# Gravitational astronomy proves its maturity

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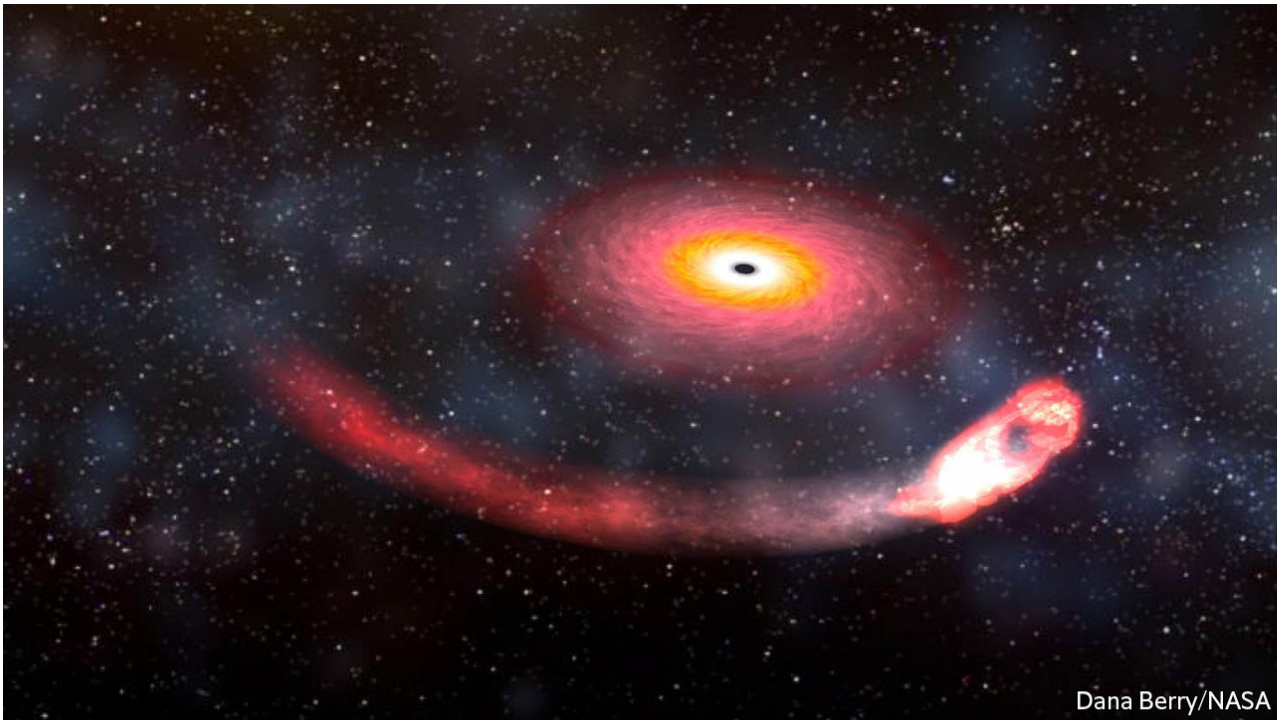


Aug 22nd 2019

ON AUGUST 14TH, just after 9pm Universal Time, a ripple of gravitational waves reached Earth. Until a few years ago no one would have noticed such an event. But 2015 saw the reopening, after an upgrade, of the Laser Interferometer Gravitational-wave Observatory (LIGO), a pair of detectors in Washington state and Louisiana. These were joined in 2017 by Virgo, an upgraded instrument in Italy. Together, the three instruments not only recorded the wave's passage, they also worked out where in the sky it had come from and then texted that information to the world's astronomers.

This stimulated the deployment of a host of other devices, to look at the wave's point of origin near the border between the constellations of Cetus and Sculptor. Telescopes capable of examining all parts of the spectrum, from gamma rays to radio waves, were brought into play. And, courtesy of IceCube, an instrument at the South Pole, the sky was also scanned for tiny particles known as neutrinos that might have been released by whatever humungous event it was that had disturbed the fabric of the space-time continuum to create such a gravitational ripple.

