ASTRONOMY

Astronomers' newfound ability to see the same cosmic events in light, particles and gravitational waves—**a synthesis called multimessenger astronomy**—gives them a fuller picture of some of the universe's most mysterious phenomena

Messengers from the Sky

By Ann Finkbeiner

Illustration by Maria Corte Maidagan

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A NEUTRINO HIT ON SEPTEMBER 22, 2017, AT 4:54 P.M. EASTERN TIME. THE NEARLY MASSLESS ELEMENTARY particle barreled through the sensors of the IceCube Neutrino Observatory, an experiment buried in the Antarctic ice. This neutrino was rare, carrying an energy of more than 100 tera electron volts, about 10 times the energy reachable by particles inside the most powerful accelerators on Earth. Thirty seconds later IceCube's computers sent out an alert with the neutrino's energy, the time and date, and roughly where it came from in the sky.

At the University of Maryland, College Park, IceCube team member Erik Blaufuss got the alert via text and knew that, with that energy, the particle probably came from beyond the solar system. Blaufuss had already seen 10 or so neutrinos in the past year with energies that high, but he thought, "It's a pretty event—let's send it out there." At 8:09 P.M. he issued a public notice over one of astronomy's heads-up networks about the particle, now called IceCube-170922A. IceCube's more than 5,000 sensors, which look for flashes of light made by neutrinos interacting with atoms in the ice, can trace the path of the flash back to the particle's origin in the sky. And Blaufuss hoped the nighttime notice would "catch observers coming online," astronomers who could look at the same area of the sky the neutrino came from. If they were really lucky, they might find the galaxy or other celestial object that sent it.

Neutrinos are just one of the many things in the sky that flare, ping, bang, shudder and shine. For a long time astronomers could see mainly those that shine, that emit light. Then, roughly 30 years ago, they started to detect little hits of neutrinos from beyond our solar system. And since 2015 they have been able to detect the rolling waves of gravity. But combining these different signals to study individual objects—a technique called multimessenger astronomy—is mostly a recent development.

One great advantage of multimessenger astronomy is that unlike light—an electromagnetic wave that can get reflected, absorbed and misdirected, obscuring information about its source—almost nothing stops gravitational waves or neutrinos. The message they carry is pure; it comes in directly and at or near the speed of light. Another plus is that their sources—colliding black holes or collapsing supernovae or merging neutron stars—are transient, unspeakably violent perplexities. They were predicted but not seen, were seen but not understood, or were by any other means invisible. But with more messengers, astronomers can finally understand these complex phenomena. "These sources are complicated," says Francis Halzen, a physicist at the University of Wisconsin–Madison and principal investigator of IceCube. "Unless you have many ways to look at them, you're not going to figure them out."

THE TEXAS SOURCE

FOUR DAYS AFTER BLAUFUSS sent the IceCube notice, scientists at the Swift Observatory's x-ray space telescope reported that since the alert they had counted nine things emitting x-rays in the area of the sky that IceCube-170922A came from.

Just two days after that, on September 28, at 6:10 A.M., the Fermi orbiting telescope, sensitive to gamma wavelengths, reported gamma rays at the same position as both IceCube-170922A and Swift's second x-ray source. Sara Buson, a member of the Fermi team at NASA's Goddard Space Flight Center, and her colleagues sent out a public notice saying that the gamma source was already known and named TXS 0506+056, which astronomers later nicknamed "the Texas source." "It was very exciting," Buson says. "The neutrino was exactly on top of the gamma, the first time we had such a nice coincidence." In the previous two weeks, Buson's notice said, Fermi had seen the Texas source flare up by a factor of six.

On the same day at 2:00 P.M., scientists working on a survey called ASAS-SN (pronounced "assassin"), operating at optical wavelengths, announced that the Texas source had in fact been brightening over the past 50 days and was the brightest it had been in several years. The next day, September 29, at 9:00 A.M., another optical telescope found that the Texas source was a blazar, a supermassive black hole at the center of a galaxy that spo-

IN BRIEF

Two recent celestial events have ushered in the age of multimessenger astronomy—the technique of observing the same phenomena through light, particles and gravitational waves.

These different messengers carry unique information, so that combining them gives scientists insight into some of the most mysterious cosmic objects.

Astronomers have traced gravitational waves and multiple wavelengths of light back to a collision of two dense neutron stars. They have also observed light and neutrino particles coming from what appears to be a huge mass-absorbing black hole.

