

Two kinds of waves from a neutron-star smashup

Gravitational and electromagnetic radiation expose a merger that triggered a gamma-ray burst and manufactured heavy elements.

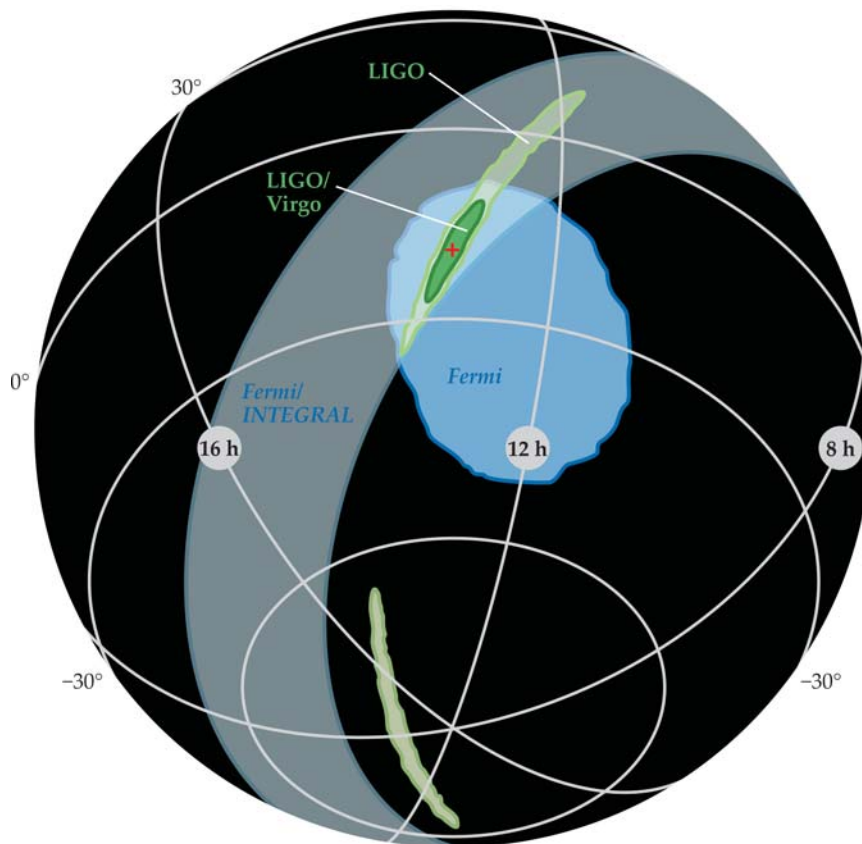
On 17 August the Laser Interferometer Gravitational-Wave Observatory (LIGO), along with sister observatory Virgo, detected a swell of gravitational waves. Less than two seconds after that signal ceased, the *Fermi* Gamma-Ray Space Telescope identified a flash in the southern sky. Though it would take several hours to verify, researchers had spotted both the buildup to and the aftermath of the violent collision between two neutron stars.¹

In the ensuing weeks, 70 telescopes in space and on the ground collected data across the electromagnetic spectrum on the event, a gamma-ray burst (GRB) that occurred 130 million light-years away in the galaxy NGC 4993, located in the constellation Hydra. The discovery, chronicled in some 50 scientific papers released on 16 October, has implications that stretch far beyond gravitational-wave astronomy.

It proves that at least some short-duration GRBs are triggered by crashing neutron stars. It offers evidence that tidal forces rip the ultradense orbs apart and that the subsequent explosion creates heavy metals such as gold, platinum, and uranium. It even provides novel means of measuring the universe's expansion rate and ruling out some modifications of general relativity, Einstein's theory of gravity. Overall, the discovery epitomizes the many research questions that can be addressed through the combined efforts of gravitational-wave and electromagnetic observatories.

Hitting the jackpot

Astronomers have puzzled over the origins of GRBs since a US satellite scanning for Soviet nuclear tests spotted one 50 years ago. A distinct class of GRBs, known as short because the primary burst lasts less than two seconds, has been thought to be triggered by the merger of neutron stars (see *PHYSICS TODAY*, November 2005, page 17).



