Investigation and analysis of Proposed Event GW170817A using gravitational wave data to posit its signal plausibility and merger characteristics

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Abstract

Recently, a candidate event was identified (GW170817A) through a new system of identification. GW170817A has gravitational wave characteristics which differentiates it from previous merger detections. In this investigation, a serious of tests are conducted using real strain data from the LIGO-VIRGO gravitational wave detectors in order to get a better understanding of whether GW170817A is an actual event. Merger characteristics are also explored via parameter estimation in order to comment on its potential origin.

1 INTRODUCTION

August 17, 2017 was a notable day for the Laser Interferometer Gravitational Wave Observatory (LIGO) and the LIGO-VIRGO Scientific Collaboration (LVC). LIGO detected its first ever binary neutron star merger, GW170817 [1] in its second observation run. However, this event is not the focus of this particular paper, nor should it be confused with GW170817A which is a candidate event that occurred on the same day [2]. The concept of gravitational waves emerged from Einstein's general theory of relativity in 1916 and can be thought-of as ripples in spacetime. Gravitational waves are the primary means through which such events are observed today.

In this investigation, the candidate event GW170817A was explored for plausibility and merger characteristics assuming the event is real. Real gravitational wave strain data from the Gravitational Wave Open Science Center (GWOSC) was analysed using Python3 and various gravitational wave signal-analysis specific packages such as GWPy, Bilby, and PyCBC. GWOSC is the official repository for public access gravitational wave strain data. Previous studies on GW170817A are compared to test whether the previous findings are consistent with the results of this investigation and if not, why not and what could be the reasons behind the differences.

In order to understand this paper, Section 2 discusses the background information pertaining to the concepts, apparatus, and analysis tools, while also giving a brief insight into previous studies. In Section 3, investigations are carried-out in order to find the proposed candidate event within the strain data. Section 4 deals with the plausibility of the findings as explored in previous studies, while Section 5 explores the merger characteristics of GW170817A via a parameter estimation assuming that GW170817A is a gravitational wave event. The results from these investigations therefore provide evidence supporting the event's merger origins. In Section 6, conclusions and scope for future explorations is discussed.

2 BACKGROUND

2.1 Gravitational Waves

The concept of gravitational waves emerged from Einstein's theory of general relativity in 1916. A gravitational wave is a disturbance in the curvature of spacetime. Its propagation can be thought of as ripples in spacetime [5, 6, 9]. There are various factors which may lead to a curvature in spacetime, for instance, the stress-energy tensor. A perturbation of spacetime is due to the existence of mass due to the fact that $E = mc^2$. Therefore, the main cause of curvature is due to the presence of energy. As it turns out, the only criterion required for the formation of gravitational waves is for a system to experience changes in the quadruple mass distribution or higher multipoles. This is unlike an electromagnetic wave, which only requires changes in dipole charge distribution. Various systems exist which cause changes in the quadruple mass distribution and are thus theorised to cause the emission of gravitational waves. Such systems include asymmetric core-collapse supernovae, binary systems, asymmetric spinning of neutron-stars, and potentially the stochastic background from the early universe.

2.2 Stages of Merging

There are three main stages of merging: the inspiral, the merger, and the ringdown [7, 9]. The inspiral stage of the merging process is usually the longest stage, where a subsidiary mass orbits the dominant. Gradually, the orbital period decreases and so does the distance between the two masses. This is because the energy of the system is gradually lost in the form of gravitational waves.

Eventually, the two masses will reach the merger stage wherein effective gravitational wave emission will take place. In this stage, orbital frequency of the system increases dramatically until the two bodies are actually merging. It should be noted that the gravitational wave frequency will be twice that of the orbital frequency. This may last for merely fractions of a second depending on the masses of the objects. Gravitational waves emitted during this time may fall into the detectable range and therefore be detected by present gravitational wave detectors. The gravitational waveform in this stage can be analysed to show the rate of change of orbital frequency or gravitational wave frequency. This stage continues until the strain amplitude reaches a maximum. This entire stretch of signal (the inspiral and merger) is called the "chirp" of the event [8]. The "chirp" is any increase in signal frequency [18]. This is also due to the fact that when the signal is scaled so as to be in the range of hearing for humans, a chirp sound can be distinctly heard.

Mass is lost by the system throughout the merger process in the form of gravitational waves. The total mass lost by the system is therefore transformed into energy which is called the chirp mass. The chirp mass of a binary merger is related to the primary and secondary masses by the following equation [18]:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \tag{1}$$

where '$\mathcal{M}$' is the chirp mass and 'm_1' and 'm_2' are the primary and secondary masses respectively in a two body system. The chirp mass is a quantity which indicates the magnitude of energy lost by the system in the form of gravitational wave emission for a binary merger event [18].

After the merging stage, the two masses are now one but are distorted due to the merging process. This distortion in shape is dissipated via the emission of more gravitational waves which brings stability to the resultant object. This process can be characterised as the ringdown stage of the merger.

2.3 Apparatus Requirements

2.3.1 Method of Detection

Unlike in Newtonian physics where the effect of gravity is considered instantaneous, in general relativity, all interactions involving gravitational waves are limited to the speed of light, and thus gravitational waves propagate at the speed of light. During gravitational wave propagation through spacetime, it "stretches" and "squeezes" the spacetime the matter occupies in its path [5, 6, 9].

Therefore, as gravitational waves propagate through matter, the matter experiences a change in displacement which is interpreted by the detector as "strain." It is this characteristic property of gravitational waves that a Michelson Interferometer takes advantage of in the detection process. A Michelson Interferometer is an instrument used in optical interferometry [10, 11]. It produces interference fringes through the splitting of a beam of light such that one component of the beam incidences on a fixed reflector and the other incidences on a movable reflector. As shown in Fig. 1A, when the two reflected components of light are brought back together, an interference pattern results. The movable reflector changes its position, resulting in changes in interference patterns. These changes in interference patterns are used as a means to detect strain and in extension, gravitational waves.

