

Neutron star merger observed through gravitational waves and light

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A series of papers published and presented Monday announced a new milestone in the era of gravitational wave astronomy: the first detection of two merging neutron stars and the first observation of an astronomical event using both gravitational waves (ripples in space and time), and electromagnetic radiation, including visible light, infrared light, radio waves, microwaves, X-rays and gamma rays.

The announcement occurred barely two weeks after the Nobel prize in physics was awarded for the first direct detection of gravitational waves on September 14, 2015. These detections now establish gravitational wave astronomy as an enduring addition to science, a triumph of technology and social labor.

The merger signal was first detected by the LIGO and Virgo gravitational wave observatories on August 17, 2017. Within six minutes of the burst, automated systems had alerted astronomers to the arrival of gravitational waves and, moreover, that the frequency of the ripples induced by these gravitational waves had a higher pitch than the preceding detections, an indication of less massive objects orbiting more tightly. The masses suggested the merging objects were not black holes, but rather another type of compact exotic object, neutron stars.

When stars at least 10 times the mass of our Sun reach the end of their lives, an instability in their internal structure develops: the outward pressure caused by the continuous generation of energy in their cores is overwhelmed by the core's own gravity and the core implodes in on itself. The paroxysm within the star ignites remaining fuel in the outer layers in an explosion seen as a "supernova," one of the most violent and energetic events in the known Universe.

Inside the core, the pressures reach such a degree that the empty space within all atoms is filled in by the

crowding atomic nuclei until they touch. If the core contains more than three times the mass of the Sun, spacetime itself is collapsed to a singularity, forming a black hole. But cores that weigh less than that live on as neutron stars.

Neutron stars are more complex objects than black holes, which essentially retain only the mass and spin of the core from which they were born. The substance of neutron stars is incredibly dense: toward the center, a teaspoonful of their matter would equal the mass of Mount Everest. They are suspected to have an internal structure, possibly layers of increasingly dense and exotic matter. In a diameter of only a dozen miles, they pack the mass of several Suns.

As such, a merger of neutron stars involves distortion of and then contact between material objects themselves, with disruption of the stars and eventual consolidation of most of the matter into a more massive remnant, generally a black hole. And unlike black hole mergers, the neutron star mergers have been predicted to eject large quantities of extremely energetic ordinary matter, making them astronomical beacons of not just gravitational waves, but also of electromagnetic radiation.

NASA's space-based Fermi telescope is one instrument that is used to look for the optical signatures of neutron star mergers. On August 17 at 12:41:06 UTC, just 1.7 seconds after the LIGO and Virgo gravitational wave detection, Fermi detected a short surge of highly energetic radiation known as a gamma ray burst. Thanks to communications channels that had already been established for precisely these types of events, researchers from all three collaborations realized almost immediately that the two events were likely from the same source. The next half hour was devoted to confirming that each instrument was

functioning properly and narrowing down the region of the sky where the burst likely occurred.

Forty minutes after the initial detection, alerts went out to a worldwide network of observatories both on Earth and in orbit to find a transient brightening in the search area that had been narrowed down to 50 candidate galaxies. Eleven hours after the burst, the first identification of a bright new object within the galaxy NGC 4993 was made by a telescope in Chile. Five other teams quickly made this discovery independently, before a bulletin announced the target to others. In the first 48 hours, 130 separate sets of observations were made with over 30 different ground-based and space-based instruments.

Over the following two weeks, a wide range of detections were made in ultraviolet, infrared, X-ray, and finally radio wavelengths to observe the aftermath of the explosion as it propagates through space and interacts with the dust and gas of its parent galaxy. To date, the observations of the neutron star merger and its aftermath have involved 3,554 authors from 952 institutions across all seven continents. This represents one-third of the world's active astronomers.

With the complexity of neutron star mergers and only two months of analysis since the event, the first generation of papers represent only an initial stage of scientific inquiry. What is known is that the two merging objects weigh together about 2.8 times that of the Sun, and that the detection of a fireball in other telescopes indicates that at least one and probably both were neutron stars.

The short gamma ray burst, of a kind with several dozen seen before, was expected to originate from these types of mergers, but the gravitational wave signature provides the first proof. Follow-up observations have shown evidence of neutron-rich elements in the cooling fireball ejected from the merger. A significant proportion (by no means all, as has largely been reported) of elements heavier than iron found in the contemporary Universe originate from these merger-ejections, which have come to be known in the last few years as "kilonovae." The result of the merger was probably a black hole, but the signature is unclear, and the physics of neutron stars are uncertain enough that we do not know and may never know the fate of this particular object.

A variety of other measurements were made using

these data. The expansion rate of the universe was measured for the first time using gravitational waves, and radio observations have observed the merger's shockwave as it collides with the gas and dust of its host galaxy. Astronomers even used the slight time delay between the gravitational and electromagnetic signal, which is predicted for neutron star mergers, to show that gravitational waves do indeed travel at the speed of light, or extremely close to it.

Within a year, new upgrades to gravitational observatories should increase the detection rates by a factor of 10, ushering in an era of new exploration. Regular detections of neutron star mergers in gravitational radiation will begin to probe not just their external properties like mass and spin, but their internal structure itself, about which many questions remain. The mastery and potential demonstrated through the organized scientific thought and labor of this tiny fraction of the world's population stands in stark relief to the chaos of human organization elsewhere. Immense achievements like the successful probing of nature through gravitational waves illuminate the possibilities for when scientific knowledge and collective labor can be brought more broadly to address the social needs of humanity.



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