Linking the collision of city-sized spheres with GRBs was impossible until the advent of LIGO and Virgo, which are optimized for detecting gravitational radiation emitted during the last throes of a compact binary system. Astronomers found no electromagnetic counterpart to any of LIGO's first four detections, but those were of coalescing black holes that presumably emit little radiation.

The 17 August gravitational-wave signal immediately stood out. The two LIGO detectors, in Louisiana and Washington State, registered 3300 oscillations during a period of more than a minute and a half, 500 times as long as each of the four chirps LIGO had previously detected. The duration and shape of the signal indicated the orbital dance of neutron stars, with a combined 2.7 solar masses, that ultimately merged to form either a single, large neutron star or a black hole.

Despite the strong signal measured by the LIGO detectors, Virgo registered only a faint blip. The observatory in Italy had begun operating just weeks earlier (see "LIGO and Virgo team up to spot

FIGURE 1. LOCALIZATION. The LIGO and Virgo gravitational-wave detectors narrowed the site (actually located at the red cross) of the 17 August neutron-star merger to the 28-square-degree region in dark green. That area fit comfortably within the boundaries set by *Fermi*'s Gamma-Ray Burst Monitor (blue) and comparisons of *Fermi* and *INTEGRAL* telescope data (gray). (Adapted from ref. 2.)

black hole merger," 27 September 2017, *PHYSICS TODAY* online). Researchers quickly concluded that the collision occurred in one of the observatory's blind spots, which narrowed the location of the source from 190 square degrees to 28. That target area fit neatly in the 1100-square-degree swath suggested by *Fermi*'s Gamma-Ray Burst Monitor, as shown in figure 1. Between the location and timing, researchers from *Fermi* and the LIGO–Virgo collaboration were confident that they had observed the same event.

A tilted, heavy-metal burst

About 10 hours after *Fermi* observed a flash, the Swope Telescope in Chile

spotted an optical counterpart to the burst, shown in figure 2. In the subsequent weeks, dozens of telescopes soaked up photons from the direction of NGC 4993. Those observations² paint a vivid picture of what occurred during and following the merger.

Unlike structureless black holes, neutron stars are susceptible to tidal forces, which ramp up quickly once the orbital frequency reaches about 50 Hz. The tidal tugs and subsequent collision stripped off about a hundredth of a solar mass of neutron-rich material, estimates Brian Metzger of Columbia University. Though he suspects that the merger briefly created a larger neutron star, the ultimate product (formed within a second) was probably a rapidly spinning black hole surrounded by a rapidly accreting debris disk. Powered by extreme magnetic fields, much of that debris got shot out in a relativistic jet. After the jet escaped the cloud of ejecta kicked up earlier in the merger, it produced the GRB.

This was no archetypal burst. Although the event was the closest short

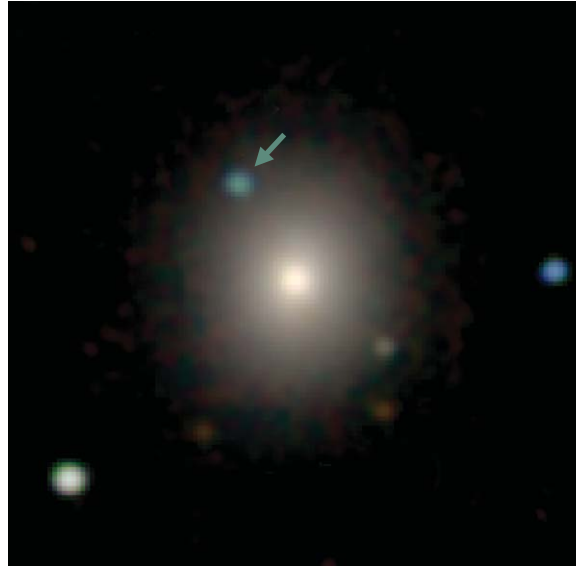


FIGURE 2. VISIBLE CONFIRMATION. The Swope Telescope in Chile made the first optical observation of the 17 August gamma-ray burst, indicated by the arrow. The emission subsequently reddened. (Courtesy of the 1M2H Team/UC Santa Cruz and Carnegie Observatories/Ryan Foley.)