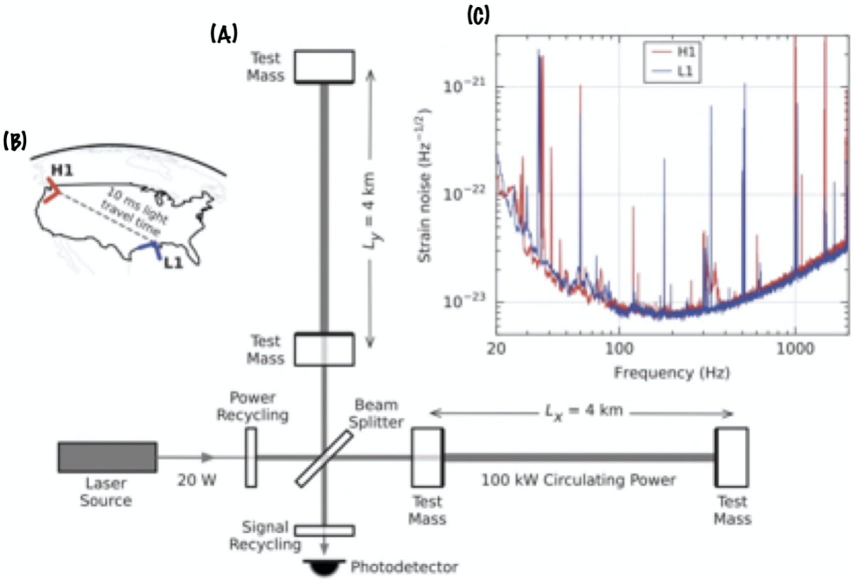

FIG. 1: (A) a simplified illustration of the Michelson Fabry-Perot Interferometer setup at LIGO. (B) relative positions and alignments of the two LIGO detectors in the United States: H1(Hanford, Washington) and L1(Livingston, Louisiana). (C) a strain sensitivity graph which represents the two detectors' individual strain sensitivities. [5]

2.3.2 Laser Interferometer Gravitation Wave Observatory and Related Detectors

The Laser Interferometer Gravitational-Wave Observatory (LIGO) also makes use of a similar instrument for the detection of gravitational waves, in particular, the Michelson Fabry-Perot Interferometer (Fig. 1A). In LIGO, both mirrors (test masses) are freely hanging. While both types of interferometers detect changes in length through changes in the interference patterns, the instrumental setup at LIGO takes advantage of "Fabry-Perot cavities". These cavities are what allows LIGO to detect gravitational waves more precisely. The Fabry-Perot cavities allow for the storage of photons which bounce between mirrors for almost a millisecond, thus increasing the time for interactions between light and gravitational waves. This added apparatus is most notably important for detections at low frequencies by increasing the sensitivity at these frequencies.

LIGO currently operates from two locations: one in Livingston, Louisiana and one in Hanford, Washington (both were funded by the National Science Foundation). Other LIGO and LIGO-like projects such as VIRGO in Italy and LIGO-India are also either operational or under construction. Increasing the number of detectors with different antenna alignments allows scientists to localise the signal of the event and increase its probability of being a real event. This is because increasing the number of detectors decreases the probability of the detection being an artificial trigger. The LVC, for instance, requires at-least two detections.

Fig. 1B shows a 10ms light travel interval between the detectors, which is a key means by which scientists can differentiate between gravitational waves and other strain inducing candidates. This is due to the fact that gravitational waves travel at the speed of light. Therefore, if one observatory detects a strain pattern resembling that of a gravitational wave, the other detector should also detect a strain pattern, only up to 10ms later. This significantly lowers the possibility of the detection being an artificial event, of terrestrial origin, or a glitch.

The graphs in Fig. 1C also indicate which frequencies the detectors are most sensitive to and which frequencies are more difficult to extract a signal from due to the presence of noise. Spikes present in the graphs represent background noise at those frequencies. Efforts have been made to minimise the effects of background noise, however it cannot always be removed. The differences between the spikes act as proof that certain types of background noise are completely dependent on the respective locations of the detectors and therefore are of local origin. Also, the frequencies blocked due to background noise in one detector may not necessarily make it impossible for detections as other detectors (which are not susceptible to background noise at those frequencies) can be used as a means to estimate gravitational wave presence regardless. This is another reason why having multiple detectors in multiple locations is important. In any case, signal processing and filtering methods account for Gaussian (normal distribution) noise and are used as a means to reduce noise or whiten the data segment under consideration. Another method of reducing noise is to create a template of a known noise-causing factor (for instance: violin modes) and subtracting it from the data segment.

2.4 LVC's Public Data Release Program

The data collected as part of scientific or observational runs by the LVC goes through a proprietary data period which initially spanned 24 months and has presently been reduced to 18 months. During the time period following an observational or scientific run, the Collaboration has exclusive access to any data acquired. This is in part due to the internal processing of data and the required validation and calibration checks. [3]

After this 18 month "embargo", the Collaboration releases LIGO data to the public for independent research purposes. The data released includes strain-data, data quality information, hardware injections, and interferometer information. This data is released in workable and user-friendly HDF5 and GWF formats. The official repository for this data is the Gravitational Wave Open Science Center (GWOSC) [17]. Here, data is currently available from LIGO Hanford (H1), LIGO Livingston (L1), and VIRGO (V1) in bulk. Data from S5 and S6 for H2 (a second detector at Hanford–no longer used) is also available. In order to allow for low barriers of entry to prospective students and researchers, the website also features relevant software information and tutorials. It is this public release program that allowed independent research groups to conduct research and analysis of LIGO-VIRGO data which led to the discovery of GW170817A and hypothesised as a potentially new form of gravitational wave signal. [4]

2.5 Hierarchical Mergers and Stellar black hole Mass-Gap

2.5.1 Hierarchical Mergers

A merger is classified as hierarchical when smaller masses merge to form a larger resultant mass. Such mergers (in relation to black holes) are thought to most likely occur within Active-Galactic Nuclei (AGN) Disks or Globular Clusters (GC) [4]. This is because the frequency density of black holes is greatest here. However, chance encounters may be another possibility, albeit of lower probability. There exist various types of hierarchical mergers.

