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Is GW170817A Real?
Investigating the Detection Confidence of GW170817A

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Since the first confident gravitational-wave detection, scientists have confirmed the astrophysical origin of signals in their data primarily based on the signals' existence in two or more observatories at the same time, barring intersite travel time of gravitational waves. GW170817A has been proposed to be a high-mass binary black hole merger, but the confidence of this candidate is a bit of a mystery because its signal has been observed in only one observatory. The confirmation of its astrophysical origin is pertinent to the fundamental theory regarding stellar-mass black holes, for the proposed black holes in GW170817A have masses that lie on the theoretical stellar-mass black hole cutoff. Therefore, this project aimed to investigate the detection confidence of GW170817A. This project replicates analysis done by the discoverers of GW170817A by performing time domain cross-correlation and optimal matched filter to verify their results. Results were presented and analyzed for their significance to the GW170817A proposal. Only a signal with SNR=6.32886 was found in the Livingston detector, and none were found in Hanford or Virgo. Two loud spikes in SNR distinct from GW170817A were also found in Livingston data and elaborated upon. No conclusions were made in this project.

I. INTRODUCTION

Gravitational waves were theorized by Albert Einstein in the early 20^{th} century, but scientists did not detect gravitational waves with confidence until 2015, a full century after the proposal of their existence [1]. Since the very first, it has been the convention for a confident gravitational-wave detection to require clear signals from at least two observatories. However, GW170817A has been proposed to be a detection with only one observatory reporting a convincing signal [2]. GW170817A was proposed to be caused by a binary black hole (BBH) inspiral with high masses. The authors' reliance on data from a single detector weakens the confidence of their detection. The goal of this project is to use data from the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States and Virgo Interferometer (Virgo) in Italy to investigate the detection confidence of GW170817A. The results are highly relevant to future gravitational wave discoveries and to whether clear signals from two gravitational wave observatories will be necessary.

II. BACKGROUND

A. Gravitational Waves

Mankind has been studying the cosmos using predominantly electromagnetic (EM) waves, which are oscillations in the electric and magnetic fields. Neutrino studies have also been available as an alternative way of studying the universe since 1987, when neutrino emission from the supernova SN1987A was detected [3, 4]. Einstein predicted the existence of another type of waves that were oscillations in the spacetime continuum, distinct from EM waves– gravitational waves [5]. While EM waves are time-varying oscillations of the EM field, gravitational waves are the time-varying oscillations of the gravitational field.

Gravitational waves are transverse waves that travel at the speed of light. They are quadrupole distortions of spacetime with two polarization directions, plus polarization "+" and cross polarization "×". The amplitude of gravitational waves are remarkably small. Consequently, their existence was not verified by observational evidence for nearly a century, until 2015, when gravitational waves were finally observed by the LIGO-Virgo Scientific Collaboration [1]. The discovery of gravitational waves opened a window for astronomers to study the universe in a way they could not before.

Gravitational waves are defined as perturbations in space-time produced by the displacement of mass that propagate out as waves. Currently, hypothesized sources of gravitational waves include: coalescence of binary systems, stochastic background, continuous wave (CW) sources, and bursts from cataclysmic events.

- Coalescence of binary systems describes merging binary systems of extremely dense objects, such as black holes and neutron stars. These events produce short bursts of gravitational wave emission. As compact objects orbit in binaries, gravitational waves carry energy away from the system and cause the orbit to descend, eventually resulting in collision and merger of the two compact objects. Gravitational waves at twice the frequency of the binary's orbit will be produced. As the objects approach each other and accelerate, gravitational waves with increasing frequency and amplitude will be produced. After the binaries collide, emission of

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gravitational waves will cease. To date, this is the only source of gravitational waves that has been detected.

- Stochastic background describes the remnant disturbances in the gravitational field resulting from the creation of the universe, just as the cosmic microwave background is remnant EM radiation from the universe's creation. A stochastic gravitational wave background has not yet been detected.

- CW sources predict objects that produce long-term continuous gravitational waves, such as spinning asymmetric neutron stars and oscillating neutron stars. Similar to the cosmic gravitational wave background, emission from CW sources have not been discovered yet.

- Bursts from cataclysmic events, such as supernovae and other events not yet detected, are also hypothesized to generate gravitational waves. These bursts require a changing quadrupole in order for gravitational waves to be produced. Spherically symmetric bursts will not produce gravitational waves.

