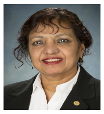
GRAVITATIONAL WAVES, BLACK HOLES, AND HEAVY ELEMENTS



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There has been a new opening for the vast knowledge in understanding the objects and processes in the universe recently, such as gravitational waves that we read about but never saw its existence, merger of black holes that we were not aware of, the heavy elements that we see on the Earth but do not quite know how they were created. It appears that all these three items are related to each other. The knowledge is certainly interesting and filling the gaps we need to know for advances. The scope has been recognized by Nobel prizes in Physics in 2017 and 2020.

What are gravitational waves?

A charged particle when accelerates or decelerates emits electromagnetic waves which travels at the speed of the light. One common example of it is the xray machines in medical facilities. Electrons traveling from cathode to anode under a voltage difference hit on a target slab and decelerate causing emission of x-rays which is used for diagnostics and therapy of a patient. Similarly when a mass is accelerating or decelerating, it produces gravitational waves which travels at the speed of the light. It was first predicted by Albert Einstein.

Just as the water ripples, gravitational waves distort all matter momentarily as they pass through them. If they pass through the Earth, everything including everyone on Earth will expand and contract back by less than the width of an atom. These distortions are minute. Gravitational waves are long and very weak and are the reasons for not being able to be detected. Explosion of a giant star can produce gravitational waves that are strong enough to be detected.

LIGO detector for gravitational waves

The idea that minute expansion in a very short time could be detected through laser interferometry was around among scientists before and in early 1960s. Around 1960, LIGO (Laser Interference Gravitational-wave Observatory) set-up was initiated in the US under the leadership of Rainer Weiss. In the set-up, a laser beam is split in to two evenly divided beams by a splitter. These two beams travel through the two arms set in L shaped but of equal length of about 2.5 miles or 4 km as seen in Figure 1. Each arm has two mirrors at the two ends that form a resonant optical cavity. The mirrors force the laser beams to bounce back and forth hundreds of times covering a distance of more than 1000 km before the beams recombine to destructive interference. So with no disturbances, the two beams cancel each other out and the photodetector will show darkness.

If a burst of gravitational waves passes through area, one beam will be slightly longer than the other by the distortion of the land and register a signal even for a split-second difference of recombination of the beams. However the first detection of gravitational waves had to wait until September 2015. The reason was that many engineering and science upgrades were needed to catch the signal. In the optical cavities, 11 kg mirrors were replaced with 40 kg ones to minimize thermal noise and were suspended from an intricate pendulum system to isolate mechanical vibrations. Another vibration isolation system was installed to continuously counteract any vibration from seismic and any other ambient activities.

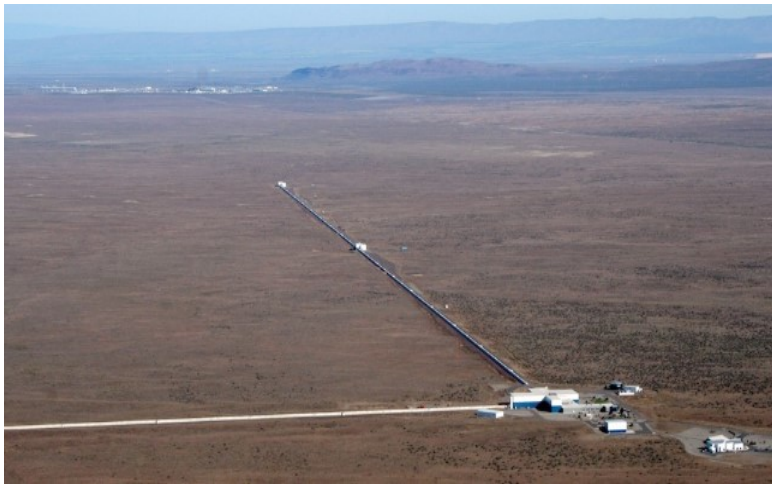

Figure 1: LIGO detector at Hanford for detection of gravitational waves.

To determine the direction of the source of waves, first two LIGO detectors were built, one in Hanford, Washington State and the other one in Livingston, Louisiana, with a distance of about 1865 miles (3000 km) apart. To reduce the uncertainty of direction, another detector was built later by VIRGO in Pisa, Italy. These facilities are in a long distance apart so that there would be a slight difference in the time when each would sense the passing of the waves. This delay enabled researchers to calculate very approximately where on the sky the gravitational waves came from or the collision had occurred.