BURIED IN THE ICE at the South Pole, thousands of sensors make up the IceCube Neutrino Observatory. These sensors look for signs of rare interactions between neutrino particles from space and atoms in the ice. A particularly high-energy neutrino observed in 2017 set off multiple observations from ground- and space-based telescopes to identify the particle's source.

FELIPE PEDREROS, ICECUBE AND NATIONAL SCIENCE FOUNDATION

radically flares up as matter falls into it, sending out jets aimed straight at us. Then, on October 17, the Very Large Array in New Mexico, operating at radio wavelengths, confirmed the light was coming from a blazar's jet.

Blazars were already well known but had never been observed in multiple wavelengths and simultaneously identified as the source of a neutrino. More interestingly, the Texas source was also the first time a high-energy neutrino coincided in space and time with a similarly high-energy gamma-ray photon. Halzen notes that over the whole sky, the number of high-energy neutrinos and the number of gamma-ray photons are roughly the same, so "the obvious thing is," he says, "it means you could be seeing the same sources." The similarity in numbers, says Imre Bartos, a physicist at the University of Florida, is "a remarkable and suggestive coincidence." But the implication that they are coming from the same cosmic objects, from blazars, Halzen adds, "is a looong extrapolation." Nevertheless, the neutrino discovery could help scientists discriminate between different theories about how blazars manage to accelerate their jets to such energies. "This is a good first step," Bartos says, "but what we need is more multimessenger observations."

A LONG WAIT

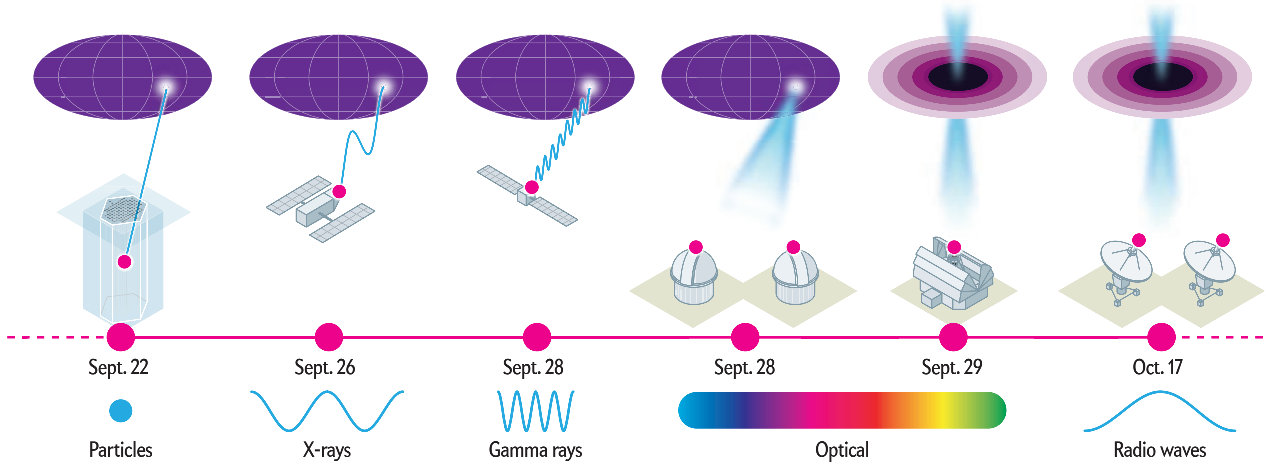
THE FIRST MESSENGER that was not light was the neutrino. It came in February 1987 from Supernova 1987A—a dying star whose core collapsed under the weight of its own gravity and then exploded. All in all, scientists detected 25 neutrinos in Japan, the U.S. and Russia. Three hours later optical light came from a shock wave breaking through the star's surface. By November x-rays and gamma rays arrived from decaying radioactive elements and infrared light came from new heavy elements, all created in the explosion. Supernova 1987A helped astronomers understand the way this type of supernova goes off, says Doug Cowen, a physicist at Pennsylvania State University, who is on the IceCube team, and how most of the explosive energy comes out in the form of neutrinos. That was 30 years ago, Halzen says, "and we've been waiting ever since." The coincidence of the IceCube-170922A neutrino with the Texas source—which was eventually observed by at least 19 instruments in gamma rays and x-rays and optical and radio wavelengths—now makes the second neutrino multimessenger event.