B. GW170817A

GW170817A is a "mystery" in the sense that it is not yet conclusive whether the candidate is a real gravitational wave detection.

After the LIGO-Virgo Scientific Collaboration confirmed the detection GW150914 in their seventh science run (S7), S7 was renamed O1, which stands for the first observing run, and all subsequent observation runs were to be named observing runs [6]. LIGO has been making its data available to the general public on the Gravitational Wave Open Science Center (GWOSC) since S5 [7]. With the recent public data release of O1 and O2, it became feasible for external researchers to analyze the LIGO-Virgo data in independent gravitational wave search efforts.

The conventional process of confirming a gravitational wave detection requires the signal to be visible in at least two detectors so to confirm that the time lag between the signals corroborate with the speed of light and minimize the possibility of a false alarm. However, a recent study by Zackay et al.[2] used a novel technique to search for gravitational wave signals in single detectors to identify, among others, a strong signal from O2 in the Livingston detector (L1). They named this event GW170817A, and it was proposed to be a BBH merger with an extremely high inferred source frame total mass of $\sim 98 M_\odot$ [2]. It is worth noting that GW170817A is not to be confused with GW170817, the famous neutron star kilonova collision that occurred on the same date [6]. Zackay et al. estimated the masses of the BBHs to be $56^{+16}_{-10} M_\odot$ and $40^{+10}_{-11} M_\odot$ [2]. It has also been suggested by other past studies that stellar mass black holes have a theoretical mass cutoff at $\sim$40–50$M_\odot$ [8, 9]. The masses of the GW170817A BBHs lie in this range and the product black hole in GW170817A has mass greater than the theoretical mass cutoff. A better understanding of GW170817A can help put a constraint on the existence and the exact location of such a mass cutoff. In a more recent study, Gayathri et al. [10] assumed GW170817A to be a gravitational-wave signal and found the event is better explained by a hierarchical black hole merger, which describes the process of multiple black holes with smaller masses merging consecutively, than a simple BBH inspiral. With even the nature of GW170817A still under debate, confirmation of the event's astrophysical origin becomes even more important.

The philosophy behind the technique presented by Zackay et al. is that since L1 is more sensitive than H1 in O1 and O2, L1 might be able to detect signals fainter than H1 could. The authors first vetted L1 data from O2 and identified single-detector triggers, which are bursts so loud that it is extremely unlikely for them to be produced by Gaussian random noise, even over the entire length of the O2 run, though glitches can produce such loud triggers. The authors then examined counterparts of these triggers in H1 and performed Bayesian analysis to determine the false alarm rate and the probability that the triggers have astrophysical causes, rather than noise. They claimed that GW170817A is an astrophysical event with 86% confidence [2].

C. Glitches

One possible explanation of the gravitational wave candidate GW170817A is a loud glitch in the L1 detector. In this work, the term "glitches" will be defined as the non-Gaussian noise transients produced by the instruments or the interactions between the instruments and their environments, the origin of which is not completely understood [11, 12]. This definition was also used by Zackay et al. [2]. A loud glitch may sometimes appear as a gravitational-wave signal. Cross checking with another independent interferometer can help estimate the probability of coincident glitches, and time shift is a common technique to achieve this goal, the details of which are detailed in [13, 14]. Thus, the presence of signals in two or more independent observatories can greatly reduce the probability of misidentifying a glitch as a gravitational wave. Conversely, GW170817A's lack of clear signal in more than one detector leaves wide open the explanation that GW170817A is the result of a loud L1 glitch.

D. Time Domain Cross-correlation and Optimal Matched Filtering

This project will use signal processing methods time domain cross-correlation and optimal matched filtering

TABLE I. Information on data files downloaded from GWOSC and the contained gravitational wave event and candidate.

GPSstart[a]	File Duration (s)	Contained Event	Event GPS time	Mass 1 ($M_\odot$)	Mass 2($M_\odot$)	χ_{eff}
1186971648	4096	GW170817A	1186974184.716	56^{+16}_{-10}	40^{+10}_{-11}	0.5 ± 0.2
1187057664	4096	GW170818	1187058327.1	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.2}_{-5.2}$	$-0.09^{+0.18}_{-0.21}$

[a] The initial GPS time of file.

to analyze strain data downloaded from LIGO.

