BY DAVIDE CASTELVECCHI

THE NEXT WAVE

A momentous signal from space has confirmed decades of theorizing on black holes — and launched a new era of gravitational-wave astronomy.

The event was catastrophic on a cosmic scale — a merger of black holes that violently shook the surrounding fabric of space and time, and sent a blast of space-time vibrations known as gravitational waves rippling across the Universe at the speed of light.

But it was the kind of calamity that physicists on Earth had been waiting for. On 14 September, when those ripples swept across the freshly upgraded Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO), they showed up as spikes in the readings from its two L-shaped detectors in Louisiana and Washington state. For the first time ever, scientists had recorded a gravitational-wave signal.

“There it was!” says LIGO team member Daniel Holz, an astrophysicist at the University of Chicago in Illinois. “And it was so strong, and so beautiful, in both detectors.” Although the shape of the signal looked familiar from the theory, Holz says, “it’s completely different when you see something in the data. It’s this transcendent moment”.

The signal, formally designated GW150914 after the date of its occurrence and informally known to its discoverers as ‘the Event’, has justly been hailed as a milestone in physics. It has provided a wealth of evidence for Albert Einstein’s century-old general theory of relativity, which holds that mass and energy can warp space-time, and that gravity is the result of such warping. Stuart Shapiro, a specialist in computer simulations of relativity at the University of Illinois at Urbana–Champaign, calls it “the most significant confirmation of the general theory of relativity since its inception”.

But the Event also marks the start of a long-promised era of gravitational-wave astronomy. Detailed analysis of the signal has already yielded insights into the nature of the black holes that merged, and how they formed. With more events such as these — the LIGO team is

ILLUSTRATION BY MARK GARLICK

Binary black holes radiate a huge amount of orbital energy as gravitational waves.

analysing several other candidate events captured during the detectors' four-month run, which ended in January — researchers will be able to classify and understand the origins of black holes, just as they are doing with stars.

Still more events should appear starting in September, when Advanced LIGO is scheduled to begin joint observations with its European counterpart, the Franco–Italian-led Advanced Virgo facility near Pisa, Italy. (The two collaborations already pool data and publish papers together.) This detector will not only contribute crucial details to events, but could also help astronomers to make cosmological-distance measurements more accurately than before.

"It's going to be a really good ride for the next few years," says Bruce Allen, managing director of the Max Planck Institute for Gravitational Physics in Hanover, Germany.

"The more black holes they see whacking into each other, the more fun it will be," says Roger Penrose, a theoretical physicist and mathematician at the University of Oxford, UK, whose work in the 1960s helped to lay the foundation for the theory of the objects. "Suddenly, we have a new way of looking at the Universe."

A MATTER OF ENERGY

Physicists have known for decades that every pair of orbiting bodies is a source of gravitational waves. With each revolution, according to Einstein's equations, the waves will carry away a tiny fraction of their orbital energy. This will cause the objects to move a bit closer together and orbit a little faster. For familiar pairs, such as the Moon and Earth, such energy loss is imperceptible even on timescales of billions of years.

But dense objects in very close orbits can lose energy much more quickly. In 1974 , radio astronomers Russell Hulse and Joseph Taylor, then of the University of Massachusetts Amherst, found just such a system: a pair of dense neutron stars in orbit around each other. As the years went by, the scientists found that this 'binary pulsar' was losing energy and spiralling inwards exactly as predicted by Einstein's theory.

The two black holes detected by LIGO had probably been losing energy in this way for millions, if not billions, of years before they reached the end. But LIGO did not register the gravitational waves coming from them until 9:50:45 Coordinated Universal Time on 14 September, when the wave's frequency rose above some 30 cycles per second (hertz) — corresponding to 15 full black-hole orbits per second — and was finally high enough for the detectors to distinguish it from background noise.

But then, in just 0.2 seconds, LIGO watched the signal surge to 250 hertz and suddenly disappear, as the black holes made their final 5 orbits, reached orbital velocities of half the speed of light and coalesced into a single massive object (see 'What made the wave').