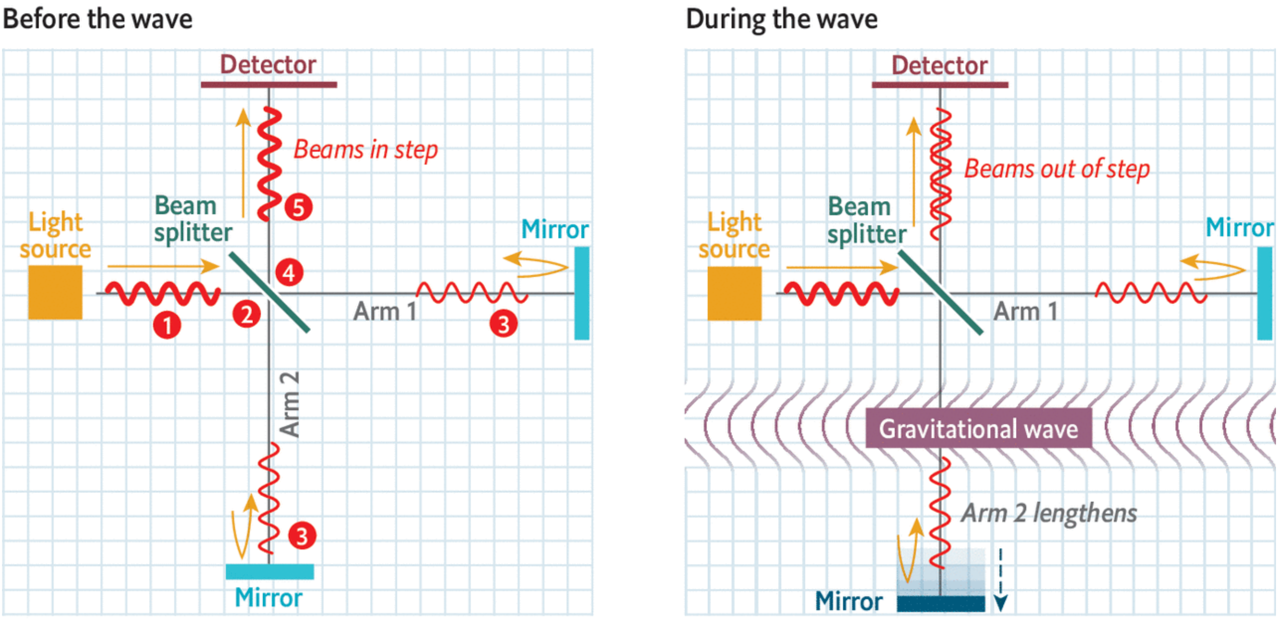
The provisional conclusion of all this "multimessenger" activity is that the detectors were witness to the merger, 900m light-years away, of a neutron star and a black hole—an event prosaically dubbed S190814bv by LIGO's masters. If confirmed, S190814bv will the first such merger discovered (previous gravitational-wave observations were of two black holes or two neutron stars colliding). As in many other walks of life, three may be taken as a trend, and the detection of this third type of event thus marks the coming of age of the new field of gravitational astronomy.

## Relative value

Gravitational waves are distortions of space-time that transmit the force of gravity from one place to another. They were predicted by Albert Einstein in 1916 as part of his general theory of relativity (which, despite its name, is really a theory of gravity). However, in the context of astronomical objects then known, the waves' expected size was so small that Einstein himself doubted they would be measurable.

That changed with the discovery of dense, massive objects such as neutron stars (the remnants of supernova explosions) and black holes (objects of various origin in which mass is so concentrated that even light cannot escape their gravity fields). Calculations showed that mergers between these sorts of objects would produce gravitational waves that might be detectable by big enough, sensitive enough instruments. Meanwhile, a century of economic growth and technical progress since Einstein's day has provided both the money and the prowess for those instruments to be constructed.

**How a Laser-Interferometer Gravitational-wave Observatory (LIGO) works**


Before the wave

During the wave

The light source sends out a beam **1** that is divided by a beam splitter **2**. The beams produced follow paths of identical length **3**, reflecting off mirrors to recombine **4**, then travel in step to the detector **5**.

When a gravitational wave arrives, it disturbs space-time, lengthening the light's path along one or both arms (here, arm 2). When the beams recombine and arrive at the detector, they are no longer in step.