As black holes of hierarchical origin are simply the result of smaller black holes, in order to differentiate between these types of black holes, a concept of "generation" needs to be employed. In this particular investigation, a merger's generation is defined as follows:

$$generation = N - 1 \tag{2}$$

where 'N' is the number of smaller black holes involved in making the present resultant mass. Therefore, a simple binary merger is defined as a '1g' merger event. Likewise, a system where three black holes in total undergo the merging process will be defined as a '2g' merger event. Similar naming is followed for higher orders of black holes involved. For simplicity and to avoid confusion, all '2g+' mergers will be referenced as hierarchical while all '1g' black holes will be referred to as binary.

In hierarchical mergers, the formation mechanism is another differentiating factor. For instance, there is a possibility for there to exist a system where two masses 'm_1' and 'm_2' orbit each-other in a subsystem named 's_1' which itself orbits around another mass 'm_3' in the system named 's'. Therefore, the subsystem 's_1' is defined here as the "inner binary" which is itself orbiting 'm_3' which is known as the "outer binary" [12]. Such a system is defined as a binary of binaries event. There is another, broadly accepted and probabilistic model in which the system initially includes only the masses: 'm_1' and 'm_2' which undergo the merger process to form a resultant: 'm_{12}'. A mass: 'm_3' is then introduced to the system through dynamic means such that now 'm_{12}' is orbiting 'm_3' to finally give a 2g merger event. This type of formation is defined as a hierarchical dynamic event [4]. For the purpose of this investigation, defining these two broad categories of formation mechanisms is enough even though various combinations of these two mergers can result to give more complex and higher generational events.

Hierarchical mergers might be detected by gravitational waves, however, require more sensitive instruments than what is currently available. Through projects such as LISA, the strain sensitivity may be enough to allow for variations in the gravitational waveform. For instance, a binary of binaries event may cause Kozai-Lidov oscillations which increases eccentricity (deviation of an orbit from circularity) and thus cause distinguishable changes in the gravitational waveform [19]. In the case of a dynamic event, a property known as the effective spin of the resultant might have a greater value than usual. The effective spin is a quantity which is related to the rotation of the resultant mass. The resultant mass is another quantity which might be a factor of differentiation.

2.5.2 Stellar black hole Mass-Gap

There exists a mass-gap in stellar core-collapse black hole formation between 52 and 150 solar masses [13]. This theory predicts that a stellar core-collapse black hole cannot be produced in that range. Therefore, the present knowledge in this field restricts the only

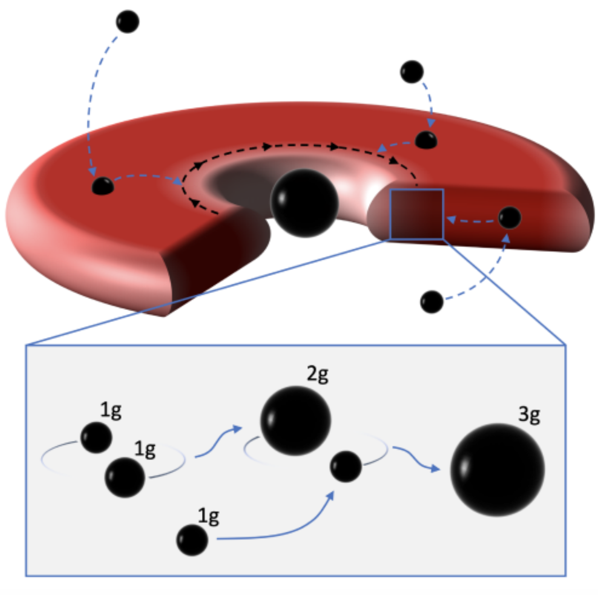

FIG. 2: An illustration of an AGN Disk. A particular region of the AGN Disk is zoomed-in to show the evolution of the black holes into higher generations in a hierarchical dynamical system through the merger process. [4].

other explanation of a black hole in this range to be a resultant of a hierarchical black hole merger. It is this property of stellar core-collapse black hole formation that will be used in this investigation as a means to comment on the possibility of GW170817A to be of hierarchical origins; that is, if the primary and or secondary masses in the system where in the mass-gap range.

2.6 Previous Studies

2.6.1 "Detecting Gravitational Waves With Disparate Detector Responses: Two New Binary Black Hole Mergers." - Zackay et. al

Through the public data release program, a group of researchers [2] were able to develop a new method for the detection of compact binary mergers. This method allowed for the detection of gravitational waves where a clear signal is only produced in one detector while other detectors measure marginal signals. This method is essential considering the fact that the current operating detectors have different sensitivities and is also advantageous when sources have unfavourable sky locations and or orientations. Through their method, two more candidate events were introduced, the most prominent of which was GW170817A.

The researchers were able to limit their sample set of triggers (a type of wave-pattern which is extremely unlikely to have been produced by Gaussian random noise due to its loudness) by accounting for the probability of glitches (artificial wave-patterns which are comparatively louder) through a ranking system. This ranking system does not depend on the trigger's signal to noise ratio (SNR) but rather on an empirical measure of the frequency of known glitches which might contaminate the surrounding phase space. The rejection of a trigger is thus dependent on an empirical procedure known as "signal-quality vetos".

The paper further provided some information of interest about the event, namely the GPS Time, the primary and secondary masses, the chirp mass and the effective spin. This investigation is built upon the above (initial) information.

