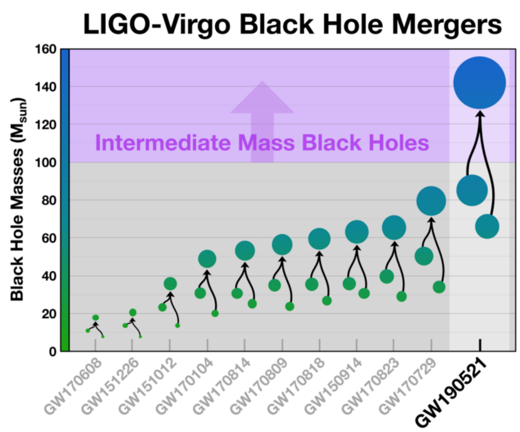
Every confirmed gravitational-wave signal to date has been from a binary merger, either between two black holes or two neutron stars. This newest merger appears to be the most massive yet, involving two inspiraling black holes with masses about 85 and 66 times the mass of the sun.

The LIGO-Virgo team has also measured each black hole’s spin and discovered that as the black holes were circling ever closer together, they could have been spinning about their own axes, at angles that were out of alignment with the axis of their orbit. The black holes’ misaligned spins likely caused their orbits to wobble, or “precess,” as the two goliaths spiraled toward each other.

The new signal likely represents the instant that the two black holes merged. The merger created an even more massive black hole, of about 142 solar masses, and released an enormous amount of energy, equivalent to around 8 solar masses, spread across the universe in the form of gravitational waves.

“This doesn’t look much like a chirp, which is what we typically detect,” said Virgo member Nelson Christensen, a researcher at the French National Centre for Scientific Research (CNRS), comparing the signal to LIGO’s first detection of gravitational waves in 2015. “This is more like something that goes ‘bang,’ and it’s the most massive signal LIGO and Virgo have seen.”

The international team of scientists, who make up the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration, have reported their findings in two papers published today (Sept. 2). One, appearing in Physical Review Letters, details the discovery, and the other, in The Astrophysical Journal Letters, discusses the signal’s physical properties and astrophysical implications.



LIGO and Virgo have observed their largest black hole merger to date, an event called GW190521, in which a final black hole of 142 solar masses was produced. This chart compares the event to others witnessed by LIGO and Virgo and indicates that the remnant of the GW190521 merger falls into a category known as an intermediate-mass black hole – and is the first clear detection of a black hole of this type. **IMAGE: LIGO/CALTECH/MIT/R. HURT (IPAC)**

In the mass gap

The uniquely large masses of the two inspiraling black holes, as well as the final black hole, raise a slew of questions regarding their formation.

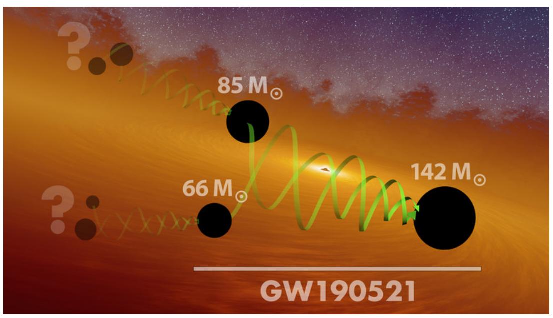
All of the black holes observed to date fit within either of two categories: stellar-mass black holes, which measure from a few solar masses up to tens of solar masses and are thought to form when massive stars die; or supermassive black holes, such as the one at the center of the Milky Way galaxy, that are from hundreds of thousands, to billions of times the mass of our sun. However, the final 142-solar-mass black hole produced by the GW190521 merger lies within an intermediate mass range between stellar-mass and supermassive black holes — the first of its kind ever detected.

The two progenitor black holes that produced the final black hole also seem to be unique in their size. They’re so massive that scientists suspect one or both of them may not have formed from a collapsing star, as most stellar-mass black holes do.

According to the physics of stellar evolution, a collapsing star should not be able to produce a black hole between approximately 65 and 120 solar masses — a range that is known as the "pair instability mass gap."

"190521 is especially exciting because it starts to challenge some conventional models of stellar evolution," said Magee. "The heavier of the two black holes is 85 solar masses, which is right in the middle of the pair instability mass gap. It's not yet clear how that black hole formed."

