The Study of Gravitational Radiation Through the Merging of Binary Neutron Stars

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Abstract – The study of gravitational waves/radiation was initially limited to only one way of detection and generally involved the study of black hole mergers. In 2017, the unanimous detection of GW170817 by LIGO and Virgo, and GRB 170817A by NASA's Fermi Space telescope led to an interest in studying binary neutron star mergers as it presented confirmation for past predictions by the Theory of General Relativity and also had new implications related to the Hubble's Constant, the resolution of stochastic backgrounds, the formation of the heavier elements in the universe and a lot more. There is also a possibility of the discovery of a new class of black holes as the nature of the post-merger remnant is unknown. This was the first discovery of its kind to have an electromagnetic component and this has led to the growth of multi-messenger astronomy, promoting further collaborations for these detections. LIGO and Virgo held another operation run later and one more binary neutron star merger candidate has been identified. Further detections and analyses are awaited.

Key Words – Relativity, LIGO, Binary neutron stars, Mergers, Multi-messenger discoveries

INTRODUCTION

Gravitational Waves, i.e., ripples through the fabric of space-time were first predicted by Einstein's Theory of General Relativity in 1916. [1] Einstein's mathematics showed that massive accelerating objects would disrupt space-time in a way such that 'waves' of space-time would propagate from the source, travelling at the speed of light in all directions. They carry information about their dramatic origins and about the nature of gravity itself. [2]

A lot of research and debate has been done on their nature and existence and they can be mathematically understood better through a simpler metric that was derived from Einstein's original equations by Asher Peres. He studied the plane wave-like line element for gravitational waves and obtained a metric defined through the proper time:

$$ds^2 = -dx^2 - dy^2 - dz^2 + dt^2 - 2f(x, y, u)(dt - dz)^2$$

where $u = t - z$ and f is a function of x, y and u. [3]

As further debate and research led to more and more conclusions on their existence, the hunt to detect gravitational waves started. Finally, nearly 100 years later, a gravitational wave signal was detected by both of the twin U.S.-based Laser Interferometer Gravitational-Wave Observatory detectors at Livingston, Louisiana and Hanford, Washington in 2015 from a black hole merger. [4] Since then, LIGO and other detectors like the Virgo interferometer at Italy have been working carefully to detect even more signals to learn more about the universe. Up until 2017, there had been no electromagnetic counterpart to the gravitational wave detections and as a result, these fields weren't really unified. However, an accidental detection of a strange signal led to a discovery that would change everything as it became the most talked-about discovery of the decade. A binary neutron star merger had been detected and it gave off both, gravitational as well as electromagnetic radiation.

DISCOVERY

On August 17, 2017, 8:41 pm EDT, a gravitational signal named GW170817 was detected by the LIGO detector at Hanford, Washington during the O2 Operation Run. It was originally identified as a single detector event at Hanford by a low-latency binary-coalescence search because the saturation at LIGO-Livingston detector prevented this from being reported as a simultaneous event. The low latency transfer of data from the Italy-based Virgo detector was also delayed. However, a visual inspection later revealed a clear chirp coming from a single source (Figure 1). A Gamma-ray burst (GRB 170817A) was also detected by NASA's Fermi space telescope around the same time. This was considered unlikely to be a mere coincidence and multiple follow up observations were launched around the world. [5]

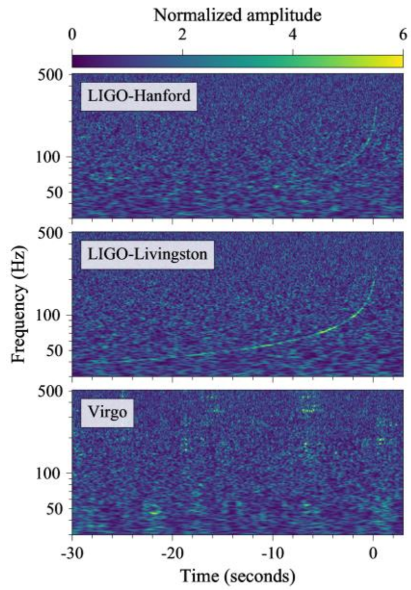

FIGURE 1: Time-Frequency plots with the upward-sweeping chirp for GW170817 from LIGO-Hanford, LIGO-Livingston and Virgo. The glitch in Livingston data has been removed. Chirp is not visible in Virgo due to low sensitivity and source location. [5]

