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LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

Discovery marks first cosmic event observed in both gravitational waves and light.

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For the first time, scientists have directly detected gravitational waves — ripples in space and time — in addition to light from the spectacular collision of two neutron stars. This marks the first time that a cosmic event has been viewed in both gravitational waves and light.

The discovery was made using the U.S.-based Laser Interferometer Gravitational-Wave Observatory (LIGO); the Europe-based Virgo detector; and some 70 ground- and space-based observatories.

Neutron stars are the smallest, densest stars known to exist and are formed when massive stars explode in supernovas. As these neutron stars spiraled together, they emitted gravitational waves that were detectable for about 100 seconds; when they collided, a flash of light in the form of gamma rays was emitted and seen on Earth about two seconds after the gravitational waves. In the days and weeks following the smashup, other forms of light, or electromagnetic radiation — including X-ray, ultraviolet, optical, infrared, and radio waves — were detected.

The observations have given astronomers an unprecedented opportunity to probe a collision of two neutron stars. For example, observations made by the U.S. Gemini Observatory, the European Very Large Telescope, and NASA's Hubble Space Telescope reveal signatures of recently synthesized material, including gold and platinum, solving a decades-long mystery of where about half of all elements heavier than iron are produced.

The LIGO-Virgo results are published today in the journal *Physical Review Letters*; additional papers from the LIGO and Virgo collaborations and the astronomical community have been either submitted or accepted for publication in various journals.

“It is tremendously exciting to experience a rare event that transforms our understanding of the workings of the universe,” says France A. Córdova, director of the National Science Foundation (NSF), which funds LIGO. “This



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discovery realizes a long-standing goal many of us have had, that is, to simultaneously observe rare cosmic events using both traditional as well as gravitational-wave observatories. Only through NSF's four-decade investment in gravitational-wave observatories, coupled with telescopes that observe from radio to gamma-ray wavelengths, are we able to expand our opportunities to detect new cosmic phenomena and piece together a fresh narrative of the physics of stars in their death throes."

A stellar sign

The gravitational signal, named GW170817, was first detected on Aug. 17 at 8:41 a.m. Eastern Daylight Time; the detection was made by the two identical LIGO detectors, located in Hanford, Washington, and Livingston, Louisiana. The information provided by the third detector, Virgo, situated near Pisa, Italy, enabled an improvement in localizing the cosmic event. At the time, LIGO was nearing the end of its second observing run since being upgraded in a program called Advanced LIGO, while Virgo had begun its first run after recently completing an upgrade known as Advanced Virgo.

The NSF-funded LIGO observatories were conceived, constructed, and operated by Caltech and MIT. Virgo is funded by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy and the Centre National de la Recherche Scientifique (CNRS) in France, and operated by the European Gravitational Observatory. Some 1,500 scientists in the LIGO Scientific Collaboration and the Virgo Collaboration work together to operate the detectors and to process and understand the gravitational-wave data they capture.

Each observatory consists of two long tunnels arranged in an L shape, at the joint of which a laser beam is split in two. Light is sent down the length of each tunnel, then reflected back in the direction it came from by a suspended mirror. In the absence of gravitational waves, the laser light in each tunnel should return to the location where the beams were split at precisely the same time. If a gravitational wave passes through the observatory, it will alter each laser beam's arrival time, creating an almost imperceptible change in the observatory's output signal.

On Aug. 17, LIGO's real-time data analysis software caught a strong signal of gravitational waves from space in one of the two LIGO detectors. At nearly the same time, the Gamma-ray Burst Monitor on NASA's Fermi space telescope had detected a burst of gamma rays. LIGO-Virgo analysis software put the two signals together and saw it was highly unlikely to be a chance coincidence, and another automated LIGO analysis indicated that there was a coincident gravitational wave signal in the other LIGO detector. Rapid gravitational-wave detection by the LIGO-Virgo team, coupled with Fermi's



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gamma-ray detection, enabled the launch of follow-up by telescopes around the world.