The LIGO and Virgo teams soon went to work extracting every bit of information possible. At the most fundamental level, the signal gave them an existence proof: the fact that the objects came so close to each other before merging meant that they had to be black holes, because ordinary stars would need to be much bigger. "It is, I think, the clearest indication that black holes are really there," says Penrose.

The signal also provided researchers with the first empirical test of general relativity beyond regions — including the space around the binary pulsar — where there is comparatively little space-time warping. There was no empirical evidence that the theory would keep its validity at the extreme energies of merging black holes, says Shapiro — but it did.

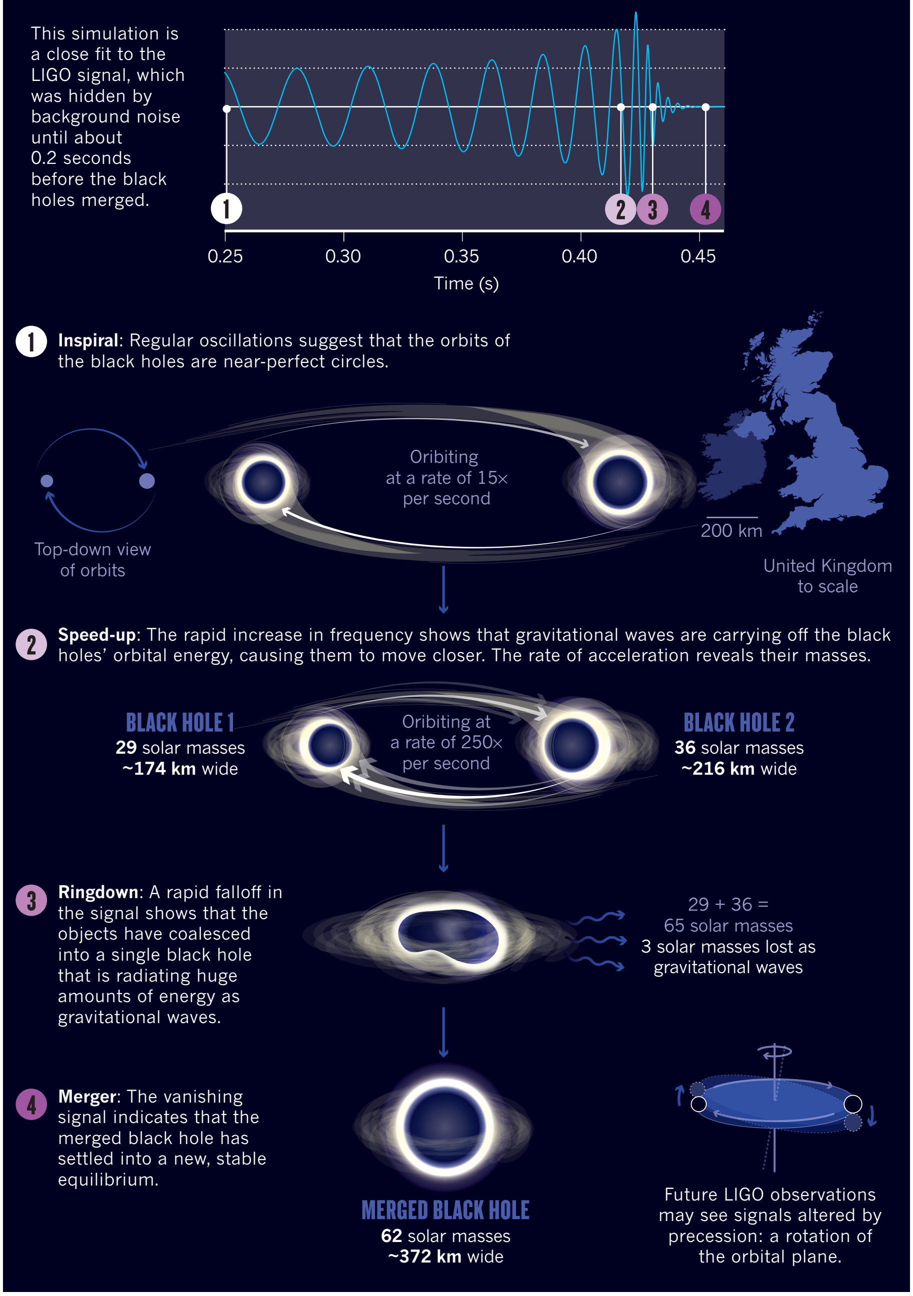
The signal held a trove of more-detailed information as well. By scrutinizing its shape just before the final cataclysm, the scientists found that it closely approximated a simple sine wave with a steadily increasing frequency and amplitude. According to B. S. Sathyaprakash, a theoretical physicist at Cardiff University, UK, and a senior LIGO researcher, this pattern suggests that the orbits of the black holes were nearly circular, and that LIGO probably had a bird's-eye view of the circles, looking almost straight down on them rather than edge-on.

