LIGO spotted waves from a pair of black holes (simulated here) with unusually high masses.

ASTROPHYSICS

Gravitational waves serve up a mystery

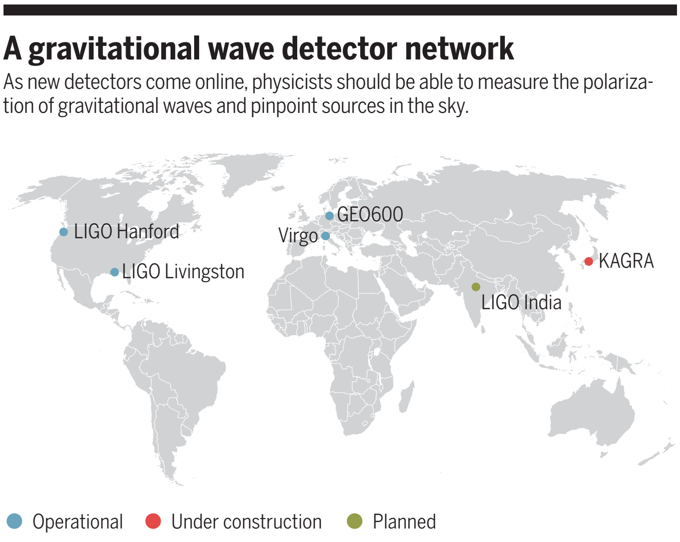
Astrophysicists puzzle over the strange black holes that produced LIGO's signal

By **Adrian Cho**

For decades, physicists had claimed that the detection of gravitational waves—ripples in spacetime set off by ultraviolent astrophysical events—would usher in a new type of astronomy and reveal new wonders. That was the rationale for spending more than $1 billion on the Laser Interferometer Gravitational-Wave Observatory (LIGO)—a duo of detectors in Hanford, Washington, and Livingston, Louisiana. Last week LIGO fulfilled on that promise, say astrophysicists, delivering both the first detection of a signal and a stellar surprise.

The gravitational waves spotted by the recently upgraded machines (*Science*, 12 February, p. 645) were predicted by Albert Einstein, whose general theory of relativity says that spacetime is a bendy thing and that gravity comes about when massive objects warp it. Computer models showed that LIGO's signal came from two black holes, 29 and 36 times as massive as the sun, spiraling together 1.3 billion light-years away. No one had ever seen a pair of orbiting black holes or detected “stellar mass” black holes so heavy, astrophysicists say—and they are hard to fit into current theory.

“I'm sure that in the next few months there will be 100 papers about the evolution pathways” of such a pair, predicts Ira Wasserman, a theorist at Cornell University. Jeffrey McClintock, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, says that spotting merging black holes was LIGO's ultimate goal, and seeing them immediately “exceeds all expectations for new, new, new. … What more do you want, mermaids?”



A gravitational wave detector network

As new detectors come online, physicists should be able to measure the polarization of gravitational waves and pinpoint sources in the sky.

A black hole can form when a huge star burns out and collapses to a point, leaving behind a gravitational field so strong near the point that not even light can escape. That field is the black hole, and thanks to Einstein's equivalence of energy and mass, $E=mc^2$, it has a mass. Astrophysicists have spotted stellar-mass black holes mostly in our galaxy by searching for systems in which a black hole consumes a companion star. From the motion of the star and the gas streaming into the black hole, researchers have deduced that the heaviest of them weighs about 15 times as much as the sun, McClintock says. (Much heavier black holes, with masses of millions of suns, lurk at the heart of our galaxy and many others.)

A star big enough to produce a 30-stellar-mass black hole would have to be very unusual. That's because any huge star peppered with elements heavier than helium will lose weight as it burns out. Ions of oxygen, calcium, and iron will absorb the star's light, which will blow the ions and most of the star's mass

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into space. "If you start with a 40-solar-mass star, by the time of collapse it's down to 10 solar masses," McClintock says.

One possibility is that the stars formed very early, when the universe was a couple billion years old and contained only hydrogen and helium. (Heavier elements were forged later, in supernova explosions.) But giant stars burn out in a few million years, Wasserman says, and it's hard to imagine how the black holes they spawned would have hung around for billions of years before spiraling together. McClintock leans toward a second explanation: The stars were born more recently, in dwarf galaxies like the Large Magellanic Cloud that are lower in heavy elements than the Milky Way is.

LIGO should be able to determine which scenario is correct, says Vicky Kalogera, an astrophysicist and LIGO team member at Northwestern University in Evanston, Illinois. In the next 2 or 3 years, LIGO could spot dozens of black hole mergers, she says. How far away and, hence, how old they are should reveal which formation scenario happened more often. "It's not one or the other," Kalogera predicts. LIGO should also be able to measure merging black holes' spins. If the spins are aligned, Kalogera says, the black holes probably formed from stars that already orbited each other; otherwise, they formed separately and hooked up later.