Time domain cross-correlation measures the similarity between two time series as a function of time lag. It usually takes in a known, shorter signal or template and an unknown, longer time series. It returns a correlation function between the two inputs over a range of time intervals at which the input time series are shifted. The cross-correlation function $X(d)$ of two time series $f(t)$ and $g(t)$, both with random noise and signal, can be expressed as:

$$X(d) = \int_0^T f(t)g(t+d)\,dt,$$

where d is the time lag between $f(t)$ and $g(t)$. Time domain cross-correlation is useful in searching for a short pattern within a long signal, such as an expected waveform template hidden inside strain data with Gaussian noise.

Optimal matched filtering, like time domain cross-correlation, measures the similarity between two time series, usually trying to detect the presence of a template inside an unknown signal. However, the difference between optimal matched filtering and time domain cross-correlation is that optimal matched filtering performs error analysis in the frequency domain and gives more weight to frequency bins with lower noise power, thus optimizing the signal-to-noise ratio (SNR). This can be a more effective method to search for gravitational-wave signals in strain data because some frequency bins in LIGO data have more noise than others [7]. Nonetheless, both cross-correlation and optimal matched filtering will be used in this project for exploration and learning purposes.

E. Project Goals

One issue with the claim that GW170817A is a high-mass BBH merger is that GW170817A has only been detected with confidence in one detector. It is reported to have only a faint counterpart signal in the Hanford detector (H1) [2]. Traditionally, the LIGO Scientific Collaboration utilizes data from at least two detectors to confirm gravitational wave detections. The fact that GW170817A can only be confidently found in a single detector reduces the confidence of the event's astrophysical origin. This project aimed to investigate the likelihood that gravitational wave candidate GW170817A is an astrophysical event and present evidence for and against the candidate discovered in the investigation. The results will be compared to Zackay et al. [2].

III. APPARATUS AND METHODS

Zackay et al. based their study of the astrophysical origin of GW170817A on primarily Bayesian analysis [2]. This project explored the astrophysical confidence of GW170817A by applying LIGO's conventional method of analysis for the existence of binary inspiral signal in strain data, which was also performed by Zackay et al., but the results were not explained in detail [2]. This project hoped to replicate parts of their analysis and present results that either match or do not match theirs. O2 strain data near the proposed GPS time of GW170817A (hereafter "the data") from L1, H1, and V1 (hereafter "the three detectors") were downloaded from the GWOSC open database (`https://www.gw-openscience.org/data/`). Time domain cross-correlation was performed between a template waveform (generated by the Python module `pycbc`'s waveform-generation function [15]) and L1, H1, and V1 data passed by a Butterworth filter near the proposed GPS time of GW170817A, respectively. Optimal matched filter of the template waveform was also performed in data near the proposed GPS time of GW170817A in L1, H1, and V1 to investigate the existence of a binary coalescence signal in the strain data.

A. Python Script

The Python script which performed the aforementioned analysis was downloaded from the third and fourth Gravitational Wave Open Data Workshop [16, 17], and combined and modified to fit the purpose of this study. The script is uploaded to a public server, ready to be downloaded by anyone for replication or verification of this project. Please contact the author for questions regarding the script.

The functionality of the modified code was tested on a confident gravitational detection close to GW170817A in time and black hole masses. Two candidates, GW170817 [6] and GW170818 [18] were considered. Although GW170817 was closer to GW170817A in time, GW170818 had much more comparable black hole masses, which played a larger role in waveform template generation. Therefore, GW170818 was chosen to test the functionality of the Python script used in analysis.