In addition, the LIGO and Virgo teams were able to use the frequency of the observed wave, along with its rate of acceleration, to estimate the masses of the two black holes: because heavier objects radiate energy in the form of gravitational waves at a faster rate than do lighter objects, their pitch rises more quickly.

By recreating the Event with computer simulations, the scientists calculated that the two black holes weighed about 36 times and 29 times the mass of the Sun, respectively, and that the combined black hole weighed about 62 solar masses[1]. The lost difference, about three Suns' worth, was dispersed as gravitational radiation — much of it during what physicists call

WHAT MADE THE WAVE

The first signal ever detected by the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) lasted just 0.2 seconds, but conveyed a wealth of information.



This simulation is a close fit to the LIGO signal, which was hidden by background noise until about 0.2 seconds before the black holes merged.

① **Inspiral**: Regular oscillations suggest that the orbits of the black holes are near-perfect circles.

② **Speed-up**: The rapid increase in frequency shows that gravitational waves are carrying off the black holes' orbital energy, causing them to move closer. The rate of acceleration reveals their masses.

③ **Ringdown**: A rapid falloff in the signal shows that the objects have coalesced into a single black hole that is radiating huge amounts of energy as gravitational waves.

④ **Merger**: The vanishing signal indicates that the merged black hole has settled into a new, stable equilibrium.

Future LIGO observations may see signals altered by precession: a rotation of the orbital plane.

SOURCE: REF. 1/NIK SPENCER/NATURE

the ‘ringdown’ phase, when the merged black hole was settling into a spherical shape. (For comparison, the most powerful thermonuclear bomb ever detonated converted only about 2 kilograms of matter into energy — roughly 10^{30} times less.) The teams also suspect that the final black hole was spinning at perhaps 100 revolutions per second, although the margin of error on that estimate is large.

The inferred masses of the two black holes are also revealing. Each object was presumably the remnant of a very massive star, with the larger star approaching 100 times the mass of the Sun and the smaller one a little less. Thermonuclear reactions are known to convert hydrogen in the cores of such stars into helium much faster than in lighter stars, which leads them to collapse under their own weight only a few million years after they are born. The energy released by this collapse causes an explosion called a type II supernova, which leaves behind a residual core that turns into a neutron star or, if it's massive enough, a black hole.

Scientists say that type II supernovae should not produce black holes much bigger than about 30 solar masses — and both black holes were at the high end of that range. This could mean that the system formed from interstellar gas clouds that were richer in hydrogen and helium than the ones typically found in our Galaxy, and that were poorer in heavy elements — which astronomers call metals.

Astrophysicists have calculated that stars formed from such low-metallicity clouds should have an easier time forming massive black holes when they explode, explains Gijs Nelemans, an astronomer at Radboud University Nijmegen in the Netherlands and a member of the Advanced Virgo collaboration. That's because during a supernova explosion, smaller atoms are less likely to be blown away by the blast. Low-metallicity stars thus “lose less mass, so more of it goes into the black hole, for the same initial mass”, Nelemans says.