2.6.2 "GW170817A As a Hierarchical Black Hole Merger." - Gayathri et. al

Another research group [4] investigated GW170817A to explore the possibility of the merger having "hierarchical" origins. The paper bases its arguments on such a possibility by exploring the magnitude of the mass and the effective spin of the system through a Bayesian model comparison. The paper identifies the event as highly in favour of the dynamic hierarchical merger classification.

3. FINDING GW170817A

3.1 When did the event occur?

In order to investigate and analyse the proposed event GW170817A, the first step was to actually find the event within the publicly available strain data from GWOSC. However, the only available reference to GW170817A (at this point in the investigation) was from the scientific publication: "GW170817A as a Hierarchical Black Hole Merger." [4] The name of the event itself was the first clue in finding the event considering the fact that the numerical digits on every candidate event and or event name are actually the date of detection. "170817" therefore translates to August 17th, 2017. Also, usually gravitational wave candidates are given the "GWC" distinction and the paper naming it "GW" is not an acknowledgement of the fact that the event is confirmed but speaks to the researchers' confidence in the plausibility of GW170817A to be an actual event.

This therefore limited the search to a time period of 24 hours. However, analysing 24 hours worth of strain data was not practical considering the computational and time restrictions for this investigation. Fortunately, the paper referenced another paper (the original claimed discovery paper of GW170817A) which provided the GPS Time for the event as 1186974184.716. GPS time is a continuous time scale defined by the GPS Control segment on the basis of a set of atomic clocks onboard satellites. This limited the data segment to 4096 seconds because GWOSC datasets are usually available in this size [14]. Therefore, the size of data to analyse for evidence of GW170817A was significantly reduced. The strain segment containing the proposed event is shown in Fig. 3.

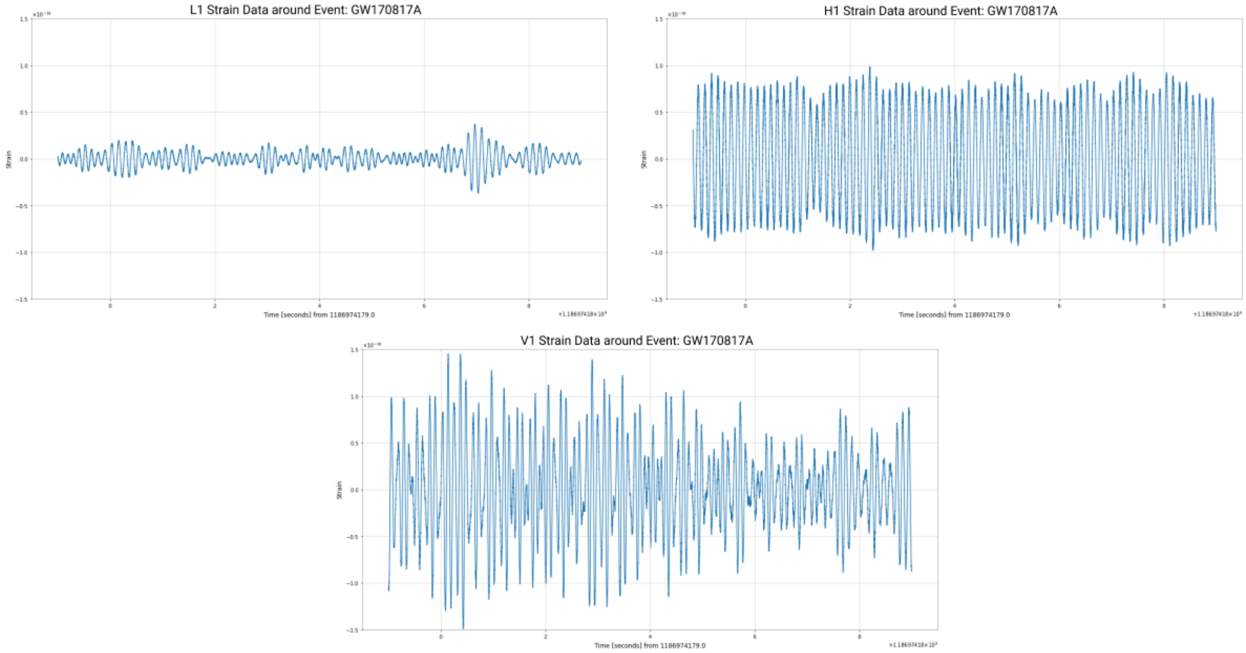

FIG. 3: The strain segment around the event GW170817A from L1, H1, and V1.

3.2 Is there a signal?

After finding and downloading the required datafile containing strain data from GW170817A (as shown in Fig. 3), the analysis stage of the investigation could begin. Preliminary analysis included the detection of gravitational wave signatures through spectral analysis of the chirp.

The strain data around the event was first whitened (re-weighted to account for frequency dependence of detector sensitivity) using the process in the GWOSC tutorial: "Find an Inspiral". This was done (especially in the higher frequencies) in order to increase the visibility of the chirp if it existed. As can be seen in Fig. 4, the proposed event was only observable in the spectrogram from L1 (a growth in the power spectral density around 0 and 200 Hz). These results were also proposed in Zackay et al. and is in fact the main objective of their paper. This nevertheless posed some doubts on whether the signal was a gravitational

