An artist's conception of the kilonova touched off by the neutron-star collision.

ASTROPHYSICS

A spacetime tremor and a celestial light show

Unprecedented view of a neutron-star collision is a scientific gold mine

By **Adrian Cho**

Four times in the past 2 years, physicists working with mammoth gravitational-wave detectors have sensed something go bump in the dark, sending invisible ripples through spacetime. This week, they announced the detection of a fifth such disturbance—but this time astronomers saw it, too, at every wavelength of light from gamma radiation to radio waves. Just as physicists had predicted, the unprecedented view of the cosmic cataclysm—in which two superdense neutron stars spiraled into each other—brought with it a cornucopia of insights, each one of them a major scientific advance.

"It's really a big gift that nature has given us," says Alessandra Corsi, a radio astronomer at Texas Tech University in Lubbock. "It's a life-changing event."

At 12:41 universal time on 17 August, physicists with three massive instruments—the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in Hanford, Washington, and Livingston, Louisiana, and the Virgo detector near Pisa, Italy—spotted waves unlike any seen before. The four previous events lasted for, at most, a few seconds, with gravitational waves rippling at frequencies of tens of cycles per second. The new siren sang for 100 seconds at frequencies climbing to thousands of cycles per second. Whereas the earlier signals came from pairs of huge black holes quickly spiraling into each other, the new signal revealed lighter neutron stars, 1.1 and 1.6 times as massive as the sun, twirling inexorably together, researchers announced 16 October in parallel press conferences in Washington, D.C., and Garching, Germany.

The gravitational waves marked the beginning of a spectacular light show. Because black holes are the gravitational fields left behind when very massive stars collapse to infinitesimal points, they contain no matter that might radiate light when an isolated pair merges. In contrast, neutron stars are balls of nearly pure neutrons, left behind when slightly smaller stars explode in supernovae. When they collide, they should spew debris glowing in all wavelengths.

That's exactly what happened. Two seconds after the gravitational signal, which only the automated "trigger" of the Hanford detector initially noticed, NASA's orbiting Fermi Gamma-ray Space Telescope picked up a blast of high-energy photons called a gamma ray burst. Within minutes, the Livingston and Virgo detectors confirmed the gravitational signal. Still, it took LIGO the better part of an hour to issue a full alert, says Julie McEnery, an astrophysicist at NASA's Goddard Space Flight Center in Greenbelt, Maryland, and a member of the Fermi team. McEnery says she first heard about the gravitational signal as a coy rumor. "A half-hour [after the Fermi alert] we got an email that said, 'This gamma ray burst has an interesting friend,'" she says.

Because all three gravitational-wave detectors saw the signal, physicists could triangulate and locate the source to within a 30-square-degree patch of sky—about 60 times the size of the moon. Astronomers swiveled telescopes large and small to the spot in the constellation Hydra. The search got off to a slow start because that part of sky was in daylight for many observatories. But within hours, five groups had identified a new source of light in the periphery of galaxy NGC 4993, which they watched fade from bright blue to dim red in a matter of days. Nearly 2 weeks later, the source began to emit x-rays and radio waves.

In the end, more than 70 observatories studied the event. "This is first time we have a 3D IMAX view of an astronomical event," says Laura Cadonati, a physicist at the Georgia Institute of Technology in Atlanta and deputy spokesperson for the LIGO collaboration.

The combination of gravitational waves and electromagnetic observations scored at least three significant advances. First, it explains the origins of some gamma ray bursts, among the most powerful events in the cosmos. Since the 1990s, theorists have thought that bursts shorter than 2 seconds originate when neutron stars merge to create a black hole. (Longer bursts, lasting minutes, are thought to spring from the collapse of individual massive stars.) The new result clinches the explanation for short bursts, says Peter Mészáros, a theorist at Pennsylvania State University in State College. "It's tremendous," he says. "If you have gravitational waves with a burst you know it has to come from a double neutron star."

Second, the event reveals a hypothesized object called a kilonova, which briefly

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shines thousands of times brighter than an ordinary nova. As two neutron stars twirl together and rip each other apart, they should expel neutron-rich atomic nuclei, forming a shroud of matter. Those nuclei beef up by gobbling more neutrons and then quickly change their chemical identities through radioactive decay. That so-called r-process—for rapid neutron capture—should make the shroud glow for a few days, and heavy elements that soak up blue wavelengths should redden the light. That's just what astronomers saw, says Brian Metzger, a theorist at Columbia University. "It's stunning. All of a sudden the curtain lifts and what we see looks pretty close to what we expected."

The observation of a kilonova scores a third advance by solving a long-standing puzzle: the origin of half the elements heavier than iron, including silver, gold, and platinum. Nuclear physicists have long thought that those elements are generated in the r-process, but they haven't known where that happens—whether in the collapse of single stars or in merging neutron stars. The new find shows that some, and quite possibly all, of the mystery elements come from neutron-star death spirals.