The LIGO data indicated that two astrophysical objects located at the relatively close distance of about 130 million light-years from Earth had been spiraling in toward each other. It appeared that the objects were not as massive as binary black holes — objects that LIGO and Virgo have previously detected. Instead, the inspiraling objects were estimated to be in a range from around 1.1 to 1.6 times the mass of the sun, in the mass range of neutron stars. A neutron star is about 20 kilometers, or 12 miles, in diameter and is so dense that a teaspoon of neutron star material has a mass of about a billion tons.

While binary black holes produce “chirps” lasting a fraction of a second in the LIGO detector’s sensitive band, the Aug. 17 chirp lasted approximately 100 seconds and was seen through the entire frequency range of LIGO — about the same range as common musical instruments. Scientists could identify the chirp source as objects that were much less massive than the black holes seen to date.

“It immediately appeared to us the source was likely to be neutron stars, the other coveted source we were hoping to see — and promising the world we would see,” says David Shoemaker, spokesperson for the LIGO Scientific Collaboration and senior research scientist in MIT’s Kavli Institute for Astrophysics and Space Research. “From informing detailed models of the inner workings of neutron stars and the emissions they produce, to more fundamental physics such as general relativity, this event is just so rich. It is a gift that will keep on giving.”

“Our background analysis showed an event of this strength happens less than once in 80,000 years by random coincidence, so we recognized this right away as a very confident detection and a remarkably nearby source,” adds Laura Cadonati, professor of physics at Georgia Tech and deputy spokesperson for the LIGO Scientific Collaboration. “This detection has genuinely opened the doors to a new way of doing astrophysics. I expect it will be remembered as one of the most studied astrophysical events in history.”

Theorists have predicted that when neutron stars collide, they should give off gravitational waves and gamma rays, along with powerful jets that emit light across the electromagnetic spectrum. The gamma-ray burst detected by Fermi, and soon thereafter confirmed by the European Space Agency’s gamma-ray observatory INTEGRAL, is what’s called a short gamma-ray burst; the new observations confirm that at least some short gamma-ray bursts are



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generated by the merging of neutron stars — something that was only theorized before.

“For decades we’ve suspected short gamma-ray bursts were powered by neutron star mergers,” says Fermi Project Scientist Julie McEnery of NASA’s Goddard Space Flight Center. “Now, with the incredible data from LIGO and Virgo for this event, we have the answer. The gravitational waves tell us that the merging objects had masses consistent with neutron stars, and the flash of gamma rays tells us that the objects are unlikely to be black holes, since a collision of black holes is not expected to give off light.”

But while one mystery appears to be solved, new mysteries have emerged. The observed short gamma-ray burst was one of the closest to Earth seen so far, yet it was surprisingly weak for its distance. Scientists are beginning to propose models for why this might be, McEnery says, adding that new insights are likely to arise for years to come.

A patch in the sky

Though the LIGO detectors first picked up the gravitational wave in the United States, Virgo, in Italy, played a key role in the story. Due to its orientation with respect to the source at the time of detection, Virgo recovered a small signal; combined with the signal sizes and timing in the LIGO detectors, this allowed scientists to precisely triangulate the position in the sky. After performing a thorough vetting to make sure the signals were not an artifact of instrumentation, scientists concluded that a gravitational wave came from a relatively small patch in the southern sky.

“This event has the most precise sky localization of all detected gravitational waves so far,” says Jo van den Brand of Nikhef (the Dutch National Institute for Subatomic Physics) and VU University Amsterdam, who is the spokesperson for the Virgo collaboration. “This record precision enabled astronomers to perform follow-up observations that led to a plethora of breathtaking results.”