The Economist

Gravitational-wave detectors work (see diagram) by splitting a laser beam in twain. The two halves of the beam are then sent down separate arms, several kilometres long, that are oriented at right angles to one another (see satellite photograph below). Each arm has a mirror at the end to reflect its half-beam back whence it came, and the reflected half-beams are then recombined. Normally, this recombination causes peaks in one half-beam's waves to overlie troughs in the other's, and vice versa, resulting in darkness. But if the lengths of the arms are distorted by a passing gravitational wave then the beams will not match in this way. Instead, they generate an interference pattern which gives away the characteristics of the passing gravitational blip. Even when the objects generating a gravitational wave are as massive as neutron stars or large black holes, the blip's effects are tiny—a distortion a thousandth of the width of a proton over the course of a 4km-long detector arm. But laser interferometry, as this technique is known, is sensitive enough to pick up such tiny differences.

LIGO bagged its first quarry, a signal from the merger of two black holes, in September 2015. Since then, it and Virgo have recorded and confirmed another nine such events, and also noted the merger of two neutron stars. If S190814bv does prove to have been a neutron star/black hole merger, that will make it easier to compare and contrast these different types of event.

## Striking gold

Gravitational waves are, as the text messages following the detection of S190814bv show, now part of a bigger endeavour involving the collation of data from many different sources. This was first done successfully after the detection, in August 2017, of the first neutron-star merger. The cosmic fireworks set off by that merger started with a burst of gravitational waves 100 seconds long. Less than two seconds after this burst had begun, a pair of space-based observatories, NASA's Fermi Telescope and the European Space Agency's International Gamma-ray Astrophysics Laboratory, detected a burst of gamma rays coming from a galaxy known as NGC 4993, 130m light-years from Earth in a constellation called Hydra. Nor did events end with the gamma rays. They were followed by a kilonova—a burst of optical and ultraviolet radiation powered by the radioactive decay of heavy elements newly formed in the explosion. For a year afterwards, the debris left behind glowed with radiation ranging from X-rays to radio waves.

GW170817, as this neutron-star merger was dubbed, was a gold mine for astronomers—literally. The kilonova's spectrum suggests gold and platinum were among the elements generated by the event, confirming that such explosions are a source of these metals, which are too heavy to be created, as lighter elements are, by ordinary nuclear processes inside stars. The near-simultaneous arrival of GW170817's gravitational waves and gamma rays also confirmed the prediction made by Einstein that gravitational waves would travel at the speed of light.

What GW170817 did not bring, which S190814bv might, is a chance to see inside a neutron star itself, if the black hole ripped it apart before the two merged. There are plenty of ideas about what might be going on inside neutron stars, but because it is impossible to replicate the conditions found there in a laboratory on Earth, no one knows for sure. Theory suggests that matter more than a kilometre below a neutron star's surface will be compressed into blobs, tubes and sheets—a state of being referred to as “nuclear pasta” because of its resemblance to gnocchi, spaghetti and lasagne. If nuclear pasta exists, it is probably the strongest material in the universe. One calculation suggests it would be 10bn times stronger than steel.

Whether S190814bv will reveal that neutron stars are cosmic *primi piatti* remains to be seen. The closer that the two objects involved turn out to have been in mass, the longer it would have taken the black hole to tear the neutron star apart, and the more time that object’s glowing innards would have been on display to the universe (and watching astronomers) before the black hole consumed them. If, however, the black hole was a lot bigger than its partner, the neutron star would probably have fallen into it with little fanfare.

Black holes and neutron stars form when large stars run out of fuel and collapse. Though both are heavy and dense, their physical natures are strikingly different. Neutron stars, as their name suggests, are made largely of neutrons. These are constituents of ordinary matter, found in the nuclei of all atoms except the lightest isotope of hydrogen, which is a lone proton. Black holes, by contrast, are “singularities”. This means they have no internal structure, only mass.

One consequence of this difference is, as Christopher Berry, an astronomer at Northwestern University and a member of the LIGO Scientific Collaboration, puts it, that “neutron stars, being made of stuff, can get distorted, whereas black holes do not.” It is from the imprint those distortions make on the gravitational waves which a collision generates that information about things like nuclear pasta can be deduced.

In the case of S190814bv the crucial mass ratio that might expose the pasta has yet to be determined. The reason astronomers believe they have witnessed a neutron star/black hole merger is the masses of the objects involved. The larger had more than five times the mass of the sun, and physics dictates that something this massive which is generating no starlight to counteract the pull of its gravity must be a black hole. The smaller object, by contrast, was below three solar masses. That is too light to have collapsed into a black hole and so it was presumably a neutron star. But the objects’ precise relative masses—and thus the likelihood of the neutron star having spilled its guts—remain to be determined.