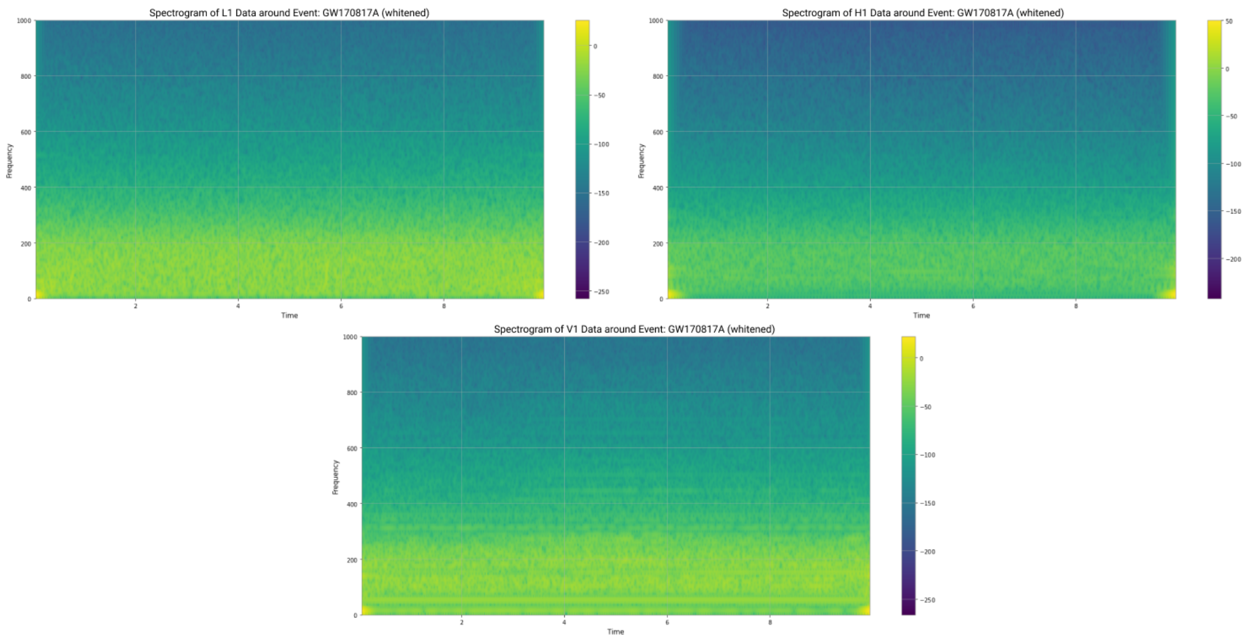

FIG. 4: The whitened spectrogram of the strain data around the event GW170817A from L1, H1, and V1.

wave event, let alone an event of hierarchical origins, because of the fact that only one of three operational detectors actually detected an observable signal. However, a spectrogram in these circumstances only provided a rough idea on whether the signal was really there or not. There are other tests which could more reliably provide insight on whether the signal truly exists in H1 and V1 or not and if not, why not.

Another method used to find the chirp of the event is the "Q-Transform" which is a signal processing technique and a variation on the Discrete Fourier transform (DFT). Unlike in a normal spectrogram where each bin-size is kept constant and given the same weight, in Q-Transform, the weight given to each bin-size can be shifted as necessary in order to focus on particular frequency ranges where the chirp or the signal is most likely to be. This therefore gave a better visual representation of the chirp (if it exists) [14].

Again, the chirp of the event was only visible in the Q-Transform of strain data from

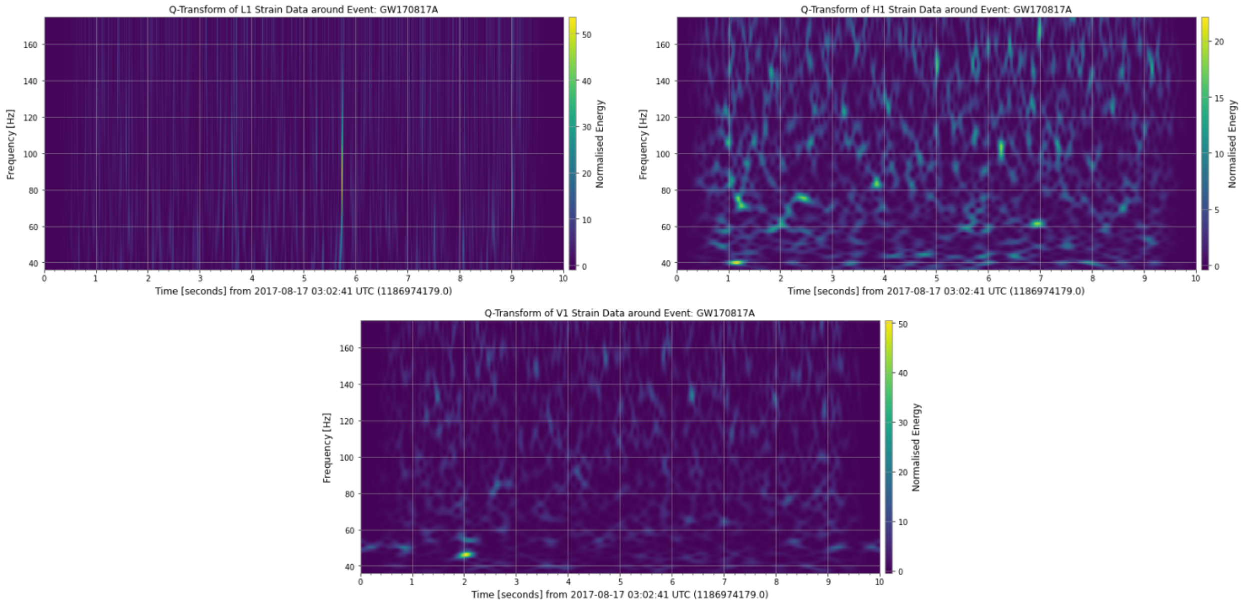

FIG. 5: The Q-Transform of the strain data around the event GW170817A from L1, H1, and V1.