GRB ever detected, the intensity of gamma rays was several orders of magnitude less than expected. In addition,

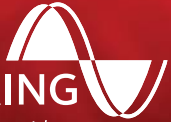
the x rays and radio waves that astronomers typically observe as quickly as they can point their telescopes didn't arrive until 9 days and 16 days, respectively, after the burst. Those factors led researchers to conclude that the jet wasn't aligned directly with Earth. It took days for the jet to slow down and widen enough to induce a glow that fell within astronomers' line of sight. Scientists have been hunting for such an off-axis GRB and its associated orphan afterglow for decades. The discovery hints that many of the roughly 20% of short GRBs that lack an x-ray component are off-axis events that are relatively nearby.

Whereas gamma-ray, x-ray, and radio telescopes were vital for understanding the GRB, measurements in UV, optical, and IR confirmed a decade-old prediction that the collision site would transform free nucleons into heavy elements. Once the relativistic jet escaped, the ejecta cloud expanded and brewed up numerous elements up to the mass of iron, Metzger says. After that first round of nucleosynthesis, the cloud was still

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hot and chock full of neutrons, which outnumbered protons as much as 10 to 1. Atomic nuclei gobbled up free neutrons faster than they could undergo radioactive decay. On the order of seconds, that rapid neutron-capture mechanism, or r-process, forged 10 000 Earth masses of gold, platinum, uranium, and other heavy elements.

The unstable products broke down via fission and alpha and beta decay, which kept the ejecta cloud heated and glowing. The radioactively driven blaze is called a kilonova, because after a day it appears about a thousand times brighter than a typical nova. The observed spectra from the kilonova agree remarkably well with predictions made over the last decade by Metzger³ and colleagues.

Linking a neutron star merger with a kilonova is crucial because astrophysicists have long debated which cataclysmic events seed the universe with r-process elements. Many theorists have favored core-collapse supernovae (see the article by John Cowan and Friedrich-Karl Thielemann, *PHYSICS TODAY*, October 2004, page 47), though simulations have had trouble producing the right conditions for nucleosynthesis. Now that hy-

pothesis is in peril. Combining the mass of heavy elements produced in the merger with even a pessimistic estimate of the frequency of neutron-star collisions comfortably accounts for the observed abundances of r-process elements in the solar system. Scientists can now confidently say that much of the universe's gold and platinum and nearly all its uranium are produced in neutron-star mergers.

Cosmological applications

Besides exploring the specifics of the burst, the researchers probed bigger-picture questions. By combining the distance to the source indicated by the gravitational-wave signal with the redshift of the host galaxy obtained optically, they estimated the Hubble constant, which is related to the universe's expansion rate. The initial estimate is rough: between 62 km s⁻¹ Mpc⁻¹ and 82 km s⁻¹ Mpc⁻¹. But future detections will narrow that figure, allowing the gravitational-wave community to chime in on the 3-standard-deviation discrepancies between the Hubble values derived via analyses of the cosmic-microwave background (about 68 km s⁻¹ Mpc⁻¹) and those of standard candles such as type 1a supernovae (73 km s⁻¹ Mpc⁻¹).

The nearly simultaneous arrival of gravitational and gamma radiation after a trip of 130 million light-years also has cosmological implications. As an alternative to the cosmological constant driving cosmic expansion, some theorists have proposed modifying gravity over large distances. Many of those theories require gravitational waves to travel faster than light, which we now know is not the case.

Unless another merger is hidden in the LIGO-Virgo data, the next detection won't come until fall of next year at the earliest—both observatories are shut down for upgrades. Yet the single detection will keep scientists occupied for that time and longer. Ongoing efforts include pinning down the strength of the tidal forces to help determine the composition and density profile of neutron stars.

Andrew Grant

References

1. B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Phys. Rev. Lett.* **119**, 161101 (2017).
2. B. P. Abbott et al., *Astrophys. J. Lett.* **848**, L12 (2017).
3. B. D. Metzger, *Living Rev. Relativ.* **20**, 3 (2017).

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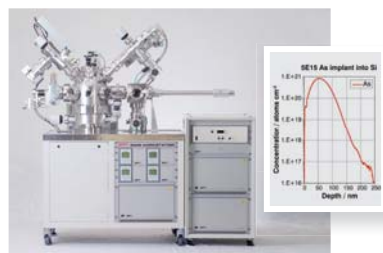
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