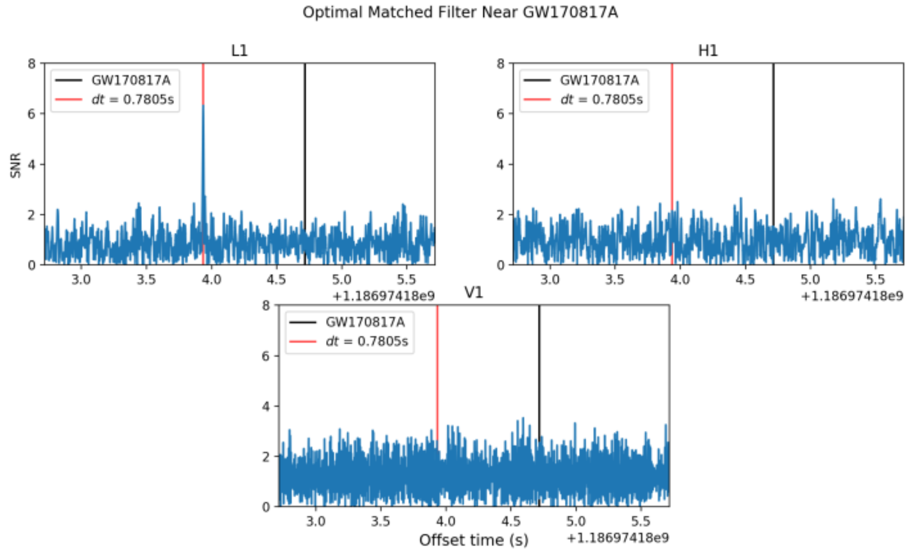

FIG. 1. Optimal matched filter results zoomed in around the time of GW170817A as reported by Zackay et al. [2]. Top left shows the results in L1, where dt is the absolute value of time interval from observed spike to the reported time of GW170817A. Top right shows the results in H1, where the red vertical line marks the location of the spike observed in L1. Bottom shows the results in V1, where the red vertical line marks the location of the spike observed in L1.

The waveform template, or expected waveform, for GW170717A used in this project was created with `pycbc`. The approximant used was `IMRPhenomD`, and BBH masses and spin used are listed in Table I. The results for this waveform is graphed in Figure 2.

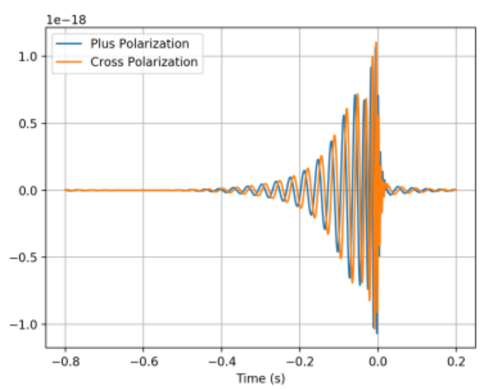

FIG. 2. The expected waveform, or waveform template, generated for GW170817A. Approximant used was IMRPhenomD, and BBH parameters used are listed in Table I.

B. Data Acquisition

All gravitational-wave strain data was downloaded from the online data portal of GWOSC [7]. Table 1 lists the details of data files downloaded for the event and candidate used in this project.

Strain data down-sampled to 4 KHz was used for development of Python script, while data sampled at 16 KHz was used in analysis and to produce final figures in this paper.

IV. RESULTS

After applying a Butterworth filter to the L1 strain data, a faint signal can be barely distinguished from noise in the band-passed strain data. Optimal matched filter with masses reported by an approximant model identical to Zackay et al. [2] was applied to strain data from L1, H1, and V1, as shown in Figure 1. Optimal matched filter in L1 ascertains the presence of a faint signal 0.7805 seconds before the reported time, with $SNR = 6.32886$. However, no clear signal could be identified in H1 or V1 around the reported time or time of the signal in L1.

Far away from the reported time of GW170817A [2], two significant spikes 861.62 seconds and 847.35 seconds before were observed, as shown in Figure 3. The spike with higher peak will be referred to as "signal 1," and the one with lower peak "signal 2." For signal 1, optimal matched filtering yielded SNR=233. Several small peaks