Collisions involving neutron stars give astronomers an insight into the properties of these bodies. But LIGO and Virgo should also be able to detect non-colliding neutron stars, as long as they are spinning rapidly. Rapidly spinning neutron stars are called pulsars. They produce a beam of electromagnetic waves that can be seen only if it points directly at an observer, in the manner of a lighthouse. They may also produce detectable gravitational waves. Any imperfection on a pulsar’s surface—even a bump just a millimetre high—would do the trick. It would broadcast gravitational waves that would likewise be beamed in a lighthouse pattern. Given the intense gravity at a neutron star’s surface, the height of any millimetric mountains, measured by the strength of the gravitational waves arriving at Earth, would provide astronomers with a way to measure how stiff the neutron star’s internal nuclear pasta really is.

Another eagerly awaited source of gravitational waves is a supernova, an explosion marking the death throes of a massive star. Watching such an explosion with modern instruments, including LIGO, Virgo and neutrino detectors such as IceCube, would not be easy. Gravitational waves from a supernova explosion are predicted to be weak, so the source would have to be close by (ie, within Earth’s home galaxy, the Milky Way) for LIGO and Virgo to be able to detect them. The estimated rate of such events in the Milky Way is one to three per century and the last known example, concealed from human eyes at the time by dust and gas but discovered subsequently by radio astronomy, occurred near the beginning of the 20th century.

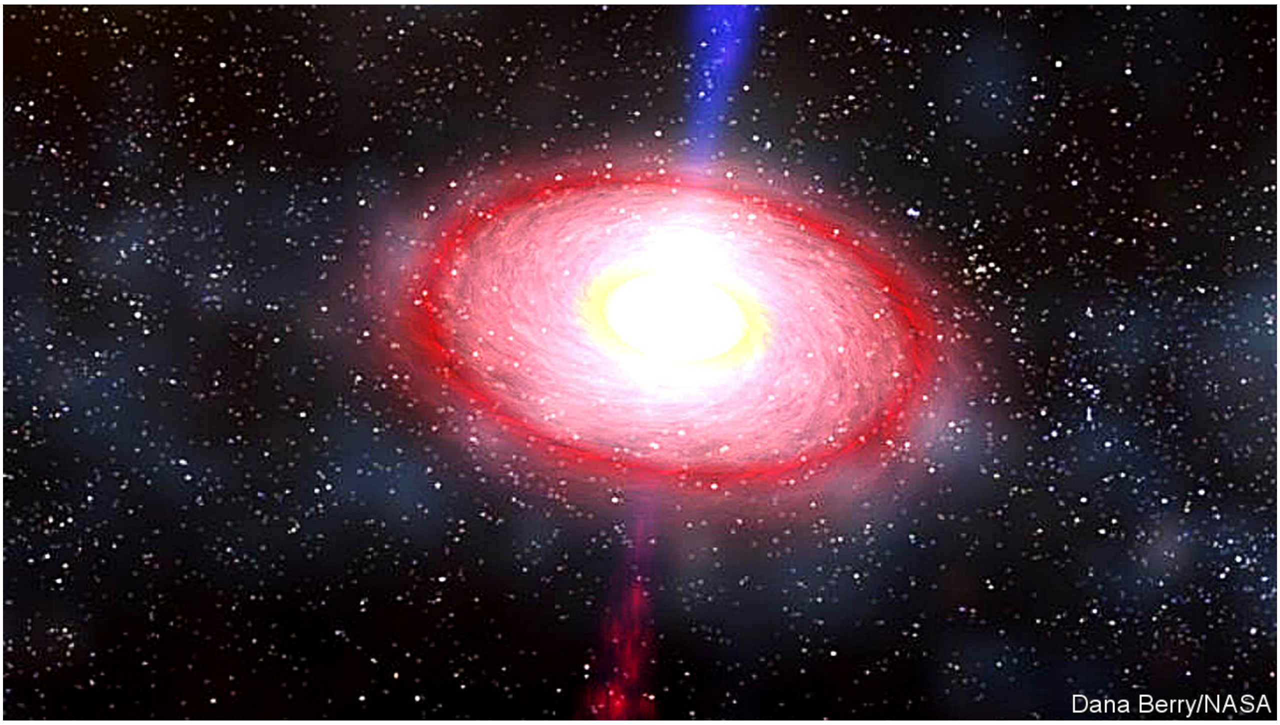
Unlike electromagnetic radiation or neutrinos, gravitational waves from a supernova could tell astronomers how the dense matter within a star was swirling around as it exploded. They could also help determine whether an exploding star collapsed symmetrically or not. And, after a supernova explosion has blown off much of the stellar material, what remains often becomes a neutron star or a black hole. By observing the evolution of a supernova, astronomers would be able to watch in real time as the material inside the original star settled and those most extreme cosmic objects were born out of it.