Neutrinos might be excellent messengers, but the most outlandish ones are gravitational waves. These once lived solely in the realm of theory, a century-old prediction of Albert Einstein's general relativity. The theory explained the attraction of one mass to another—the apple to Earth—by proposing that mass curved the spacetime around it; the greater the mass, the deeper the curvature. The apple does not so much fall to Earth as it spirals down along the curvature our planet's mass has made in spacetime. The theory went on to predict that if a mass accelerates, the curvature moves outward in waves. The waves are

Cosmic Chain of Events

Over three and a half weeks in 2017, astronomers observed the same celestial event—what they believe to be a flare-up from matter falling into a supermassive black hole—through multiple wavelengths of light, as well as particles called neutrinos. The combined observations offer scientists much more information about these mysterious phenomena than any measurement alone.

1. First, the IceCube Neutrino Observatory at the South Pole detected a high-energy neutrino and issued an alert.
2. The orbiting Swift x-ray telescope reported finding nine sources of x-rays coming from the same area of the sky as the neutrino.
3. Two days later the Fermi space telescope identified gamma rays coming from one of the same sources Swift found.
4. A network of ground-based optical telescopes called ASAS-SN announced that this source had been brightening over the past 50 days.
5. Another optical telescope found evidence that the source was a blazar—a huge black hole emitting jets as it swallowed mass.
6. The Very Large Array in New Mexico, observing in radio light, confirmed that the source of all these signals was a jet from a blazar.



spacetime itself compacting and stretching. So if a gravitational wave moved, for example, through the body of Szabolcs Marka, a physicist at Columbia University, he "would be taller and thinner," he says, "then shorter and wider."

General relativity is widely accepted, and scientists have seen, indirectly, the predicted curvature made by star- and galaxy-sized masses. Gravitational waves themselves, however, had not been seen. In 2014 physicists upgraded an experiment called the Laser Interferometer Gravitational-Wave Observatory (LIGO): two observatories, each with two four-kilometer tubes at right angles to each other. A laser shot from one end of each tube first hits a mirror at the other end, then bounces back, its travel timed. A gravitational wave moving through LIGO would compact and stretch the tubes so that the lasers' travel times would change by one part in 10^{21}, meaning that the four-kilometer tube would be altered by 1/10,000th the diameter of a proton, Marka says, which is like changing the U.S. national debt by one millionth of a cent.

Even with that extraordinary level of precision, LIGO can detect gravitational waves only from extremely dense and massive sources, such as neutron stars: the dropping apple also makes gravitational waves, but comparing an apple's waves to those of a neutron star is not a meaningful exercise. And LIGO's resolution—its ability to locate sources in the sky—is as good as it can be but is still dreadful. With three detectors, one on either side of the U.S. and a third called Virgo in Italy, scientists can trace gravitational waves back to within tens of degrees (the full moon is 0.5 degree across). For an astronomer, says Andy Howell of the University of California, Santa Barbara, that is like waving your hand at the sky and saying, "It's probably somewhere over there."

Between September 14, 2015, and August 14, 2017, LIGO-Virgo detected five different sources of gravitational waves, each produced by the collisions of two black holes that merged into single black holes. These were triumphant observations—the first direct proof not just of gravitational waves but also of the existence of black holes themselves. But they were not multimessenger astronomy. Black holes, being black, are single-messenger events. Current dogma is that they are so dense that light cannot escape them, so their merger is detectable only via gravitational waves. No one expected to see light or neutrinos from these collisions, and although many detectors looked, none did.

COSMIC CRASH

THEN THREE DAYS AFTER the most recent black hole merger sighting, an event occurred that became a poster child for multimessenger astronomy. On August 17, 2017, LIGO-Virgo detected gravitational waves. Just 1.74 seconds later the Fermi telescope saw a burst of gamma rays. The event, called GW170817, seemed to be created by the collision and merger not of black holes but of the densest of all stars: neutron stars.

Neutron stars are the collapsed cores of past supernovae, so compact that all their protons and electrons have squished together to make neutrons; they are the final state of stars not quite massive enough to form black holes. The gravitational waves LIGO-Virgo saw would have come from the two stars'

Illustration by Nigel Hawtin

inspiral right before they smashed and the gamma-ray burst from their blazing merger—when "all hell breaks loose," says Penn State's Peter Mészáros.

Over the next 24 hours—"like dropping raw meat into a bear pit," says Maryland astronomer M. Coleman Miller—detectors in all frequencies of light on the ground and in the sky scrambled to observe the signal. They pinpointed the merger to a nearby galaxy called NGC 4993 and watched most of its light immediately fade.

