ESO Electromagnetic Counterpart to Gravitational Wave Detection FAQ

Q: What is a gravitational wave?

A: Gravitational waves are ripples in the fabric of spacetime. These ripples, detected by extremely sensitive instruments on Earth, are produced by some of the most energetic and massive events in the Universe — for example supernovae, the merging of two black holes, or the merging of two neutron stars.

In 1916 Einstein predicted that gravitational waves could exist in his general theory of relativity. According to this theory, as massive objects accelerate, they produce “waves” in spacetime which ripple out from the source, like a pebble landing in a pond. These ripples provide information about where, when, and how they were produced. They were predicted, and have now been confirmed, to travel at the speed of light.

Prior to Einstein’s general theory of relativity it was thought that changes in gravity would travel instantaneously. According to Newton, as the Earth moves, its gravitational field shifts instantly, immediately detectable from any point in the Universe. We know that when a pebble disturbs the water in a pond, it takes some time for the ripples to reach the ponds edges; with the detection of gravitational waves, we can see that this is also true for gravity.

Q: How is this detection of GW170817 different?

A: This is the first detection of gravitational waves from merging neutron stars, and the first gravitational wave detection for which an electromagnetic counterpart was found. The four earlier gravitational wave detections were of binary black hole mergers, but the nearly 100 second detection, across the entire frequency range of LIGO, meant researchers at LIGO and the Virgo Interferometer knew this was a different type of gravitational wave event. An accompanying detection of a short gamma-ray burst (sGRB) by both ESA’s INTEGRAL telescope and NASA’s Fermi Gamma-ray Space Telescope gave further indication that this event was likely a neutron star merger, since these mergers are theorised to be the cause of sGRBs.

Black holes probably do not emit light when they merge, but neutron star mergers are theorised to set off a bright electromagnetic counterpart known as a kilonova. Traces of a kilonova had been observed before (see opo1329a on spacetelescope.org), but these observations, for the first time, directly connect kilonovae to neutron star mergers.

Q: What is a neutron star?

A: A neutron star is the dense remnant of a large star which started its life with an initial mass between about 8 and 30 times larger than our Sun. At the end of the star's life, when it's a red supergiant, the stellar core runs out of fuel and collapses under its own gravity. The pull of the material compresses the matter at the core to a density where even atomic nuclei are squeezed and only neutrons remain. The collapse ignites a brilliant supernova.

Neutron stars typically measure about 20 kilometres across, approximately the size of a big city, yet they can have a mass twice that of the Sun. A mere teaspoon of neutron star material has a mass of about a billion tonnes; they are the smallest and densest stars known to exist.

Different sub-types of neutron stars exist, such as radio pulsars, magnetars, X-ray pulsars, and radio-quiet neutron stars.

Every so often, neutron stars form binary systems. These stars spiral towards each other, eventually merging. Researchers are not completely sure what remains after the merger, but theories predict these pairs could merge into a black hole, a stable neutron star, or a supermassive neutron star. Even with this detection, astronomers still aren't sure what remains when two neutron stars merge.

Q: What is a kilonova?

A: A kilonova, or macronova, is a fast-evolving supernova-like transient, which can last between days and weeks following the merger of compact, binary objects and is an electromagnetic counterpart to gravitational waves. Kilonovae are powered by the radioactive decay of heavy, neutron rich elements — that is, the decay of nuclei by r-process into atomic nuclei heavier than iron. The r-process describes a succession of rapid neutron capture on heavy atomic nuclei which occurs in locations with a high flux of free neutrons.

Within the small volume of space where a merger occurs, the combination of a huge amount of energy, and a large number of neutrons, is the instigator for the r-process.The high density favours this rapid capture of neutrons by nuclei, leading to the formation of new elements with high atomic numbers (number of protons in atomic nucleus) and high atomic weights (high number of protons and neutrons in the atomic nucleus). Many elements heavier than iron form in these environments, including many rare elements, most notably platinum (atomic number 78) and gold (atomic number 79). It was long thought that the r-process could also occur during core-collapse supernovae, but the density of neutrons within supernovae appears to be too low.

This decay of heavy atomic nuclei leads to the radioactive heating and a release of electromagnetic radiation. The heat cannot easily escape as radiation, because of the high opacity of the ejected material. The heat is radiates thermally, heating up the nearby matter, which can be then seen by telescopes.

The presence of caesium and tellurium was suggested by observations of the kilonova associated with GW170817, but many elements predicted by models could not be definitively determined. Observational astronomers will need to work with theoretical astronomers to create new models that best match the observed spectra in order to find signatures of other elements.

Q: Is it unusual for these elements to be scattered into space?

A: Most elements are formed in stars: either during their main life of the stars, as the stars explode as supernovae, or, in the case of heavy elements, during mergers of stellar remnants. These newly synthesised elements are scattered into the circumstellar environment, the space that surrounds the dying star. With time, these atoms drift into the surrounding galaxy and are recycled in the formation of new stars. Some atoms end up in the protoplanetary disk that surround each newly formed star and later in the final planetary system around the star. Our Solar System is no exception, that’s why we find all these elements, in various abundances, on the Earth itself.