Merging of black holes or neutron stars - a kilonova event

When a star looses all its hydrogen in nuclear fusion to form elements, mainly helium, it collapse and expands. If the mass of the star is large, it can end up to collapsing and going through supernova explosion and then collapsing the materials to form a dense core of a neutron star or a black hole. If the core is massive, it may form a black hole, which has a very strong gravitational pull that matter even light can not escape. A less massive core will form a neutron star. Its gravitational pull of a neutron star is strong enough to crush protons together with electrons to form neutrons. A neutron star is small, typically with diameters of about 12 miles but is very dense such that a neutron star's mass may be about the same as that of the sun or somewhat higher. Using the general theory of relativity, Roger Penrose extended and completed the work of Einstein to show that formation of a black hole is a singularity where space and time merge and shared the 2020 Nobel prize in Physics for his work.

Two black holes or neutron stars can merge in a cataclysmic event known as kilonova that produces enormous amount of energy and part of the mass is converts to strong gravitational waves. The merger takes place in a sort amount of time, from seconds to about a minute. The merger of two neutron stars, detected on August 14, 2019, was about a minute compared to 1-2 seconds for two black holes.

LIGO detector is sensitive to gravitational radiation in the 20-2000 Hz range which are created by the mergers of some combination of black holes and neutron stars. In 2015, gravitational waves, created by merger of two black ho,es, were detected for the first time. During 2015 - 2019, LIGO detectors detected 4 black hole mergers and one neutron stars merger. In one merger of the two black holes, one 25 times the mass of our Sun and the other 31 times the mass of our star, produced a new spinning black hole with 53 times the mass of the Sun. This means that about three solar masses were converted into gravitational-wave energy during the coalescence. In 2020 the LIGO and Virgo Collaborations detected the gravitational waves released from the heaviest kilonova ever documented where a 65-solar-mass black hole and an 85-solar-mass black hole merged into a gigantic 142-solar-mass black hole, sometime called as the monster black hole. Physics Nobel prize in 2017 went to 3 members, Rainer Weiss, Barry C. Barish, and Kip S. Thorne, of the LIGO projects that detected gravitational waves from mergers.

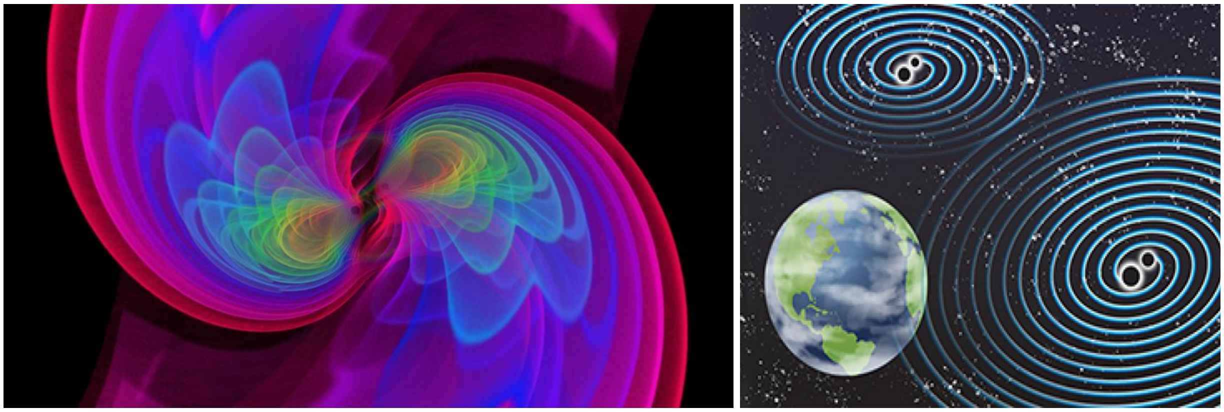

Figure 2. L: A computer simulation of gravitational waves radiating from two merging black holes. R: Gravitational waves emitted by mergers.