## A fair crack of the whip

While some astronomers seek to use gravitational waves to understand the structure of cosmic objects, others want to employ this new era of astronomy to test the limits of the general theory of relativity. So far, every prediction made by this theory has been borne out, yet physicists know that relativity cannot be the last word on matters gravitational because it stubbornly refuses to mesh with quantum theory, which is the best available explanation for everything else in the universe. Szabolcs Marka, a physicist at Columbia University in New York, and one of those who pioneered the collaborative ideas behind multimessenger astronomy, thinks that gravitational astronomy might square this circle. He reckons the best bet would be to look for deviations from relativity’s predictions in the waves given out by two black holes orbiting each other.

A longer-term goal for gravitational-wave astronomers is to see further back in time than has been possible with electromagnetic radiation. Until the universe was around 400,000 years old, it was so hot and dense that any light generated was instantly absorbed, and so no electromagnetic signal remains. The early universe would, however, have been transparent to gravitational waves. Detecting these so-called cosmological waves could provide a picture of the moment when the singularity from which the universe was born began its Big Bang expansion.

After 13.8bn years of the expansion of space since the Big Bang happened, cosmological gravitational waves would now be tenuous things indeed. They would be hidden under layers of background hum composed of gravitational waves from random astrophysical processes going on all over the sky. If astronomers did manage to detect them, however, they would be able to study the earliest seconds of the universe, answering long-asked questions about how quickly it expanded to start with and how uniform that expansion was.



Dana Berry/NASA

After that they will seek to check some highly theoretical ideas. Gravitational waves could help with the search for cosmic strings—putative enormous, superdense filamentary structures in space. “If they do exist, those cosmic strings can kind of wriggle and wiggle around, and every so often, the wiggling leads to a cracking, like cracking a whip,” says Patrick Brady, an astronomer at the University of Wisconsin-Milwaukee who is the LIGO Scientific Collaboration’s spokesman. “And,” he continues, “the whipcrack generates gravitational waves that could be detectable by us.”

The true excitement, says Dr Brady, would be if astronomers saw a blip inexplicable by neutron stars, black holes, supernovae or even cosmic strings. “We’re constantly looking for such things—we refer to them as unmodelled bursts of gravitational waves because, as yet, we don’t have physical theoretical models for them. If we ever did find a blip that was a confident gravitational-wave detection, but was not explained as a compact binary, then it would be incredibly exciting.”

## The once and future subject

If all goes well, the current generation of gravitational-wave observatories will be joined at the end of the year by the Kagra interferometer in Japan and, by 2024, by LIGO-India, which is under construction at a site 450km east of Mumbai. Detectors placed all around the world like this will allow astronomers to improve their ability to locate which part of the sky future gravitational-wave discoveries come from, as well as providing independent verification of individual detections.

LIGO itself is due for another upgrade within the next few years. This will almost double its sensitivity, permitting it to observe with the same rigour a volume of space seven times larger than now. Beyond that, the European Space Agency's Laser Interferometer Space Antenna (LISA), scheduled for 2034, will be the first orbiting gravitational-wave instrument. Its detectors will be arranged in an equilateral triangle with sides 2.5m kilometres long. LISA will be sensitive to low-frequency waves that currently get lost in the noise.

Looking still further ahead, another generation of ground-based observatories is competing to take over once LIGO's useful life is at an end. Europe is offering the Einstein Telescope, a proposed interferometer with three arms arranged in an equilateral triangle buried underground and cooled to within ten degrees of absolute zero, to improve its sensitivity. America proposes the Cosmic Explorer, a version of LIGO with arms 40km long. Either would be able to spot black-hole mergers almost anywhere in the universe.

The promise of gravitational astronomy is, then, enormous. It will show better how heavy elements are created. It could answer questions about the early universe that have nagged physicists for decades. It might even reconcile general relativity with quantum theory. From Copernicus to Kepler to Newton, understanding gravity and how it binds objects in the universe together was the project that launched physics as an intellectual discipline. The latest results from LIGO and Virgo show that there is life in the old dog yet.■