The sources were predicted to be neutron stars, i.e., extremely dense remnants from the collapse of massive stars. This was because they were not as massive as the previously detected black holes; their masses were estimated to be somewhere between 1.1 to 1.6 solar masses, which lies close to the mass range for neutron stars. Scientists gave this mass estimation after analysing the recorded chirp. According to the theory of general relativity, the gravitational waves emitted by inspiraling compact objects during a quasi-circular orbit are characterized by a chirp like time evolution in their frequency that depends on a combination of the component masses and on the mass ratio and spins of the components. The equation used is:

$$M = \frac{c^3}{G}\left(\left(\frac{5}{96}\right)^3 \pi^{-8} (f_{GW})^{-11} \, (f'_{GW})^3\right)^{\frac{1}{5}}$$

where $M = \frac{(m1m2)^{\frac{3}{5}}}{(m1+m2)^{\frac{1}{5}}}$ is the chirp mass and $f'_{GW} = \frac{df_{GW}}{dt}$ is the rate of change of frequency. [5][6]

The chirp mass was measured to be $1.188^{+0.004}_{-0.002}$ $M \odot$, and the chirp, in this case, lasted 100 seconds and was seen through the entire frequency range of LIGO. This was unusual as binary black hole mergers produce chirps lasting a fraction of a second and are detected only by LIGO's sensitive frequency band. This meant that their masses were significantly lower than that of black holes. The LIGO data also gave their location to be quite close to Earth; around 130 million light-years. Collected data indicated that they had been spiralling in towards in the past and as they spiralled faster and came closer together, they stretched and distorted the surrounding space-time, releasing energy as gravitational waves, and then finally smashed into each other. [5]

This was the first time a cosmic event was detected in both gravitational waves and electromagnetic radiation. Due to the multiple detectors, we were able to quickly pinpoint the location of the event in the sky and launch multiple follow up observations. It was later confirmed that the signal was the result of the merger of two neutron stars in the lens-shaped galaxy NGC 4993, which was 140 million light-years away. [5] The results of these observations and further analysis had major scientific implications and confirmed several predictions made by the Theory of General Relativity by Albert Einstein.

IMPLICATIONS

I. Confirmations about the speed of gravitational waves in agreement to the Theory of General Relativity

GRB 170817A was observed 1.7 seconds after GW 170817. This leads to strong constraints being forced on the nature of gravity and gravitational waves when you combine this observed delay in evidence with knowledge of the source luminosity distance. Placing these bounds required a very deep understanding of waveform modelling and the uncertainties associated with it. The Shapiro time delay effect (also called gravitational time delay effect) is one of the classic tests of general relativity and in it, radar signals experience space-time dilation and there is a time delay because of the increase in path size. The observations were in agreement with this and after doing the required adjustments, the speed of gravitational waves was finally found to be equivalent to the speed of light to very high precision. This verifies the assumption in the Theory of General Relativity that gravitational waves travel at the speed of light in a vacuum (c). Various other tests were also conducted and they were all in good agreement with the Theory of General Relativity. [5][7]

II. Estimating the Hubble's Constant and expansion of the universe

Direct measurement of the luminosity distance of the source can be obtained from the gravitational wave signal and after calculating the redshift, we can infer cosmological parameters without relying on the cosmological distance ladder, which is not always accurate. The Hubble's Constant is calculated to be $H_o = 70^{+12}_{-8}\ km\ s^{-1}\ Mpc^{-1}$ when you use the association with the galaxy NGC 4993. This is the most probable value (minimum 68.3% probability) when compared with Plank Hubble's Constant, which is $H_o = 67.90^{+0.55}_{-0.55}\ km\ s^{-1}\ Mpc^{-1}$. This was consistent with the estimated value of Hubble's Constant through EM studies. Now, this provides confirmation and the calculations about the expansion of the universe can be more accurate. We can also assume the cosmological constants to be known and then calculate the luminosity distance of the source using the redshift and the above association. This would lead to improved measurement of the inclination angle of the source and would also help in figuring out the gamma-ray burst opening angle. [5][8]