Creation of heavy elements

It has been found that heavy, such as heavier than Zn in the periodic table, element are produced by rapid process, called the r-process, during supernova explosions. However, there is lack of understanding of the r-process. Heavy elements are also created inside the star through neutron captures but in a very slow process called s-process.
During the discovery of merger of two neutron stars on Aug. 17, 2020, LIGO and Virgo detectors detected a gravitational-wave signal possessing an extraordinary amount of

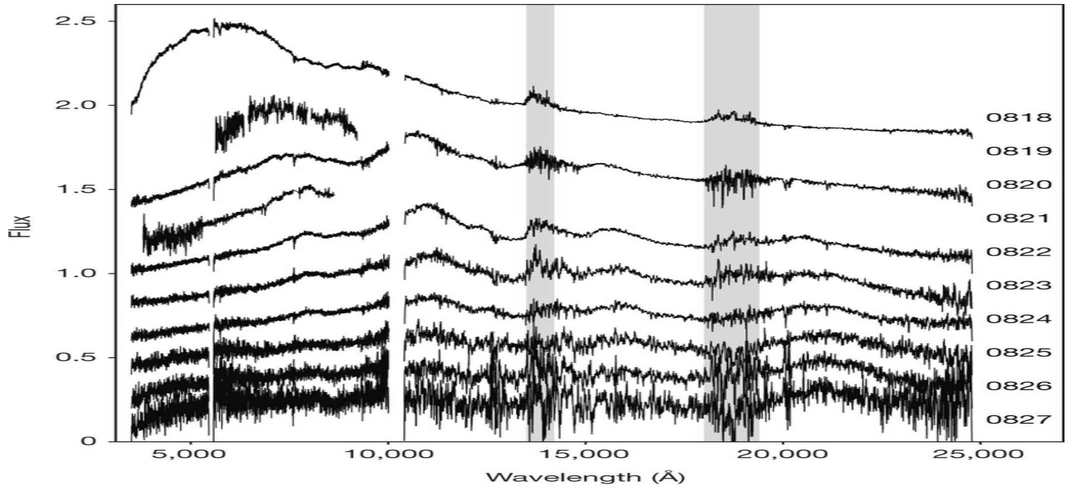

Figure 3: Time variation of kilonova spectra from August 18 (top curve) to 27 (lowest curve) in 2017 shows the peak emission in the optical wavelength range ($\sim 5000\mathring{A}$) shifting to NIR 2.5 μm (Pian et al 2017). The spectra correspond to emission of lanthanides.

electromagnetic energy, something like a billion times the energy of the luminosity of the Milky Way. The electromagnetic energy corresponded to emissions by heavy elements, called the lanthanides (Figure 3).

Lanthanides are the 15 elements in row of elements with atomic numbers from 57 (La - lanthanum) to 71 (Lu - lutetium) in the periodic table, the row above the last one in Figure 4. The chart below shows the periodic table of elements from the NIST (National Institute of Standards and Technology).