TWO BY TWO

But how did these two black holes end up in a binary system? In a paper[2] published at the same time as the one reporting the discovery, the LIGO and Virgo teams described two commonly accepted scenarios.

The simplest one is that two massive stars were born as a binary-star system, forming from the same interstellar gas cloud like a double-yolked egg, and orbiting each other ever since. (Such binary stars are common in our Galaxy; singletons such as the Sun are the exception, rather than the rule.) After a few million years, one of the stars would have burned out and gone supernova, soon to be followed by the other. The result would be a binary black hole.

The second scenario is that the stars formed independently, but still inside the same dense stellar cluster — perhaps one similar to the globular clusters that orbit the Milky Way. In such a cluster, massive stars would sink towards the centre and, through complex interactions with lighter stars, form binary systems, possibly long after their transformation into black holes.

Simulations made by Simon Portegies Zwart, an astrophysicist at Leiden University in the Netherlands, show[3] that massive stars are more likely to form in dense clusters, where collisions and mergers are more common. He also finds that once a binary black-hole system forms, the complex dynamics of the cluster's centre would probably kick the pair out at high speed. The binary that Advanced LIGO detected may have wandered away from any galaxy for billions of years before merging, he says.

Although the LIGO and Virgo teams were able to learn a lot from the Event, there is much more that gravitational waves could teach them, even in the case of black-hole mergers. The detectors showed that immediately after the black holes merged, the waves quickly died down as the resulting black hole settled into a symmetrical shape. This is consistent with predictions made by theoretical physicist C. V. Vishveshwara in the early 1970s, a time when “gravitational waves and black holes both belonged to the realm of mythology”, he says. “At that time, I had not imagined that it would ever be verified,” says Vishveshwara, who is director emeritus of the Jawaharlal Nehru Planetarium in Bangalore, India.

But LIGO saw only just over one cycle of the Event's ringdown waves before the signal became buried once more in the background noise — not yet enough data to provide a rigorous test of Vishveshwara's predictions.

More-stringent tests will be possible if and when LIGO detects black-hole mergers that are larger than this one, or that occur closer to Earth than the Event's estimated distance of 1.3 billion light years, and thus give 'louder' waves that stay above the noise for longer.

Alessandra Buonanno, a LIGO theorist and director of the Max Planck Institute for Gravitational Physics in Potsdam-Golm, Germany, says that a more detailed picture of the ringdown stage could reveal how fast the final black hole rotates, as well as whether its formation gave it a 'natal kick', imparting a high velocity.

In addition, says Sathyaprakash, "we are especially waiting for systems that are much lighter, so they last longer". Such events could include the mergers of lighter binary black holes, of binary neutron stars or of a black hole with a neutron star. Each type would deliver its own signature chirp, and could produce a signal that stays above LIGO's threshold of sensitivity for several minutes or more.

"GW150914 is in some sense a very vanilla system," says Chad Hanna, a LIGO member at Pennsylvania State University in University Park. "It's beautiful, of course, but it doesn't have all the crazy things that one might expect."

SPACE ARTISTRY

One phenomenon that Sathyaprakash is eager to observe is a 'precession' of the black holes' orbital plane, meaning that their paths trace a kind of 3D rosette. This is a relativistic effect that has no counterpart in Newtonian gravity, and it should produce a characteristic fluctuation in the strength of the gravitational waves. But orbital precession occurs only when two black holes have axes of rotation that point in random directions, and it disappears when the axes are both perpendicular to the orbital plane. The occurrence of a precession could provide clues to how the black holes formed.

It's hard to be sure about that possibility because there are many uncertainties in simulating supernovas. But astrophysicists suspect that parallel spins generally signify that the original two stars were born together out of the same whirling gas cloud. Similarly, they think that random spins result from black holes that formed separately and later fell into orbit around each other. Once the observatories find more mergers, they may be able to determine which type of system occurs more frequently.