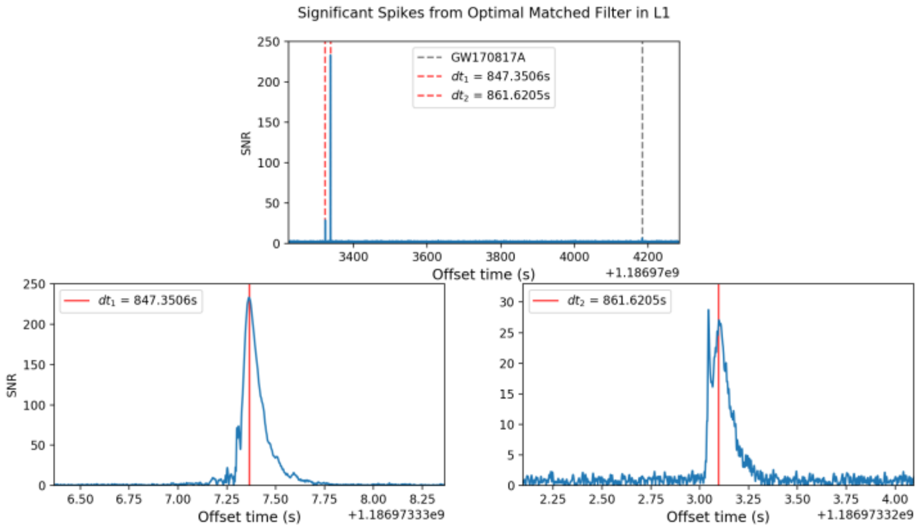

FIG. 3. Top is the optimal matched filter results of L1 data zoomed in around the three SNR spikes in question. Bottom left is the results zoomed in around signal 1. Bottom right is the results zoomed in around signal 2. dt is the absolute value of time interval from each spike to the reported time of GW170817A, where dt_1 refers to that for signal 1 and dt_2 for signal 2.

in SNR right before the main peak can be observed, and the main peak tails off in a fashion more gradual than the onset. For signal 2, optimal matched filter yielded SNR=28.8. The onset of signal 2 is abrupt. A secondary peak with SNR=27.0 can be observed shortly after the tallest peak, which then diminishes more gradually than the onset, similar to signal 1.

V. ANALYSIS

In the results from optimal matched filters, only one spike in SNR could be observed near the reported time in L1, and H1 and V1 were featureless around the reported time. This is not evidence in support of GW170817A, for it inclines towards the possibility that GW170817A was a misidentified glitch.

Moreover, two high SNR spikes far from the reported time were also present in L1 exclusively. These two spikes have shapes distinct from the spike near the reported time, which could imply they are loud glitches and not identical in nature to the solitary spike, thus being a slightly supportive evidence for GW170817A. Interestingly, these two spikes were not mentioned in Zackay et al. [2].

Zackay et al. reported SNR^2=98.5 for GW170817A [2], or SNR≈9.9. This does not match the SNR observed in this project (≈ 6.3), but the error could be contributed to unidentical template parameters, for Zackay et al. did not exhaustively specify all parameters used in template generation. These results do not increase the detection confidence of GW170817A as Zackay et al. reported [2].

The difference in time between the L1 spike and reported time is greater than the intersite travel time window (used by LIGO since the GW150914 [1]) by 420.3%. Due to the potential deviations in correlation analysis from Zackay et al., it is inconclusive whether the observed spike is the reported GW170817A.

VI. FUTURE EFFORTS

This project was carried out during the regular school year with a strict deadline. Due to this nature, not every planned analysis was performed due to the time constraint. Analysis ideas for future investigations on GW170817A include:

- Analyze if the SNR=6.32886 bump 0.7805 seconds before the reported time of GW170817A is, in fact, the same signal as the one in Zackay et al. [2]

- Vary approximant types in waveform generation and study SNR from optimal matched filer as a function of approximant type.

- Study the effect of changing black hole masses on how well the waveform fits strain data.

- Try cross-correlation between strain data from the three detectors to investigate if there is a signal present in more than one detector.

VII. CONCLUSIONS

GW170817A is a proposed BBH collision only detected in one gravitational wave detector, which leaves open the possibility of a detector glitch in disguise. This project performed correlation analysis between an expected waveform and data from the three LIGO-Virgo Scientific collaboration observatories. A faint signal was found in L1 near the reported time of GW170817A, but no signal was observed in H1 or V1. Two strong signals were also identified in exclusively L1 far from the reported time of GW170817A, which were not reported in Zackay et al. [2]. The absence of template matches in H1 and V1 near the expected time of GW170817A does not support its astrophysical nature, but the difference in SNR shape of two strong glitch-like signals in L1 argue slightly in the proposed detection's favor. More neutral evidence was provided in the Analysis section. So far in this project, it is inconclusive whether GW170817A is a gravitational wave detection. The scientific value of future studies of GW170817A remains, for the candidate was proposed to have individual black hole masses that lie on the theoretical stellar-mass black hole cutoff [2], and confirmation of the astrophysical origin of GW170817A would impact the scientific community's theoretical basis for stellar-mass black holes.

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