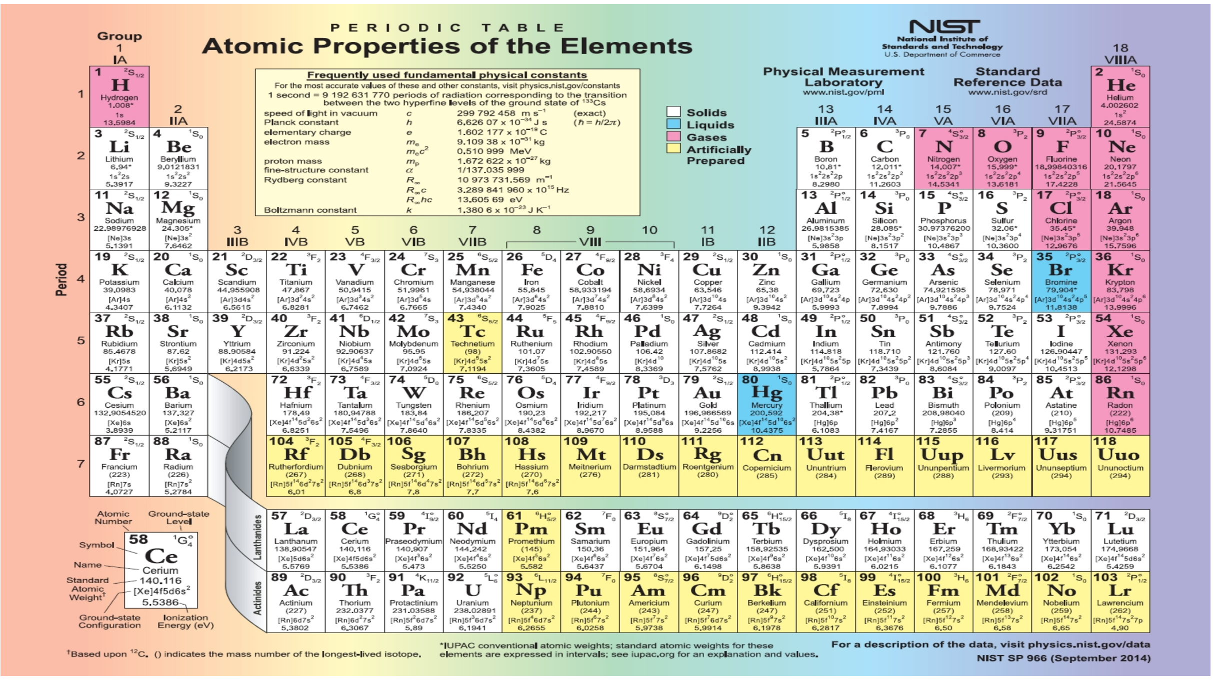

Figure 4: Periodic table of elements

It may be noted that the periodic table lists 118 elements. The yellow boxes contain the heavy elements that have been artificially produced in the laboratory. They are not found on the Earth. However, some of them have been detected in the astrophysical spectra indicating these elements form naturally.

Detection of lanthanides has revealed that kilonova event of mergers of neutron stars or black holes is another way of having the r-process for creation of heavy elements. J. Johnson (Science 2019) of OSU has created a version of the periodic table, Figure 5, that shows the origin of the elements that we know.

This version of the table includes all seven processes for the creation of all elements in the periodic table where colors in each element box indicate the process of creation of the element: 1) Big bang fusion (black), 2) cosmic ray fission (purple), 3) exploding massive stars (turquoise), 4) exploding white dwarfs (light blue), 5) merging neutron stars (orange), 6) dying low-mass stars (yellow), 7) Very radioactive isotopes. Although this version of the periodic table is becoming popular, there is another version produced by another team using theoretical model which has some disagreement with this present version. More accurate version will come with more observations and more accurate calculations.

These recent developments will increase our knowledge considerably in the near future.

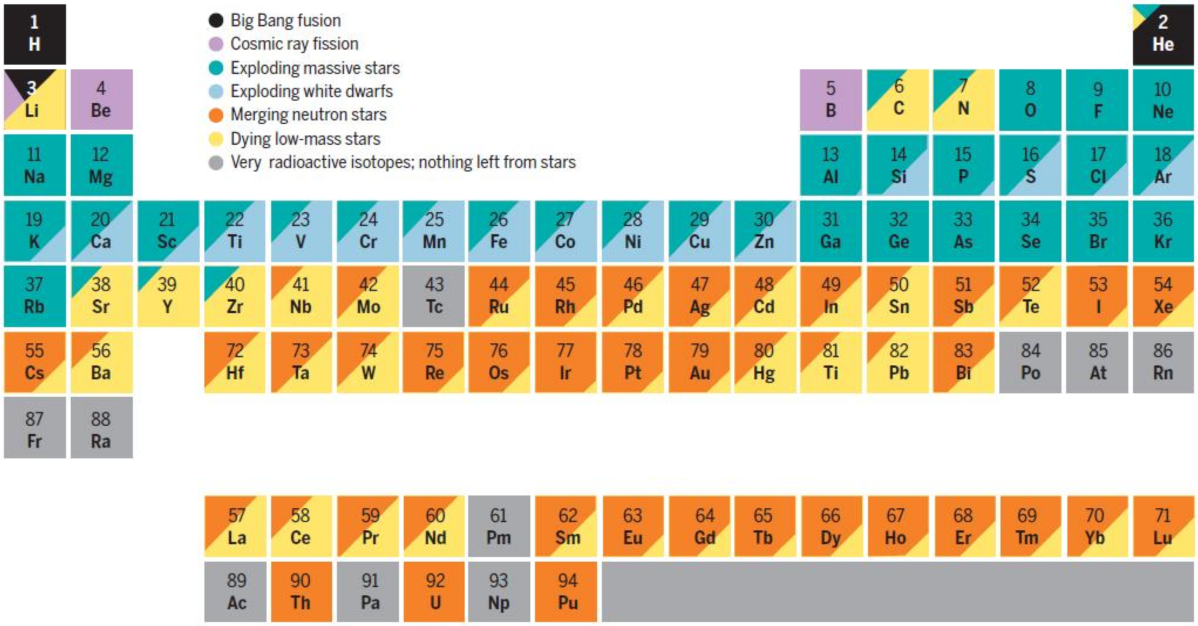

Figure 5. A version of the Periodic table showing origin of creation of elements (Johnson 2019)