The neutron-star merger presents some puzzles of its own. For example, the gamma rays were relatively faint, even though the burst was closer than any previously measured short burst by a factor of 10, McEnery notes. That could be because observers saw the merger from a funny angle, she says. A gamma ray burst is thought to emerge when jets of hot matter shoot out along the rotational axis of the newborn black hole, beaming radiation like a lighthouse. In this case, observers on Earth may be looking at the jet not straight on, but from a slight angle, McEnery says.

The long lag before the detection of radio and x-ray emissions supports that picture, says Raffaella Margutti, an astrophysicist at Northwestern University in Evanston, Illinois, who studied the event with NASA's orbiting Chandra X-ray Observatory. The radio and x-ray signals also came from the jet, which at first would have beamed them too narrowly to be seen from Earth. As the jet slowed, however, radiation emerged at wider angles, making the signals detectable off-axis.

The race to see visible light from the collision was won by Ryan Foley of the University of California (UC), Santa Cruz, and colleagues. At 23:33 universal time, 10 hours and 52 minutes after the gravitational waves arrived, the team used a 1-meter telescope in Chile to snap an image of NGC 4993, and Charles Kilpatrick, a postdoc at UC Santa Cruz, saw a bright spot not visible in archival images. "Found something," he remarked coolly in an online messaging exchange. Within 40 minutes, four other teams had independently discovered the same optical object.

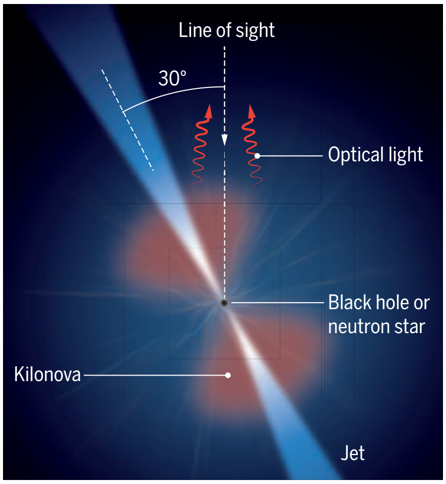
Rumors spread almost instantly over the internet. Within days, other scientists and journalists knew the outlines of the discovery, and the LIGO and Virgo teams struggled to keep a lid on the news. That was no easy task, given the fact that astronomers tend to work in small, competitive teams, says Andrew Howell, an astronomer at UC Santa Barbara and staff scientist with the Las Cumbres Observatory (*Science*, 5 May, p. 476), which also saw the kilonova. Used to working as a huge team, LIGO physicists "were absolutely unprepared for the chaos that is the astronomical community," he says.

Nonetheless, astronomers and astrophysicists came together to write a single compendious paper about the event. It has been submitted to *The Astrophysical Journal Letters* and reputedly has 4600 authors—roughly one-third of all astronomers. In addition, individual groups are publishing dozens of other papers in *Science*, *Nature*, and other journals (see p. 301).

With one spectacular event in the bag, the era of gravitational-wave astronomy has begun. The next step is simply to see more such events and begin to do statistical analyses on them, astronomers say. But for the moment, the entire community is basking in the glow of the discovery and the stunning success of its models. "Sometimes I wonder whether we're all just mucking around," Howell says. "It's moments like this that reassure me that science works." ■

A many-splendored explosion

As two neutron stars merged into a larger neutron star or black hole, they powered jets that beamed gamma radiation into space. They also sparked a kilonova that glowed for days as it generated heavy elements.



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DEMOGRAPHY

Analysis of China's one-child policy sparks uproar

Colleagues call demographer's findings flawed and irresponsible

By **Mara Hvistendahl**

A new study of China's one-child policy is roiling demography, sparking calls for the field's leading journal to withdraw the paper. The controversy has ignited a debate over scholarly values in a discipline that some say often prioritizes reducing population growth above all else.

Chinese officials have long claimed that the one-child policy—in place from 1980 to 2016—averted some 400 million births, which they say aided global environmental efforts. Scholars, in turn, have contested that number as flawed. But in a paper published in the journal *Demography* in August, Daniel Goodkind—an analyst at the U.S. Census Bureau in Suitland, Maryland, who published as an independent researcher—argues that the figure may, in fact, have merit.

By extrapolating from countries that experienced more moderate fertility decline, Goodkind contends that birth-planning policies implemented after 1970 avoided adding between 360 million and 520 million people to China's population. Because the momentum from that decline will continue into later generations, he suggests, the total avoided population could approach 1 billion by 2060. Some scholars worry such estimates could be used to justify, ex post facto, the policy's existence, and feel that Goodkind's criticisms of previous work fall outside the bounds of scholarly decorum.

"For the top journal to publish that paper was quite something," says Nancy Riley, a demographer at Bowdoin College in Brunswick, Maine. Goodkind's central estimate, she adds, relies on "building a house of cards" through a series of assumptions about data inputs.

Demography was born decades ago from a fixation with population growth, particularly in the developing world, where birth rates were highest. When China adopted the

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