The infrared light, however, kept brightening until day three, a sign that as the stars merged, they ejected detritus in which the heaviest of chemical elements were forming. Over the next weeks x-ray and radio light brightened as well, meaning that a near-light-speed jet was pushing through the ejecta. No neutrinos came through, however, so the jets must not have been aimed at us; neutrino detectors "would definitely have seen if it had pointed in our direction," Halzen says. Put together, the messengers were evidence of a phenomenon predicted but never seen, let alone watched in real time: the explosive collision of two neutron stars, called a kilonova. The end stage was either another neutron star, a neutron star on its way to becoming a black hole, or a black hole.

Put together, the messengers were evidence of a phenomenon predicted but never seen, let alone watched in real time: the explosive collision of two neutron stars.

Two months after the kilonova, astronomers announced GW 170817 to the world. That day, October 16, 2017, arXiv.org, a Web site that publishes preprints of science's scholarly papers, received 67 papers. In two months the number of papers roughly doubled: "arXiv is too much," Alessandra Corsi of Texas Tech University says. "I'm having a hard time keeping track."

And just like that, several of astronomy's unsolved problems dropped like swatted flies. The particular kind of gamma-ray burst, a variety that had been seen for decades but whose source had never been directly identified, was now known to come from neutron star mergers. And kilonovae were now understood for the first time to be the birthplaces of a large fraction of the universe's heaviest elements, including platinum, uranium and "about 100 Earth masses in gold," says Samaya Nissanke of Radboud University in the Netherlands. In the weeks afterward, chemists had to rejigger their listings of the sources of the elements on the periodic table. Furthermore, the details of the forms of the gravitational waves cast doubt on the set of alternatives to general relativity proposed to account for the existence of dark matter—possibly excluding the alternative that the universe exists in more than four dimensions.

As always, the finding brought up just as many questions. Astronomers want to know what happens after neutron stars merge. They want to see a neutron star merging with a black hole and to discover how jets arise and what powers them. They still do not know how the cores of stars collapse into supernovae, and they want to watch supermassive black holes in the centers of galaxies merging with other supermassive black holes in the centers of other galaxies.

Thus, aside from the multitude of new and planned detectors of light, scientists envision a whole raft of new multimessenger detectors. LIGO has siblings under construction in Japan and India. The Laser Interferometer Space Antenna (LISA) will be an orbiting gravitational-wave detector scheduled to launch in the 2030s; its arms are lasers zipping among three spacecraft arranged so they form a triangle with sides extending around a million miles. And new high-energy neutrino detectors are in the works, including a next-generation IceCube and KM3NeT, a cubic kilometer of sensors 3,500 meters down in the Mediterranean Sea.

THE WAGER

MEANWHILE ASTRONOMERS like nothing better than finding things in the sky they were not sure they would ever see. Nissanke got her physics Ph.D. in 2007 from the Paris Institute of Astrophysics, and every day since, she says, she has been thinking about how to see the sources of gravitational waves in light. She would give talks on the subject and would get critical questions. "Astronomers would say, 'You have huge uncertainties, you're measuring tiny displacements, you have huge sky errors.'" When they were not asking questions, they were unimpressed: "Half the audience would look at me like I was on something," Nissanke says. "The other half was asleep." She did this for 10 years.

On August 17, 2017, while speaking at a conference in Amsterdam, she predicted that the first multimessenger events with light and gravitational waves would come in the 2020s. "And the hands went up," she says: "'Samaya, aren't you being overly optimistic?'" After the talk, she had lunch with the LIGO-India consortium, during which she upped her ante: "I don't [usually] bet, but I said I think we'll see the first neutron star merger." Scientists on LIGO-India said not before 2019 and took the wager, a "gentleman/woman's handshake bet," Nissanke says. An hour later LIGO-Virgo saw the neutron star merger. A member of the consortium wrote to her: Before the next conference, let's "tempt nature" and talk about whether we'll see a neutron star–black hole merger.

Nissanke pauses in her story. "I did predict the neutron star's merger, this golden binary, but it took several hours for it to sink in that we were really seeing it," she says. "There's going to be more excitement and many, many, many more papers. It's amazingly fun." SA

MORE TO EXPLORE

Multi-messenger Observations of a Binary Neutron Star Merger. B. P. Abbott et al. in *Astrophysical Journal Letters,* Vol. 848, No. 2, Article No. L2; October 20, 2017. http://iopscience.iop.org/article/10.3847/2041-8213/aa91c9

FROM OUR ARCHIVES

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