Q: Why does this discovery matter?

A: This discovery is historic for many reasons.

First of all, this is the first time that an electromagnetic counterpart to gravitational waves has been detected. The detection of a visible counterpart with conventional telescopes is an independent confirmation that the gravitational wave detectors work, and can lead us to the source of gravitational waves.

Having multiple ways to study these rare events allows scientists to study the relationship between gravitational waves and electromagnetic radiation as well as providing another way of observing the causes of gravitational waves. The success of this campaign shows the potential for future multi-messenger observations, in this case of gravitational and electromagnetic waves.

This detection adds weight to the connection between neutron star mergers and gravitational waves, sGRBs, and kilonovae. This was only theorised before, brought together with observations in bits and pieces. This is the first substantive record of a merger from the initial release of gravitational waves to the end of the kilonova.

Gravitational waves have now allowed us to study neutron stars in a whole new dimension: by ‘listening’ to ripples in space. Future studies and multi-messenger campaigns will give us new understanding of the most extreme events in our Universe, from GRBs to the violent deaths of large stars as supernovae to merging black holes and neutron stars.

Gravitational waves are also fascinating in themselves, because of what they tell us about our understanding of space, time, gravity and matter. The detection of gravitational waves adds to the many successes of Einstein's general theory of relativity, in this case under extreme conditions of gravity which the theory has never been tested with before.

Neutron star mergers were predicted to be the sites for the production of heavy elements. With these observations, we have seen for the first time that this theoretical prediction occurs in nature. The observation could explain some of the heavy elements we observe on Earth.

Q: What is ESO's involvement in the discovery?

A: ESO quickly responded to "target of opportunity" triggers from astronomers around Europe following the discovery of the gravitational waves and sGRB, and launched its biggest such observing campaign yet. On the first night following the discovery, ESO's Visible and Infrared Survey Telescope for Astronomy (VISTA) and VLT Survey Telescope (VST) at the Paranal Observatory along with the Italian Rapid Eye Mount (REM) telescope at ESO's La Silla Observatory where part of the multi-telescope search for the new transient. VISTA and REM captured some of the earliest data of the electromagnetic counterpart.

Whenever possible for the following two weeks, 7 of ESO and ESO-partnered telescopes, including ESO's Very Large Telescope, with a total of 14 instruments, observed the kilonova in wavelengths from ultraviolet to millimetre. The survey with ESO telescopes logged over 115 hours of observations, capturing more than 5000 scientific images and spectra. This large, detailed data set initially resulted in six high-impact papers involving nearly 200 researchers across Europe. These papers extensively examined the kilonova, some including data from less than 24 hours after the gravitational wave discovery. Many more papers are currently in preparation.

The 7 ESO-related telescopes and 14 instruments that participated in the observing campaign were:

1. VLT
    a. FOcal Reducer and low dispersion Spectrograph 2 (FORS2) (UT1)
    b. Nasmyth Adaptive Optics System (NAOS) – Near-Infrared Imager and Spectrograph (CONICA) (NACO) (UT1)
    c. X-shooter spectrograph located on Unit Telescope 2 (UT2)
    d. VIsible Multi-Object Spectrograph (VIMOS) (UT3)
    e. VLT Imager and Spectrometer for mid-Infrared (VISIR) (UT3)
    f. Multi Unit Spectroscopic Explorer (MUSE) (UT4)
    g. High Acuity Wide-field K-band Imager (HAWK-I) (UT4)
2. VST observed using the OmegaCAM
3. VISTA observed with the VISTA InfraRed CAMera (VIRCAM)
4. NTT
    a. Visible spectra were observed with the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) spectrograph
    b. infrared spectra were observed with the Son of ISAAC (SOFI) spectrograph.
5. The MPG/ESO 2.2-metre telescope observed using the Gamma-Ray burst Optical/Near-infrared Detector (GROND) instrument.
6. Italian Rapid Eye Mount (REM) telescope

7. Atacama Large Millimeter/submillimeter Array (ALMA)

Q: Why is ESO well equipped to respond to events like kilonovae?

A: ESO operates, hosts, or is partnered with over 20 telescopes, equipped with instruments to cover wavelengths from ultraviolet all the way to millimetre, including the VLT, VISTA, and VST. The VLT, one of the largest optical telescopes in the world, can be operated in an automatic rapid response mode, which allows it to react to transient phenomena within minutes; this is a unique feature offered by ESO.

Q: What is next for ESO? Are you going to try to pull this kind of thing off again?

A: Scientists have already submitted requests for observing time at ESO telescopes to observe more kilonovae. Their research as observers, coupled with the work of theorists will enable them to construct realistic atomic models to describe the spectra they measure in order to learn how precisely the heavy elements form and in what abundances.

In the meantime, ESO will continue to provide exceptional tools for astronomers to discover the universe.

More frequently asked questions about gravitational waves can be found on the LIGO website at https://www.ligo.caltech.edu/page/faq.

An online version of this FAQ is available at https://www.eso.org/public/news/eso1733/