One possibility, which the researchers consider in their second paper, is of a hierarchical merger, in which the two progenitor black holes themselves may have formed from the merging of two smaller black holes, before migrating together and eventually merging.



This artist's concept illustrates a hierarchical scheme for merging black holes. LIGO and Virgo recently observed a black hole merger with a final mass of 142 times that of the sun, making it the largest of its kind observed in gravitational waves to date. The event is thought to have occurred when two black holes of about 66 and 85 solar masses spiraled into each other and coalesced. Theoretical models indicate that nature is not likely to form black holes of this heft; in particular models identify a range of masses between 65 and 120 solar masses, called the "pair instability mass gap," in which it is thought that black holes cannot be formed by a collapsing star. So how did the two merging black holes observed by LIGO and Virgo originate? Scientists think that these black holes may have themselves formed from the earlier mergers of two smaller black holes, as indicated in the illustration. **IMAGE: LIGO/CALTECH/MIT/R. HURT (IPAC)**

'Something unexpected'

There are many remaining questions regarding GW190521.

As LIGO and Virgo detectors listen for gravitational waves passing through Earth, automated searches comb through the incoming data for interesting signals. These searches can use two different methods: algorithms that pick out specific wave patterns in the data that may have been produced by compact binary systems; and more general “burst” searches, which essentially look for anything out of the ordinary.

The LIGO group at Penn State helped in the detection of GW190521 using a search algorithm dubbed “GstLAL” that cross-correlates the raw data against a set of template wave patterns. The algorithm, which the Penn State team helped to develop, “picks out” a gravitational wave when the match is significant and passes a designated threshold.

In the case of GW190521, a burst search that picked up the signal slightly more clearly, opening the very small chance that the gravitational waves arose from something other than a binary merger. However, a simulation study included in the paper describing this discovery, shows that even though GW190521 is an extreme example of gravitational wave signal, the present GstLAL algorithm is capable of detecting signals similar to it.

In their paper, the scientists briefly consider other sources in the universe that might have produced the signal they detected. For instance, perhaps the gravitational waves were emitted by a collapsing star in our galaxy. The signal could also be from a cosmic string produced just after the universe inflated in its earliest moments — although neither of these exotic possibilities matches the data as well as a binary merger.

"Intermediate mass black holes have been suspected to be the ‘missing link’ or an intermediate step between your vanilla stellar mass black holes and the supermassive black holes,” said Debnandini Mukherjee, a postdoctoral researcher and member of the LIGO team at Penn State. “Observations like these can help us understand more about the methods of formation of these black holes and solve other such astrophysical puzzles."

In addition to Magee and Mukherjee, the LIGO team at Penn State includes Bangalore S. Sathyaprakash and Chad Hanna. This research was funded by the U.S. National Science Foundation.

Additional information about the gravitational-wave observatories:

LIGO is funded by the NSF and operated by Caltech and MIT, which conceived of LIGO and lead the project. Financial support for the Advanced LIGO project was led by the NSF with Germany (Max Planck Society), the U.K. (Science and

Technology Facilities Council) and Australia (Australian Research Council-OzGrav) making significant commitments and contributions to the project. Approximately 1,300 scientists from around the world participate in the effort through the LIGO Scientific Collaboration, which includes the GEO Collaboration. A list of additional partners is available.

The Virgo Collaboration is currently composed of approximately 520 members from 99 institutes in 11 different countries including Belgium, France, Germany, Hungary, Italy, the Netherlands, Poland and Spain. The European Gravitational Observatory (EGO) hosts the Virgo detector near Pisa in Italy, and is funded by Centre National de la Recherche Scientifique (CNRS) in France, the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and Nikhef in the Netherlands. A list of the Virgo Collaboration groups is available. More information is available on the Virgo website.

MEDIA CONTACTS

Ryan Magee, rzm50@psu.edu

Debnandini Mukherjee, djm7112@psu.edu

Chad Hanna, crh184@psu.edu
Work Phone: 814-865-2924

Sam Sholtis, sjs144@psu.edu
Work Phone: 814-865-1390

Last Updated September 02, 2020