Although detecting more events will help LIGO to do lots of science, its interferometers have intrinsic limitations that make it necessary to work together with a worldwide network of similar detectors that are now coming online.

First, LIGO's two interferometers are not enough for scientists to determine precisely where the waves came from. The researchers can get some information by comparing the signal's time of arrival at each detector: the difference enables them to calculate the wave's direction relative to an imaginary line drawn between the two. But in the case of the Event, which recorded a difference of 6.9 milliseconds, their calculations limited the field of possibilities merely to a wide strip of southern sky.

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Had Virgo been online, the scientists could have narrowed down the direction substantially by comparing the waves' arrival times at three places. With a fourth interferometer (Japan is building an underground one called KAGRA, for Kamioka Gravitational-Wave Detector, and India has its own LIGO in planning), their precision would improve much more.

Knowing an event's direction will in turn remove one of the biggest uncertainties in determining its distance from Earth. Waves that approach from a direction exactly perpendicular to the detector — either from above or from below, through Earth — will be recorded at their actual amplitude, explains Fulvio Ricci, a physicist at the University of Rome La Sapienza and the spokesperson for Virgo. Waves that come from elsewhere in the sky, however, will hit the detector at an angle and produce a somewhat smaller signal, according to a known formula. There are even some blind spots, where a source cannot be seen by a given detector at all.

Determining the direction will therefore reveal the exact amplitude of the waves. By comparing that figure with the waves' amplitude at the source, which the researchers can derive from the shape of the signal, and by knowing how the amplitude decreases with distance, which they get from Einstein's theory, they can then calculate the distance of the source to a much higher precision.

This situation is almost unprecedented: conventionally, astronomical distances need to be estimated by looking at the brightness of known objects in locations that range from the Solar System to distant galaxies. But the measured brightness of those 'standard candles' can be dimmed by stuff in between. Gravitational waves have no such limitation.

RAISING THE ALARM

There is another important reason why scientists are eager to have precise estimates of the waves' provenance. The LIGO and Virgo teams have arranged to give near-real-time alerts of intriguing events to more than 70 teams of conventional astronomers, who will use their optical, radio and space-based telescopes to see whether those events produced any form of electromagnetic radiation. In return, the LIGO and Virgo collaborations will be sifting through data to search for gravitational waves that could have been generated by events, such as supernova explosions, seen by the conventional observatories.

Some 20 teams tried to follow up on the Event, mostly to no avail. NASA's Fermi Gamma-ray Space Telescope did see a possible burst of γ-rays about 0.4 seconds later, coming from an equally vague but compatible region of the southern sky[4]. But most observers now consider it to be a coincidence. Such γ-rays could, in principle, have been produced when gas orbiting the binary black hole was heated up during the merger, says Vicky Kalogera, a LIGO astrophysicist at Northwestern University in Evanston, Illinois. But "our astrophysical expectation has been that the gas from stars that formed the binary black hole has long dispersed. There shouldn't be any significant gas around", she says.

Going forward, however, matching gravitational waves with electromagnetic ones could usher in a new era of astronomy. In particular, mergers of neutron stars are expected to produce short γ-ray bursts. Researchers could then measure how far the light from those bursts is shifted towards the red end of the spectrum, which would tell astronomers how fast the stars' host galaxies are receding owing to the expansion of the Universe.

Matching those redshifts to distance measurements calculated from gravitational waves should give estimates of the current rate of cosmic expansion, known as the Hubble constant, that are independent — and potentially more precise — than calculations using current methods. "From the point of view of measuring the Hubble constant, that's our gold-plated source", says Holz.

The LIGO and Virgo teams estimate that they have a 90% chance of finding more events in the data that LIGO has already collected. They are confident that by the time the next run finishes, the event count will be at least 5, growing to perhaps 35 by the end of a run scheduled to start in 2017.

"To be honest," says Holz, "I find it really hard to believe that the Universe is really doing this stuff. But it's not science fiction. It really happened." ■ SEE EDITORIAL P.413

Davide Castelvecchi *is a reporter for* Nature *in London.*

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