L1 while the other two Q-transforms showed no sign of any signal (Fig. 5) whatsoever. Furthermore, the clarity of a chirp-like pattern in the Q-Transform for L1 was subjective at best. These results pointed towards the possibility of the chirp-like pattern in L1 being the result of an artificial trigger or a glitch. However, in Zackay et al, the authors implemented a ranking system in order to estimate the probability of a glitch to an actual event. Therefore, assuming that this ranking system is in fact reliable, a next step would be to provide evidence that H1 and L1 could not have detected a signal such as GW170817A.

4. TESTING THE CLAIMS MADE IN ZACKAY ET. AL

In Zackay et al, the explanations of why the signal for GW170817A is not evident in H1 and V1 stem from the possibility of differences in sensitivities of the detectors, unfavourable sky locations, and or antenna orientations of the detectors themselves. Therefore, in order to test that these possibilities are in fact the reason behind the absence of a signal in H1

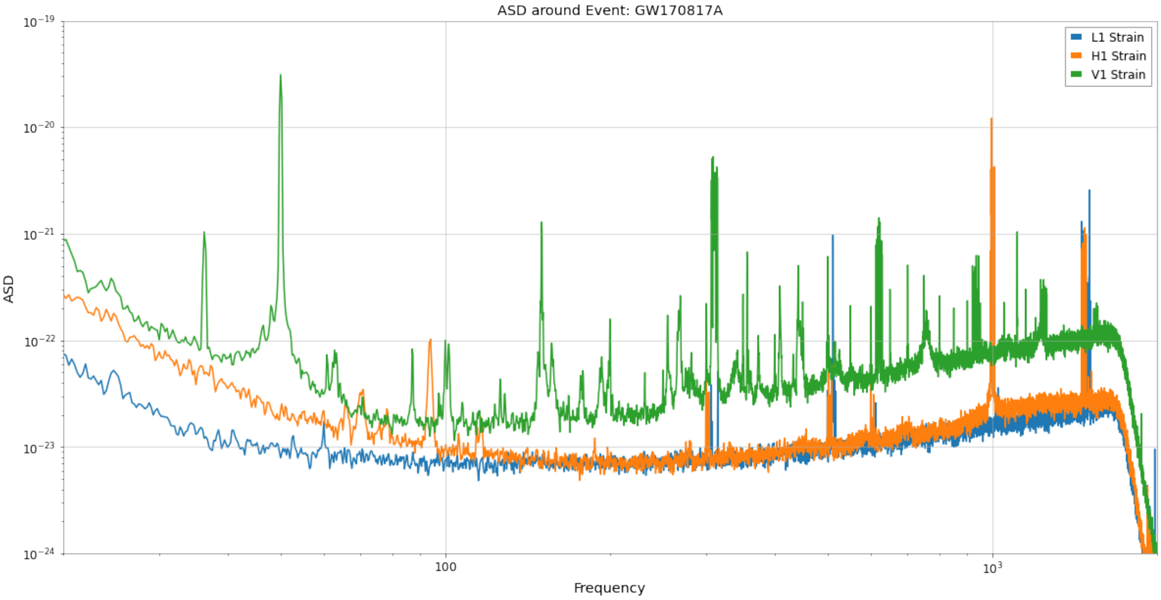

FIG. 6: The amplitude spectral density of L1, H1, and V1 for a time interval of 100 seconds near the proposed event GW170817A.

and V1, a few tests were carried out.

4.1 Detector Sensitivity

In order to obtain sensitivity information of the detectors in that time period, an amplitude spectral density (ASD) of the strain was graphed. The ASD is simply the square-root of the power spectral density (PSD) which provides information about the power present in a signal in a particular frequency range. This was taken for a time interval of 100 seconds near the proposed event GW170817A.

As is evident in Fig. 6, the sensitivity of L1 was in fact much greater than V1 and slighter greater than H1 in the required frequency range (30 Hz to 150 Hz). This is because the ASD curve for H1 and V1 is above that of L1 and is thus less sensitive. This therefore confirmed the first of the three justifications given in Zackay et al. However, this might not be enough evidence for the claims made in Zackay et. al and therefore more testing is required.

4.2 Software Injections to Recover Signal

The recoverability of a signal from noise is another factor which might affect the possibility of an event's detection from a detector. Therefore, conducting a software injection in order to test for the recovery of signal in each detector would provide substantial evidence on whether a detection was possible or not. A software injection is a process wherein a simulated signal waveform is added to a segment of noise.

In order to simulate the signal waveform of GW170817A, PyCBC's 'get-td-waveform' was used. The 'SEOBNRv4-opt' waveform approximant type was used. For the primary and secondary masses, the literature values as given in Zackay et al were used ($m_1 = 56, m_2 = 40$). The paper however did not provide any other parameter of use for this purpose such as the luminosity distance, which could greatly increase the investigation's effectiveness. Therefore, to make the software injection more detailed and reliable, a parameter estimation was conducted for the event. This will be discussed later in Section 5. Through the parameter estimation, a luminosity distance of 2500Mpc was estimated. Using these parameters, the signal from GW170817A could be better emulated.

The test was conducted near the event in order to account for similar noise as the event itself. After embedding the signal into the noise, the recovery stage of the test could begin. Here, the waveform as described above (this time, to recover the signal) was recreated and a matched-filtering algorithm was used in order to find the signal to noise ratio (SNR). The value of the SNR gives a quantitative understanding of the recoverability of the signal.