Even sooner, LIGO could test Einstein's theory of gravity, general relativity, in new ways. For example, says Clifford Will, a theorist at the University of Florida in Gainesville, just as light waves can be polarized horizontally or vertically, gravitational waves can wriggle in various more complex polarization patterns or modes. General relativity predicts that gravitational waves will have just two distinct polarization modes. But some alternative theories of gravity predict as many as six. Because of the way they're aligned, LIGO's detectors can't determine the waves' polarization, Will says. But they should be able to do it with the help of the upgraded Virgo detector near Pisa, Italy, scheduled to restart later this year. "If any other modes were detected, that would be bad news for general relativity," Will says.

Farther down the road, LIGO researchers hope to greatly improve their ability to pinpoint sources in the sky by adding a fourth detector to the LIGO-Virgo network, in India (*Science*, 14 February 2014, p. 717). Scientists also hope to launch a space-based detector array, which could sense much lower frequency waves from objects such as stars circling the massive black hole in the heart of our galaxy (*Science*, 20 November 2015, p. 894). But well before then, gravitational wave astronomy may pay early dividends. ■

The scientist who spotted the fateful signal—and let the cat out of the bag

By **Adrian Cho**

Of the more than 1000 physicists working with the Laser Interferometer Gravitational-Wave Observatory (LIGO), the first to see the long-awaited sign of gravitational waves was a soft-spoken postdoc who plays classical piano and has published two fantasy novels. Marco Drago, a 33-year-old native of Padua, Italy, was at his office at the Max Planck Institute for Gravitational Physics in Hanover, Germany, where 30 members of the LIGO team work on data analysis. Drago oversees one of four data "pipelines" that automatically comb the raw data from LIGO's detectors in Hanford, Washington, and Livingston, Louisiana, for promising signals.

On 14 September 2015, while Drago was on the phone with a colleague, his pipeline sent him an email alert telling him that both LIGO detectors had registered an "event" (a nonroutine reading) 3 minutes earlier, at 11:50:45 a.m. local time. It was a big one, with a signal-to-noise ratio more than twice as high as usual, Drago says. At first, he didn't believe the signal was real—and with good reason. To test the detectors, LIGO physicists have developed a system to "inject" artificial signals, and the signal seemed too good to be true. "No one was expecting something so huge," Drago says, "so I was assuming that it was an injection."

If all had gone as planned, Drago would have carried on thinking just that. However, the story veered off-script. LIGO researchers perform injections in two ways: openly when they tune up the machines and secretly when they are taking data. Those "blind" injections are supposed to prevent team members from knowing whether a signal is real or not. Only four LIGO leaders know when they're made, and they reveal that information only after a signal has been written up for publication. That's how things unfolded in 2010, when LIGO physicists learned at the last minute that a tantalizing signal was in fact a blind injection (*Science*, 15 March 2013, p. 1260).

This time, however, LIGO physicists were still reviving their machines after a 5-year upgrade, and Drago knew that the injection system was supposed to be off. He wondered whether he had misunderstood and someone had performed an open injection and perhaps failed to record it. Drago asked his fellow postdoc in Hanover, Andrew Lundgren, to check. Lundgren found no evidence of an injection. Next, Drago and Lundgren called the control rooms in Livingston and Hanford, where it was the small hours of the morning, to see whether anybody had monkeyed with the detectors or noticed anything unusual. Drago reached only one of them—"Livingston, I think," he says—but was told all was normal.

Finally, about an hour after receiving the alert, Drago broadcast an email to the entire LIGO collaboration. "I asked if anybody was aware of anything that could be an injection," Drago says. Nobody said yes. But now everybody in the collaboration knew that the instruments had seen a whopping big signal that on the face of it could not be a blind injection—exactly what they were not supposed to know. A few days later, LIGO leaders sent around a notice saying that the signal probably was not an injection.

On 18 September 2015, LIGO switched to data-taking mode. A press release said the hunt for gravitational waves had resumed, but researchers were collecting data primarily to validate the signal they already had, says Gabriela González, a physicist at Louisiana State University, Baton Rouge, and spokesperson for the LIGO scientific collaboration. By 5 October 2015, they had enough data to estimate the signal's statistical significance. The team even spent weeks investigating whether the signal could have been a prank before writing up the results.

Meanwhile, word of the discovery leaked out on social media and theorists' blogs. González says it was stressful addressing—or ignoring—inquiries, especially from the press. "It's been a lot of pressure, answering to people, not answering to people," she says. "But we never lied." ■