III. Resolving stochastic background from unresolved Binary Neutron Star mergers

To create a background, we need the rate of merger and through this discovery, we have a very reliable source for calculating the rate in Binary Neutron Stars. Within LIGO's O2 Operation Run, GW170817 was the only discovery to have a false alarm rate below 0.01 year and by using this as a foolproof source, we can infer the local coalescence rate density (R) of Binary Neutron Star (BNS) systems. For GW 170817, we assume the mass distribution of the components to be flat between 1 and 2 solar masses, and their dimensionless spins to be below 0.4. $R = 1540^{+3200}_{-1220}\ Gpc^{-3}\ yr^{-1}$ when we impose the upper limit of $12600\ Gpc^{-3}\ yr^{-1}$ which was found as a result of LIGO's O1 Operation Run earlier. Through this inferred rate, countless unresolved BNS mergers can be localised and compared in magnitude to existing Binary Black Hole (BBH) mergers. This can be used to create a combined as well as separate stochastic background for BNS and BBH mergers which will help detect gravitational waves in the future for further research. [9]

IV. Study of the post-merger remnants as a possible new class of black holes

The object resulting from the merger is 2.7 solar masses and it's a kilonova, i.e., the remaining material from the merger is being blown out into space and it can reach up to 1000 times the brightness of a classical nova. The kilonova AT2017gfo is the first kilonova for which detailed optical spectra has been recorded. [10] Binary neutron star mergers may result in a short or long-lived neutron star remnant that could emit gravitational waves following the merger and there are 4 predictions about its nature:

1) It could form a black hole directly,
2) It could form a hypermassive neutron star that would collapse into a black hole within a second,
3) It could form a supramassive neutron star that would collapse into a black hole on timescales larger than 1 second or,
4) It could form a stable neutron star. [11][12]

The result depends upon the final mass as well as the chemical properties of the neutron stars. This post-merger remnant is predicted to be a hypermassive neutron star that has collapsed into a low-mass black hole by now. [13] This would mean the discovery of a new class of black holes by LIGO. However, other options cannot be ruled out yet and this can only be confirmed once the gravitational waves from this remnant are detected and analysed. Several attempts were made at detecting these in vain but continued observations over the next several years may confirm or refute this prediction. [11]

V. Origin of the heavier elements in the universe

Because we were able to pinpoint a specific location in the sky due to LIGO and Virgo's observations, Electromagnetic (EM) follow-up observations were possible and they revealed that a large fraction, roughly half, of the universe's heavier elements were created by neutron star mergers. The key method used to figure this out was by looking at the optical spectrum of the event as the light of the kilonova AT2017gfo comes from the material released by the neutron stars as they merged. It was observed that the material contains abundant heavy elements and this provides a plausible explanation for their origins. Now, it's widely accepted that all elements starting from Niobium (Atomic number 41) to Uranium (Atomic number 92) excluding Technitium (Atomic number 43) and Promethium (Atomic number 61) have been created in large quantities during and as a result of binary neutron star mergers. [14]

FUTURE RESEARCH AND CONCLUSION

LIGO and Virgo started their O3 operations run in April 2019 with more sensitivity than the last time and on 25 April 2019, the LIGO Livingston Observatory picked up what appeared to be gravitational ripples from another collision of two neutron stars. This has been named GW190425 and it serves as confirmatory evidence for the implications of the previous discovery. [15] LIGO suspended its O3 run earlier in March 2020 instead of April 2020 due to the COVID-19 Pandemic. [16] Multiple candidates have been identified as possible Binary Neutron Star, Binary Black Hole and Neutron Star-Black Hole mergers, but further analyses of the data sets are required before any confirmed detections. [17]

When dealing with gravitational wave detections, it has been observed that the low sensitivity of the instruments being used is often a hindrance to accurate detections, leading to a lot of time being lost while working with incomplete data. To counter this, a more interferometers could be built and upgraded from time to time, thereby increasing their sensitivity and detection range. Another suggested solution to the common problem of high false alarm rates in observations could be to build a space-based detector as that would largely prevent any noisy disturbances from Earth. The list of possible improvements or upgrades is endless and so are the possibilities of what we might uncover because of them in the future.

The most remarkable aspect about this infamous discovery is that it wouldn't have been possible without the cooperation of several astronomers and physicists spread across the globe. The communication was swift and collaboration was easily facilitated. This demonstrates the strength of multi-messenger astronomy in projects of such crucial importance dealing with gravitational waves. Now, data sets and possible gravitational wave detections by the LIGO-Virgo Collaborations are being made public as soon as possible as Open Public Alerts to facilitate gravitational-wave transient event detections. The era of multi-messenger astronomy is here with a bang, especially so for gravitational radiation research [17], and the author believes that in the future, physical barriers would be almost non-existent as the entire planet would transform into a giant observatory, uniting in the quest to uncover the secrets of the mysterious cosmos.

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