A matched-filtering algorithm is a process through which similarities between the generated waveform and the embedded signal can be found. The greater the similarities between

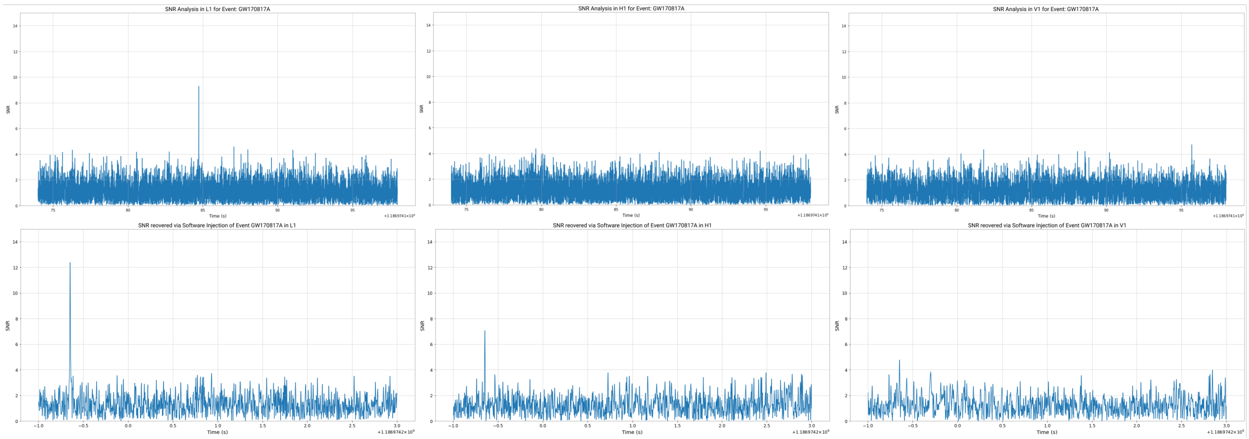

FIG. 7: The upper-row represents the SNR for the actual event with the SNR for L1 to the left, H1 in the middle, and V1 to the right while the lower-row represents the recovered SNR of the software injection in the same order.

the waveforms, the higher the SNR. After redoing this process for each of the three detectors, the same matched filtering algorithm was implemented on the actual strain-data of the event itself. This was done in order to compare the recovered SNR with the actual SNR as a means to qualitatively assert the effectiveness of this method. The results are shown in Fig. 7.

Through the SNRs in Fig. 7, it is most evident that the SNR for L1 was the highest (in the acceptable range) for both the actual event and the recovered signal. This was in accordance with the other evidence provided. In V1, the SNR was quite similar in both actual and recovered signals and fell below the acceptable threshold of an SNR of 8. In H1, there was an evident spike in the SNR for the recovered signal whereas no such spike exists in the actual event. Although the SNR is still below the acceptable range, the spike seen in H1 cannot be dismissed. Therefore, more research may be required here. For instance, the antenna pattern of H1 and V1 might be the reason for there not being a signal in the actual data. This is however beyond the scope of this investigation and hence should be discussed in a future research. Nevertheless, through this test, some evidence was provided on the subject of whether GW170817A was really an event.

5. Parameter Estimation of GW170817A

For a binary merger, there are (in general) 15 parameters that completely define its characteristics. These include their individual masses, their spins, luminosity distance, etc. Most if not all of these parameters have an effect on the gravitational waveform and therefore parameters can be estimated by analysing it.

The parameter estimation of GW170817A shown in Fig. 8 was made possible through Bilby, which is a Python package for gravitational wave analysis. The only prior, which is essentially the known information about the event mentioned as input for the estimation, was the GPS time of the event. The more priors inputted, the less computation required for the result. The sampler used was Bilby's 'Dynesty' which requires relatively less computational time. A sampler runs all possible samples (combinations of the 15 parameter values) and measures the resulting SNR using a matched-filtering algorithm. The number of live-points used was limited to 500 as was the maximum number of steps per sample. This was in order to reduce the computational time by as much as possible while still retaining a level of accuracy.

A few notable parameter estimation details provided through this process include the primary and secondary masses of the black holes, the spin parameters, and the luminosity distance of the proposed event. The last of which was used for the software injection test described above in Section 4.2.

According to Gregory et al [16], for the most accurate results, the sampler of choice should be 'CPNest' with the number of live points and maximum number of steps per sample as

