FAQ on *Hubble observes source of gravitational waves for the first time*

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 explosions or most massive interactions in the Universe — for example supernovae, the merger of two black holes, or the merging of two neutron stars. In 1960, Albert Einstein predicted that gravitational waves could exist in his general theory of relativity. According to Einstein's theory, as the massive objects accelerate, they cause "waves" of distorted 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 and were predicted, but are now confirmed, to travel at the speed of light.

Before 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 as a pebble disturbs the water in a pond, it takes some time for the ripples to reach the ponds edges, and 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 by the NASA/ESA Hubble Space Telescope (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 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 are typically about 20 kilometres across, about the size of a big city, yet they can have a mass twice that of the Sun. A mere teaspoon of neutron stars material has a mass of about a billion tons. This makes them the smallest but densest stars known to exist.

There are different sub-types of neutron stars, including 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 theory predicts 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 of the two neutron stars.

Q: What is a kilonova?

A: A kilonova, or macronova, is a fast evolving supernova-like transient, which lasts from days to 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 r-process nuclei 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 where the merger occurs, there is a huge amount of energy and neutrons, which instigates the r-process. The high density favours rapid exchange of neutrons and 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). Typically, all elements heavier than iron form in these environments. This includes 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 the supernovae star appears to be too low.

This decay of heavy atomic nuclei leads to radioactive heating of the surrounding matter as well as the production of electromagnetic radiation. The heat cannot easily escape as radiation, because of the high opacity of the ejected material. It is this light and heated matter that is the visible counterpart to gravitational waves. If kilonovae are produced in neutron star binary mergers then the observable signal includes gravitational waves.

Caesium and tellurium were suggested by observations of the merger associated with GW170817, but many elements predicted by using models could not be definitively determined. Observational astronomers will need to work with theoretical astronomers to create models that best match the observational spectra in order to find signatures of other elements.

Q: Is this unusual to see these elements being scattered into space?

A: These elements must be scattered into space for us to see them. Most elements are formed in stars: either during their lives or during their explosions or, in the case of heavy elements, during merger of stellar remnants. These many newly synthesised elements are scattered in the circumstellar environment, i.e. in the space that surrounds the dying star. With time, these atoms drift into the galaxy that hosted the stars and their explosions and are recycled in the formation of new stars. Some atoms end up in the protoplanetary disks that surround the newly formed stars and in the final planetary systems around them. Our Solar System is no exception, that's why we find all these elements, in various abundances, in our world.

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 this event with telescopes is an independent confirmation that the gravitational detectors work.

Having multiple ways to study these rare events will allow scientists to study the relationship between gravitational waves and light as well as provide 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, with observations of bits and pieces here and there. This is the first substantive record of the merger from the initial release of gravitational waves to the end of the kilonova.

We now know for certain that the merger of two neutron stars can lead to the production of gravitational waves and sGRB. This was something which was thought to be possible, but never seen through observation.

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

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, 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.

Factsheet on electromagnetic observation of gravitational wave event GW170817

Gravitational wave detection
Name: GW170817
Date and time of detection: 17 August 2017 12:41:04 UT
Wave duration: approx. 100 seconds
Detected by: LIGO in Hanford, Washington, USA and Livingston, Louisiana, USA
Non-detection by Virgo Interferometer in Italy helped localised the source

Short Gamma-ray Burst Detection
Name: GRB170817A
Date and time of detection: 17 August 2017 12:41:06.48 UT
Duration: approx. 2 seconds
Detected by: NASA's Fermi Gamma-ray Burst telescope and ESA's INTEGRAL telescope

Neutron Star Merger Source
Name: AT2017gfo/SSS17a
Location: NGC 4993, a galaxy in the constellation of Hydra.
Distance: 40 Megaparsecs or approx. 130 million light-years
Merged object sizes: Between 1.1 and 1.6 solar masses

Kilonova
Mass ejected: Between 0.03 and 0.05 solar masses (about 13 000 Earth masses)
Initial ejecta speed: one-fifth the speed of light