“This result is a great example of the effectiveness of teamwork, of the importance of coordinating, and of the value of scientific collaboration,” adds EGO Director Federico Ferrini. “We are delighted to have played our relevant part in this extraordinary scientific challenge: Without Virgo, it would have been very difficult to locate the source of the gravitational waves

Fermi was able to provide a localization that was later confirmed and greatly refined with the coordinates provided by the combined LIGO-Virgo detection. With these coordinates, a handful of observatories around the world were



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able, hours later, to start searching the region of the sky where the signal was thought to originate. A new point of light, resembling a new star, was first found by optical telescopes. Ultimately, about 70 observatories on the ground and in space observed the event at their representative wavelengths.

“This detection opens the window of a long-awaited ‘multi-messenger’ astronomy,” says Caltech’s David H. Reitze, executive director of the LIGO Laboratory. “It’s the first time that we’ve observed a cataclysmic astrophysical event in both gravitational waves and electromagnetic waves — our cosmic messengers. Gravitational-wave astronomy offers new opportunities to understand the properties of neutron stars in ways that just can’t be achieved with electromagnetic astronomy alone.”

A fireball and an afterglow

Each electromagnetic observatory will be releasing its own detailed observations of the astrophysical event. In the meantime, a general picture is emerging among all observatories involved that further confirms that the initial gravitational-wave signal indeed came from a pair of inspiraling neutron stars.

Approximately 130 million years ago, the two neutron stars were in their final moments of orbiting each other, separated only by about 300 kilometers, or 200 miles, and gathering speed while closing the distance between them. As the stars spiraled faster and closer together, they stretched and distorted the surrounding space-time, giving off energy in the form of powerful gravitational waves, before smashing into each other.

At the moment of collision, the bulk of the two neutron stars merged into one ultradense object, emitting a “fireball” of gamma rays. The initial gamma-ray measurements, combined with the gravitational-wave detection, also provide confirmation for Einstein’s general theory of relativity, which predicts that gravitational waves should travel at the speed of light.

Theorists have predicted that what follows the initial fireball is a “kilonova” — a phenomenon by which the material that is left over from the neutron star collision, which glows with light, is blown out of the immediate region and far out into space. The new light-based observations show that heavy elements, such as lead and gold, are created in these collisions and subsequently distributed throughout the universe.

In the weeks and months ahead, telescopes around the world will continue to observe the afterglow of the neutron star merger and gather further evidence about various stages of the merger, its interaction with its



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surroundings, and the processes that produce the heaviest elements in the universe.

“When we were first planning LIGO back in the late 1980s, we knew that we would ultimately need an international network of gravitational-wave observatories, including Europe, to help localize the gravitational-wave sources so that light-based telescopes can follow up and study the glow of events like this neutron star merger,” says Caltech’s Fred Raab, LIGO associate director for observatory operations. “Today we can say that our gravitational-wave network is working together brilliantly with the light-based observatories to usher in a new era in astronomy, and will improve with the planned addition of observatories in Japan and India.”

The Virgo collaboration consists of more than 280 physicists and engineers belonging to 20 different European research groups: six from Centre National de la Recherche Scientifique (CNRS) in France; eight from the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; two in the Netherlands with Nikhef; the MTA Wigner RCP in Hungary; the POLGRAW group in Poland; Spain with the University of Valencia; and the European Gravitational Observatory, EGO, the laboratory hosting the Virgo detector near Pisa in Italy, funded by CNRS, INFN, and Nikhef.

LIGO is funded by the NSF, and operated by Caltech and MIT, which conceived of LIGO and led the Initial and Advanced LIGO projects. 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) making significant commitments and contributions to the project.

More than 1,200 scientists and some 100 institutions from around the world participate in the effort through the LIGO Scientific Collaboration, which includes the GEO Collaboration and the Australian collaboration OzGrav. Additional partners are listed at <http://ligo.org/partners.php>

RELATED LINKS

Paper: “GW170817: Observation of gravitational waves from a binary neutron star merger.”

*** Paper will be available to read online at 10:00 AM EDT on Oct. 16, 2017.*

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