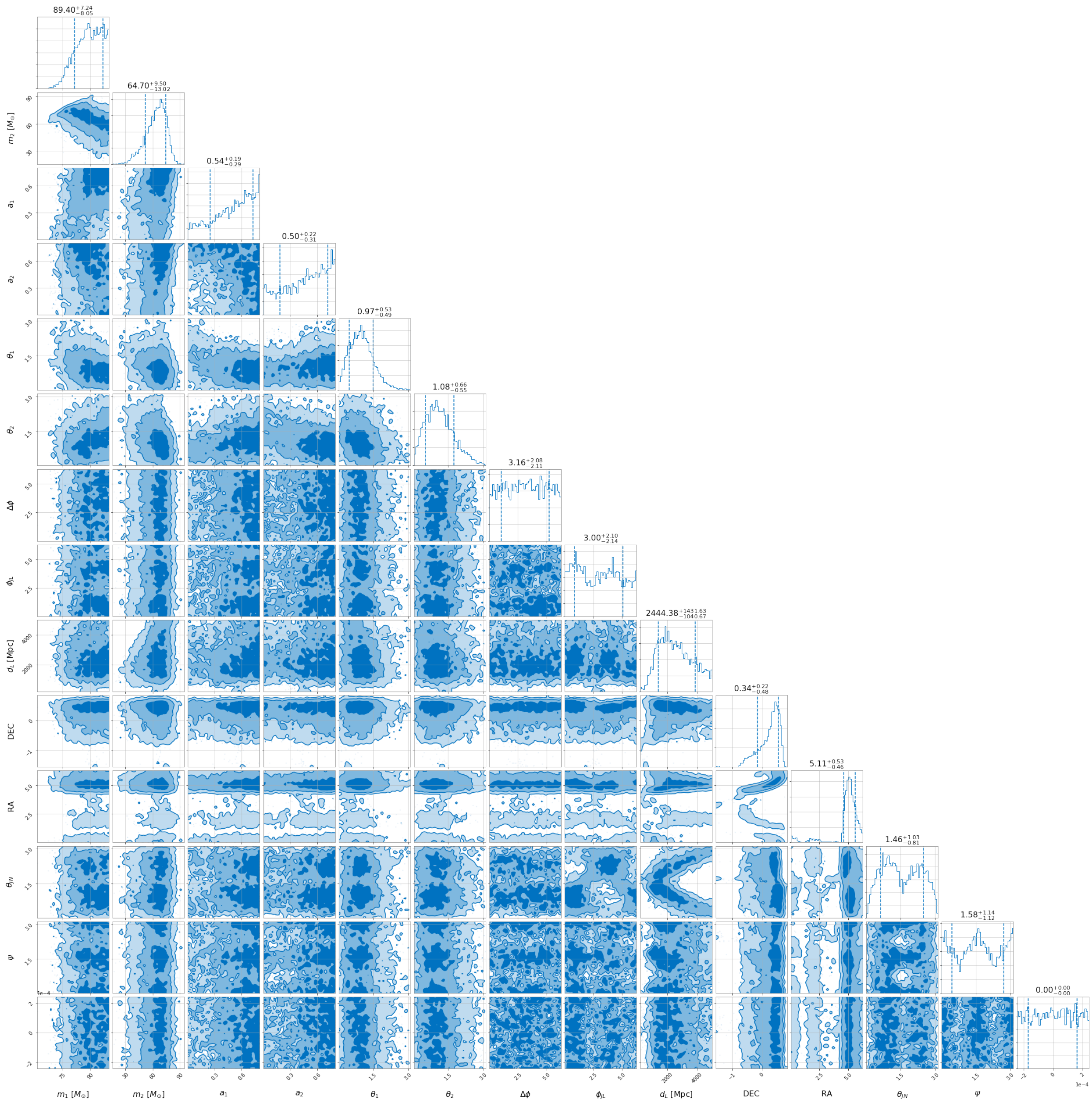

FIG. 8: The results of the parameter estimation of event GW170817A. All 15 parameters which completely define the properties of the merger are shown.

5000. This however would require approximately 60 days worth of computation (Tab. 1) which is not feasible due to the limitations of this investigation [15]. Therefore, the results in Fig. 8 should be treated as rough estimates only. 'VItamin' on the other hand would take considerably less time compared to other samplers, however, is not likely to provide a

sampler	run time (seconds) min	max	median	ratio $\frac{\tau_{\text{VItamin}}}{\tau_X}$
Dynesty[a]	602	1538	774[b]	2.6×10^{-6}
Emcee	2005	11927	4351	4.6×10^{-7}
Ptemcee	3354	12771	4982	4.0×10^{-7}
Cpnest	1431	5405	2287	8.8×10^{-7}
`VItamin`[c]	$\mathbf{2 \times 10^{-3}}$			1

TAB. 1: Run-times required depending on the sampler chosen. [15]

good estimate due to the lesser number of samples it coniders.

As a result of the parameter estimation, the primary and secondary masses were '$89.4M_\odot$ ' and '$64.7M_\odot$ ' respectively. Although these values were quite different from those reported in Zackay et al (which were '$56.0M_\odot$ ' and '$40.0M_\odot$ ' respectively) they nevertheless favoured the hierarchical origin model. This is because the reported mass of the primary is much greater than the stellar mass gap. This cannot be conclusively stated however due to the uncertainties regarding this parameter estimation. Another factor which might be a cause for uncertainty in both estimations is to do with a process known as accretion of surrounding matter. Through this process, the two black holes may have gained additional mass and thus crossed the stellar mass gap rather than through a hierarchical means.

While this therefore increases the probability of the proposed event having hierarchical origins, the type of hierarchical merger and its generation are still speculative at best. However, according to Gayathri et al, the merger has a greater probability of following the hierarchical dynamical model.

6. CONCLUSIONS

Through the investigation and analysis of GW170817A, the proposed event's plausibility was tested via spectral analysis and the use of Q-Transforms. Considering its observation to be limited to a single detector (in this case: L1), exploration of various factors which might limit detections in certain detectors and under what circumstances can such discretion be allowed was conducted. All these tests were conducted in order to draw parallels if any, to the original research on this event as was conducted by Zackay et al and was a means to build upon their original investigation. It was therefore an effort to test that their assumptions were in fact rightly made or were subject to scrutiny. Furthermore, exploration of the proposed event's parameters was conducted as a means to gain insight into the properties of the merger and the respective black holes which caused it. The hierarchical origin probability was also considered throughout the investigation process in order to comment on the credibility of the findings made in Gayathri et al.

There were however experimental and investigational limitations which dictated the level of in-depth analysis possible. Two major causes of this include time and computational power at disposal. This therefore leaves room for improvement and further investigation. For instance, the reliability of Zackay et al's ranking system might be tested in order to understand the factors which eliminate the possibility or more practically reduce the probability of GW170817A being simply a glitch. The ideal guidelines for an accurate and full parameter estimation can be followed to get a better insight about the parameters of the event. A comparison between GW17017A and GW170729 could be made in order to understand large-mass object mergers. Other waveform approximants can be explored in order to understand which template gives the greatest SNR. Effective spin is a complex parameter associated with hierarchical mergers which can be explored in context to this event and or other similar events such as GW170729. It would also be meaningful to consider other methods of filtering as a means to uncover the signal in H1 or V1 if it exists.

7. SUMMARY

In this investigation the background of gravitational waves and the apparatus required to detect them, along with subject specific concepts such as hierarchical mergers, stellar black hole mass-gap, etc. was introduced and discussed at some length. GW170817A was found in real LIGO data using information provided from previous studies. The identified candidate event was then visualised using spectrograms and Q-Transforms. Then, the claims made in Zackay et. al were tested through the amplitude spectral density of the detectors and software injections. Finally, a parameter estimation of GW170817A was conducted in order to estimate the merger characteristics.

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